Trucking Fleet Concept of Operations for Automated Driving System-equipped Commercial Motor Vehicles

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FOREWORD

Commercial motor vehicles (CMVs) equipped with Automated Driving Systems (ADS) offer the potential to improve safety in long-haul trucking by eliminating human limitations such as fatigue, impairment, and distracted driving behavior. By decoupling some freight operations from the limitations of driver hours of service (HOS), ADS can improve delivery times, enhance value during driver HOS, and increase the utilization of capital equipment. Additional benefits may be realized that impact the management of limited resources, such as the charging and refueling of electric and green-fuel heavy vehicles, as well as flexibility to schedule operations to reduce congestion and energy demands.

This project was funded by a U.S. Department of Transportation Automated Driving System Demonstration Grant from 2020-2024 and managed by the Federal Motor Carrier Safety Administration. The purpose of this project was to provide the trucking industry with clear guidelines on how to safely implement, integrate, and benefit from ADS-equipped CMVs among mixed fleets and across operating domains. The project included technical information collection, industry outreach, and ADS-CMV operational demonstration, as well as data collection and sharing. This report is intended to serve as a comprehensive concept of operations describing ADS characteristics from the viewpoint of trucking fleets, covering eight primary topics:

- Fleet Specifications
- ADS Installation and Maintenance
- ADS Inspection Procedures
- Test Driver State Monitoring
- Motor Carrier Guide to Insuring ADS-equipped Trucks
- ADS Safety Metrics/Variables
- ADS Road Assessment System
- Data Transfer and Cybersecurity Best Practices

NOTICE

This project was performed by the Virginia Tech Transportation Institute and organized by the U.S. Department of Transportation and Federal Motor Carrier Safety Administration. The Virginia Tech Transportation Institute and the U. S. Government do not endorse products or manufacturers named herein. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of this report.

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ABSTRACT

The primary goals of the CONOPS project were to: i) collect information and practices on how to safely integrate ADS-equipped CMVs into the U.S. road transportation system; ii) provide the USDOT with data; iii) demonstrate how to integrate and deploy ADS-equipped trucks in a productive and cooperative way into the existing road freight ecosystem; and iv) collaborate with a broad and diverse group that includes government entities, university and research institutes, trucking associations, and private partners. This research found that the path forward to maintain public acceptance and achieve goals of ADS-equipped CMV operational cost-effectiveness, increased freight productivity, and reduction of crashes is through human operational assurance of vehicle, automation, freight, and public safety through specification, maintenance, inspections, monitoring, insurance, metrics, roadway assessment, and secure communications, as well as continuous lifecycle performance checks.

SI* (MODERN METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume (volumes greater than 1,000L shall be shown in m^3)		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		Mass		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		Temperature (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		Illumination		
fc	foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		Length		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		Area		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		Volume		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		Mass		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		Temperature (exact degrees)		
°C	Celsius	1.8c+32	Fahrenheit	°F
		Illumination		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-lamberts	fl
		Force and Pressure or Stress		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Acronym	Definition
AADT	annual average daily traffic
ABS	anti-lock braking system
AC	air conditioning
ACL	access control list
ACU	automation control unit
ADAS	advanced driver assistance systems
ADS	Automated Driving System
AEB	automatic emergency braking
AI	artificial intelligence
AID	alcohol interlock device
AIS	Aftermarket Installation System
AOZ	autonomous operating zone
API	application programming interface
ASE	Automotive Service Excellence
ATA	American Trucking Associations
AV	automated vehicle
AVSC	Automated Vehicle Safety Consortium
BAC	blood alcohol concentration
BMS	battery management system
BPM	beats per minute
CAN	Controller Area Network
CC0	Creative Commons 0
CCMTA	Canadian Council of Motor Transport Administrators
CDL	commercial driver’s license

Acronym	**Definition**
CFR	Code of Federal Regulations
CMV	commercial motor vehicle
CONOPS	Concept of Operations
CVSA	Commercial Vehicle Safety Alliance
DADSS	driver alcohol detection system for safety
DAS	data acquisition system
DBW	drive by wire
DDT	dynamic driving task
DGPS	differential Global Positioning System
DOI	digital object identifier
DSM	driver state monitoring
DPF	Diesel Particle Filter
DPS	Department of Public Safety (Texas)
DSRC	Dedicated Short Range Communication
DUI	driving under the influence
DVIR	Driver Vehicle Inspection Report
DWI	driving while intoxicated
EAP	emergency action plan
ECU	electronic control unit
ECG	electrocardiogram
EDA	electrodermal activity
EEG	electroencephalogram
EU	European Union
EV	electric vehicle
EVI	Electronic Vehicle Identification
FCC	Federal Communications Commission

Acronym	**Definition**
FER	facial emotion recognition
FMCSA	Federal Motor Carrier Safety Administration
FMCSR	Federal Motor Carrier Safety Regulations
FMVSS	Federal Motor Vehicle Safety Standards
FO	freight operator
fps	frames per second
FY	fiscal year
GIS	geographic information system
GMSL	Gigabit Multimedia Serial Link
GNSS	Global Navigation Satellite System
HMI	human-machine interface
HOS	hours of service
HPMS	Highway Performance Monitoring System
HR	heart rate
HRA	human reliability analysis
HRV	heart rate variability
IDS/IPS	intrusion detection and prevention system
IEP	intermodal equipment provider
IMU	inertial measurement unit
IO	input/output
IoT	internet of things
IR	infrared
IRI	Internation Roughness Index
ITB	integrated tug/barge
ITS	Intelligent Transportation System
LED	light-emitting diode

Acronym	**Definition**
lidar	light detection and ranging
LTCCS	Large Truck Crash Causation Study
MARAD	Maritime Administration
MCMIS	Motor Carrier Management Information System
MMIP	Mandatory Mechanical Inspection Program
MMW	millimeter wave
MRC	minimal risk condition
MUTCD	Manual on Uniform Traffic Control Devices
NAS	North American Standard
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
NSC	National Safety Code (Canada)
OBD	On-Board Diagnostics
ODD	operational design domain
OEM	original equipment manufacturer
OOS	out-of-service
ORD	Observer Rating of Drowsiness
PAR	Police Accident Report
PERCLOS	percent eye closure
PIC	person in charge
PIF	performance influencing factor
PII	personally identifiable information
PM	preventative maintenance
PoLP	principle of least privilege
PPG	photoplethysmography
PRC	percent road centre

Acronym	**Definition**
RBAC	role-based access control
RFID	radio frequency identification
RID	Roadway Information Database
RODS	record of duty status
RTK	real-time kinematic
SHRP 2	Second Strategic Highway Research Program
SMS	Safety Measurement System
SORC	State Operated Railroad Corporation
SpO2	saturation of peripheral oxygen
SVD	service vehicle disconnect
TCP	Transmission Control Protocol
TMC	Technology Maintenance Council
TPMS	tire pressure monitoring system
TSB	Technical Service Bulletin
UDP	User Datagram Protocol
UEI	unique electronic identification
USDOT	U.S. Department of Transportation
V2I	vehicle-to-infrastructure
V2P	vehicle-to-pedestrian
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VDC	volts direct current
VPN	virtual private network
VTTI	Virginia Tech Transportation Institute
ZMTP	ZeroMQ Message Transport Protocol

EXECUTIVE SUMMARY

Automated Driving Systems (ADS) are set to revolutionize the transportation system. In this project, we developed and documented a concept of operations (CONOPS) that informs stakeholders, decision-makers, and all interested personnel in the trucking industry on the benefits of ADS and the best practices for implementing this technology into fleet operations. The project was completed with a focus on three crucial aspects of implementation. The first focus was to demonstrate the applications of ADS technology in day-to-day truck-driving tasks to fleet personnel and the general public. The idea behind this was to provide personnel with a first-hand experience with ADS and to showcase how this technology can improve truck driving safety, support drivers, reduce human errors, and optimize fleet operations. The research team also used this opportunity to collect information on personnel expectations of ADS technology and what applications of the technology would be attractive to their operations. The second focus of the project was to document how ADS technology can be customized to support fleet operations under specific trucking use cases such as port queuing conditions, over-the-road trips, and fleet integration, and to collect data that inform policymakers on the readiness of existing infrastructure to support the implementation of ADS technology on U.S. roadways. The third focus of the project was to pool information on the existing practices of various stakeholders involved in the ADS ecosystem and use this information to provide fleets with guidelines on how to manage implementation and policy issues related to ADS technology. A high-level summary of the insights from the research activities based on these focus areas is provided here.

Public Demonstrations of ADS Truck Technology

The research team engaged personnel in the trucking industry at three major public events, the Intelligent Transportation Systems (ITS) America annual meeting, the Technology Maintenance Council (TMC) annual meeting, and the Commercial Vehicle Safety Alliance (CVSA) annual conference, of which many of the attendees were from the trucking industry. The first public outreach at the ITS America annual meeting, held in December 2021, featured exhibition booths, presentations, technical sessions, one-on-one question and answer sessions, and real-time displays of an ADS-equipped truck deployed in this project actively operating on U.S. roadways. Attendees were given an interactive behind-the-scenes look at ADS-equipped truck cross-country trip operations as well as the port queuing deployment use case to showcase the safe deployment of ADS technologies under real-world fleet operating conditions. Readers can go to section 2.1 of this document for more details on this outreach. Other resources can be found in the research brief summarizing activities at the meeting (https://www.vtti.vt.edu/PDFs/conops/ITS-Roadshow.pdf).

The TMC annual meeting, held in March 2022, featured similar research activities as the TMC meeting described above. However, the research team took a step further to provide on-site demonstrations of an ADS-equipped truck operating under simulated safety-critical roadway conditions such as work zone driving. The team provided attendees with the opportunity to ride along in an ADS-equipped truck to have a first-hand experience of the technology. This not only allowed the team to showcase the importance of ADS technology to fleet operations but also collect information directly from stakeholders in the trucking industry (fleet, suppliers, government personnel, maintenance/analytics personnel, manufacturers, inspection/law enforcement agents, and many others) on their expectations of the technology and potential

future use case demonstrations of ADS technology. This provided crucial information on the steps towards increasing fleet interest in the technology. The team found that the existing public perception of ADS technology is generally positive. More interestingly, a before-and-after survey provided to attendees showed that the perception and acceptance of the technology improved after their first-hand experience of the technology. However, attendees who participated in the demonstration further requested future specific use case demonstrations. Sixty-two percent of the attendees requested future demonstrations on ADS application to Automated Trailer Parking, 43% requested demonstrations on Truck Platooning and on Intermodal Yard, 35% requested demonstrations on Lane Keeping Assist, 25% requested demonstrations on Exit-to-Exit, 22% requested demonstrations on Truck Teleoperation, and 14% requested demonstrations on Queueing Operation. Future work is needed to address these requests. Readers can go to section 2.2 of this document for more details on this demonstration. Other resources, including the research brief summarizing activities at the meeting (https://www.vtti.vt.edu/PDFs/conops/TMC-Roadshow.pdf), video showing the ride and drive in an ADS-equipped truck (https://youtu.be/djWIsFFWw08}, and video showing conference activities and stakeholder interviews (https://youtu.be/eBnlxkS7i_4) are also available publicly using the associated links.

The final outreach was held at the CVSA Annual Meeting in September 2023. The primary activity demonstrated how ADS developers are implementing the CVSA Enhanced CMV Inspection Program within their operational policies and procedures. The Virginia Tech Transportation Institute (VTTI) sponsored a CONOPS booth in the exhibit hall that was staffed by project personnel for the duration of the conference to support the Enhanced CMV Inspection Program demonstration. Project personnel spoke to attendees who visited the booth about the CONOPS project and how the CVSA Enhanced CMV Inspection Program and Electronic Roadside Communication activities supported the CONOPS goals. VTTI drove their newly refurbished Peterbilt truck and the CONOPS trailer to Texas and showcased it in the CVSA exhibit hall for the demonstration. VTTI also partnered with Kodiak Robotics to demonstrate their procedures for implementing the Enhanced CMV Inspection Program within their fleet and daily operations. This allowed attendees to consider questions they may want to address to better understand the program. The second element of the outreach included a joint partner presentation to give ADS developers, OEMs, and fleets an opportunity to share their experiences with the Enhanced CMV Inspection Program and certification and training process. Readers can refer to section 2.3 of this report for a full report on this outreach event. Additional information can also be found using the following links: research brief summarizing ADS-equipped truck's inspection procedures (https://www.vtti.vt.edu/PDFs/conops/ADS-CVSA-Brief.pdf) and video showing the ADS-equipped truck's inspection procedure and interviews (https://youtu.be/rcgJYd_gDnA).

Feedback on lessons learned from these events was also distributed on a rolling basis at various other academic conferences. The VTTI team attended over 20 conference sessions, sharing information about the project as it was obtained.

ADS-equipped Truck Deployment for Fleet Operational Use Cases and Data Collection

As part of the CONOPS effort, ADS-equipped trucks were deployed for three operational use cases. This research effort is detailed in section 3.1. The aim was to explore and showcase how

ADS-equipped trucks can be customized for specific fleet use cases and to collect data on the readiness of existing infrastructure on U.S. roadways to support ADS implementation. The fleet use cases were port queuing, cross-country trips (similar to over-the-road operations), and fleet integration.

The port queuing use case was deployed at the Port of Oakland in California. This use case focused on refining ADS technology for loading and unloading operations in port queuing operations. During this use case the research team collaborated with Pronto, an ADS technology developer, to refine their driving algorithms to account for the unconventional behaviors of other drivers (such as speeding and cut-ins) at ports. Pronto modified the ADS behavior to include reduction in transition time (from being stationary to reinitiating motion when the queue resumed), maintaining tighter gaps with preceding vehicles, and improving object detection and tracking to prevent collision during aggressive low-speed cut-ins from surrounding vehicles. Following fine-tuning, the research team operated and showcased the ADS-equipped truck delivering containers for five days. A live stream was provided to attendees at public events as reported in the previous section. During this deployment period, over 50 GB of data was generated. This part of the research effort is detailed in section 3.1. The data is publicly available on the CONOPS Dataverse developed for this project by VTTI. Interested readers can find more details on this use case using the following links to access the port queuing operations data (https://dataverse.vtti.vt.edu/dataset.xhtml?persistentId=doi:10.15787/VTT1/ZYMSEM), video showing the queuing demonstration (https://www.youtube.com/watch?v=DCs8uGJAuks), and a research brief summarizing the port queuing activities (https://www.vtti.vt.edu/PDFs/conops/Port-Queuing-Brief.pdf).

For the cross-country trips, the team deployed ADS-equipped trucks on select routes to collect data on the readiness of the existing infrastructure to support ADS technology. The five routes were selected to cover states across the country with various roadway classifications, terrains, weather conditions, and times of day. The first trip was a round trip from California to Texas, the second was from Calgary, Canada, to California, the third was a round trip from California to Florida, the fourth was a nationwide cross-country loop, and the final trip traversed routes that linked California, Oregon, Washington, Idaho, Montana, Wyoming, Utah, Arizona, Nevada, and back to California, in that order. This part of the research effort is detailed in section 3.2. The team deployed various sensors on the ADS-equipped truck to collect real-time data on the infrastructure required for the technology to function optimally, such as lane marking quality, Global Positioning System (GPS) strength, availability of cellular connectivity, and road condition. Data from this deployment was used to develop a road readiness rating system that provides a detailed evaluation of the infrastructure required to support ADS trucks on each roadway section traversed. This is especially useful for government agencies and decision-makers, both at State and Federal levels, that are interested in utilizing truck automation technologies. The data is publicly available on the VTTI CONOPS Dataverse (https://dataverse.vtti.vt.edu/dataset.xhtml?persistentId=doi:10.15787/VTT1/ZYMSEM). Interested readers can find more details including the cross-country deployment data (https://dataverse.vtti.vt.edu/dataset.xhtml?persistentId=doi:10.15787/VTT1/ZYMSEM), video showing the cross-country deployments (https://www.youtube.com/watch?v=DCs8uGJAuks), and a research brief summarizing the cross-country deployments (https://www.vtti.vt.edu/PDFs/conops/Cross-Country.pdf) using the associated links.

The fleet integration use case was conducted at the Whittier port in Alaska. The goal of this task was to thoroughly define the organizational elements as they exist at an operational level to better understand the implications of introducing ADS into an intermodal fleet operating heavy trucks for repetitive driving actions on a private yard—in this case between a barge and rail cars. This goal was accomplished by collecting relevant observational and interview data and using those data to perform various task, risk, and organizational systems analyses. The objective for the approach was to establish a baseline evaluation of the organization at the operational level for future use in identifying the impacts of incorporating automated vehicles (AVs). The analyses address both organization- and person-level elements and relate those across a macrocognitive model for human involvement within their tasks and roles. This part of the research effort is detailed in section 3.3.

Guidelines on Implementation and Policy Issues for ADS-equipped Trucks

To develop a comprehensive understanding of the present practices regarding ADS implementation and policy issues for fleets, the research team consulted with various stakeholders involved in ADS technology development. This included technology developers, insurance agencies, commercial motor vehicle (CMV) safety agencies, inspection agencies, and cybersecurity experts. Information was pooled from these sources to provide fleets with guidelines on how to navigate each of these issues. The CONOPS includes eight key sections: Fleet Specifications, Installation and Maintenance, Inspection Procedures, Driver State Monitoring, Insuring ADS-Equipped Trucks, ADS Safety Metrics/Variables, Road Readiness Rating System, and Data Transfer and Cybersecurity. Below, we provide a high-level description of the focus of each section. Each of these is documented in detail in chapter 5 of this report. It is recommended that readers treat each section as a stand-alone guide that addresses different aspects of ADS implementation and policy concerns.

The ***Fleet Specifications*** guidelines are provided in section 5.1. Considering that the adoption of ADS technology by fleets is more likely to be a gradual process rather than a one-time, full-scale adoption, the research team took an industry-first approach and conducted discussions with truck industry partners regarding the use cases that have the most appeal to truck fleets. The goal of this task was to identify the most desirable set of use case specifications for fleet users to support the development of the fleet ADS. This was to ensure that truck fleets specified their needs as a function of their real-world operational experiences and that guidelines provided on integrating ADS would meet those needs. Based on the discussions held by VTTI with fleets, three use cases were identified and research was conducted to understand stakeholder expectations of ADS technology in these use cases. Further, various systems such as safety equipment, electrical components, batteries, sensors, controls, and displays on conventional trucks that may require special consideration towards the integration of ADS technology for these use cases were outlined and practices on how these are handled were provided.

ADS Installation and Maintenance guidelines are provided in section 5.2. One of the goals of this CONOPS is to prove the viability of an ADS in mixed fleets composed of trucks from a variety of makes and models equipped with a range of driving automation systems that assist drivers or carry full responsibility for sustained control and monitoring. The research team developed this section to serve as a guide for the installation and maintenance of ADS equipment for fleets. The ADS used during the project varied based on the operational use case for deployment. These systems are examples demonstrating how ADS technologies and their assembly with the vehicle can vary based on the operational design domain (ODD) and automation functions required for operation. This section provides two separate installation guides and related maintenance practices for each system demonstrated in this project. The first system was developed to support operations on public highways (as demonstrated with the port queuing cross-country deployments). The second system was developed to support operations in limited geofence private yards or ports (as demonstrated with Fleet Integration). The section gives a product-focused overview of the installation process of an ADS developer, Pronto, on CMVs. The installation practices are heavily guided by Pronto's goal to provide an ADS that can be installed in a straightforward manner and validated in different CMV makes and models.

ADS Inspection Procedure guidelines are provided in section 5.3. The development of vehicle automation and ADS show potential for significant safety improvements. However, there will be a need to inspect the vehicle and its systems that operate without a driver onboard to ensure proper performance and safety. This creates a challenge for the National Highway Traffic Safety Administration (NHTSA), Federal Motor Carrier Safety Administration (FMCSA), and the CVSA to create policy and inspection procedures to ensure the safety of both CMVs and the motoring public. VTTI reviewed the Federal Motor Carrier Safety Regulations (FMCSRs) and the existing research literature to better understand the current state of practice regarding truck inspections and the implications of driverless vehicles. In conducting the literature review, the study team searched various terms related to truck inspections—roadside, pre-trip, Driver Vehicle Inspection Report (DVIR), periodic, and the link between mechanical failures and truck crashes. Additionally, the VTTI study team interviewed nine experts involved in motor carrier enforcement, motor carrier safety, and ADS technology development to better understand the challenges that ADS-equipped vehicles pose to existing truck inspection processes, to identify the changes needed in the FMCSRs, and to identify alternative truck inspection procedures. The section also provides insights into the enhanced CMV Inspection Program by CVSA specifically for ADS-equipped trucks. Lastly, recommendations, next steps, and future areas to consider are highlighted.

Driver State Monitoring guidelines are provided in section 5.4. Safety operators (or safety drivers) supervise the performance of prototype Level 4 (L4) ADS-operated vehicles in on-road traffic for testing purposes. Their role is to respond to unexpected events in case an ADS, on rare occasions, executes an incorrect or unsafe driving maneuver. Hence, ensuring the driver is actively engaged with the vehicle operations while the ADS is active is of utmost importance. Present practices involve implementing in-vehicle technologies that monitor driver states in real time and can nudge a driver when alertness or attention to the ADS is compromised. In this section, we document the state-of-practice on driver state monitoring (DSM). DSM systems are designed to track metrics (i.e., physical, physiological, psychological, and/or behavioral variables) that may be indicative of driver inattention or inability to react appropriately. First, we document some of the performance indicators used for monitoring driver states, including distraction, impairment, drowsiness, mental workload, and emotions. Then, we conducted a technology scan to identify commercially available DSM technologies that could be used to assess the ability of a safety operator to take over control of an ADS-equipped CMV during a planned or unplanned ADS disengagement. This technology scan established what DSM technologies and systems are available and their functions, capabilities, limitations, and use cases when integrated and applied with ADS operations. Further, the research team conducted interviews with personnel from two critical sectors involved with ADS technology: ADS developers and DSM technology providers. The interviews gathered information about the integration of DSM into ADS-equipped CMVs through questions about barriers to integration, roles of a safety operator, and current use of DSM technology. Finally, a pilot study was conducted to explore the capabilities of two DSM systems by documenting possible shortcomings and by exploring how effectively a state-of-the-art DSM system meets the needs of safety operator monitoring. Findings in this section inform stakeholders on the existing practices and capabilities of DSM systems and identifies future research directions.

Guidelines on ***Insuring ADS-Equipped Trucks*** are provided in section 5.5. In this section, we focus on insurance practices involving AVs in general, with specific consideration for heavy vehicles. The section was to answer questions on what the current and future AV trends are, how auto insurance will meet society's needs in an AV world, and what the critical insurance-related components for AV regulation are. A comprehensive review of publicly available information on insurance policies for AVs was conducted. The materials reviewed were based on resources from the Travelers Institute, an education and public policy division of The Travelers Indemnity Company, a home, vehicle, valuables, and business insurance provider. Most of the information herein was released in a position paper published by Travelers in January 2021 titled, "Insuring Autonomy: How Auto Insurance Will Lead Through Changing Risks." We examined the discussions in the paper and modified the findings and conclusions to focus on trucking fleets. We also provided insights based on a technical session hosted by the S.18 Automated Vehicles Study Group at the TMC annual meeting on February 28, 2023. It should be noted that the information and positions stated in this section are shared to inform the developing conversation about insuring AVs. The information is based on the publicly available resources mentioned and is not necessarily representative of positions held by VTTI or the U.S. Department of Transportation.

Guidelines on ***Identifying Truck Safety Metric/Variables*** are provided in section 5.6. Traditional safety metrics, such as crashes and moving violations, may be inadequate for monitoring the performance of ADS-equipped trucks once they are deployed or for convincing the public of the safety of these technologies. In this section, we conducted an extensive literature review to identify potential variables that might be used by fleet decision-makers and the public to evaluate the safety of the ADS. We also examined the data required to assess the safety of an ADS before implementing ADS-equipped vehicles into their operations and to monitor ADS performance when deployed. Our findings revealed two major categories of safety metrics: lagging metrics and leading metrics. The lagging metrics, such as incidents per vehicle counts, year-over-year number of vehicle crashes, and incidents per million miles, are often used to measure system safety performance after deployment. They measure incidents based on the continuous operation of the ADS. Hence, they are poor measures for preventing safety incidents. On the other hand, the leading metrics (such as near-crash events, disengagements, traffic violations, and safety envelope violation) are good indicators for future events and they measure activities carried out to prevent and control safety incidents. These metrics are proactive and provide information on how the ADS is performing on a regular basis. We identified the application of both categories of safety metrics and how it can be used to inform policy making.

ADS Road Readiness Assessment guidelines are provided in section 5.7. In this section, we developed and documented a basic road readiness assessment system for ADS-equipped trucks using the cross-country deployment datasets. The idea is to use this system to distinguish roadways that are suitable for the operation of ADS-equipped trucks from roads that are not, in which case intervention by a human operator may be needed. The system was developed using a combination of roadway infrastructure data and the ADS-equipped vehicle's perception of the roadway conditions based on its kinematics. Understanding that the operation of ADS technology across various developers is not homogeneous and may differ in terms of the systems and algorithms used to develop them, an advanced road readiness system was also designed to be flexible enough such that future applications are adaptable to specific ADS developers' proprietary algorithms. This advanced system was designed as a variation of the basic road readiness system. The section further demonstrated how the systems can be applied to U.S. interstate highway systems using the data collected by Pronto, an ADS developer. As a first step towards ADS implementation, government agencies can also evaluate their State roadway system using the road readiness system developed in this section. Recommendations and next steps are also provided to stakeholders on preparing U.S. roadways for ADS trucking operations.

<u>Data Transfer and Cybersecurity</u> guidelines are provided in section 5.8. Like many new technologies, ADS development continues to evolve at a rapid pace, especially regarding cybersecurity. This section provides detailed information on data transfer and cybersecurity topics that are directly relevant to *end users* who adopt ADS technologies. More specifically, the focus is on cybersecurity from the point of view of an ADS-equipped CMV fleet as opposed to an ADS developer. General guidelines for understanding cybersecurity, how mixed fleets (both conventional and automated trucks) and cybersecurity relate to each other, and how fleets should tailor these guidelines to meet their specific systems are provided. The section addresses cybersecurity topics from a unique angle that has not previously been studied in detail and is continuously evolving. As such, this section does not focus on technical details for implementation. Rather, it is best viewed as a starting point for CMV fleets and other audiences with a general interest in the practical, real-world implementation of cybersecurity measures in ADS deployment. The section goes into more detail on various possible vulnerabilities in an ADS environment, potential security challenges for ADS-equipped CMVs, and challenges of mixed fleets. We also discuss various security aspects to consider such exposure, access, security assurance, failure and recovery, emergency action plan, life cycle, and those involving data transfer such as storage, processing, sharing, logging, and auditioning. We wrap up the section with insights on best practices for fleet cybersecurity to protect their ADS technology from various potential sources of cyberattacks.

1. INTRODUCTION

The introduction of Automated Driving Systems (ADS) technology on heavy trucks is expected to increase safety, productivity, and efficiency. This will significantly affect all commerce in the United States, as over 70% of our goods are moved by trucks. However, it is yet unclear how ADS-equipped trucks should be integrated into fleet operations with conventional trucks. Further, the technical progress in ADS technology is moving at a faster pace than truck fleets and associated industries can keep up with and plan for its deployment. As a result, stakeholders in the road freight ecosystem (for-hire and private truck fleets, shippers, brokers, truck manufacturers, and service and maintenance providers) do not have a clear picture of how ADS should be implemented into their daily operations. This drawback may adversely affect its adoption, thereby delaying the improved safety, productivity, and efficiency benefits of ADS-equipped trucks. Hence, there is a need to understand the real-world operational impacts of ADS technology and fill the existing knowledge gap on how trucking executives can gradually and successfully integrate ADS into their fleet operations by providing current stakeholders and new entrants in the trucking industry with data-driven guidance.

Towards this end, the Virginia Tech Transportation Institute (VTTI) assembled a team of experts in the field of ADS, data collection, safety data analysis, naturalistic driving, roadway infrastructure, data repositories, statistical methods, and truck fleet operations to develop and demonstrate a Trucking Fleet Concept of Operations (CONOPS). The CONOPS documents and describes ADS characteristics from the viewpoint of truck fleets and provides the trucking industry with clear guidelines on how to safely implement and benefit from ADS-equipped trucks. Overall, the CONOPS is intended to (1) provide commercial motor vehicle (CMV) fleets with practical information on how to integrate ADS-equipped trucks into their operations, (2) demonstrate the safe integration of ADS-equipped trucks into the U.S. on-road transportation system, and (3) investigate public and stakeholder attitudes towards ADS-equipped trucks.

Given the tremendous potential safety, efficiency, and productivity benefits of automated trucks, and the fact that 100% of all consumer goods are delivered via trucks, the CONOPS is expected to benefit all road users and consumers, in addition to those working in the trucking industry. Reductions in traffic congestion and the associated pollution could be reduced with ADS-equipped trucks. Beyond the costs associated with reduced efficiency and increased pollution, trucks pose a safety concern. Compared to the general U.S. working population, heavy-truck drivers are 12 times more likely to die on the job and three times more likely to suffer an injury involving time off work. In 75% of fatal interactions between heavy trucks and passenger vehicles, it is the driver and/or passenger(s) in the passenger vehicle that are killed. All these effects degrade the quality of life of the public.

With ADS-equipped trucks, there is a possibility of preventing and mitigating these safety issues. Further, there is an increasing demand for consumer goods and just-in-time inventory strategies (i.e., receiving goods only as they are needed). This places a significant demand on truck drivers and the U.S. highway system as increasing amounts of goods are delivered by trucks. In 2023, the American Trucking Associations estimated the truck driver shortage at roughly 60,000 drivers. The driver shortage has been one of the trucking industry's top concerns for years. In its annual survey to truck fleets in 2023, the American Transportation Research Institute found the lack of qualified drivers to carry the Nation's freight is the second most important issue, just behind the economy as number one. The current shortage of quality drivers, along with the high turnover rates inherent in the trucking industry, puts tremendous pressure on human resources to find quality drivers.

The VTTI team is also cognizant of the potential disruptive yet beneficial impact of ADS-equipped trucks on the U.S. economy. Approximately 9 million professional truck drivers haul more than 11 billion tons of freight annually in the United States. The demand for freight services has increased in recent years, and truck drivers have needed to move more goods. As of December 2021, 813,844 interstate motor carriers were actively operating in the United States. The trucking industry contributes significantly to the nation's economic portfolio, employing millions of people and hauling more than two-thirds of the total freight transported in the United States. Thus, delivery of goods via trucks is vital to the health of the U.S. economy, and ADS-equipped trucks have the potential to significantly increase economic output.

This CONOPS was intended to transcend a simple technology demonstration and include areas critical to the safe integration of ADS into the U.S. on-road transportation system. As shown in Figure 1, the CONOPS covered eight aspects of ADS integration: ADS Installation and Maintenance Guide for Fleets, ADS Inspection Procedures, Driver-Monitor Alertness Management, Truck Fleet Guide to Insuring ADS-Equipped Trucks, Identification of ADS Safety Metrics/Variables, ADS Road Assessment System, Data Security/Transfer Protocol and Cybersecurity Best Practices, and Operational Use Cases Demonstrations.

Figure 1. Diagram. CONOPS critical areas for operating ADS-equipped CMVs in mixed fleets.

As shown in Figure 2, the research adopted an iterative process of collecting information on existing ADS trucking practices, demonstrating the operations of ADS technologies on trucks under naturalistic and controlled environments, and sharing the lessons learned from these previous steps with stakeholders to update existing practices. The "Collect" stage of this cycle involved gathering ADS trucking technology capabilities and practice information to obtain insights on the best practices for installation and maintenance of ADS-equipped trucks, inspection procedures, driver state monitoring, insurance considerations, metrics to measure the safety performance of ADS-equipped trucks, the readiness of roadway systems for ADS technologies, and potential cybersecurity concerns as these technologies are implemented. These practices and guides were updated throughout the project as new information came to light.

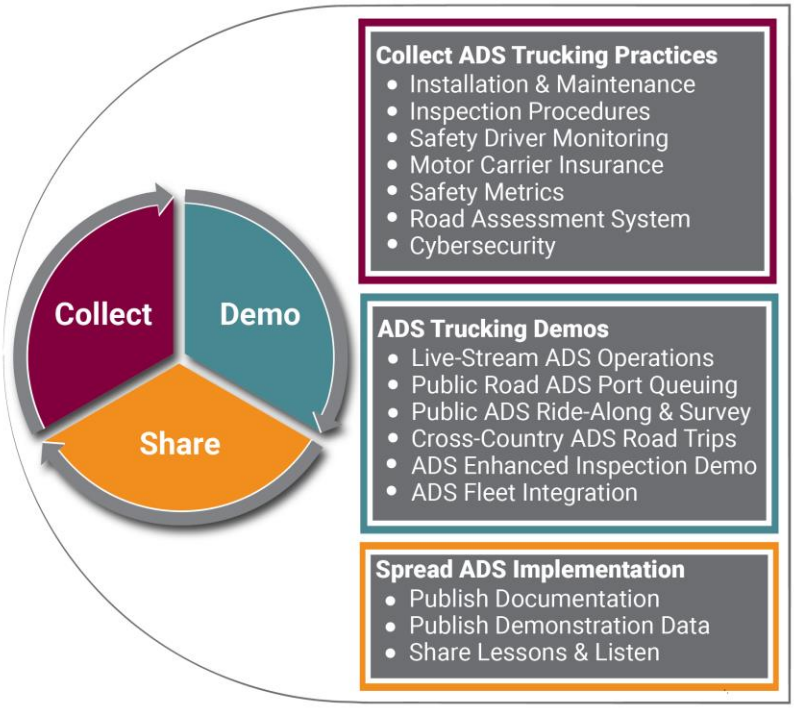

Figure 2. Diagram. CONOPS approach to continuous cycling of new technology innovation, application, and dissemination.

The "Demo" stage involved public demonstrations of the safe and efficient integration of ADS-equipped trucks into realistic use cases, including port queueing operations, cross-country road trips, and freight integration. These operational use cases represent example equipment and conditions where the benefits of ADS-equipped trucks could be observed, and data collected with live traffic. These deployments built towards a network of fully deployed ADS trucks integrated into a truck fleet's traditional commercial operations that move freight in a safe, repeatable, and commercially viable manner, providing insights into ADS-equipped truck performance in revenue-producing operations. In addition to the deployments, hands-on ADS roadshows were held to allow end users, stakeholders, and the public to experience ADS technology on closed test tracks. The roadshows, hosted at national and international industry conferences across the country, engaged the public with driving automation systems to share information about their functionality, benefits, and limitations. This was to understand public attitudes toward and perception of ADS-equipped trucks, specifically their attitudes towards ADS-quipped trucks before and after the demonstration.

During these demonstrations, VTTI worked with an industry team member, Pronto, a leading developer in the truck ADS space, to use their ADS platform in the demonstrations. The approach to conducting these demonstrations ensured the results translate directly to real-world settings that are of practical importance to the trucking industry, regulators, and the public at large. Hence, rather than moving from one automation level to the next simply for the sake of demonstrating technical feasibility in the abstract, the VTTI team focused on demonstrating the ability of traditional truck fleets to integrate ADS functionality into their current fleets and business models.

The third stage ("Share") involved sharing the findings through publishing documentation, demonstration data, and the lessons learned to stakeholders and the public. This involved activities such as webinars, conferences, roadshows, and exhibitions. Research briefs and videos were provided to the public on the project website (https://www.vtti.vt.edu/projects/conops.html) at each stage of the project. The VTTI team also developed a publicly accessible data repository, the Federal Highway Administration (FHWA) CONOPS Dataverse, to house the data from the demonstrations. This data was shared with the United States Department of Transportation (USDOT) and the public in near-real time through the Dataverse. The data includes survey responses from the roadshows and public outreach, vehicle kinematic and ADS state data, and roadway readiness detection data from the real-world deployments.

Disclaimer: This report does not imply endorsement of any products or companies mentioned herein.

2. DEMONSTRATIONS, PUBLIC OUTREACH, AND TECHNOLOGY REFINEMENT

To support the CONOPS documentation and provide the trucking industry with clear information on how to implement ADS-equipped trucks among mixed fleets, VTTI hosted a series of roadshows and public outreach with support and participation from ADS partners. Pronto.ai partnered with VTTI during a live demonstration event and a ride-and-drive event. Kodiak Robotics, Inc., partnered at another event with VTTI to record and demonstrate an enhanced inspection for ADS-equipped CMVs. These were critical to enlightening stakeholders and users on the functionality, benefits, and limitations of ADS, as well as providing guidance to government, insurance, and inspection agencies and the public who are likely to shape policy in this area. The roadshows demonstrated how ADS can be implemented in trucking fleets in a manner that is (1) safe, (2) repeatable, and (3) commercially viable. Since ADS are new and most fleets have yet to encounter or operate an ADS, the outreach and roadshows provided opportunity for direct interaction with different technology solutions under development. Using existing contacts, three conferences and meetings, including the Intelligent Transportation Society of America (ITS America) Annual Conference, the Technology Maintenance Council (TMC) Annual Meeting, and the Commercial Vehicle Safety Alliance (CVSA) Annual Conference and Exhibition, were selected for the outreach and roadshow events. These events focused on providing the public with a focus on commercial fleet operators, with the opportunity to meet ADS technology developers and original equipment manufacturers (OEMs). The events also provided the attendees with opportunities to participate in hands-on technology demonstrations, such as in-vehicle demonstrations and closed-course roads. Feedback was also collected from attendees to understand their perception and acceptance of the technology and obtain insights on the potential use cases for different automation technologies and document their concerns that might be addressed in the CONOPS. The following sections provide extensive information on the three roadshows, including the participating technology vendor/OEM, exhibition booth experience, technical sessions, closed-course demonstration setup, and survey data collection on perception of the technology.

2.1 ROADSHOW – ITS AMERICA ANNUAL MEETING

The first of the three roadshows was held at the ITS America Annual Conference in Charlotte, North Carolina. This roadshow highlighted two testing demonstrations of ADS, including an interactive and behind-the-scenes look at ADS-equipped truck cross-country corridor operations (https://www.vtti.vt.edu/PDFs/conops/Cross-Country.pdf), as well as a port queuing demonstration highlighting the safe deployment of ADS technologies in port operations (https://www.vtti.vt.edu/PDFs/conops/Port-Queuing-Brief.pdf). Technical sessions were also held to provide information and answer questions related to the CONOPS project. A research brief was created to summarize the event and roadshow activities (https://www.vtti.vt.edu/PDFs/conops/ITS-Roadshow.pdf).

2.1.1 ADS Truck On-road Testing Demonstration

An interactive visualization of a prototype truck ADS database and map created from data being collected during the ADS cross-country operations was shown to the attendees. The visualization allowed participants to experience the ADS truck driving a wide variety of Interstate highways and rating the highways based on the availability, quality, and strength of required supporting infrastructure. The behind-the-scenes presentations highlighted the ADS cross-country operations, including preparation, planning, training, data inputs, and real-world applications. Activities on the fleet instrumentation, setup, and measurement of metrics were presented to the attendees. Real-time data streams and performance metrics collected from the ADS-equipped trucks during the cross-country operations were also displayed at the demonstration. Attendees had the opportunity to ask questions and have a chat with a Pronto engineer who was monitoring the cross-country data collection from the ADS truck cab in real time. Lastly, a slideshow on the ongoing port queueing deployment was provided to attendees to illustrate how ADS-equipped trucks can relieve major congestion points in daily port operations (https://youtu.be/DCs8uGJAuks).

2.1.2 Highlights from the Technical Session

The technical session was given as an information session by a Pronto engineer. The session provided an overview on the existing knowledge gaps in ADS technology development, including the absence of a public dataset on the metrics required to measure the deployability of ADS-equipped trucks and how policy makers and ADS developers are presently relying on secondary data when developing automated vehicles (AVs). Following this, the presenter provided the CONOPS project objectives and how the project intended to fill some of these knowledge gaps by developing a first-of-its-kind national dataset of infrastructure readiness, developing ADS performance metrics required for autonomous operations, and demonstrating an automated truck safely traversing the United States, coast to coast, without a driver. The approach to ADS data collection, including driving automated trucks across routes under a variety of road conditions (traffic, weather, time of day) to measure infrastructure quality, and sharing this data, was presented to the attendees. Insights on the key infrastructure metrics (connectivity, lane marking quality, road bumpiness, and GPS satellite coverage) needed to support ADS integration on the various routes and how they were measured and rated were also presented. The session wrapped up with questions and answers, and attendees were directed to follow the project progress on the project website.

2.2 ROADSHOW – TMC ANNUAL MEETING

The second roadshow was conducted at the TMC annual meeting in Orlando, Florida. A research brief (https://www.vtti.vt.edu/PDFs/conops/TMC-Roadshow.pdf) and video (https://youtu.be/eBnlxkS7i_4) were created to summarize the event and roadshow activities. This featured an ADS-equipped truck running closed-course demonstrations, an exhibitor booth, and a technical session. The closed-course demonstrations involved a ride-and-drive to allow end users, stakeholders, and the public to experience ADS technology on closed test tracks and share information about their functionality, benefits, and limitations. The exhibitor booth showcased the ongoing overall CONOPS project and active deployments, including ADS Port Queuing and ADS Cross-Country Road Testing. VTTI personnel networked and interacted with attendees who visited the booth in the exhibit hall to further market the CONOPS project and disseminate information (https://www.vtti.vt.edu/PDFs/conops/Tech-Brief.pdf). Additionally, a video of the outdoor ride-and-drive was displayed at the booth to garner additional attention for the dynamic demonstration (https://youtu.be/djWIsFFWw08). On the other hand, the technical session included a panel of experts in the automated commercial trucking industry to share information and address important issues that fleets, shippers, brokers, State governments, and service/maintenance providers need to understand to plan for ADS deployment.

2.2.1 ADS Truck Ride-and-Drive

The ride-and-drive provided the attendees with a first-hand experience of the capabilities of an ADS truck. Attendees had the opportunity to ride in a Pronto ADS truck (accompanied by a safety operator) as it followed a traditional truck on a closed-course route (Figure 3) around the Orange County Convention Center where the TMC conference took place. The closed course involved the ADS truck starting from a complete stop and performing various maneuvers, including left turns, right turns, mandatory lane changes, and coming to a complete stop. Along the closed-course route, the ADS truck navigated a small work zone (Figure 4), which was designed and executed with the support of the Florida Department of Transportation. The work zone involved traffic cones set up along the route to guide the ADS truck. A “road worker” mannequin (see Figure 5) was also programmed to perform a sudden unexpected crossing as the truck traversed the work zone, and the truck was expected to react by coming to a stop at a safe distance ahead of the worker. This was done to re-create a typical safety-critical and complex driving situation as it would be experienced under real-life driving conditions. The research team created a handout highlighting truck crashes in work zones to support the safety benefits of the operational use case for ADS trucks in work zones.

Figure 3. Map. Closed course for demonstration at the TMC Annual Meeting (in red).

Figure 4. Photo. Work zone setup as part of the closed-course testing at the TMC Annual Meeting.

Figure 5. Photo. Unexpected crossing scenario at work zone.

Early signups for the ride-and-drive were available beginning one month prior to the event, and TMC organizers helped to disseminate the information by sending daily email blasts to the registrants. Over the course of the two-and-a-half-day conference, VTTI and Pronto conducted 54 ride-and-drive trips with a total of 161 attendees. Among the participants, 29.7% had a commercial driver's license (CDL), 17.8% worked as a CMV driver, and 70.3% had not previously experienced a commercial truck ADS. Figure 6 shows the distribution of the ride-and-drive participants based on their profession. To collect information from the attendees about their opinions, perceptions, and attitudes towards ADS applications in fleet operations, the VTTI team collected questionnaires both before and after attendee participation in the ride-and-drive. This allowed researchers to observe any changes in opinions and perception that could be attributed to their experience during the demonstration. A total of 101 paired pre- and post-roadshow questionnaires were collected from the attendees who participated in the ride-and-drive. The questions obtained insights on their perception of the technology, such as the effectiveness, safety, desirability, cost-effectiveness, acceptability, performance, readiness for deployment, commercial viability, and integration into fleet operations.

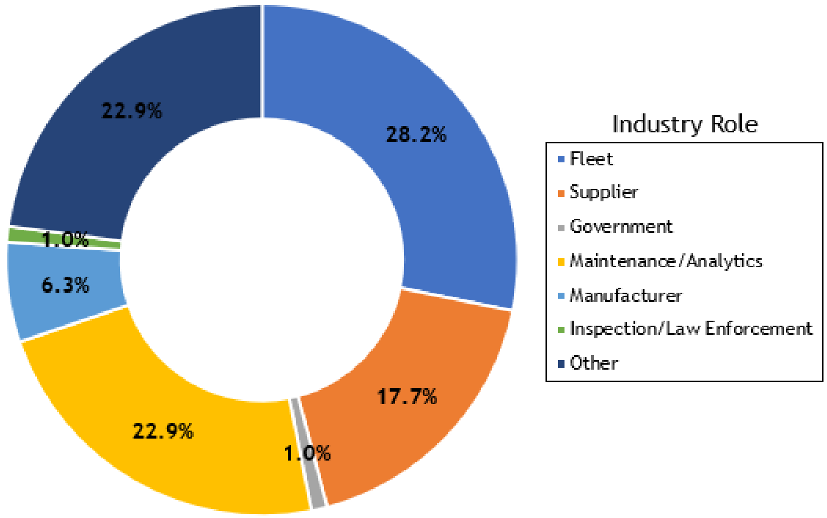

Figure 6. Chart. Ride-and-drive participant distribution based on industry role.

Figure 7 shows the responses to the survey questions, which were framed as pairs of polar opposites. Participants were asked to respond using a scale of 1 to 5, where "1" represented the first pole and "5" represented the second pole. Careful attention should also be paid to the questions, as the positive and negative valences of the responses were alternated between left and right in the pairings. In general, feedback from participants on ADS opinions and acceptance was positive and did not change drastically before and after demonstration participation. Specifically, questions on whether the technology was effective/superfluous, raising alertness/sleep inducing, unsafe/safe, cost-effective/too expensive, acceptable/unacceptable, performs well/performs poorly, and if training was difficult/easy received more positive responses after the demonstration. Questions on whether the technology was useful/useless, bad/good, irritating/likeable, assisting/worthless, or undesirable/desirable received a slightly less positive response. This could mean that more demonstration or exposure to use cases is required to have a much better judgment of the technology. Further, no changes were observed in the other survey responses. However, in all cases, all the responses were positive. Lastly, participants also requested future use case demonstrations, as shown in Figure 8. Participants were able to select multiple options for future demonstrations.

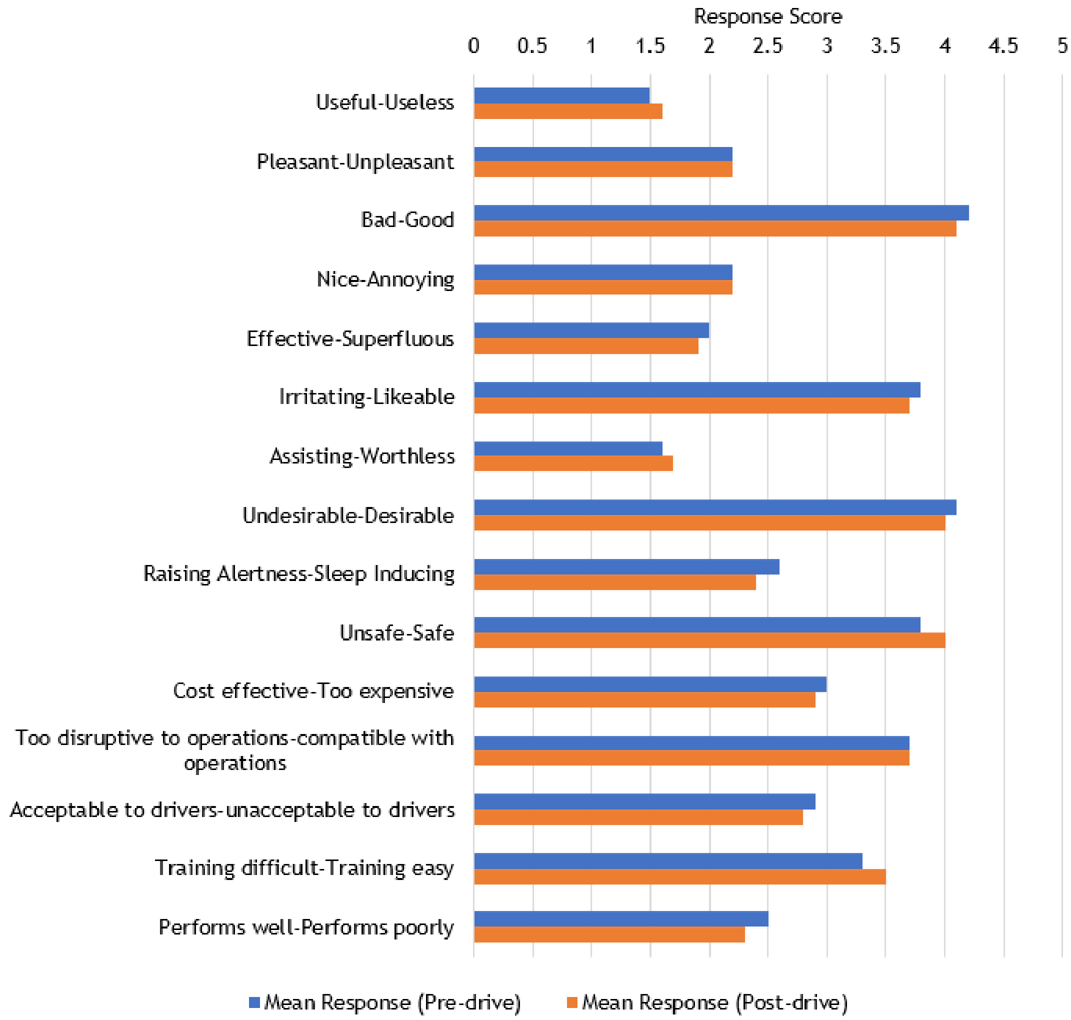

Figure 7. Chart. Participant responses to survey questions pre- and post-drive.

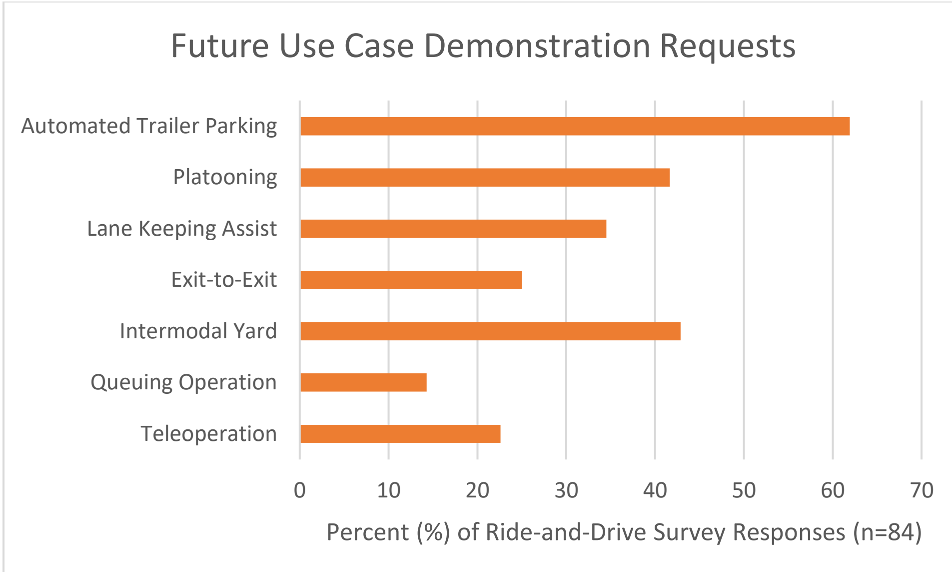

Figure 8. Chart. Future use case demonstration request.

2.2.2 Highlights from the Technical Session

The technical session was presented by a panel of experts involved in the CONOPS project and moderated by Tom Keane, Associate Administrator of the Office of Research and Registration at the Federal Motor Carrier Safety Administration (FMCSA). The assembled panel included experts in the automated commercial trucking industry to address important issues that fleets, shippers, brokers, State governments, and service/maintenance providers need to understand to plan for ADS deployment. Dr. Rich Hanowski, Division Director of Freight, Transit, and Heavy Vehicle Safety at VTTI, provided an overview of the active research project and pointed to some operating environments where automation might help drivers perform consistently and safely. Next, Jeff Loftus, Division Chief at the FMCSA Technology Division, shared information about the role that FMCSA is playing in supporting and guiding ADS trucking deployment. Jessica Kearney, Assistant Vice President at Travelers Institute, spoke about what the future of insuring ADS-equipped trucks may look like. Assuring that ADS-equipped trucks are well maintained through the right level of electronic and manual interactions was discussed by Will Schaefer, Director of Safety Programs at CVSA. Additionally, the fleet perspective was covered by Vice President of Maintenance at Bison Transport, Mike Gomes, who discussed his fleet's experience with automation that supports drivers on the road. Finally, an expert who has watched the development of ADS vehicles for years, Ognen Stojanovski, Chief Operating Officer and Co-founder of Pronto.ai, discussed the beginnings of automation and where it can do the greatest good to support the safety and efficiency goals of every fleet.

2.3 ROADSHOW – CVSA ANNUAL CONFERENCE

The final roadshow was held at the CVSA Annual Conference and Exhibition in Grapevine, Texas, in September 2023. This roadshow focused on the CVSA Enhanced CMV Inspection Program. To capture early marketing footage and generate discussion prior to the roadshow activities, the research team conducted a site visit near Dallas, Texas, with Kodiak Robotics to film, photograph, and document their protocols and the procedures surrounding their pilot of the Enhanced CMV Inspection Program. Technical sessions were also held at the conference with representatives from ADS developers and OEMs to discuss their experiences with the enhanced inspections and facilitate discussion about other important related ADS inspection topics. A research brief summarizing ADS-equipped trucks' inspection procedures (https://www.vtti.vt.edu/PDFs/conops/ADS-CVSA-Brief.pdf) and video (https://youtu.be/rcgJYd_gDnA) were created to summarize the site visit and roadshow activities.

2.3.1 Site Visit Activities

On Day 1 of the site visit, the research team (VTTI and FMCSA) worked with Kodiak and partners, the Texas Department of Public Safety (DPS) and Drivewyze, to film demonstrations of the electronic roadside verification communication procedures to highlight real-world applications and operational integration of the enhanced inspection standard. The demonstrations and filming took place along Interstate 45 and the weigh station in Wilmer, Texas. The team documented staged runs of the Kodiak ADS-truck driving on the interstate past the Wilmer weigh station to capture the truck wirelessly communicating the enhanced CMV inspection status, via the Drivewyze platform, to the DPS trooper monitoring the weigh station. The VTTI team set up multiple video cameras to capture different angles inside the truck cab (Figure 9). The team also captured the Drivewyze interface inside the weigh station to document the information communicated from the truck to the DPS trooper and how this messaging was received and displayed. During the demonstration, the Drivewyze team collected real-time data from their back-end interface and provided this to the VTTI team to help with data documentation and creation of the demonstration videos.

Figure 9. Photo. Internal view of truck cab.

To accompany the demonstrations, brief interviews were conducted with members of the Texas DPS and the Drivewyze team to gain their opinions and insights into the purpose, value, and next steps for the ADS enhanced inspection and electronic roadside verification communication activities. The interviews provided an overview of Drivewyze's approach to the roadside screening of ADS-equipped trucks as they approach a stationary weigh station, including the development of software (Inspection Client) congruent with CVSA's enhanced pre-trip inspection procedures. The Inspection Client is the enhanced inspection that the CVSA-trained ADS developer goes through, certifying a defect-free inspection, before the truck is dispatched. The approach also includes inspection forms and public application programming interfaces (APIs) for data transfer from ADS developers to the Drivewyze AV database, which are then used for a pass/fail screen decision. Expectations on the potential benefits of the ADS enhanced inspection technology include reducing crashes stemming from human factors such as fatigued or aggressive drivers and improving overall highway safety.

On Day 2 of the site visit, the research team visited Kodiak's office and garage facilities in Lancaster, Texas, to demonstrate and document Kodiak's internal enhanced inspection procedures as an example implementation of the CVSA Enhanced CMV Inspection Program on their trucks. With CVSA's enhanced inspection certification program, other ADS personnel (not just law enforcement officers) are now able to complete training and certification to become certified inspectors. The industry is looking to developers, like Kodiak, to learn about the internal inspection processes and procedures in place at garage facilities and how these are being done thoroughly and efficiently prior to an ADS truck being dispatched. To document this, the VTTI team recorded a CVSA-certified inspector with Kodiak as he conducted a full enhanced inspection on a Kodiak truck. To highlight key elements of the enhanced inspection, CVSA recommended five areas to capture and reinforce the process. The following elements of the inspection were documented in detail with accompanying narrative from the Kodiak inspector: (1) interior checks including air loss/build up testing; (2) inspection of undercarriage and measurement of brakes under the CMV; (3) inspection of rear tractor and trailer lighting; (4) checking the securement and movement of the 5^{th} wheel; and (5) checks of the ADS and components (i.e., cameras, lidar, radar, etc.).

Brief interviews were also conducted with the VTTI and the FMCSA teams to gain information on how these demonstrations support the research objectives of the CONOPS project as well as the future of ADS trucking. Team members from Kodiak were interviewed to discuss Kodiak's involvement in the ADS Enhanced CMV Inspection Program and how these programs support and advance ADS trucking initiatives. A comprehensive video documentation of the enhanced inspection process and interviews can be found on the project website (https://youtu.be/rcgJYd_gDnA).

2.3.2 Roadshow Activities

2.3.2.1 CONOPS Booth

VTTI sponsored a CONOPS booth in the exhibit hall that was staffed by project personnel for the duration of the conference to support the Enhanced CMV Inspection Demonstration. Project personnel spoke to attendees who visited the booth about the CONOPS project and how the CVSA Enhanced CMV Inspection Program and Electronic Roadside Communication activities supported the CONOPS goals. The video summarizing the site visit and roadshow activities was shown on a loop at the booth (https://youtu.be/rcgJYd_gDnA). Demonstration handouts (https://www.vtti.vt.edu/PDFs/conops/ADS-CVSA-Brief.pdf) and VTTI giveaway items were distributed to attendees, and VTTI staff verbally advertised the Enhanced CMV Inspection Demonstration, which was held during the CVSA reception.

2.3.2.2 Enhance CMV Inspection Program Demonstration

The primary Roadshow activity demonstrated how ADS developers and OEMs are implementing the CVSA Enhanced CMV Inspection Standard within their operational policies and procedures. VTTI drove their newly refurbished Peterbilt truck and CONOPS trailer to Texas and showcased it in the CVSA exhibit hall for the demonstration. VTTI partnered with Kodiak Robotics and their Head of Service and Support and Hardware Manager, Matthew Cearnal, to demonstrate their procedures for implementing the Enhanced CMV Inspection within their fleet and daily operations. In addition to advising on the development of the CVSA Enhanced CMV Inspection training and certification program, Mr. Cearnal completed the training and is a certified inspector himself. The presentation and demonstration by Mr. Cearnal allowed attendees to consider questions they may want to address to better understand the program. Now that personnel are completing training and certification on enhanced inspections, what are the processes and procedures in place at shops? What does this business model look like? What do the in-transit versus dispatch inspections look like? How are certified inspectors completing these inspections efficiently? The demonstration was available during the opening reception, exhibit hall hours, and during lunch and midday breaks for the duration of the conference.

2.3.2.3 Enhanced CMV Inspection Program Presentation

The second element of the CONOPS roadshow demonstration at CVSA included a joint partner presentation at the Enforcement and Industry Modernization Committee Meeting to give ADS developers, OEMs, and fleets an opportunity to share their experiences with the Enhanced CMV Inspection Program and certification and training process. Presenters included Tom Kelly (FMCSA), Andrew Krum (VTTI), Kodiak (Brett Fabbri and Matt Cearnal), and Drivewyze (Miranda Leadbeater and Todd James). Mr. Kelly provided an overview of research of interest to the committee being conducted by FMCSA, including the CONOPS project. Mr. Krum presented an overview of the CONOPS project and showed the full video that was created during the June site visit to showcase the Enhanced CMV Inspection Program and electronic roadside communication activities and pilot program. Kodiak and Drivewyze closed the presentation with a discussion of their roles, perspectives, results and takeaways, and next steps from their pilot program. Topics of discussion during the presentations extended into other ADS inspection topics: What are the internal policies for checking the function of the ADS sensors and perception processors? How can the status of the vehicle's inspection be communicated electronically and securely? How will ADS-equipped trucks interact with roadside enforcement agents in emergencies? The presentation was well received by the committee and generated thoughtful discussions during and after the meeting.

2.4 CONFERENCES AND OUTREACH

Including these major outreach events and demonstrations, the research team spoke at and or attended 20 conference sessions to share information about the grant, collect new information, and provide feedback on lessons learned. These conferences covered topics such as automated truck operations, maintenance, roadway metrics, ADS safety metrics, CMV inspections, sensors, insurance of CMVs, and global trucking automation research.

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3. OPERATIONAL USE CASES

3.1 PORT OF OAKLAND – AUTONOMOUS QUEUEING DEMONSTRATION

There is a growing problem of increasing wait times at U.S. ports and other major shipping facilities. In the past decade, container ships have gotten considerably larger. The number of 20-foot containers that these mega container ships can carry has grown from 8,000 or so to more than 20,000 containers. Port improvements, and technologies, including reservation systems for trucks, have not been able to keep pace with the sheer number of shipping containers. As a result, wait times for loading and unloading containers onto trucks have increased considerably; in some cases, a driver must wait more than 6 hours (Figure 10). Wait times reduce driver and carrier productivity because they diminish a driver's available hours of service (HOS). Typically, a commercial driver can drive a total of 11 hours in a 14-hour workday. When paid by the mile, as most commercial drivers are paid, increased wait times can greatly reduce driver earnings.

Figure 10. Photo. Typical truck queueing at U.S. ports.

ADS offer the potential to allow the vehicle to drive itself in "Level 4" mode while queueing to be loaded or unloaded. With an ADS-equipped truck, a driver could go off duty and rest in a sleeper berth or leave the ADS to obtain rest in a motel or port facility. Since the waiting would be used for rest, it would not count against the driver's HOS, thereby increasing the driver's overall productivity, the carrier's bottom line (more distance could be covered in the day), and safety (drivers would be better rested and less pressured by time). Alternatively, for local delivery, it could change the operations at port facilities. A driver could manually drive the truck in city traffic to the port waiting line, then switch the truck into autonomous mode and pick up an already loaded ADS-equipped vehicle. This could greatly increase the number of turns that a driver could make in a workday.

As a first step towards addressing the problem of wait times at ports and demonstrating how ADS technology could be safely deployed in a port queuing operational design domain (ODD), the VTTI study team conducted an autonomous queueing deployment at the Port of Oakland in

Oakland, California. The study team conducted considerable outreach for this deployment. The team briefed principals within the FMCSA and Maritime Administration (MARAD) regarding the study effort and the Port Queuing demonstration. MARAD assisted VTTI with briefing the port facilities in Northern California, including project managers at the Port of Oakland. The team also briefed the California Highway Patrol, California Department of Motor Vehicles, and California Department of Transportation on this demonstration project.

For this effort, VTTI partnered with Pronto, an ADS technology developer, to deploy their technology. Pronto has been at the forefront of the most important advances in the AV industry and is the only company to successfully drive coast-to-coast in the United States without a single driver input. In 2020, Pronto conducted testing at the Port of Oakland. They subsequently made refinements in their driving algorithms to account for cut-ins and aggressive driving behaviors. To better understand how the SAE Level 4 ADS-equipped vehicle would affect loading and unloading operations in port queuing settings, Pronto conducted a series of tests at the Oakland Ports to better understand the suitability of this technology in relieving major port congestion points in daily port operations.

For 4 months, Pronto developed and tuned their ADS platform to participate in daily port queueing activities at the Oakland ports. Initially, the ADS was already proficient at traversing the routes of the different queues but was unable to handle the speed and aggressive driving of other drivers. For example, as the queue progressed, any significant gap between the ADS-equipped vehicle and a leading truck would be a target for another driver cutting the line. In addition, if the ADS-equipped vehicle was driving too slowly or pausing when the queue started moving, it would be a target of aggressive honking and yelling by other drivers. For the ADS-equipped vehicle to be successful at participating in queue operations, Pronto spent most of the testing time tuning the system to be an effective driver under those circumstances. Key modifications to Pronto's base algorithms included reducing the transition time between the ADS being stationary and reinitiating motion when the queue resumed; improving the finesse of the ADS's adaptive cruise control to keep tighter gaps between leading vehicles; and improving object detection and tracking algorithms to prevent collisions during aggressive low-speed cut-ins.

To showcase the capabilities developed during those months, VTTI and Pronto set up a week of Port Queueing deployments where the ADS-equipped vehicle delivered at least one container a day for an entire week (5 days). The Pronto ADS operated flawlessly, negotiating heavy traffic and intersections. During the deployment, seven containers were delivered, 50–60 GB of data were generated (operating 2–3 hours each day), and each delivery was live streamed via Zoom to showcase the ADS capabilities to a wider audience at conferences as stated in Chapter 2.

3.2 CROSS-COUNTRY ROAD TRIPS

As part of the CONOPS project, the objective of the cross-country road trips is to demonstrate the application of ADS technology under typical fleet operations such as over-the-road operations, and especially to collect real-world data to understand how ready the existing roadway infrastructure across the United States is to support ADS technology. Drivers are often involved in long-haul operations that can include interstate travel under various roadway, weather, and time-of-day conditions. With such long driving hours, drivers are often fatigued and usually must take breaks over the course of the trips. ADS technology provides an opportunity to enable collaboration between human drivers and ADS such that ADS can take over the vehicle when drivers are fatigued (without having to stop the vehicle while resting) and within the ADS's ODD. This reduces the driving task load on the drivers, improves driving safety for drivers and other road users interacting with trucks, and allows the maximization of fleet resources since longer trips can now be assigned to drivers with the support of ADS. While these are the potential benefits of ADS-equipped trucks, the cross-country trips here focused on the first step towards future integration, i.e., assessing the existing roadway infrastructure to understand how they can support ADS. Hence, this part of the CONOPS collected roadway data related to lane marking quality, cellular connectivity, road conditions, and GPS connectivity. ADS-equipped trucks drove selected cross-country trips and collected information in real time over the course of these trips.

Five routes were selected for the cross-country trips. The routes were selected to ensure that the data obtained from the deployments can provide insights on infrastructure readiness and ADS performance on some of the most common driving conditions on U.S. roadways and can be used to measure the potential of ADS technology to serve fleet operations on these routes. The team also ensured the routes selected are often traversed by fleets, involved complex driving conditions (various terrains, times of day, weather conditions), covered interstate travel, and imitated over-the-road operations as often conducted by fleets. The trips covered States nationwide, thereby providing comprehensive data to measure infrastructure readiness and useful to stakeholders and decision-makers. Below are the routes.

- California to Texas, roundtrip
- Calgary, Canada, to California, one-way trip
- California to Florida, round trip
- Nationwide Cross-country Loop
- California – Oregon – Washington – Idaho – Montana – Wyoming – Utah – Arizona – Nevada – California

For these deployments, a number of ADS-equipped trucks, with similar ADS capabilities, were used. Although the trucks were capable of operating at Level 4 driving automation, safety operators were also onboard to take over at any point necessary during the trip. Hence, the deployments included both the ADS actively driving and the human drivers taking over when necessary. This ensured that the ADS operated within its ODD and control was transferred to the safety operator when not within the ODD. However, in both cases, vehicle sensors were actively collecting the data required to assess infrastructure readiness. The idea was to collect infrastructure data across these routes (whether ADS was active or not) and improve our understanding of how ready these routes are to support the deployment of ADS technology.

The trucks were retrofitted with sensors and high-performance computing technologies including high-definition cameras, front radars, six-axis inertial measurement units (IMUs), GPS, communication antennas, 8-core CPU + GPU, 4 terabyte storage devices, and a Controller Area Network (CAN) interface board. This enabled the collection of data, including encoded and timestamped video streams from cameras (including driver-facing), numerical data, positional data, vehicle motion data, radar cluster data, CAN data, and other high-level perception and planning information. Additionally, VTTI's proprietary data acquisition system (DAS), FlexDAS, was installed in all participating vehicles. This includes a core i7 CPU, support for high-definition USB cameras, onboard IMU and GPS, and data storage devices. The FlexDAS collected a wide range of data while remaining unobtrusive to participant drivers. As a sample use case, roadway readiness indicators (such as lane marking, GPS and cellular signals, and road bumpiness/smoothness) were obtained from these sensors and used to assess roadway infrastructure readiness for all roadway segments along the trip routes. A summary of the data use case is provided in the next paragraph and detailed in section 5.7. Further, safety performance indicators including traffic violations, near-crash events, and disengagements can be obtained from the data to assess the safety performance of ADS-equipped trucks (see section 5.6 for more) while the technology is active.

Section 5.7 details how some of the data obtained from these cross-country deployments have been used to develop a road readiness rating system for ADS technology. The rating system combined data from FHWA's Highway Performance Monitoring System (HPMS) database with data collected from the ADS-equipped trucks, including the ADS-detected real-time lane marking quality, cellular connectivity (i.e., signal strength), GPS connectivity (i.e., count of GPS), and road condition (i.e., bumpiness/smoothness). The assessment used the ADS data to provide a detailed evaluation of the lane marking quality (using a 0 to 10 scoring scale) on all the roadway segments traversed by the truck. Cellular strength (using percentages) and GPS counts on these segments were assessed, and each of these metrics was geolocated on a geographic information system (GIS)-based map to visualize the readiness of the roadways on these cross-country routes to support ADS technology.

3.3 FLEET INTEGRATION – WHITTIER, ALASKA

The introduction of automated heavy vehicles has the potential to revolutionize the transportation industry, offering unprecedented opportunities for freight efficiency and road user safety. As sensing technology advances and developers better understand the roadway system, integrating AVs into the industry becomes an increasingly attractive option. However, there are many implications for implementing ADS on public roadways or private yards. Implementing ADS at a fleet- or operations-level is a complex undertaking that requires careful planning, analysis, and data collection in defining the domain space and evaluating the impact automation has across all organizational levels.

The goal of this task was to thoroughly define the organizational elements as they exist at an operational level to better understand the implications of introducing ADS into an intermodal fleet operating heavy trucks for repetitive driving actions in a private yard. This goal was accomplished by collecting relevant observational and interview data and using those data to perform various task, risk, and organizational systems analyses. The objective for the approach is to establish a baseline evaluation of the organization at the operational level for future use in identifying the impacts of incorporating AVs. The analyses address both organization- and person-level elements and relate those across a macro cognitive model for human involvement within their tasks and roles.

3.3.1 Manual Truck Operations

3.3.1.1 Methods

Documentation Review: The research team was provided with a set of materials from the fleet describing the safety guidelines for all on-site personnel, as well as the training documentation for lift operators. These documents contained significant reference material to guide the research team's observations and questions while performing site walk-throughs and visits. The location of the site was in Whittier, Alaska.

Walk-through: The research team employed two distinct types of walk-throughs to collect data: a non-barge yard visit and an active barge video review. The non-barge yard visit took place during a period when a barge was not docked at the port in Whittier; therefore, there were fewer personnel in the yard, and work consisted of preparation for an active barge. The non-active barge visit allowed the team to gather contextual information, observe surrounding infrastructure, and interview personnel involved in the operations. The active barge video review involved reviewing recorded footage of a large barge off-load. The team closely examined barge operations, identified patterns, and extracted valuable data about various aspects of the process. By leveraging these two walk-throughs, the team aimed to gather comprehensive and complementary data that would contribute to a more holistic understanding of the research objectives.

Non-Active Barge Site Visit: During the non-active barge site visit, the research team viewed the location of important barge tasks during non-active hours and visited the yard office where the crew keeps their equipment. This effort provided the team with an overview of the layout of locations, as well as a general description of where activities would occur during active unloading periods. The walk-through provided the research team with an opportunity to observe performed tasks on-site as well as to interview personnel. Additionally, the site manager reviewed performance indicators around the yard, such as the number of picks off the barge per minute and the time taken for each trip.

Active Barge Activity Video Review: In addition to the site walk-through, the team viewed footage captured during the barge operations in the previous week. Management collects footage like this to review possible incidents or understand efficiency on the yard. The footage showed an aerial view of the yard facing the southwest corner near the crossing. The video supplemented the information the team gained from the site visit. During the site visit, the team saw where each high-traffic area was and the ideal movement of barge operations. However, the video illustrated more clearly how each of the vehicles, pedestrians, and cargo movement interacted. The aerial view and playback control allowed for an illustrative method of observing how inefficiencies can build up over time. Overall, the barge activity video helped the team build a mental model of the moving parts present during barge operations and served as good preparation for the on-ground observations.

Interviews: The research team performed nine employee interviews during the data collection period in Whittier. Interviews were semi-structured and primarily done in the field during active work. Participants included seven freight operator (FO) employees and included two truck drivers, three forklift operators, two maintenance workers, and one executive. Further, one safety driver and one engineer from an automation developer were interviewed.

On-Site Active Observation: The most valuable data collection came from observing active barge operations on-site. The team arrived on-site at 11:00 a.m. on April 20, 2023, as the barge and railroad crews arrived and observed operations for approximately 9 hours. It is important to note that during these observations, the weather was moderate with no ice or snow on the ground except the plowed piles left over from the previous week's storm. However, site personnel mentioned that inclement weather often impacts how efficiently barge operations work.

While the lifts were moving the empty containers and cargo brought in by the railroad, the team was positioned at the "crossing," or the narrow section of tracks separating the lower yard from the upper yard. During observations, the team had access to a radio channel used by lift operators so communications could also be noted. This vantage point allowed the team to understand how the lifts move across the yard, communicate with each other, and interact with the railcars while the crew waits for the rail to be pulled from the barge.

During the off-loading of both the barge railcars and containers, the team moved to a more central location midway between the stern ramp and the side ramp. This position gave a better view of how the lifts move on and off the barge to other locations around the yard. Additionally, this position was directly in front of where the trucks park while waiting to be loaded with a container. Therefore, the team had an excellent view of how the lifts interact with the truck during the off-load. Lastly, the team had the opportunity to ride along with the two truck drivers and one safety operator. The three team members each interviewed their respective driver and were able to learn what tasks the truck drivers are expected to complete during barge operations. Overall, the on-site active barge operations allowed the team to solidify what variables the trucks, lifts, and other personnel experience as part of the fast-paced barge off-load environment.

3.3.1.2 Sociotechnical System

Primary Organizations: The primary organizations working at the Whittier port are the FO and the State Operated Railroad Corporation (SORC). Our primary engagement was with the FO, the organization overseeing the barge operations at the Whittier port. The FO holds responsibility for various crucial components, including the barge, barge workers, shipment equipment, drayage trucks, lift equipment, lift operators, and overall logistics. All parts of the shipping process, up to but not including the transport of rail, are covered by the FO.

SORC is another crucial organization in the Whittier port activities. SORC is responsible for bringing empty containers and outgoing shipments to Whittier for the FO to handle, pulling rail from barges, setting up the rail for reloading, and transporting the bulk of the goods (~70%) out of Whittier to other locations in Alaska. Furthermore, the yard is owned by SORC, making them responsible for yard maintenance. Any snow removal or yard-related maintenance is at the discretion of the railroad.

One major difference between the SORC and the FO is the way workers are staffed for unloading barges. The FO employs a group of workers to live in Whittier on a rotating schedule of 4 days on and 3 days off. The FO employees have their room, board, and food covered while in Whittier and can earn unlimited overtime. SORC employees operate following government regulations and union contracts that prohibit working beyond 12 hours. The Rail Safety Improvement Act of 2008 provides strict guidelines for how often rail workers should be on and off duty.(1) Furthermore, rail workers commute to Whittier rather than living there for stretches of time.

The difference between the FO and SORC work culture can extend already long and challenging barge off-loading events. A barge needing 30 hours to unload, for example, will require three railroad crews. Three railroad crews mean potentially waiting for rail-critical actions, like setting up new lines of rail to be loaded with shipments, which may hold up the unloading process as staffing is found and crews shift in. In many cases, SORC crew shifts do not impact the barge unload, but in some cases, they can. The FO operators are trained to unload the barge quickly and safely. A tugboat can cost tens of thousands of dollars a day, so keeping tugboats from being held up can be essential.

Equipment:

- Trucks – The Whittier port activities rely on older trucks that have accumulated hundreds of thousands of miles. These trucks frequently require repairs to remain operational, with the exhaust system being one of the primary challenges. The trucks are primarily responsible for hauling substantial loads from the lower yard to the upper yard, making a low-speed, 1-mile loop. Transportation of heavy cargo within this distance is critical for the trucks' operations at the port. Nevertheless, low speeds and short distances do not allow Diesel Particle Filters (DPF) to regenerate efficiently. DPF regeneration occurs with either high-speed highway operations or driver/technician-activated periodic "burn-offs" of the DPF build-up to remain operational.

  Another challenge regarding the trucks used in Whittier is the difficulty of finding CDL drivers to operate them. The trucks observed were manual transmissions, requiring more knowledge to operate safely, and as equipped, could not be installed with ADS, which requires electronic gear control through automatic transmissions. Staffing for a weekly barge operation is difficult due to the short periods of operation and the unpredictable arrival of the barge each week. Finding experienced truck drivers to travel to Whittier for a variably arriving barge for an undisclosed amount of time can be difficult when truck drivers can make more consistent money transporting goods. Instead, the FO workers are expected to learn each role in the yard to be flexible in their placement based on the needs of the specific barge, including performing the job of a truck driver.

  The port operations currently use truck-tractors pulling double chassis trailer combination vehicles. In practice, this creates a longer vehicle for drivers to be cognizant of and a larger payload for each of the trucks to handle. More trucks with single chassis could fulfill the same cargo transportation requirements but would require more collective trips, would create more traffic in the yard, would require more staffing, and could create more maintenance needs.

- Lifts – Lifts play a vital role in facilitating the movement of shipments between the barge, railcars, and the yard. Due to the unique shape of the yard and the irregular shapes of some shipments received in Whittier, lifts are an essential tool in barge operations. The FO operators in Whittier primarily rely on fork and top pick lifts for barge operations. It is worth noting that various types of lifts exist, but these configurations are the key types utilized by the FO operators in Whittier.

The lifts used by the FO, at the time of this report, are Svetruck S1150s, which have several notable characteristics. First, the Svetrucks that FO operators use can carry 115,000 lbs. at once. Second, the two types of Svetrucks have different height lifting capabilities, with forklifts being able to stack containers up to five high and top picks being able to stack containers four high. Third, lifts do not have suspension in the way that passenger vehicles or freight trucks have suspension. Lifts have a three-point suspension system designed for carrying heavy loads to reduce the jostling of cargo.

- Railcars – The SORC manages all operations related to the railroad and owns the port where the FO operates. Optimally, the railcars used in the Whittier operation will arrive before or when the barge arrives. Once the railcars arrive, the FO lift operators work to remove and stage the empty containers and outgoing shipments from the railcars. The empties and outgoing shipments replace the now empty space on the barge and are subsequently sent to Seattle.

  The SORC has strict guidelines regarding the types and sizes of freight they accept for transport.(2) First, all shipments must conform to the current industry standards. Second, shipments must conform to one of the accepted sizes in the SORC load manual. The acceptable container lengths for rail shipments are 20, 24, 28, 40, 45, 48, and 53 feet. The acceptable platform lengths are 20, 24, 28, 40, and 53 feet. Rail cars can vary in size, but the primary sizes used in the Whittier operation are 89 feet and 56 feet.

- Barge – The main barge used in the Whittier shipping operation is a weekly vessel that starts its journey in Seattle. It typically takes around 8 days to reach Whittier, with the target arrival set for every Wednesday. These barges are 420-ft by 100-ft rail/container vessels designed to accommodate eight lines of rail and 32 rows of overhead storage.(3) It is important to note that the contents and organization of the barge change on a weekly basis.

  When the barge arrives in Whittier, the barge is docked and two ramps are set, one on the stern and one on the side of the barge. The stern ramp is where the rail is removed from the barge and lifts can access the port row of containers. The side (starboard) ramp is set after all of the rail is removed and gives lifts access to the starboard, port, and bow containers. See Figure 11 and Figure 12 for more information about barge layout.

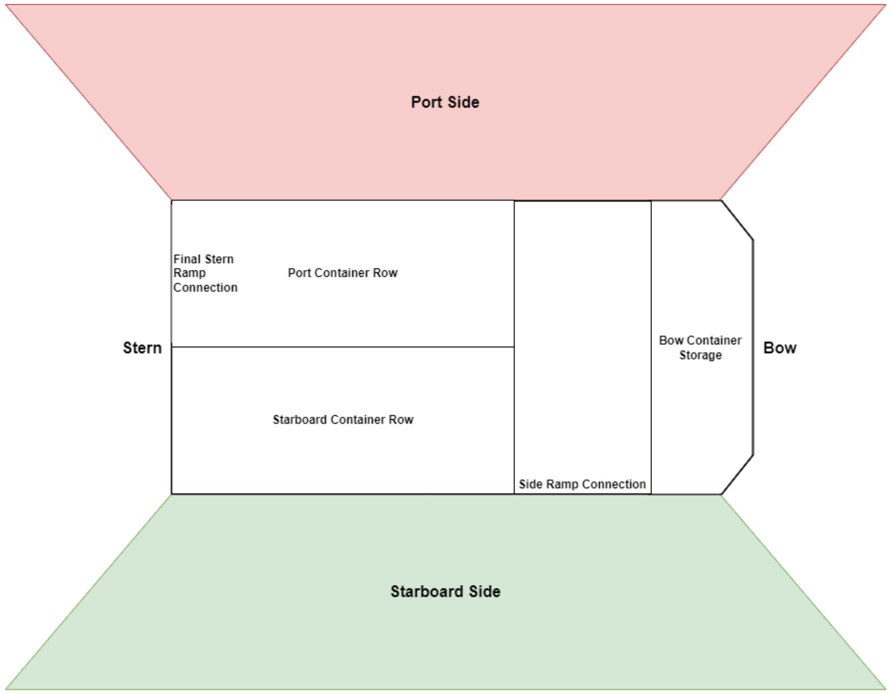


Figure 11. Diagram. A diagram of a barge with relevant locations labeled. The rail lines are located under the raised port and starboard container rows.

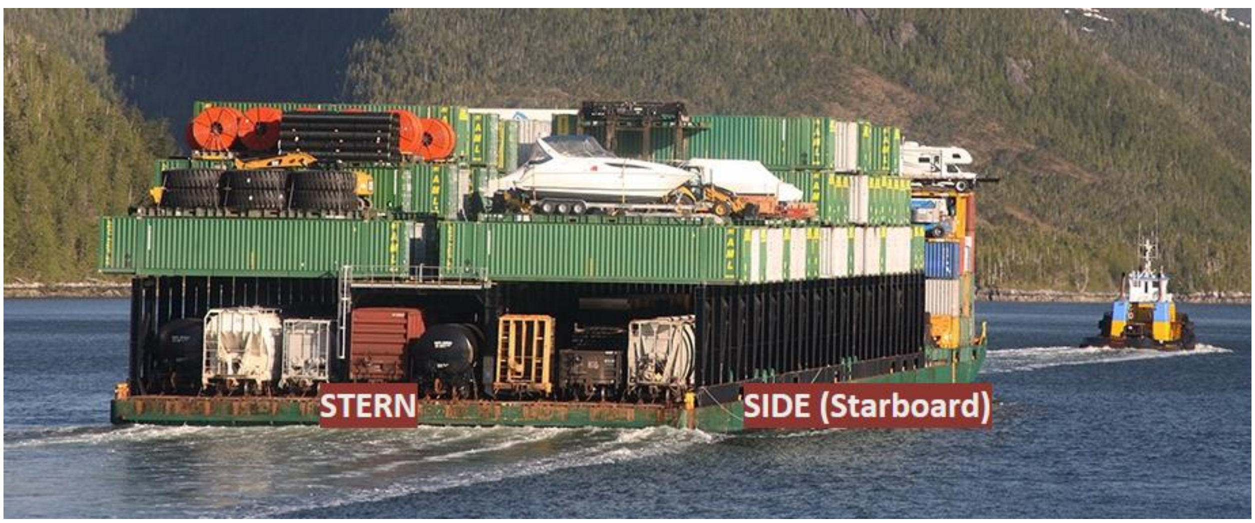


Figure 12. Photo. An image of a barge with the ramp connections labeled. (Source: Freight operator webpage.)

Location Description

Whittier is a port town with a population of 273, only accessible through a 2.5-mile, one-way, railroad-highway tunnel. Whittier is a prime shipping port for goods coming from Seattle by sea for several reasons: (1) To reach Anchorage by sea would take an extra two days; (2) Whittier is a deep-water and ice-free port; and (3) The town provides easy transportation through rail, road, or sea to Valdez, Anchorage, Cordova, and Fairbanks. Whittier provides a good location for receiving and sending shipments to the lower 48 States via Seattle. However, despite the location being ideal in terms of geography, the climate and port layout are essential to consider.

The climate in Whittier poses challenges for transporting barge shipments. While Whittier Port is one of Alaska's few year-round, ice-free ports, the combination of rain, wind, and snow throughout the year creates difficult working conditions for lift and rail operators. Whittier receives an annual precipitation of 196 inches of rain and 241 inches of snow, accompanied by winds commonly reaching 40–60 mph.(4) This situation leads to less-than-ideal snow storage locations, exacerbating the difficulties faced by workers and trucking operations.

The port layout in Whittier is also less than ideal. According to several lift operators, the ideal port for receiving shipments has ample acreage near the barge, has storage areas for containers, and minimizes distances that lifts need to travel. The Whittier port is narrow and long and has limited areas to store containers, which leads to long distances for lifts to move shipments to reach the train cars. According to Google Maps, a round trip from the barge to the train cars is approximately 1 mile. This round trip becomes problematic for lifts, as the extra driving distance increases exposure to risk for yard workers, increases lift tipping risk, increases the wear on lifts, increases the amount of time for barge unloading, and introduces an additional potential for shipment damage as lifts do not have shocks. More details regarding the port layout are given below in Figure 13.

Maps Data: Google, ©Airbus, CNES/Airbus, Maxar Technologies, Municipality of Anchorage

Figure 13. Map. A Google Maps capture of the Whittier Port yard with primary locations labeled. Green star = lower yard, green line = lower main track, red star = upper yard, red line closer to water = upper bay track, red line closer to bottom of picture = upper mountain, orange rectangle = the crossing. The ITB is the Integrated Tug/Barge where shipments for Cordova/Valdez are placed.

The Whittier Port yard is an area extending from east to west. Apart from the barges, the port can be divided into two primary areas: the lower yard (green) and the upper yard (red). Most lift operations occur in the lower yard, also known as the “Southside” among operators. The upper yard, sometimes called “Northside,” is where the train cars are loaded with Alaska-bound goods unloaded from the barge. Currently, the lower yard is utilized for loading trucks, specifically two double chassis trucks. The barge unloading process typically involves one forklift operator and two top-pick operators, although additional operators may be involved. Upper-yard operations usually consist of one top pick operator unloading the cargo transport trucks. During the observation of the operations, three top picks and two forklifts were present in the yard.

The upper and lower yard can be subdivided into specific areas based on the work performed. Within the upper yard, three notable locations exist: upper bay, upper mountain, and “no man’s land.” Upper bay refers to the rail line closer to the bay, while upper mountain designates the inland rail line. These locations are indicated as red lines in Figure 13. Approximately 70% of the cargo unloaded from barges is loaded onto these rail lines, heading westward out of Whittier. No man's land is the central area within the upper yard, between the upper bay and upper mountain rail lines. No man’s land is a storage space for various items, including occasional snow accumulation, and creates a loop that cargo transport trucks must navigate to return to the lower yard.

In the lower yard, there are two specific locations where shipments bound for Alaska are sorted. The first is the Integrated Tug/Barge (ITB), a smaller barge transporting goods across Prince William Sound to Valdez and Cordova. The second location is the “lower main” line of rail. Although the ultimate destination may vary, the FO operators typically reserve this rail line for shipments heading to Fairbanks, Alaska.

The crossing is a section of recessed rail operators need to cross to transition between the upper and lower yards. The crossing is a critical junction in the yard where visibility is limited for truck and lift operators. Furthermore, when approaching the crossing from the lower yard, drivers are ascending a small incline, requiring trucks to increase their acceleration to get over the crossing when fully loaded. The crossing is colored in orange in Figure 13.

Primary Actors: Outside of the equipment and location, there are various actors and job roles that are essential for unloading a barge. The two primary groups working in the yard during a barge unloading are the FO and the SORC. Table 1 outlines the primary actors from each group present on the yard during operations.

Table 1. A list of the relevant actors related to unloading barges. The quantities and descriptions are those of a typically operating environment, not a hard and fast rule.

Actor	Quantity	Description	Organization
Forklift Operators	1	A forklift operator is typically the most experienced operator in the yard. A forklift can lift a wider variety of cargo, making their placement more important. Forklifts also require a higher skill level than top picks due to greater risk of dropping cargo off the forks.	FO
Top-pick operators	3	Typically, two in the lower yard unloading items from the barge and one in the upper yard transferring cargo from the trucks to train cars.	FO
Truck Drivers	2	These drivers may be lift operators who do not have a CDL. This is a hard position to fill with temps or part-time truck drivers, as the barge only comes weekly and the drivers would need to go to Whittier. Additionally, more money can be made with a CDL in other careers. The truck drivers drive in a loop from the side ramp to the upper yard and back.	FO

Actor	Quantity	Description	Organization
Yard Lead	1	Also known as the "person in charge," the yard lead manages the yard activities on the FO side. The yard lead watches for safety violations, manages efficiency, and makes operational calls.	FO
Maintenance	2	Maintenance personnel are on standby for any emergency repairs that may be required during operations.	FO
Barge Crew	# Set by Barge Manager	The crew that works on and arrives along with the barge.	FO
Safety Driver	1	In charge of the AV. Sets the vehicle path and manages system validation.	FO
Railroad Crew	# Set by SORC Manager	These are the railroad personnel responsible for rail-related operations, such as setting rail, pulling rail, and reorganizing rail. The railroad is also responsible for yard maintenance; e.g., snow removal. The yard typically sees two crew changes in one barge unload.	SORC

3.3.1.3 Activity Overview

To fully understand the interaction between the personnel, equipment, and processes during a barge off-load at Whitter, an overview of general operations is needed. The primary goal of the operation is to offload full containers from the barge onto the railcars to send off via train. There are subprocesses that support this goal. It is important to note that all railroad operations are handled by the SORC. The barge arrival time is tracked so that the SORC staff and outgoing railcars ideally arrive at the same time as the barge.

The first step in the process for the FO is to off-load the railcars entering Whittier from Anchorage. Empty containers and outgoing freight are removed from the railcars and stored at various places in the yard to allow incoming freight from the barge to be loaded onto the railcars. Simultaneously, the FO crew and barge operators work to secure the barge to the dock so SORC can begin removing the railcars from the barge. The rail cars need to be removed from the barge before any freight can be taken off by the lifts.

Once the railcars are clear to be reloaded with freight, the crew has a safety briefing. During this time, the SORC crew completely remove all the railcars from the barge. After the briefing and all railcars are removed, the forklift operator removes the barrier between the barge and the dock, then places and secures a ramp to allow the lifts access to the barge. Once the side and stern ramps are secure, the process of removing the freight from the barge begins. This freight is moved to various places around the yard, including the upper yard to load onto rail, the upper yard to load onto truck chasses, the ITB, rail for other destinations, on the yard for temporary placement, and the FO-based equipment for use or storage at Whittier. After the barge is fully off-loaded, the empty containers and outgoing shipments brought in by rail are backloaded to the barge returning to Seattle. Figure 14 illustrates this high-level workflow.

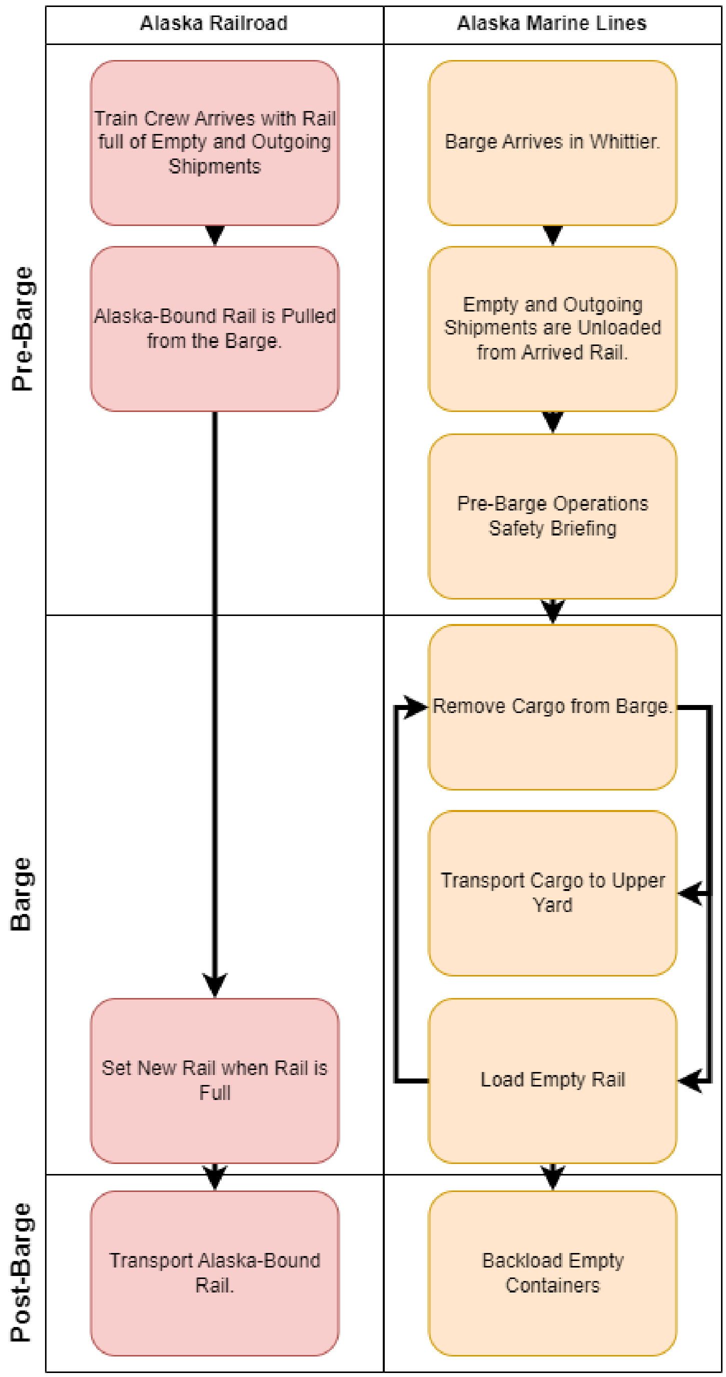


Figure 14. Diagram. A high-level workflow of the entire process from the barge's arrival in Whittier to before the barge's departure. The left lane pertains to the activities the SORC performs, and the right pertains to the activities the FO performs. Some activities, like the FO barge activities, are cyclical and repeat until all of the cargo is unloaded from the barge.

3.3.1.4 Detailed Activities

With Whittier being such a diverse port, there are many tasks completed simultaneously to support operations. The high-level workflow above represents many of these tasks; however, the main purpose of this analysis is to capture the tasks related to the trucks being used to move freight from the barge to the upper yard, which only represents a piece of these operations. Therefore, the following sections break down these higher-level tasks into pre-barge, barge, and post-barge activities, where only the truck-relevant tasks are described in greater detail.

Analysis Approach: Beyond capturing the workflow, the team also analyzed the workflow using an approach inspired by the macrocognitive perspective and Human Reliability Analysis (HRA).[5,6,7] The macrocognitive model was designed as a naturalistic model of cognition. Rather than focusing on finite components of cognition, macrocognition focuses on categories of processing and action that occur in real-life settings. The macrocognitive model breaks human processing into five major components: Detecting, Sensemaking, Decision-Making, Action, and Coordination. The macrocognitive components are interactive but independent components of the greater system of cognition. For example, detected objects can feed into decision-making, but do not need to.

HRA is another perspective infused into the analysis approach. HRA employs a concept called Performance Influencing Factors (PIFs) to help predict failure or human error (see Table 2). PIFs are contextual, circumstantial, organizational, and individual factors contributing to human performance.[8] For example, some common PIFs include task complexity, time pressure, attention, and stress.[9] While some PIFs are commonly found in diverse HRA methods, many methods are domain specific. Still, integrated frameworks attempting to generalize PIFs for HRA have been proposed.[10,11] See Table 2**Error! Reference source not found.** for an example PIF t able.

Table 2. Example PIF table adapted from reference 9. The PIFs captured in this table are combined from multiple HRA methods applied in the nuclear power industry.

Organization-based	Team-based	Person-based	Situation/stressor-based	Machine-based
Training program	Communication	Attention	External environment	Human-system interface
Availability	Availability	To task	Conditioning events	Input
Quality	Quality	To surroundings	Task load	Output
Corrective action program	Direct supervision	Physical and psychological abilities	Time load	System response
Availability	Leadership	Alertness	Other loads	
Quality	Team coordination	Fatigue	Non-task	
Other programs	Team cohesion	Impairment	Passive information	
Availability	Role awareness	Sensory limits	Task complexity	
Quality		Physical attributes	Cognitive	
Safety culture		Other	Execution	
Management activities		Knowledge/experience	Stress	
Staffing		Skills	Perceived situation	

Organization-based	Team-based	Person-based	Situation/stressor-based	Machine-based
Scheduling		Bias	Severity	
Workplace adequacy		Familiarity with situation	Urgency	
Resources		Morale/motivation/attitude	Perceived decision	
Procedures			Responsibility	
Availability			Impact	
Quality			Personal Plant	
Tools			Society	
Availability				
Quality				
Necessary Information				
Availability				
Quality				

The goal is not to include a full range of PIFs that can be applied in every circumstance related to barge unloading. Instead, the goal is to help identify many of the core factors that non-human factors professionals can apply. Furthermore, the tables we include in subsequent sections do not constitute a comprehensive list of all PIFs that can impact yard work but rather list some of the most crucial PIFs related to yard work. A PIF-oriented macrocognitive approach provides a detail-oriented and empirically backed method for understanding the threats to performance, no matter the task.

In the rest of this section, we explore each component of the approach we apply to analyze the workflows. First, we examine Detection, then Sensemaking, Decision-Making, Action, and Coordination. In each section, we define the cognitive process and then highlight threats to the successful completion of the process based on literature and expertise. Please note that the primary focus is to outline and analyze the tasks performed on the yard at the port in Whittier, and a full review of human performance factors is beyond the scope of the paper. The detailed analysis of the overall workflow will refer to the threats of completion highlighted for each process.

Detection: Detection includes the process of filtering an immense amount of information and noticing relevant stimuli in the environment.(12) In contrast with traditional cognitive psychology, detection in macrocognition includes sensation, attention, and perception while taking a more practical look at how people perform in complex environments outside of laboratories.(13) For example, a driver must sense, attend, and perceive a pedestrian to predict the pedestrian's behaviors and decide how to act. The yard where lift and truck operators work contains a host of moving objects and numerous threats to detection. Note that detection includes auditory, visual, and other modes of sensing the environment.

One aspect of failures that is important to note is that error likelihoods are extremely low.(14) Specifically, the likelihood of the individual not detecting a specific object, especially a relevant one, is quite low. Accidents and failures are a result of multiple failures in a system that compound on one another.[15,16] Table 3 lists potential threats to performance for detecting pertinent environmental information.

Table 3. Environmental, human, and object characteristics that impact a worker's ability to detect objects. The example risks are extracted from a combination of references 7, 10, and 11, manuals provided by the FO, and observation by human factors professionals.

Risks to Detection	Description
Ambient Noise	Background noise not related to the important information can interfere with picking up important auditory signals – e.g., a walkie-talkie chirp.
Attention	Inattention can lead to workers missing important information in their environment – e.g., a pedestrian in the yard.
Experience	Experience can inform where to focus attention, whereas inexperience can do the opposite.
Fatigue	Physical and/or mental weariness from the lack of rest, high-task demands, or overexertion can lead to poor object detection (lower attention capability).
Low Visibility	Low visibility, from fog or darkness, can reduce the likelihood of detecting a work or safety-relevant item in the environment.
Object Salience	How noticeable an object is may impact how likely someone is to detect the object. For example, safety vests increase salience by increasing luminance and using a bright color.
Occlusions	Obstructions in the yard can block operators from detecting relevant information in their surroundings – e.g., vehicles can block other vehicles from view.
Stress	Stress, caused by work or personal life, can create a lapse in attention and missed detections.
Workload	The more information a worker needs to process to complete their job, the more likely they are to miss relevant information in their environment.

Sensemaking: Sensemaking is the process of interpreting perceived information using experience and context to generate understanding of a situation.[17] In other words, sensemaking is making sense of our environment and building situation awareness. The process of sensemaking ranges from fast, automatic processing to slow, effortful thinking, and includes forming explanations, projecting future states, seeing relationships, and identifying problems.[18,19] Situation awareness and a good mental model of the yard state are paramount for yard operators to perform their job safely and efficiently. See Table 4 for more information about risks to sensemaking and how performance is impacted.

Table 4. Various characteristics that impact a worker's ability to make sense of their environment. The example risks are extracted from a combination of references 7, 10, and 11, manuals provided by the FO, and observations made by human factors professionals.

Risks to Sensemaking	Description
Attention	Attention to a task will increase an individual's ability to pick up on crucial information to make sense of their environment.
Experience	Experience helps yard workers know which information is relevant. This repeated exposure helps workers translate the complexity of yard work and can increase situational awareness.
Failed Detection	Workers can fail to make sense of a situation when critical information is lost during detection.
Fatigue	Physical and/or mental weariness decreases the ability to connect information and a good mental model of a situation.

Risks to Sensemaking	Description
Human-Machine Interface (HMI)	The design of the HMI can impact a worker's understanding of the system's states.
Incorrect Detection	Workers can fail to make sense of a situation when incorrect information is collected during detection.
Motivation	Low motivation can lead to poor use of contextual information and an inaccurate mental model.
Stress	Stress can reduce a worker's ability to focus on relevant information to make sense of their situation.
Training	Poor training can lead to a poor mental model of work and lead to inaccurate assumptions.
Trust	Low trust in other teammates can lead to reduced accuracy of contextually accurate mental models and situational awareness.
Workload	Increased cognitive resources to complete a task can reduce a worker's ability to unify contextual information and form a good mental model.

Decision-making: Decision-making is the cognitive process of choosing between different possibilities.[20] Despite the straightforward definition of decision-making, the cognitive process is complex. Decision-making can be quick and automatic or slow and resource intensive.[21] Decisions related to practiced activities tend to become more automatic and rely heavily on knowledge from previous experiences.[22] On the other hand, less exposure to a situation forces a greater reliance on the information absorbed from the environment, experience, and the ability of an individual to think through potential decision outcomes.[23] For yard operators, where information is constantly changing, decision-making can be impacted by various environmental and individual characteristics. Table 5 lists how different human and environmental characteristics can impact decision-making ability.

Table 5. Various characteristics that impact a worker's ability to make decisions. The example risks are extracted from a combination of references 7, 10, and 11, manuals provided by the FO, and observations made by human factors professionals.

Risks to Decision-making	Description
Expectation	A separation between reality and what an individual expects can lead to poor decision-making. The wrong mental model of a situation can lead to inaccurate application of rules and procedures.
Experience	Experience and the building of expertise can lead to more efficient and accurate decisions.
Fatigue	Mental and/or physical weariness has been found to negatively impact decision-making.
HMI	The design of alerts that provide workers with system information can impact the way decisions are made.
Incorrect Sensemaking	Misinterpreting a situation can lead to less efficient or incorrect decision-making.
Personality	Individual characteristics, such as impulse control, can impact decision-making ability.
Safety Culture	A poor safety culture can lead to less invested decision-making by workers, potentially reducing safety.
Stress	Stress can reduce the efficiency of decision-making when too much or too little is present. Both too little and too much stress can lead to poor performance.
Training	Lack of proper training can lead to an incorrect mental model of a situation, which can then lead to poor decisions.

Workload	Fewer cognitive resources can lead to poorer decision-making, as decision-making can require extensive cognitive resources.

Action: Action encompasses observable behaviors performed by an individual. Actions do not include the underlying cognition that led to the action but are limited to the execution of physical behavior.(24) For our purposes, this means the only errors falling into the category of action would be related to execution failures and would not include decisions leading to the action.(25,26) Reaching for one button but overshooting and hitting another or putting a vehicle in Reverse instead of Drive are good examples of execution errors. The intended action is performed incorrectly, no matter the correctness of the decision. Table 6 describes the impacts to the successful performance of actions.

Table 6. Various characteristics that impact a worker's ability to perform an action. The example risks are extracted from a combination of references 7, 10, and 11, manuals provided by Lynden, and observation made by human factors professionals.

Risks to Action	Description
Attention	Inattention can lead to inaccurate motor movements or slips of behavior.
Experience	The more experience someone has performing an action, the more automatic behaviors become. Inexperience can lead to less efficient and less successful behaviors.
Fatigue	Physical and/or mental weariness can lead to less efficient visual acuity, attentional capability, and motor accuracy.
Human-Machine Interface	A poorly designed interface can lead to poorly executed actions. For example, a poorly designed interface might not space buttons out appropriately and lead to mis-pressed buttons.
Road Conditions	Poor road conditions can include ice, potholes, or other contextually relevant factors. For example, slick roads can lead to poor traction, which can lead to poorly executed vehicle maneuvers.
Stress	Stress can create urgency in actions, potentially reducing accuracy.
Training	Lack of training can lead to less safe and more inefficient and ineffective actions.
Temperature	Colder temperatures, or bulky clothing due to temperature, can impact physical sensation and motor control, making actions more difficult to complete.
Vibration	Vibration can add variation to physical actions through repetitive physical movement. Vibration can also cause fatigue and physical stress.
Wind	Wind can be an issue for lift operators, as the wind can impact the stability of lifted containers, especially light and empty ones.
Weather	Weather conditions, including temperature, wind, and precipitation, can impact motor control and action execution.

Coordination: Coordination includes the processes related to people adjusting their behaviors to others in order to reach a common goal; this is similar to the Teamwork component in reference 7.(27,28) Coordination takes all of the other components in the macrocognitive process and places them in the context of teamwork, where work cannot be completed independently. Regarding a shipping yard, at least two trucks and five lift operators perform various duties around each other and must coordinate their movements to accomplish the common goal and avoid accidents or injuries. Communication, verbal and nonverbal, is critical for coordination efforts. See Table 7 for a list of risks to coordination performance.

Table 7. Various characteristics that impact a worker's ability to coordinate with others. The example risks are extracted from a combination of references 7, 10, and 11, manuals provided by the FO, and observations made by human factors professionals.

Risks to Coordination	Description
Attention	Lack of attention can increase the likelihood of missed visual and auditory communications. Inattention can also lead to poor situational awareness and therefore poor coordinated efforts.
Ambient Noise	Ambient sound can block auditory communications that are important for coordination.
Equipment Failure	Equipment failures on the yard can lead to unplanned reduction in manpower and access to work. Communication equipment failure can leave teammates without proper knowledge about the progress on the yard.
Experience	Experience can impact frequency and quality of communications as well as shape the forms of coordination.
Fatigue	Physical and/or mental weariness can lead to difficulty maintaining situational awareness and staying apprised of coordinated efforts.
Stress	Stress, internal or external, can create inattention, missed communication, and poor situational awareness.
Low Visibility	Low visibility reduces the ability for visual communication and situational awareness.
Role Awareness	Role awareness is important for workers to stay coordinated with others. Performing the correct duties at the correct time in relation to others is important for group work.
Safety Culture	Safety culture can impact the way workers take risks around other workers in the yard.
Training	Poor training can lead to a poor mental model of work in the yard and potential errors. For example, determining who has the right-of-way in relation to trucks, pedestrians, and lifts.
Workload	Higher workloads can lead to a reduced ability to stay engaged with relevant information to stay coordinated with others.

3.3.1.5 Macrocognition Examples in the Workflow

The following sections are broken into three major categories to provide specific examples for each of the barge tasks. First, we discuss everything that occurs before the barge unloading takes place, up to and including the setting of the side ramp. Second, the unloading of the barge is discussed. Finally, we discuss the post-barge activities, or the work occurring after the barge is unloaded. The analyses are limited to examining the FO employees, primarily the truck and lift operators. While SORC operations are critical for successful yard and barge operations, the primary goal is to capture the interactions between the trucks and lifts. Each section details specific instances of the risks to macro-cognitive processes pertaining to barge activities.

Pre-Barge: Before unloading the barge, the FO and the SORC must complete several tasks. While workflow information pertaining to the inbound rail being pulled from the barge by SORC, the pre-barge operations safety briefing, and the setting of the side ramp are included in the pre-barge tasks, the focus for pre-barge activities is the unloading of empty containers and outgoing shipments from the rail brought in by the SORC. In other words, the work done by the FO lift and truck operators working in the yard are the focus of the pre-barge tasks.

Pre-barge activities rely on several moving parts to operate smoothly. First, the arrival time of the barge is highly dependent on the weather patterns and can vary greatly. Second, the arrival time of SORC impacts the timing of almost all the other work in the yard. The SORC arrives in Whittier with empty containers and outgoing shipments that must be unloaded into the yard or loaded onto the barge. The rail SORC arrives with is the same rail that the FO loads for shipments coming into Alaska from the barge. The ideal timing is for the barge and SORC to arrive around the same time so that the rail can be pulled from the barge as the FO empties the arrived rail.

Rail Is Pulled from Barge: SORC pulling the incoming rail from the barge is a critical step in the pre-barge activities. The barge arriving in Whittier from Seattle typically has eight lines of rail that need to be removed before the FO can start unloading cargo with lifts. The removal of the rail can take several hours (3 hours during our observations). During this time, the FO is unloading the empty containers, and outgoing shipments from the SORC into Whittier.

Pulling the rail from the barge is an involved process. Once the barge arrives, the barge crew from the FO sets to work on unlocking the rail from the barge. As each line of rail is unlocked, SORC uses winches to push and pull the barge so that the unlocked portion of the rail on the barge lines up with the rail on the stern ramp. Once the rail is aligned, a locomotive is attached, and the rail is pulled from the barge. The process of aligning the rail, attaching the rail to a locomotive, and pulling the rail off the barge is repeated until all the rail has been removed. See Figure 15 for a diagram of the process.

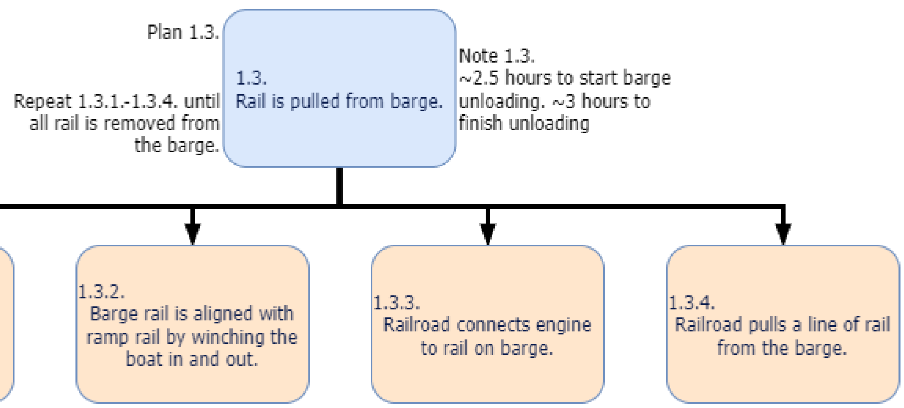


Figure 15. Diagram. A high-level hierarchical task analysis of rail being pulled from the barge.

Before any other cargo can be removed from the barge, all the rail needs to be removed. This step typically happens concurrently with the FO removing the empty and outgoing containers from the rail brought to Whittier by SORC. Any delay in the pulling of rail from the barge can delay the rest of the process and, depending on the speed of the lift and truck operators in removing the containers from the rail, can lead to significant downtime for the FO yard operators. This potentially compounds fatigue occurring during the barge unload.

Empty and Outgoing Containers Are Unloaded from Rail: Once SORC has arrived with the outgoing shipments and empty containers on the rail, the FO lift team can begin removing containers from the rail. Typically, lift operators remove containers from the rail and place them in various staging areas in the yard. This process relies heavily on experience, understanding the cargo's final destination, and knowledge of the barge unloading procedure. For example, empty containers may be placed in an area of the yard that is unused during barge unloads but close enough to the barge where, if the empty containers are being backloaded (loaded onto the barge after incoming cargo is removed), they are easy to access. At the same time, outgoing shipments need to be stacked in specific ways to avoid damaging any containers or causing any interactions between the contents of the containers, but also so that they are out of the way for other operations. This procedure is performed by top pick and forklift operators; no trucks are involved in this process. See Figure 16 for a workflow diagram of the entire process.

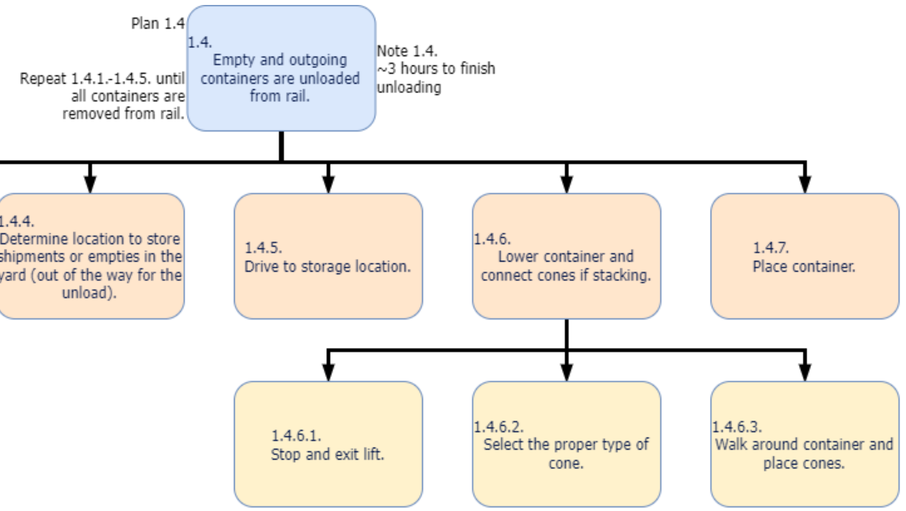


Figure 16. Diagram. A high-level hierarchical task analysis of unloading the empty and outgoing containers from rail. This task is completed by lift operators.

Removing empty and outgoing containers from the arrived rail is critical to the efficient operations of later barge activities. While off-loading the arrived rail is straightforward and occurs early in the lift operator's workday, experience is an operator's friend. Where to place the cargo in the yard, the proper procedures for stacking containers safely, and clear communication are all critical for safe operations. In the following sections, we will assess the macrocognitive levels associated with off-loading the arrived rail and preparing the yard for off-loading the barge. Example risks for each macrocognitive level will be discussed.

Macrocognition and Unloading Empty and Outgoing Containers from Rail: Detection is a fleeting but critical safety component and occurs repetitively throughout all the subtasks identified for unloading empty and outgoing shipments from rail (see Figure 16). Anytime an operator interacts with their environment, detecting relevant information is critical. While driving, an operator needs to be aware of pedestrians, other vehicles, road conditions, equipment state, and debris in the yard that could become dangerous. While lifting containers, operators must detect connection points for their lift, cargo placards, pedestrians, and other vehicles nearby. Detection is constant.

There are various risks to detection, as outlined in Table 3, and all are pertinent. Fatigue can serve as one example. Since the off-loading of the incoming rail occurs early relative to the scope of barge-related activities, work-related fatigue is less of a contributing factor to detecting safety or job-critical objects in the yard. However, non-work-related fatigue can still detrimentally impact detection ability. For example, if a barge arrives at 2:00 a.m. and operators are not used to working at that time, fatigue due to poor sleep could contribute to less competent detection. Object salience could provide another example. The salience of objects can serve as a second example. Pedestrians walking through the yard need to make themselves as visible as possible by using reflective safety gear and appropriate lighting for the conditions. Vehicles driving in the yard are expected to use a flashing beacon. Missing safety gear on vehicles or pedestrians and poor lighting conditions can reduce the likelihood of detection by lift operators. On top of that, detection can be challenging for lift operators because of the poor field of view available from lifts. Different locations in the yard will have different environmental hazards and threats to object detection.

Sensemaking is relevant for any detected object, but our analysis will focus specifically on the subtasks outlined in Figure 16. Sensemaking is especially relevant for choosing what containers to unload, determining where to store shipments and containers in the yard, and connecting cones if stacking cargo. While all the risks to sensemaking from Table 4 are relevant, experience and training are especially relevant here. Knowing what containers to remove from the train and where to put them requires understanding the barge unloading procedure, knowing the accessible areas in the yard, and having an accurate mental model of other operators' work. Training can bridge this gap, but experience is required for the most efficient and accurate understanding of where to store cargo. The same is true for knowing which stacking cones to use and where to place them on cargo if stacking in the yard.

Decision-making is most relevant for choosing containers to unload and determining where to store them in the yard. While sensemaking focuses on the understanding of the most efficient objects to take and understanding where they can go, decision-making focuses on the actual end choice made. Some relevant examples of risks to decision-making from Table 5 are experience and stress. Experience, like in sensemaking, can help guide operators to the best choice of location for storing empties or outgoing shipments. Communication and training may be able to make up for lower levels of experience, but less experience can lead to less efficient decisions. Stress, on the other hand, can create a sense of time urgency, where choice of cargo to take from the train and storage location can be less than optimal for backloading.

Action, like detection, is a constantly applied aspect of the macrocognitive approach. Actions are being taken for all subtasks, except choosing containers and determining where to place them, as identified in Figure 16. Some relevant examples of risks to action execution from Table 6 include weather and fatigue. During icy conditions, forklift operators need to be cognizant that their load does not slip off their forks. This is especially true when roads might be slick, and fatigue slows their reaction time. If a forklift operator were to slam on their brakes while driving over the crossing to the lower yard because of an oncoming vehicle, their cargo could slip off their forks.

Coordination is an overarching issue that permeates all tasks. All subtasks identified for unloading empty and outgoing containers from the rail include working around and with others. Some relevant examples of risks to coordination from Table 7 include training, role awareness, and visibility. Training can help give lift operators a sense of what vehicles have the right of way, how to drive around other operators, and how to communicate with other operators. However, low visibility can impact the ability of operators to communicate and predict each other's behaviors nonverbally. For example, another lift operator making eye contact can be a powerful cue of mutual awareness. Role awareness can also help direct other actions like knowing what objects the forklift operator needs to handle.

Pre-Barge Operations Safety Briefing: Prior to barge operations, the FO personnel involved in the off-loading meet to perform a safety briefing. The briefing is an important safety precaution to ensure all team members know what to expect during the off-loading. The team discusses any difficult cargo or known hazards that may be present, identifies possible unsafe conditions such as weather, and ensures that the person in charge (PIC) is clearly identified. The team also checks personal protective equipment, communication devices, and safety barriers. See Figure 17 for more information on the workflow.

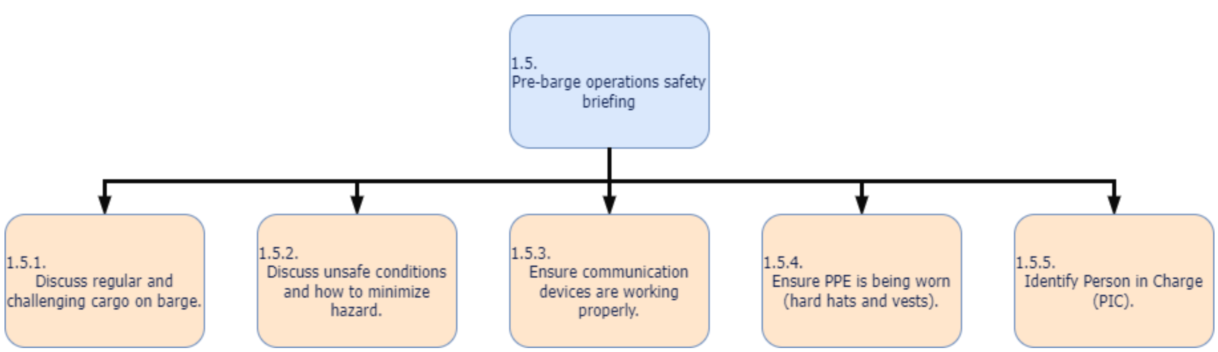


Figure 17. Diagram. A high-level hierarchical task analysis of pre-barge operations safety briefing.

The safety briefing is an important time to review best practices in order to prevent errors caused by complacency. Additionally, the safety briefing allows the yard manager to highlight any potential hazards in the yard, such as new potholes or poor visibility due to weather. Lastly, based on interviews with the lift operators, most operators rely heavily on experience to guide their decisions. Therefore, these safety briefings give more experienced operators time to guide newer employees.

The safety briefing acts as a barrier to safety incidents, improves efficiency, and sets an expectation of safety before operations. However, while the overall impact of the safety briefing is likely positive, something to consider is the amount of information communicated. An overload of new information can cause an additional mental load on less experienced operators. Less experienced operators are already coping with additional load, as they are performing their duties with less exposure to typical yard operations. For example, a newer employee may be so focused on properly tilting their lift while driving around three other operators in the yard that they forget about a pothole discussed during the safety briefing. On the other hand, more experienced employees are more likely to absorb and apply more of the information passed on in a safety briefing. This is not to say that safety briefings are a problem or should omit crucial information but rather serves as a reminder that it is good to be aware that holding onto new information is difficult while performing an unfamiliar task. The safety briefing is a critical component of safe yard operations.

Forklift Operator Sets Side Ramp: During the rail off-load process, the barge is moved a considerable distance, via winches, from the edge of the side dock. This leaves a large gap between the boat and the dock where equipment or personnel could easily fall into the water below. To prevent accidents like this, a large, metal frame barricade is placed between the edge of the dock and the side ramp.

After the SORC crew communicates to the FO crew that all of the rail is off-loaded from the barge and the team has their safety meeting, the forklift operator performs an action called "setting the side ramp," where the operator moves the frame barricade out of the path and pushes the side ramp up against the side of the barge so the lifts can begin off-loading cargo. Setting the side ramp typically happens very early in the operation where, ideally, the effects of fatigue and vigilance decrement have not set in. However, the simplicity of this task may leave the forklift operator vulnerable to complacency, as the operator must remain vigilant to possible hazards while carrying the heavy barricade. Still, there is an extremely low likelihood that this step could go wrong. The completion of this step marks the end of pre-barge operations, and the activity now transitions to barge operations.

Barge: The barge activities begin once the lift operators can begin removing cargo from the barge and end after the last container is removed. The three main components of barge activities are removing the cargo from the barge, transporting the cargo to the designated yard location, and placing the cargo in the designated yard location. These activities occur cyclically for each cargo item removed from the barge.

There are several locations that cargo can be brought to depending on the eventual destination. Generally, cargo can be delivered to the upper yard rail, the lower yard rail, and the ITB. The ITB cargo is always reserved for cargo delivered to the cities of Cordova and Valdez in Alaska. The other locations can be designated for delivery to other parts of Alaska, such as Fairbanks or

Anchorage. About 70% of the containers are delivered to the upper yard on the rail, which is called the "Upper Bay Track." See the map in Figure 13 for a better idea of the yard layout.

Remove Cargo from Barge: After the side ramp is set and the forklift operator removes the barrier, the lift operators begin removing the cargo from the barge. There are two main access points on the barge where lift operators can remove cargo: the side ramp and the stern ramp. The stern ramp provides access to the portside row of containers, whereas the side ramp provides access to both rows of containers and the bow containers. Lift operators choose the ramp they will use to access the cargo based on the cargo availability for their lift types, the cargo's end location, and congestion in the yard and on the barge. Typically, there are four lifts in the yard: two top picks unloading the barge, one top pick unloading the trucks in the upper yard, and one forklift floating between locations based on non-pickable cargo. See Figure 18 for a more detailed task description of removing the cargo from the barge.

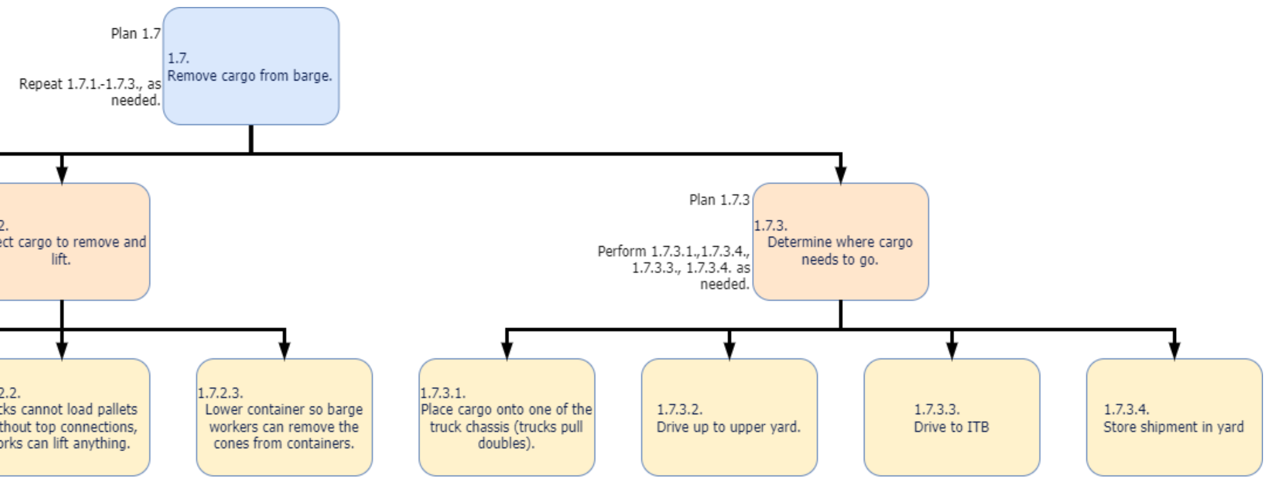


Figure 18. Diagram. A high-level hierarchical task analysis of removing the cargo from the barge. Note: task 1.7.3 can be broken down significantly more but was trimmed for space. This task is primarily done by lift operators, but trucks can be a core component of 1.7.3.

There are several notable aspects of barge unloading. First, the forklift operator is typically the most experienced lift operator on duty because this is the only type of lift that can move irregular cargo. Whenever non-pickable cargo is accessible on the barge, the forklift operator tries to move the cargo to avoid blocking any work the top picks can handle. The added responsibility can lead to forklift operators frequently moving between different locations in the yard. The forklift can also be more challenging to operate, as the metal forks can become slippery with ice, making carrying objects more difficult in inclement weather.

Second, the lift operators must make various decisions based on the location of other lifts, the types of cargo available for unloading, the locations to which the cargo needs to be brought, and the availability of trucks. If the cargo must go to the ITB or the lower main rail (see Figure 13 for a map), the lift operator will drive the cargo without the trucks. If the cargo needs to go to the upper yard, the lift operators will try to place the cargo on one of the trucks if one is available. If a truck is not available, the lift operator may drive the cargo to the upper yard themselves, which can be inefficient and may damage the cargo.

Third, lift operators must perform their work with poor visibility, a high mental load, and a complex environment with pedestrians and vehicles moving around them. First, lifts do not provide operators with great visibility, which only worsens when carrying cargo. Second, lift operators must be cognizant of how loads and the weather impact their lift's dynamics. A lift operator must be exceedingly careful to prevent their lift from becoming unstable due to their load, how high their load is lifted, the wind, and the terrain. Finally, lift operators must be aware of other vehicles and pedestrians moving through the yard. Two locations where this is especially true are on the barge and at the crossing. On the barge, pedestrian workers remove cones from cargo and keep the barge surface clean of debris. At the crossing, limited visibility can lead to collisions with trucks or other lifts if the operator is not careful.

The rest of this section focuses on a more detailed macrocognitive analysis of the "Remove Cargo from Barge" task.

Macrocognition and Removing the Cargo from the Barge: Detection is a fleeting but critical safety component and occurs repetitively throughout all the subtasks identified for removing cargo from the barge (see Figure 18). Some relevant example risks to detection from Figure 18 are attention and occlusions. For example, while driving onto the barge, attention to the various workers who may be moving around the barge is critical to avoid injury. Along with attention, experience using a lift and compensating for the visual occlusions caused by the lift structure can also be critical in avoiding an accident.

Sensemaking is primarily relevant for driving onto the barge, selecting the cargo to remove from the barge, and determining where to go with the cargo. Some relevant examples of risks to sensemaking from Table 4 are attention and experience. First, understanding which ramp to use to access the barge cargo requires the operator's attention to keep an accurate mental model of the current state of the barge. A mixture of experience and attentiveness is required for the appropriate level of situational awareness. Second, knowing what containers to remove from the barge and where to put them requires knowledge of the container destination, knowing where containers for each destination are brought in the yard, and having an accurate mental model of other operators' work.

Decision-making is also relevant for all three second-level subtasks. While sensemaking focuses on understanding, decision-making focuses on the actual end choice someone makes. Some relevant examples of risks to decision-making from Table 5 are experience and workload. When driving onto the barge, lift operators must consider the type of lift they are driving and what type of cargo is available to remove. A high workload can impact an operator's ability to keep the types of loads available on each side of the barge and may lead to inefficient decisions about where to best access the barge. More experienced operators can better handle higher workloads and will likely position themselves better for unload procedures.

Action, like detection, is a constantly applied aspect of the macrocognitive approach. Actions are being taken for all subtasks identified in Figure 18. Some relevant examples of risks to action execution from Table 6 include road conditions and experience. While driving in the yard, lift operators need to be cognizant of the road conditions and how angles can impact their lift's center of gravity. Typical actions can lead to accidents due to potholes and hills. Experience can offset the impact of poor road conditions, as more experienced operators will change their actions to fit the environment more accurately than less experienced operators.

Coordination for the barge unload is similar to the rail unloading. All subtasks identified for unloading the barge include working around and with others. Some relevant examples of risks to coordination from Table 7 include training, role awareness, and visibility. Training can help give lift operators a sense of what vehicles have the right of way, how to drive around other operators, and how to communicate with other operators. However, low visibility can impact the ability of operators to communicate and predict one another's behaviors nonverbally. For example, a barge worker making eye contact with a lift operator while taking cones out of their cargo can communicate mutual awareness. Role awareness can also help direct other actions like knowing that lifts always have the right-of-way.

Transport Cargo via Truck: Trucks have a primary role in transporting goods to the upper yard. Truck operators park in the lower yard between the stern and side ramps, waiting to be loaded with cargo designated for the upper yard rail. Depending on the lift operators' needs, truck operators may adjust their parking location to accommodate more cargo coming from one of the ramps. For example, if the side ramp has several pieces of cargo designated for the upper yard, the lift operators might signal the trucks to pull closer to their location for more efficient loading. After being loaded, the truck driver drives to the upper yard and waits to be unloaded by a lift operator. See Figure 19 for a breakdown of this task.

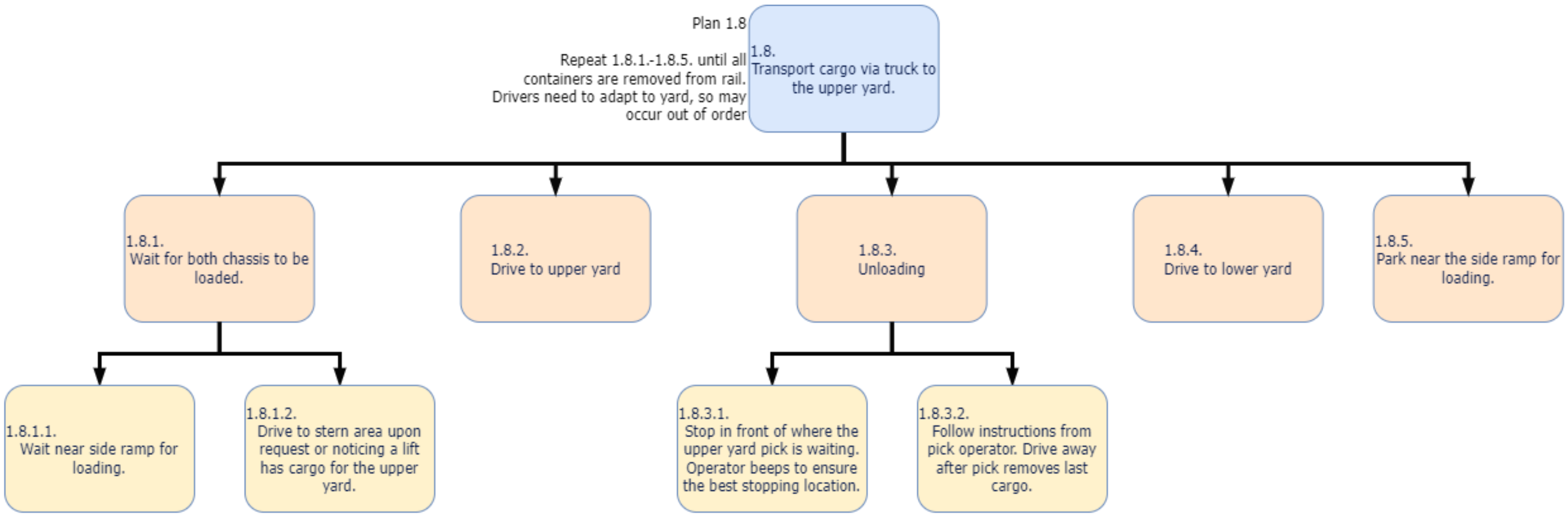


Figure 19. Diagram. A high-level hierarchical task analysis of transporting cargo to the upper yard via trucks. Primarily performed by truck operators.

Transporting goods from the lower to the upper yard via trucks involves several notable factors. First, the trucks are limited to 10 mph while driving through the yard. However, there is a general understanding that drivers need to vary their speed based on the environment. For example, when the road surface is slick due to weather, drivers need to accelerate and let go of the gas to overcome the incline at the crossing from the lower yard when fully loaded. Second, the crossing is a narrow location in the yard with potentially limited visibility. Great care needs to be taken when traversing the crossing. Third, the trucks are currently running double-trailer chassis.

Finally, when unloading, the truck driver stops in line with the lift operator in the upper yard or stops when they hear the lift operator's horn. The lift operator in the upper yard has to organize where each bit of cargo is being placed on the rail and tries to minimize their travel between the truck and the rail. The remainder of this section examines the transportation task through a detailed macrocognitive approach.

Macrocognition and Transportation of Cargo via Trucks: Detection is a fleeting but critical safety component and occurs repetitively throughout all the subtasks identified for transportation of cargo to the upper yard via trucks (see Figure 19). Some relevant example risks to detection from Table 3 are attention and ambient noise. For example, when the upper yard lift operator wants the truck driver to stop their vehicle, they honk their horn exactly where they want the truck to stop. If a truck driver is not paying attention, they may not detect the honk and park in a less efficient spot for the lift operator to transfer the cargo from the truck chassis to the rail. In addition to attention, fatigue can impact the reaction time to detecting the truck driver's horn. Ambient sound can also serve as a mask to the honk.

Sensemaking is primarily relevant for getting the truck chassis loaded, the unloading of their chassis in the upper yard, and parking near the side ramp. Some relevant examples of risks to sensemaking from Table 4 are attention and experience. First, truck drivers need to be paying attention to know where to place their vehicle near the barge to have their chassis loaded. Looking for visual signals or listening for a radio call can help the truck driver determine if they need to be closer to the side or stern ramp. Experience can also play a big part in this, as more experienced drivers will be able to keep an accurate mental model of the state of the barge better than inexperienced drivers; the same goes for knowing where to stop in the upper yard to be unloaded. Experience and attention can both help a driver determine where they need to be to best serve the lift operator.

Decision-making is mainly relevant for the same tasks as sensemaking. While sensemaking focuses on understanding, decision-making focuses on the actual end choice someone makes. Some relevant examples of risks to decision-making from Table 5 are experience and workload. When a driver parks the truck to be loaded or unloaded, more experience can help determine the best place to be to serve each operator. High workloads or inexperience driving trucks can lead to less efficient placement. Training may help alleviate the difference in performance as drivers learn where best to park.

Action, like detection, is a constantly applied aspect of the macrocognitive approach. Actions are taken for all subtasks identified in Figure 19. Some relevant examples of risks to action execution from Table 6 include road conditions and attention. While driving in the yard, truck drivers need to be cognizant of how road conditions impact their load and speed. For example, more experienced operators will know that to get over the crossing from the lower yard with a fully loaded double chassis in icy conditions requires accelerating into the incline and releasing the gas as they go over the crossing. If they do not accelerate or let go of the gas, drivers' risk not being able to get over the crossing or sliding into the Upper Mountain rail. Attention to road conditions is paramount to knowing how behavior needs to change.

Coordination for transporting cargo in the yard via truck is similar to other coordination tasks in the yard. All subtasks identified for unloading the barge include working around and with others. Some relevant examples of risks to coordination from Table 7 include training and role awareness. Training can help truck drivers better understand the equipment, what vehicles have the right of way, how to drive around other operators, and how to communicate with other operators. As a side note, as previously noted, few truck drivers in the yard have a CDL or have been formerly trained to drive trucks as they operate in a private yard, and formerly trained truck drivers are difficult to staff. Role awareness can also help direct other actions, like knowing that lifts always have the right-of-way in the yard.

Load Train: Loading the empty rail in the upper yard links well with the previous task, "Transport Cargo via Truck". After the truck arrives in the upper yard, the lift operator needs to assess the state of the rail, determine what kind of cargo the truck is transporting, decide where the cargo needs to be placed on the empty rail, tell the truck driver where to stop (through a horn or radio call), lift the cargo from the truck, transport the cargo to the train, and place the cargo. Choosing the correct location for the cargo is a crucial part of the upper yard activities. Early mistakes in placement can lead to less efficiency as the barge unloading continues. Sometimes, the upper yard lift operator will help unload cargo from the barge early in the unload and will only move up to the upper yard when needed. See Figure 20 for more detail on this task. The rest of this section examines the process of "Load Train" in more detail.

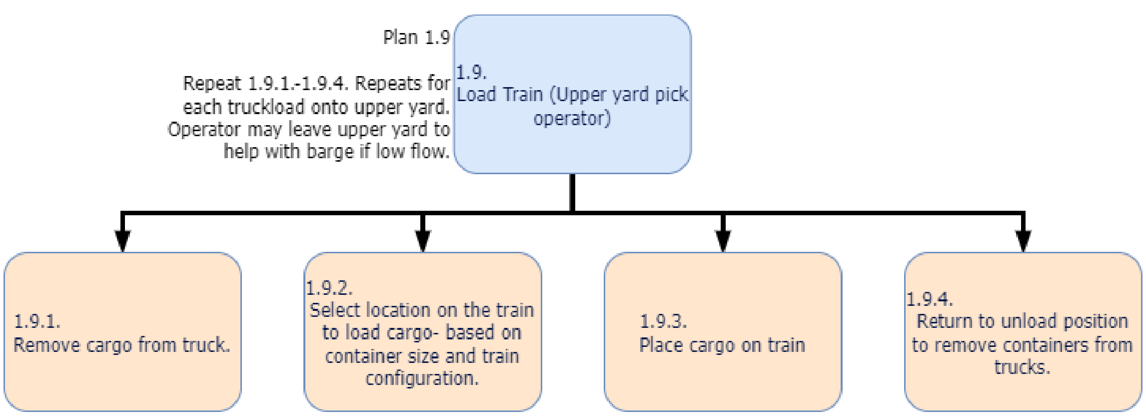


Figure 20. Diagram. A high-level hierarchical task analysis of loading the train with incoming shipments. A combination of lift and truck operators.

Macrocognition and Loading the Train: Detection is a fleeting but critical safety component and occurs repetitively throughout all the subtasks identified for loading the train in the upper yard (see Figure 20). Some relevant examples of risks to detection from Table 3 are stress and fatigue. Little other traffic outside of trucks is present in the upper yard. High stress and fatigue can work independently or together to prevent detection of pedestrians or to prevent other unexpected vehicles from being detected. Stress and fatigue can also impact the detection of leftover cones in cargo crates. Cones are not particularly salient objects, and fatigue can quickly reduce the likelihood of noticing them.

Sensemaking is mainly relevant for selecting the location of cargo placement. Lift operators are tasked with efficiently organizing cargo placement on the rail lines. The task requires knowing cargo sizes, compatibility of cargo sizes with rail, and what cargo is coming up from the barge. Some relevant examples of risks to sensemaking from Table 4 are attention and experience. For one thing, keeping apprised of the types of cargo coming from the barge and the available rail space requires consistent attention. For another, experience with different cargo types and matching sizes to chassis can help make the process more efficient with less likelihood of mistakes.

Decision-making is also relevant to cargo placement. While sensemaking focuses on understanding, decision-making focuses on the actual end choice someone makes. Some relevant examples of risks to decision-making from Table 5 are experience and stress. Experience can help lift operators place cargo in the best location, given how far the barge unload has progressed. Early in the barge unloading, loading containers in the front of the train will save travel distance at later points in the barge unloading. Extra stress caused by time pressure can reduce this efficiency and lead to less beneficial decisions.

Action, like detection, is a constantly applied aspect of the macrocognitive approach. Actions are being taken for all subtasks identified in Figure 20. Some relevant examples of risks to action execution from Table 6 include road conditions and experience. Similar to other instances of lift operation, operators need to be cognizant of the road conditions and how angles can impact their lift's center of gravity. Actions that would be fine in typical conditions can lead to accidents due to potholes and hills. More experienced operators are more likely to adjust their actions to fit the environment than less experienced operators and with more accuracy.

Coordination for the loading of the train is more direct than the initial train unloading. All subtasks identified for train loading include verbal and non-verbal communication between the lift operator and truck drivers. Some relevant examples of risks to coordination from Table 7 include training and visibility. Training can help truck drivers and lift operators understand how to perform their tasks to stay safe and efficient. For example, training truck drivers on where and when to stop for lift operators to unload their cargo could improve safety and efficiency. The same is true for training lift operators to use the best practices for communicating with truck drivers about where they need them to be. However, like other communication-oriented tasks, visibility can impact the effectiveness of nonverbal communication and cues workers use to stay safe.

Post-Barge, Backload Empty Containers: Backloading the empty and outgoing shipments is the final process lift operators perform in the yard related to a specific barge. The goal is to place all the empty containers and outgoing shipments on the barge in a way that would be beneficial for the unload team in Seattle. The research team did not stay to observe this process, but a high-level flow can be found in Figure 21.

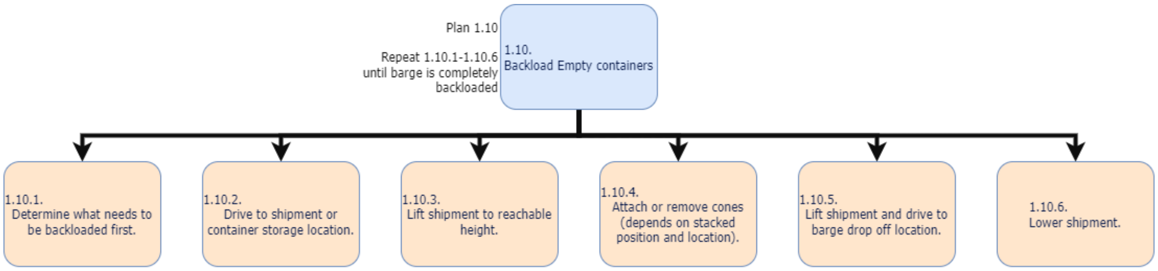


Figure 21. Diagram. A high-level hierarchical task analysis of backloading the barge. This task is primarily completed by lift operators.

3.3.2 ADS Trucking Operations

3.3.2.1 Methods

The research team employed various tools to examine the impact of ADS-equipped trucks on port operations. Some of the tools the team implemented are similar to those implemented in their initial analysis of port operations when there were only manual trucks in the yard. For example, interview and observation techniques were used to collect data, and the methods were modified to fit the available employees, equipment, weather, and timing. The following subsections outline the interviewing and observation techniques the researchers used for this portion of the demonstration.

Interviews: The research team conducted a mixture of group and individual interviews with nine participants during the data collection period in Whittier. The interviews were semi-structured and conducted during active work in the yard and office outside of active work. Participants included one safety driver/trainer from the ADS company, an engineer from the ADS company, a project manager from the ADS company, four forklift operators, a field manager, and one executive. The interview structure varied due to the dynamic nature of the port work and the availability of the subjects.

Walk-through: The research team was given equipment, functionality, and procedural walk-throughs of the ADS by the ADS company safety driver. First, the safety driver described the equipment and functionality of each device installed on the truck. Second, the safety driver walked the researchers through the process they take to inspect, start, and verify ADS truck operations as they currently work. Both walk-throughs were done in the garage with both automated trucks, three researchers, and the safety driver present.

Observations: The FO's eventual goal is to use the ADS-equipped trucks during barge unloads. However, the research team could not observe a barge unload with the trucks running in automated mode. Instead, the research team worked with the FO and ADS company to set up two demonstrations. The first demonstration focused on the functionality of the ADS-equipped truck. The second demonstration involved a pilot test with one automated truck interacting with a lift in the upper yard.

The first demonstration focused on how the automation was designed to work, the procedures to operate the automation, and how the automation would interact with the environment. Researchers parked in the yard while the safety driver laid a trail, drove in automation mode, and demonstrated different maneuvers. The researchers were in contact with the safety driver for the entire demo using walkie-talkies.

The second demonstration, or pilot test, focused on the interactions between the ADS truck and lift operators. First, the safety driver laid down a trail from the lower to the upper yard. Next, one lift driver positioned themselves in the upper yard where they might wait for trucks to arrive during a barge, and the other waited in the lower yard by the stern ramp. The ADS truck was loaded and unloaded multiple times with various dynamic stop points in the upper yard. The truck would start and be loaded in the lower yard, drive into the upper yard on the set path, stop in the upper yard to be unloaded, and be sent back to the lower yard. The controls and communication strategies of the lift operators were observed. The pilot test included a researcher riding along in the upper yard lift and researchers observing from the lower yard.

3.3.2.2 Sociotechnical System

ADS: ADS implementation complexity increases as the control over operational or environmental elements decreases. Public road deployment, in which the least control is present, requires the most advanced perception and decision-making systems. Factors that influence control within a private yard can include characteristics such as repetitiveness of routes, degree of mixed traffic, presence of vulnerable road users, and public access to the site, among others.

Fundamentally, ADS technologies consist of a perception system that allows for referential placement of other vehicles and objects, localization of the ADS-equipped vehicle based on a mapping of the environment, a control system to execute the driving actions, and algorithms responsible for the planning and decision-making of those driving actions. Secondary elements of the ADS are expected to include redundancy systems, cybersecurity measures, effective power supply and energy management, and built-in validation checks.

The circuitous port activities in Whittier makes a GPS trail-based automation system the best fit. The work at the Whittier port is highly dynamic, and no lane-lines are available for the vehicle to use for navigation. Furthermore, the weather could cause an issue for visual navigation methods. Instead, a safety driver is required to record the path the vehicle will travel along that day. Once the path is set and the automation is engaged, the truck will follow the path, stopping at preset points decided by the driver, who records the path for loading and unloading.

The stop points along the path are static or dynamic. Static stop points are those created by the safety driver when recording the path the ADS will follow. The static stop point will always be in the lower yard, where lifts can load the truck from the stern and the side ramp. Lift drivers can change the dynamic stop point and will be located in the upper yard. Unloading the trucks in the upper yard requires more flexibility than loading in the lower yard because as the train is filled, the truck needs to adjust to accommodate the lift operator. Instead of a manual driver deciding where to line the truck up for the lift operator, the lift operator will indicate where they need the ADS truck to stop. Stop points are essential to the ADS implementation in Whittier.

The sensory system implemented by the ADS at the Whittier port is also essential for understanding the overall system. The ADS trucks will have cameras, but the primary method the ADS will use to detect and avoid collisions in the yard is rovers. Non-ADS vehicles in the yard will have a rover that provides the ADS trucks with high-resolution location data for all recovered vehicles. The ADS truck can then use the rover location data to alter the truck's behavior. ADS trucks will slow down when too close to a recovered vehicle, but the rovers allow that buffer to be significantly smaller than using another technology.

ADS Equipment: One significant change to the sociotechnical system in Whittier comes from the new equipment required for ADS operations. The ADS in Whittier can be broken into three major components: (1) the "brain," (2) the ADS truck, and (3) the external equipment. The brain, sometimes called the central server, is the central location where all of the ADS's individual parts connect and communicate through. See Table 8 for a general overview of equipment. The ADS truck and auxiliary equipment (see Figure 22) will be discussed in the following sections.

Figure 22. Photo. The primary ADS equipment. See Table 8 for equipment descriptions.

ADS Truck-based Equipment: The ADS trucks in Whittier are new, automatic transmission tractors with ADS components integrated into the original hardware. For simplicity, the ADS hardware comprises three distinct yet interdependent systems: sensory, control, and communication. Though each system is tightly interwoven, categorizing the equipment in this manner allows for a more organized and efficient discussion of the ADS technology. For example, some devices, such as a camera, may fit in sensory and control systems. However, the discussion about equipment is organized based on their primary functions.

The sensory system is dedicated to perceiving the vehicle's location in space and the vehicle's relation to other objects. The onboard sensory system for the Whittier ADS trucks includes differential GPS (DGPS) and front- and rear-facing cameras. The DGPS is a GPS sensor capable of tracking the location of an object with a higher degree of accuracy than traditional GPS.(29) The ADS truck has a DGPS on the front of the tractor cab, which is the primary method of determining the truck's location in the yard. The front- and rear-facing cameras are in the center of the front and rear windows of the tractor cab, respectively. The front- and rear-facing camera use computer vision algorithms to detect objects in, or around, the ADS's projected path of travel. According to the ADS developer, the cameras can trigger the ADS to stop the truck's motion and have the capability to detect people, vehicles, and traffic cones. Rovers are the primary method of object detection for ADS trucks, but as they are installed on other vehicles they will be discussed with the external equipment.

The control system is dedicated to issuing commands and programming new behaviors into the vehicle. The control system includes the automation control unit (ACU), the automated brake control, and the Service Vehicle Disconnect (SVD). The SVD knob is one of the two main controls used to engage the automated driving mode on the ADS trucks. Two SVD knobs need to be set to activate for the automation mode to be engaged, one on the outside rear of the tractor cab and one on the inside control panel. The automated brake control is another control needed to engage the automated driving mode. The automated brake control lever must be set to automation mode before the automation can control the parking and trailer brakes.

The ACU is the primary control method for ADS functionality for safety drivers. The ACU is in the center of the truck dashboard above the vehicle's radio and can control all the automation functions. The ACU has 15 mappable buttons with the secondary SVD knob for automated functioning. The ACU controls allow safety drivers to set a path, start automation mode, pause automation mode, stop all automated vehicles, change the exterior driving mode indicator lights' (hereto referred to as Andon lights) brightness, and ignore the AV's stop rule for external vehicle proximity using an override button. Currently, some buttons are labeled with a symbol representing their function, while other buttons lack a label representing their function. For example, the "drop points" button, located directly to the right of the play button is unlabeled but is required for creating a new trail. The button labels will not be finalized until the automated system is officially deployed. See G in Figure 22 for an image of the ACU in the ADS truck and I in Figure 22 for an image of the ACU in a lift.

The communication system transfers information to the central for processing and communicating with people around the vehicle. Communication with the central server is achieved using cell connectivity and does not have a user-facing indicator of status when devices are working correctly. The Andon lights indicate the vehicle's status to people in the yard. There are two automation status lights, each located by the side mirror of the tractor cab, and each contains three separate color lights: blue, green, and amber. The amber light represents the status of the parking brake and blinks when the parking brake is engaged. The blue light indicates automation mode, and the green light indicates manual driving mode. The amber light is always accompanied by a green or blue light, depending on whether the vehicle is in automated or manual driving mode while parked. See E in Figure 22 for an image of the Andon lights.

Table 8. Overview of equipment descriptions corresponding to Figure 22.

Letter	Equipment	Description
A	DGPS	A high-accuracy GPS device that determines the truck's location in the yard.
B	Front-facing Camera	A camera mounted at the top of the windshield facing forward that serves as the primary source of visual information for the automation system. Through computer vision and the front-facing camera, the automated system can detect vehicles, people, and cones.
C	SVD	The switch needs to be set to "On" for the automation system to be functional. Another switch inside the vehicle must also be set to "On" for the automated system to operate.
D	Rear-facing Camera	A camera mounted in the back window of the tractor cab. This camera can also detect objects like the front-facing camera but is mostly there to read the numbers on the containers.
E	Andon Lights	Three indicator lights are mounted on both sides of the tractor cab, right below the side mirrors. Blue indicates the automated system is active, green indicates manual driving, and amber indicates the parking brake is active. The lights flash continuously to indicate the mode the vehicle is in, and amber (parked) is always paired with the control mode.
F	Automated Brake Control	A lever used to switch between automated and manual braking. This lever needs to be set to automated mode before the automated system can drive. This lever allows the ADS computer to control the parking and trailer brake.
G	ACU	A customizable keypad for controlling the automated system.
H	Internal SVD	The internal SVD switch. Both the internal and exterior SVD switch need to be set to "On" before the vehicle can be put in automated mode.
I	Lift/ Remote ACU	Similar functionality and control capabilities as the ACU installed in the ADS truck. Every lift will be able to control the ADS trucks through the use of the keypad.

ADS Equipment on Other Vehicles: The ADS equipment includes the additional devices outside the ADS truck and central server that allow for remote control of the ADS truck and perception of mobile objects. Rovers and external/lift ACUs are the primary ADS equipment not installed on the ADS trucks. Rovers are an offboard sensory system installed on other vehicles, and the lift ACUs allow lift operators to control ADS trucks.

Rovers are the primary method the ADS uses to detect vehicles. Rovers are radio beacon devices placed on vehicles, such as lifts, driving around the yard during automated operations. The DGPS on the tractor and the rovers on other vehicles repeatedly send a heartbeat signal to the central server with their location. The location data is then used to prevent collisions in the yard using known vehicle geometry and movement information.

A buffer zone is an essential concept regarding rovers and ADS truck interactions. A buffer zone is the "safety bubble" around each ADS truck, where the truck will stop if something enters the bubble. There are two buffer zones: a slowdown (blue in Figure 23) and a stop zone (pink in Figure 23). The slowdown buffer zone is furthest from the ADS truck, while the stop buffer zone has a smaller tolerance. For example, if a vehicle with a rover passes into the slowdown buffer, the ADS truck will decelerate to a preset speed. If a vehicle with a rover enters the stop buffer zone, the ADS truck will stop. Buffer zones need to be tuned based on the context and operations.

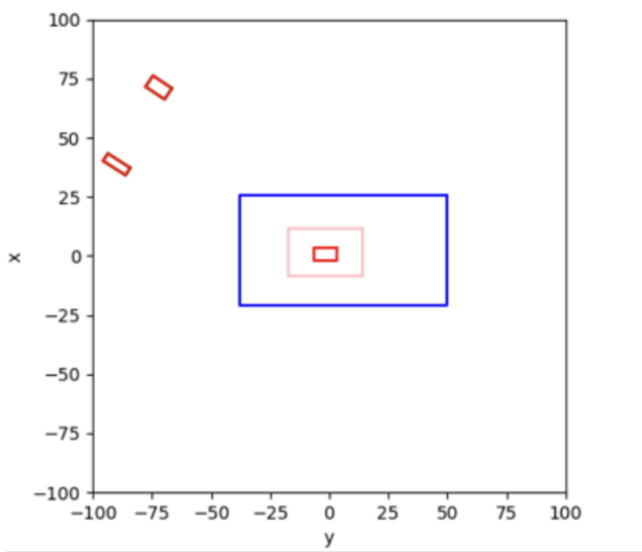


Figure 23. Illustration. Buffer zones surrounding a truck. The truck is the center red box, the blue box is a slowdown buffer, and the pink is a stop buffer. Note: The buffers are not to scale.

The main control component external to the ADS truck is the ACU installed in each lift. During barge off-loading, lift operators must be able to send commands to the ADS trucks. In some cases, the lift operators may need to create a new stop point, stop the ADS operations, or override the established buffer zone during conflicts. For example, suppose an ADS truck blocks a lift operator's destination because of a lift-ADS truck buffer conflict. In that case, the lift operator may press an override button to allow the truck to continue moving. See letter I in Figure 22 for an image of an ACU installed in a lift.

ADS Site Requirements: Several considerations for establishing or altering logistical or operational site components exist for the implementation of ADS technologies. These considerations are required both to establish the operational functionality of the ADS within its operational constraints while also ensuring the safety of all users during deployment.

> Operational Zones – The ADS technology functions by establishing several operational zones, manually determined during development of the system and defined using GPS-coordinate boundaries. These zones define the boundaries of the ADS during several automation modes and are required for functional operation. The zones are carefully defined within the ADS software and are based on rigorous testing and evaluation of potential paths of the ADS trucks. Zones may be further tweaked over time but should be relatively consistent and not dependent on temporary yard features such cargo storage or snowbank locations.
>
> First, the Autonomous Operating Zone (AOZ) determines the boundaries for where automation may be active and where a trail may be established (see Figure 24 for estimated zone locations; AOZ in green). The trail, or path of the ADS during barge unloading operations, is explicitly established within the AOZ and any points set outside the AOZ will prevent the trail from being confirmed within the management system app. Upon any deviation of the ADS outside the AOZ, a redirection into the AOZ will be attempted. If the deviation is not corrected, vehicle automation will be disabled until the truck is manually rerouted back into the AOZ.
>
> Second, the parking zone is established to stage vehicle automation during pre-trip inspections, as well as track where vehicles are when temporarily parked or kept during non-active barge time. The parking zone is separated from the AOZ as its use is primarily to hold or stage vehicles, and vehicles would not operate autonomously; however, automation modes can be tested for functionality and connectivity.
>
> Last, the dynamic zone represents the area in which the upper yard lift operator will have authority to establish a dynamic, temporary stopping point for the ADS truck. A dynamic stopping point is set by the operator based on where the operator would like to unload cargo from truck to railcar.

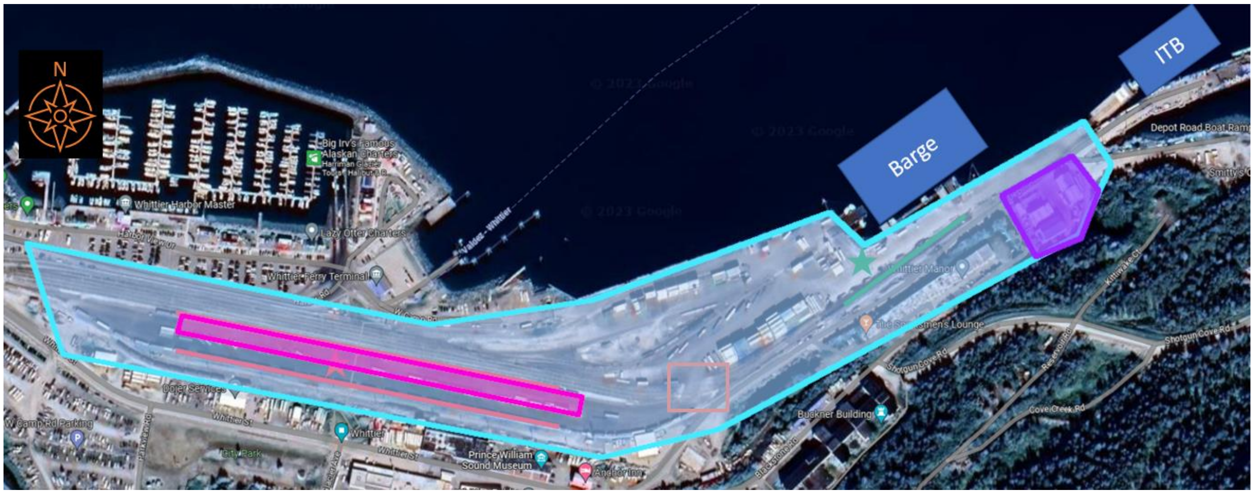


Figure 24. Illustration. Operational zones overlaid on the port. The blue area represents the AOZ, the purple area represents the parking zone, and the pink represents the dynamic zone.

Yard Requirements – Although the operability of the ADS is built based on the operations at the port, there are still several additional considerations throughout the introduction of automated systems. These limitations, or restrictions, placed on the private port/yard are required for minimal operation of ADS technologies, with the intention to optimize cargo haulage around the port. Given the ADS functions using GPS-tracing and tracking, robust and reliable connectivity is mandatory for operation of both the autonomous mode of the ADS-equipped vehicle as well as the proximity sensors attached to the rovers throughout the yard. Reliability in connectivity is threatened during certain severe weather or strong electromagnetic interference events. Other unrelated events, such as a large pull on the network from passing cruise ships, have led the ADS developer to install an LTE tower specifically for use by the ADS technology. This personalized tower ensures maximum connectivity upkeep and minimal interference across any GPS corrections applied. Further challenges to connectivity may result from the Alaskan yard, as GPS is reliant on satellite geometry, and if the arrangements of satellites over Alaska are insufficient, it may reduce GPS accuracy or signal.

An additional consideration is to ensure the layout of containers, cargo, equipment, and other large items or objects is functional for the purposes of operating within the AOZ. This may require establishing boundaries for where items may or may not be placed, including establishing the locations of high automation activity or AOZ trail width to ensure the capabilities of the ADS trucks are unhindered during operation and for ensuring proper sightlines for lift operators to identify locations of the ADS trucks.

Weather Considerations – During snowfall and severe weather, ensuring the routine plowing and clearing of the operating zone of the port is essential for the efficient operation of automated vehicles within its premises. While these vehicles may be capable of operating during severe weather (barring poor GPS signal), the physical movements of the heavy truck during severe weather conditions are not built into the automation algorithm. That is, if large amounts of snow or ice are present on the pathways of the ADS-equipped truck, the enacted behavior of the automation may be inappropriate. As such, regular plowing is crucial to prevent the accumulation of snow and ice that can hinder the mobility of AVs. Failure to maintain the infrastructure could lead to disruptions, delays, and potential damage to both the AVs and the cargo they transport.

However, the issue arises when the responsibility for the port's maintenance falls on the railroad corporation, the owner of the port. The railroad corporation may primarily focus on rail operations and may not have the immediate priority for routine port maintenance sufficient for ADS operation. This misalignment of responsibilities can result in challenges, as the port requires consistent attention to meet the needs of AV operations. The lack of timely plowing and cleaning could lead to operational inefficiencies, increased risk of incidents, and potential financial losses for businesses relying on the smooth functioning of the port. Collaborative efforts between the railroad corporation and marine transportation port operations are crucial to finding effective solutions that prioritize routine maintenance for the successful integration of automated vehicles within the port environment. One such effort may be to clearly set boundaries for defined operational zone maintenance and cleaning between the longshoremen and railroad engineers.

Pedestrian Restrictions – Other requirements based on specific ADS features rely on the absence of pedestrians for unfettered automated operations. The forward-facing camera within the ADS technology is continuously running a pedestrian-trained detector algorithm to determine the presence and location of pedestrians in view. The current application of the ADS requires no pedestrians visible during transit, such that any continual detection will immediately disengage the automation. This effort is planned to be extended only to the system AOZ; however, more research is required on effectively validating the distance measurements of the pedestrian detecting algorithms. This system functionality requires the addition of appropriate signage to indicate to the working longshoremen and to the public (of which none are authorized to be on site) that driverless systems are in operation. Although the detection of a pedestrian does disable automated features, any cycles involving the forced stop and subsequent restart of the automated system provides some level of risk as the cycling introduces an additional touchpoint between human and machine.

Training Requirements – Adding ADS to the port activities in Whittier will require workers present during ADS operations to receive additional training. In general, anyone who may encounter ADS vehicles needs a basic understanding of best safety practices for interacting with ADS trucks. For example, railroad workers must understand how the ADS trucks are expected to behave to avoid unexpected conflicts. For example, a rail worker could walk in the path of an ADS truck and cause an unexpected stop that may cause undesirable interactions with lift drivers.

More specific training will be required for the lift operators and other workers directly controlling the ADS trucks. Training for operators will need to capture laying a new trail, expected ADS truck behaviors, best practices for interacting with ADS trucks, and best practices for controlling ADS trucks all need to be trained. A mismatch between system capability and users' mental models can spell disaster in the right circumstances. Danger from misunderstandings is particularly risky if the integration of ADS changes the overall focus of the system. For example, if the system was lift-centric and lifts always had the right-of-way, but the integration of ADS trucks makes the system truck-centric, training needs to capture and transition that change. Training programs must be developed to capture the changes in the sociotechnical system ADS introduces.

Equally important to general-use training, site work crews should also be trained to recognize signs when equipment is not behaving as intended. ADS-equipped vehicles are not immune from failure or improper decision-making, and complacency could lead to problems for the FO. A partially occluded sensor, improper camera alignment, or reflective surfaces could lead to unexpected behavior. For example, improper distance location in the ADS could lead to an unexpected stop or collision. Workers should be equally prepared for and anticipate an ADS vehicle failing to stop for them, whether on foot or in a vehicle. By delivering training from both approaches, workers will likely interact more safely with the ADS-equipped trucks operating inside the port.

3.3.2.3 Base System Interactions

Pre-ADS port operations in Whittier are, or were, primarily lift-centric. Lifts enter the barge as soon as possible during a barge unload and begin transporting containers to their respective destinations in the yard. Truck drivers would adapt and adjust to lift operations with the prescript that lifts always have the right-of-way. The main goal of the trucks is to shorten the distance lift operators need to travel by providing a closer drop-off point for containers being transferred to the upper yard. Trucks are an important component to the off-loading of barges, but they are not the primary actor in the pre-ADS sociotechnical system.

Post-ADS implementation, lifts are still central to the operation, but trucks are elevated in the system hierarchy. While the general workflow in the yard stays close to the pre-ADS workflow, the trucks become an extension of lift operators. ADS trucks will follow their base path and be set to react to a limited number of contextual features. For example, ADS trucks will slow down or stop for detected pedestrians and vehicles, both those with and without rovers. Other behaviors, such as continuing to drive after the ADS detects a vehicle with a rover in the vicinity, creating a new stop point, or fully stopping the automation will be controlled by lift operators. The set behaviors of the ADS trucks require lift operators to understand ADS base behaviors, predict ADS behaviors, and adapt their own behaviors around the ADS.

The rest of this section will identify the base operations of lifts from the perspective of operators and ADS trucks from a behavioral perspective. First, we briefly outline the controls and displays from a lift operator’s perspective. Second, we discuss how ADS trucks will operate, including the new responsibilities of lift operators.

Lift Operations: Lifts will have an additional control panel, the ACU, installed in their cabs. The ACU will contain all the controls needed for the lift operator to control the ADS trucks and needs to be integrated into the tasks operators already complete. In other words, while lift operators drive the lift, lift containers, make decisions regarding containers, and navigate the yard, they may also need to control the trucks. The high-skill bar required for successful lift operations makes working with operators to determine the location and timing of use for an automation control panel imperative. The placement and integration of new technology must take the current lift cab (see Figure 25) and operator’s workflow into account.

Figure 25. Photo. Cab of a lift used in the port of Whittier. Logos are redacted.

Currently, lift operators control various aspects of their lifts. First, lift operators must drive the lift. Driving the lift can be performed using the steering wheel or the mini-wheel. See Figure 25 for an image of a lift cab and Figure 26 for an image of the mini-wheel. Second, lift operators must control their mast and pick, paying attention to the angles and positions of each component. See Figure 27 for a mast and pick control panel. Finally, lift operators must also control the auxiliary equipment on lifts, including lights and wipers. In tandem with control, other cognitive processes, such as staying situationally aware and judging how weather impacts operations, are also occurring.

Figure 26. Photo. Mini wheel can be used to control the lift in lieu of the steering wheel. The mini-wheel folds down and takes the place of the left armrest. The brand name has been redacted.

Figure 27. Photo. Mast and pick control panel.

Truck Operations: Pre-ADS and post-ADS truck operations are similar but with slight differences. Pre-ADS trucks were manually driven and, as such, relied on the expertise of drivers for their efficiency and efficacy. Manually driven trucks with an experienced driver could increase the efficiency of a barge unload, but a novice driver might reduce efficiency. Experienced drivers in manual trucks benefit from the following:

1. Situational awareness: Maintaining awareness of their surroundings in a way that allows them to anticipate bottlenecks, navigate tight spaces, and adjust their routes based on real-time conditions.
2. Adaptability: The ability to adapt swiftly. A human driver can rapidly reroute, switch tasks, and respond to emergencies in a dynamic environment.
3. Predictive skill: The ability to predict where they are needed next. Based on lift behaviors and locations, an experienced driver could change their loading point and meet lifts in a location that reduces the lift's distance traveled.

ADS trucks, on the other hand, follow a strict set of behavioral guidelines. ADS trucks in the context of the port benefit from:

1. Consistent behavior: ADS trucks always behave the same way, with no deviations or improvisations. When this consistency of behavior is known to others in the sociotechnical system, it can ensure safety and efficiency.
2. Predictability: ADS trucks have set routes and loading points. Set loading points to ensure predictable locations for lift operators to find the trucks. Set routes ensure other workers in the sociotechnical system know the path ADS trucks will take and can work around them.
3. Growth: Based on system feedback, ADS can be improved over time. As the ADS trucks are used in context, the systems can be tailored to increase efficiency reliably and consistently. Loading locations can be identified, safety buffers improved, and new trucks added.

Truck operations will continue to achieve the same goals, but the rules and procedures through which these goals are achieved are less mutable with ADS. The experience and staffing of drivers cease to be a concern with the implementation of ADS. ADS trucks will always behave the same way by following the same routes, stopping in predetermined locations, and reacting to others in predictable ways. Where flexibility and adaptability are lost, consistency and predictability are gained.

3.3.2.4 Detailed Activities

The Whittier port is highly dynamic, and various activities are performed there. However, exploring the detailed activities we will discuss below will only apply to unloading barges. Furthermore, our exploration will highlight aspects of the system that will change with the implementation of ADS but will likely capture only some of the impact ADS implementation will have. The general workflows will follow the detailed activities outlined in section 3.3.1.4 and the analysis approach from the same section. The activities flow will be captured using hierarchical task analyses mixed with HRA techniques outlined in the same section. As the ADS implementation at Whittier has not been finalized, processes may change.

The task analyses will be broken down into pre-barge with ADS truck, barge with ADS truck, and post-barge with ADS truck activities. Pre-barge includes the ADS truck inspection and dropping of a new trail for automated operations. Barge with ADS truck includes removing cargo from the barge, transporting cargo via truck, and loading the train. Finally, post-barge with the ADS truck includes disengaging the automation. Safety drivers will likely be present in the initial stages, but the end goal of ADS implementation is to have lift operators control the ADS trucks as needed. Therefore, each task will be from the perspective of lift operators and assume no safety operator is present in the AVs. Our analysis also assumes that the automated system works as intended.

Pre-Barge with ADS truck: In the context of pre-barge activities, the goals remain fundamentally the same. Before the barge unloading, the FO and the SORC must complete a series of tasks. These tasks include extracting the inbound rail from the barge by the SORC, the pre-barge operations safety briefing, and the setting of the side ramp. For more information on pre-ADS implementation pre-barge activities, see section 3.3.1.4 (Pre-barge). However, despite the same primary activities, several new activities are introduced with the implementation of ADS. Two primary additions to the pre-barge activities are the ADS truck inspection and dropping a new trail for automated operations. As with the rest of this section, these activities are subject to change as the ADS is further developed.

ADS truck inspections are a new task the FO will need to perform before using the ADS trucks for barge operations. While pre-trip inspections are typical for tractor-trailers, adding the ADS and the equipment required to make ADS work requires additional inspection procedures. Operators must examine all the exterior and interior ADS equipment for damage, loose wires, or sensor occlusions to ensure the vehicle is fit for automated operations. Once the operator ensures the hardware is free from damage, the functionality of the automation system needs to be tested. During the inspection process, the functionality test finishes with evidence that the system can enter an ADS-ready state, not a demonstration that the ADS can successfully drive a previously dropped trail. Some of the hardware inspection can occur in tandem with the base pre-trip truck inspection, but the functionality inspection, where the ADS functionality is turned on, requires additional time. A high-level representation of the ADS inspection process can be found in Figure 28.

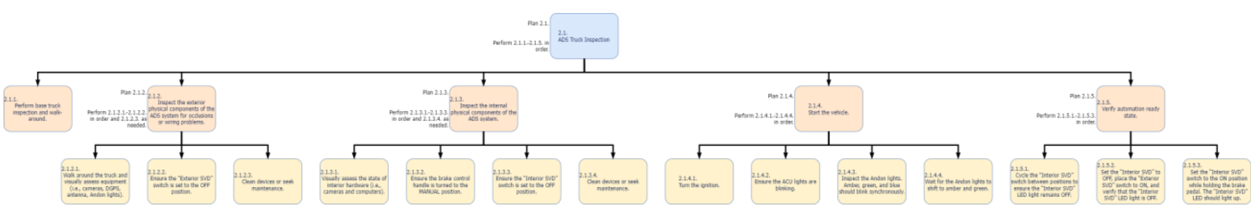


Figure 28. Diagram. A high-level hierarchical task analysis of ADS truck inspection. Note: tasks can be further broken down but were simplified for space. Lift operators or other FO employees will perform this task.

The ADS truck inspection is a crucial addition to pre-barge activities. Any issues with the ADS can result in a loss of efficiency or a potential disaster. In the case of a loss of efficiency, any time the ADS shuts down during operations, another worker will need to leave their post and restart the automation. In the worst-case scenario, a lift operator may need to drive the truck manually for the duration of the barge, or the truck might need to be decommissioned while repaired. In the case of a potential disaster, a dirty camera or issue with the DGPS could lead to a collision in the yard. A collision could cause damage to pedestrians and equipment.

The rest of this section focuses on a more detailed macrocognitive analysis of the "ADS Truck Inspection" task.

Macrocognition and ADS Truck Inspection. Detection is a critical and repetitive process for ADS truck inspection required for every subtask in the procedure (see Figure 28). The primary goal of the ADS truck inspection is to detect problems with the ADS equipment before attempting to use the technology in actual operations. Some relevant examples of risk to detection for the ADS inspection from Table 3 are object salience, stress, and fatigue. For example, detecting physical flaws with equipment will depend on how conspicuous the damage is. A frayed DGPS wire could be far less noticeable than the sensor puck being damaged, especially if the wire damage is at an entry point. Barges can also arrive at any time of day, causing fatigue and potentially stress that may interfere with taking the time or having the mental capacity for detecting problems.

Sensemaking is relevant anywhere detection is relevant during the ADS truck inspection. Sensemaking for the ADS inspection process culminates in the operator determining the system's state based on their equipment observations. If damage is detected on a wire, the operator must use their experience to determine if the damage is cosmetic or functional. Some relevant risks to sensemaking for the ADS inspections from Table 4 are failed detections or poor training. For example, if an operator has not had sufficient training to understand the ADS equipment and how each part impacts the whole, they may not know if the system is or is not at risk based on the equipment's state. Missed detections, resulting from a lack of experience or training, could also give an operator an incorrect mental model of how the system is functioning. The HMI design can also impact starting the vehicle and verifying the automation ready state in Figure 28. Clear and understandable signals are required to understand the system state.

Decision-making is essential for the ADS truck inspection after the operator recognizes a problem with the ADS equipment. Some relevant examples of risks to decision-making during the ADS inspection process, as shown in Table 5, include poor training and previous experience. For example, if the inspection operator had previously ignored damage or occlusions on devices and the ADS worked without incident. Experience can be compounded by poor training, and inspectors can choose to allow trucks to operate despite the potential dangers.

Action is crucial to any interaction, and the ADS inspection is no exception. Interacting with the truck's ADS controls is pivotal to the inspection process, for example, in step 2.1.5. in Figure 28. Despite action being critical to the ADS inspection process, action errors are unlikely. Action errors are rare, to begin with, but in a situation where time pressure, lighting, and weather are not likely to be a problem, action errors become even less likely. Still, stress and the HMI could provide examples of risks, as shown in Table 6. The HMI design could provide a venue where a correct intention could lead to an improper action in the right conditions. A stressed or fatigued operator may press or turn incorrect inputs if the layout of inputs allows for mistouches.

Coordination is more critical for the overall process of ADS inspection than it is for any individual step. While one operator will likely complete all the inspection processes, the completion of the ADS inspection needs to be known to the supervisory and safety staff. Examples of risks to coordination for the ADS inspection are shown in Table 7, which includes safety culture and role awareness. Depending on the safety culture at the facility where the ADS inspection occurs, communication might not occur after a completed ADS inspection. In a highly dynamic setting, the lack of communication or the assumption of a successful inspection could lead to a situation where the vehicle is not inspected, or problems are never communicated to the appropriate individuals.

Trail Drop for Autonomous Operations. Creating a path for the ADS trucks to follow, called "dropping a trail," is another new task the FO must complete during the pre-barge preparations. The ADS in Whittier operates using a record-play model where a manual drive is recorded by a driver and then repeatedly replayed by the ADS. Dropping a new trail is the process of recording the initial drive that the ADS trucks will continue to drive during operations. During the initial drive recording, the manual driver can also create locations where the ADS trucks will stop, called stop points. After the manual drive is completely recorded, the driver would contact a supervisor, who has access to the ADS web app (see section 3.3.2.2), to ensure the trail was properly recorded. Once a trail is properly recorded, the driver can prepare the truck for automated operations and proceed to their typical shift location. See Figure 29 for a more detailed workflow for dropping a new trail.

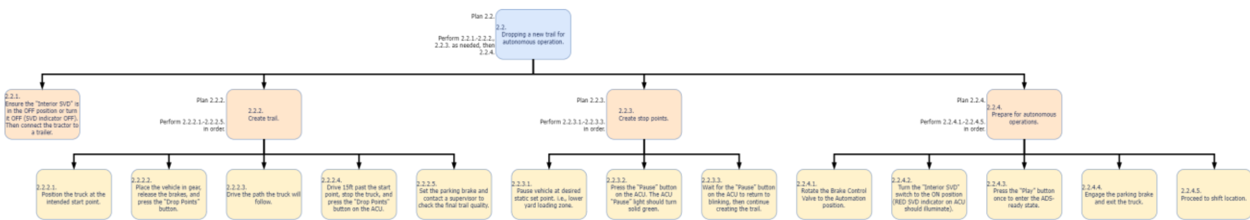


Figure 29. Diagram. High-level hierarchical task analysis of dropping a new trail for autonomous operations. Note: tasks can be further broken down but were simplified for space. Lift operators or other FO employees will perform this task.

The ability to create new trails is an important feature of the ADS trucks at the Whittier port. For one thing, the Whittier port is a highly dynamic space that is always changing. The yard's overall layout and the operators' needs are always shifting. The number of stored containers, the location of stored containers, the locations containers need to be transported, and even how crowded the port is during operations remain fluid. The weather also makes the ability to lay new trails important. Whittier weather can be unforgiving, with abundant rain, snow, wind, and ice throughout the year. As ice builds up in the yard, previously set trails may no longer be safe to continue using as the uneven ground and slick texture can lead to operation problems. The ability to set new trails with each barge fits the dynamic nature of the sociotechnical system and ensures the ADS can continue being useful throughout the year.

The rest of this section focuses on a more detailed macrocognitive analysis of the "Trail Drop for Autonomous Operations" task.

Macrocognition and Trail Drop for Autonomous Operations. Detection is critical for driving the vehicle and monitoring the state of the trail creation. Port operations are dynamic, and the continuous perception of hazards is crucial to the safety and efficiency of operations. Some relevant examples of risks to detection from Table 3 are attention and workload. For example, during a trail's creation (step 2.2.2. in Figure 29), detecting environmental hazards such as pedestrians is critical to continue safe operations. The increased workload of monitoring an automated system and paying attention to one's surroundings could lead to worse environmental hazard detection. Unexpected pedestrians or unseen potholes can lead to potential issues with a new trail or operations in general.

Sensemaking is relevant for creating new trails, creating stop points, and preparing for automated operations (see Figure 29). An accurate mental model of barge operations, the needed trail to fit operations, and the functionality of the ADS is required to set an effective new trail. Some relevant examples of risks to sensemaking from Table 4 are the HMI and training. For example, an inexperienced operator might be able to set a standard trail, but they would not be able to adapt to a new yard configuration as well as a veteran barge worker. Furthermore, depending on the quality of the feedback provided by the HMI, the operator may or may not be able to determine what, if any, data was recorded. Feedback is crucial for a good mental model of a system.

Decision-making is more critical for setting a new trail at the management level than at the operator level. By the time a new trail is set, the operator will likely be following predetermined routes and stop points that have been agreed upon by the entire operations team. The actual path and the location of stop points depend on the specific characteristics of the barge, yard layout, and weather conditions. Either way, the decisions will not likely be in the moment but rather premeditated. Some relevant examples of risks to decision-making from Table 5 are expectation and experience. The expectation of a particular barge's progress based on weather conditions, personnel, and yard layout might not align with reality. Inexperience or experiences that challenge previous experience may impact a trail planner's ability to foresee the impact of a particular trail or stop points.

Action is present in every subtask identified in Figure 29. Actions about driving, controlling ADS functions, and communicating with other operators can all be impacted by risk factors. Some relevant examples of risks to action from Table 6 are the weather, road conditions, and fatigue. While laying a new trail takes place before a barge, a barge can arrive any time of the day, making irregularity in sleep potentially impact fatigue. Besides the impact of fatigue on one's actions, making them less smooth, weather and road conditions can also impact actions. Severe winter conditions frequently impact Whittier, and a cold, icy port could lead to inaccuracy of behavior. For example, one might slide when braking and place a stop point further along a trail than intended.

Coordination is important in both validating the capture of a trail, ensuring the safety of the operator enabling the ADS, and ensuring all personnel working around the ADS grasp the expected locations of the trucks (one of the goals of Figure 29). In a team environment where each operator has a control panel that can command the ADS trucks to move, communication is crucial when moving around the trucks on foot. Without clear communication, a lift operator can give the truck a "Play" command while another operator is leaving the truck. Additionally, a predictable path is important for lift operators to be able to work around the ADS trucks. Some relevant examples of risks to coordination from Table 7 are equipment failures and safety culture. For example, set safety procedures and consistent communication can prevent a lift operator from pressing the "Play" button to start the ADS while an operator is still around the truck. Complacency and poor equipment maintenance could lead to risks for personnel.

Barge with ADS Truck: Post-ADS implementation barge activities have similar goals to the pre-ADS barge activities. However, unlike the pre-barge activities, the implementation of ADS impacts the tasks being performed rather than adding new ones. Similar to pre-ADS, barge activities begin once the lift operators can begin removing cargo from the barge and end after the last container is removed. The lift operators' goal is to unload the barge as quickly as possible by bringing the containers to their respective destination locations in the port. See section 3.3.1.4 (Barge) for more information regarding the pre-ADS barge activity task flows and goals. As with other parts of this section, these activities are subject to change as the ADS is further developed.

Remove Cargo from Barge after ADS Implementation. Removing cargo from the barge post-ADS implementation is similar to pre-ADS implementation. The primary difference between pre-and post-ADS operations is the added task lift operators have of controlling the ADS trucks. Choosing the cargo to remove from the barge and transporting it to its final destination is essentially the same. Even keeping track of where the trucks are located if an operator needs to get their cargo to the upper yard is similar to pre-ADS. However, keeping track of moving ADS trucks, loading them, and commanding them to continue their path are altered.

Keeping track of where the ADS vehicles are is important for all lift operators post-ADS implementation, not just the lift operators transporting goods to the upper yard. Given the strict capabilities of ADS trucks, the system is forced to shift from a lift-centric to a truck-centric model. Pre-ADS, lifts always had the right-of-way. Pre-ADS lift operators did not ignore other moving vehicles, but if a truck and a lift needed to cross paths, the lift was given precedence due to their limited field of view and the importance of unloading the barge. However, ADS trucks are limited in their ability to perceive and react to the world like a real driver, requiring lift drivers to be more flexible.

The loading and commanding of automated trucks have also changed in post-ADS port operations. In pre-ADS implementation, experienced truck drivers could predict and adapt to the needs of lift operators. For example, a lift exiting the barge from the stern ramp might be met by a truck as they clear the barge. Post-ADS, the trucks will always be in the same loading zone, have indicators communicating they are parked, and require the lift operator to press a button to have them continue on their way—efficiency in the form of standardization rather than expertise. See Figure 30 for a high-level task breakdown of removing the cargo from the barge after ADS implementation.

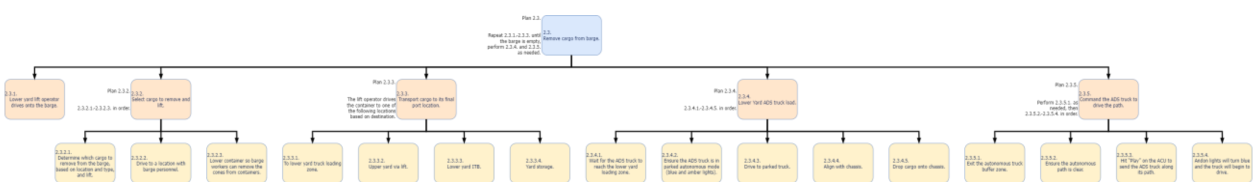


Figure 30. Diagram. High-level hierarchical task analysis of removing the cargo from the barge with ADS implemented. Note: tasks can be further broken down but were simplified for space. Lift operators will perform this task.

The rest of this section focuses on a more detailed macrocognitive analysis of the "Remove Cargo from Barge after ADS Implementation" task.

Macrocognition and Removing Cargo from Barge after ADS Implementation. As in most other processes, detection plays a critical role in removing cargo from the barge after ADS implementation. A lift operator must detect and attend to workers on foot, other vehicles, cargo identification numbers, and ADS trucks, to name a few. Detection is essential for every subtask of Figure 30, especially for steps 2.3.3–2.3.5. Some relevant examples of risks to detection from Table 3 are attention and workload. With the added workload of closely attending to the ADS vehicles and controlling them, detecting critical items in the environment could suffer. The increased workload, though minimal during some tasks, like selecting and removing cargo from the barge and having to attend to the ADS trucks while driving during other tasks could reduce performance.

Sensemaking, like detection, is vital for most subtasks. However, removing cargo from the barge post-ADS implementation, detection is most relevant for driving in the yard and controlling the ADS (steps 2.3.3–2.3.5. of Figure 30). Some relevant examples of risks to sensemaking from Table 4 are the HMI and training. The HMI of the ACU in the lift can serve as a direct view into the ADS truck's behaviors if designed well. Take the override for example. If an ADS truck stops near two lift operators, the HMI can provide feedback as to which entered the truck's buffer. If there is no visual feedback that an operator's lift stopped the truck, then both lift operators are blind to the cause of the lift's behavior. On the other hand, if an LED lights up above the override button to indicate the lift has entered a truck's buffer, then the lift operators know if they need to move or use the override button. Better training can also prepare lift operators to understand the behavior of ADS trucks.

The main decision-making points for removing cargo from the barge post-ADS implementation are determining which cargo to unload, the cargo's destination in the yard, and if waiting for an ADS truck is worthwhile (steps 2.3.2.1, 2.3.3.1, and 2.3.3.2 in Figure 30). Regarding automation, the primary decision point occurs when an ADS truck is not in the lower yard loading zone, and the cargo needs to be transferred to the upper yard. The lift operator can transfer the cargo without a truck or wait for a truck to enter the lower yard loading zone. Some relevant examples of risks to decision-making from Table 5 are experience and personality. Depending on the lift operator's impulsivity and experience, they may drive to the upper yard at inopportune moments. A more experienced or less impulsive lift operator might make a better decision regarding waiting for an ADS truck to reach the loading zone or driving to the upper yard themselves. Driving to the upper yard in a lift increases exposure to other vehicles and can lead to inefficient barge offloading.

Action is relevant for all unloading the barge post-ADS implementation subtasks. However, commanding the ADS truck to continue driving along its path (step 2.3.5 of Figure 30) is particularly interesting concerning post-ADS operations. New required tasks can add a new point of potential failure, and interacting with the ACU is new. Some relevant examples of risks to action from Table 6 are workload and fatigue. An unintentional slip of the hand or selecting the wrong button on the ACU is more likely as workload and fatigue increase. Unloading a barge could take a significant amount of time at irregular hours.

Coordination is paramount for removing cargo from the barge post-ADS implementation. Lift operators already coordinate through CB radio and body language regarding their intended behaviors and the cargo they remove. Post-ADS implementation will also require lift operators to communicate regarding the ADS trucks and their behaviors. For example, communication might be critical in a lift operator's decision to independently drive cargo to the upper yard (see Figure 30). Some relevant examples of risks to coordination from Table 7 are role awareness and visibility. Post-ADS implementation, all lift operators are expected to have control of ADS vehicles via the ACUs in the lifts. An ADS truck could stop because of lifts close to its buffer zone, but poor communication due to a lack of role awareness could lead to confusion and inefficiency. Lack of visibility due to fog or location could also impact the head lift operator from seeing an issue with an ADS truck, and each lift operator needs to know what their role is in controlling the trucks to react appropriately.

Transport Cargo via Truck after ADS Implementation. The transportation of containers via truck from the lower to the upper yard is completely handled by the truck's automation, with a few exceptions. First, the trucks can be paused, told to continue, or stopped by any lift operator at any time. Second, the upper yard lift operator can create dynamic set points. Dynamic set points are unique to the upper yard and allow a lift operator to move the stop location of the ADS trucks as the train is filled. Without input from lift operators, the ADS trucks will drive between the lower yard static set point and the upper yard dynamic set point along the prescribed route (See Figure 24). At each stop point, the vehicles will stop until a lift operator sends the continue command.

The ADS truck behavior, a secure AOZ, and the mental model of workers are particularly important regarding safe port operations. The ADS truck behaviors, including speed, buffer zone conflict reactions, conflict reactions with objects or pedestrians not tagged with a rover, to mention a few, impact safety. For example, how the ADS truck reacts to a pedestrian along the ADS trail can impact the safety of everyone around the truck. A secure AOZ mixed with accurate mental models should be a protective barrier for incidents. A secure AOZ ensures a clear space where the ADS vehicles can operate and ensures minimal unexpected conflicts; fewer unexpected pedestrians translate to fewer unexpected stops. Accurate operator mental models of ADS behaviors, ensure maximum situational awareness and better predictive operator behaviors; a better understanding of the ADS behavior should lead to a better understanding of how to navigate safely around them.

Load Train after ADS Implementation. Loading the train in the upper yard post-ADS implementation is significantly impacted by the presence of ADS. While the overall task mirrors the pre-ADS train loading task described in Figure 20, the upper yard lift operators are now responsible for navigating around and controlling the ADS trucks. The most efficient location for the trucks to stop in the upper yard to be unloaded hinges upon where empty train car spaces are. Depending on the rate of trucks coming into the upper yard, two ADS trucks are planned, the control of the dynamic unload point can take time to manage. The upper yard operator needs to set the stop point, wait for a truck to be in position for unloading, remove the container, send the truck along its way, and load the cargo on an appropriate empty train car while also planning for the next truck and the next stop location. If trucks follow one after another, the ability to set another dynamic set point may be hindered.

Additionally, the upper yard presents a unique challenge for lift operators due to the narrowness of the loop ADS trucks will drive along (see Figure 13). The narrowness of the upper yard vehicle loop means that the lift operator may need to operate up to two ADS vehicles at a time in close quarters, and that stop points could be placed in the wrong location. The close-quarters operations pose a challenge due to the limited field of view lift drivers have and the lift operator's responsibility to control the ADS trucks. The narrowness of the loop may cause issues for the dynamic stop point locations because the stop points will stick to the path nearest to the lift operator. A truck continuing along the automated path to stop on the mountainside of the upper yard could cause a severe slowdown, especially if the upper yard operator sets a new stop point on the bay side before the first vehicle stops. A truck that misses its stop point would continue to the lower yard loading zone with its original cargo until commanded to return to the upper yard. See Figure 31 for a high-level breakdown of the loading the train task after ADS implementation.

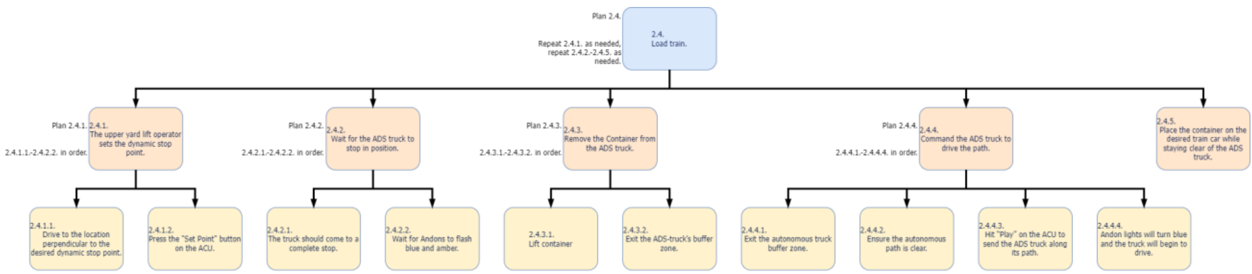


Figure 31. Diagram. High-level hierarchical task analysis of loading the train in the upper yard with ADS implemented. Note: tasks can be further broken down but were simplified for space. Lift operators will perform this task.

The rest of this section focuses on a more detailed macrocognitive analysis of the "Load Train after ADS Implementation" task.

Macrocognition and Loading Train after ADS Implementation. Detection is essential for every subtask of loading the train in the upper yard after the implementation of ADS. Waiting for the ADS truck to come to a complete stop (2.4.2 in Figure 31) and placing the container on the train while watching out for ADS trucks (2.4.5 in Figure 31) have safety implications for failed detections. For example, some relevant examples of risks to detection for those two tasks from Table 3 are visibility and workload. Lift operators in the upper yard will take on a more significant workload after ADS implementation than manual vehicles. Navigating around other vehicles, deciding where each type of cargo needs to go on the train, setting up stop points based on train car availability, and being aware of both truck states will be required for lift operators in the upper yard. For example, not detecting what state the automated trucks are in could lead to a collision or cargo being damaged. Not detecting an ADS truck could lead to a collision or inefficient operations.

Sensemaking is also essential for each loading the train subtask after ADS implementation. However, sensemaking is particularly interesting for choosing a dynamic stop point (see Figure 31) and loading the train while staying clear of the ADS trucks (see Figure 31). Some relevant examples of risks to sensemaking from Table 4 are attention and fatigue. Understanding where to place a dynamic stop point requires knowledge of the container size transported to the upper yard and where that container must be put on the train. If fatigue sets in or there is a lapse of attention, inefficient stop points might be set. Additionally, predicting when the two trucks will arrive and how to handle each stop point requires a complete understanding of how to best load the train.

Fatigue and lapses of attention can reduce the load operator's capability to gather the necessary information for efficient stop-point creation after a long shift.

Decision-making is most relevant for setting the dynamic stop point for ADS trucks (see Figure 31) while loading the train. Setting the stop point is essential for efficiency and safety in the upper yard, as poor stop point placement could lead to longer distances for lift operators to travel and trucks being parked in unexpected places. Some relevant examples of risks to decision-making from Table 5 are workload and experience. Decision-making regarding where stop points should be based on the train composition will benefit significantly from experience and vice versa. The time a barge takes, tied in with a high workload, could lead to more inefficient placement of stop points as the lift operator's mental bandwidth is reduced and becomes more strained.

Action is particularly relevant for removing the container from the ADS truck (see Figure 31) and commanding the ADS truck to return to the lower yard (see Figure 31). Some relevant examples of risks to action from Table 6 are road conditions and fatigue. The placement and removal of containers require precise placement of the top-pick cone locks. Fatigue may lead to more variability in the lift operator's movements and impact their precision as time passes. Furthermore, road conditions can lead to unexpected impacts on the placement of their lift. For example, a large divot in the road caused by ice could lead to an unexpected drop in tire elevation and change lift tilt, potentially reducing action accuracy.

Coordination is relevant for loading the train in that good coordination throughout the task can lead to a reduced workload for upper yard lift operators. Good coordination and communication can provide information about the types of loads transported to the upper yard and the locations of ADS trucks. Without communication, the upper yard lift operator needs to track each ADS vehicle, determine the type of cargo the trucks are carrying, and determine where the lift needs to be based on the gathered information. Some relevant examples of risks to coordination from Table 7 are equipment failures and ambient noise. For example, typical operating noises can make the radio challenging to hear but add wind noises and potential equipment failures, and all the workload falls on the upper yard lift operator. The expanded workload can lead to safety and efficiency problems.

Post-Barge with ADS Truck: The post-barge activities post-ADS implementation will have one additional task on top of the ones outlined in section 3.3.1.4 (Post-Barge). Pre-ADS implementation, backloading the empty and outgoing shipments is the final process lift operators perform in the yard related to a specific barge. Post-ADS implementation, lift operators will also need to disengage the automation. While manual trucks would be parked by their drivers after a barge, the ADS will need to be disengaged and then be parked.

Routine Shutdown. After a barge is completely unloaded, the ADS trucks will no longer be needed for port operations. The backloading process, described in Figure 21, is performed without the use of trucks. Therefore, before the backloading process begins, an FO employee will need to disengage the automation, disable remote control, and store the truck out of the way of operations. Disengaging the automation using the "All Stop" button ensures that the trucks exit automation mode and makes the trucks safe to approach on foot. Once the trucks have been approached, the "Exterior SVD" switch can be used to disable automation engagement and then the operator can store them out of the way. See Figure 32 for a high-level breakdown of a routine shutdown.

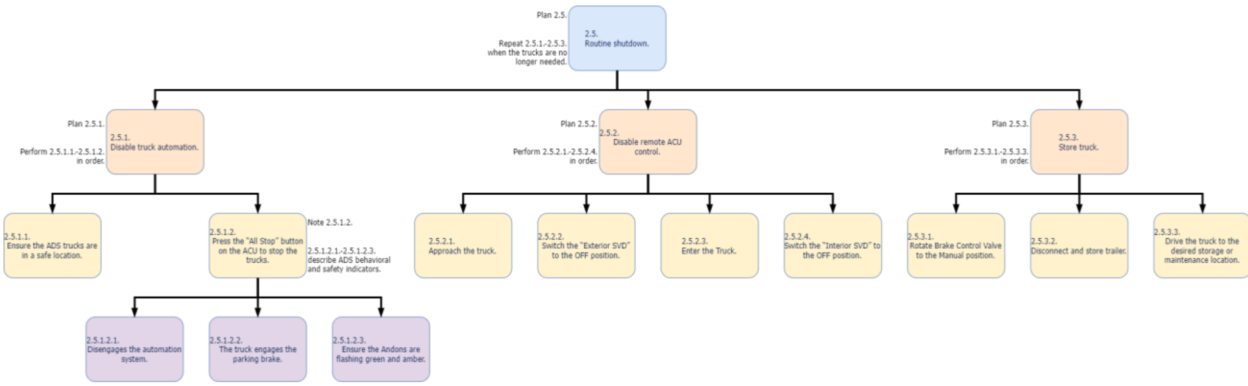


Figure 32. Diagram. High-level hierarchical task analysis of a routine shutdown of ADS vehicles. Note: tasks can be further broken down but were simplified for space. Lift operators or other FO employees will perform this task.

The rest of this section focuses on a more detailed macrocognitive analysis of the "Routine Shutdown" task.

Macrocognition and Routine Shutdown.

Detection is essential for every subtask of routine shutdowns on the ADS trucks but is particularly important when disabling automated trucks (see Figure 32). Approaching the ADS truck (see Figure 32) involves risks if the truck is capable of moving independently. For example, some relevant examples of risks to detection for those two tasks from Table 3 are occlusions and fatigue. The routine shutdown will always occur at the end of a shift; therefore, fatigue can play a significant role in all forms of detection. For routine shutdowns, detecting the state of the Andon lights is crucial to the safety of operators. If the truck is still in automation mode (Andon lights are blue), the vehicle can begin moving while the operator approaches the truck. Occlusions, or fatigue, can lead to an operator missing the Andon indicators and finding themselves in a potentially dangerous situation.

Sensemaking is also essential for the routine shutdown of ADS trucks. While disabling the truck automation (see Figure 32) and disabling remote ACU control (see Figure 32), a correct understanding of the vehicle's abilities in each state is paramount. If an operator misunderstands the truck's functionality while it is in parked/automated mode (Andon blue and amber), they may approach the ADS when it can still operate. Some relevant examples of risks to sensemaking from Table 4 are training and motivation. For example, poor training of the ADS vehicle states can lead to a pedestrian-truck conflict that might easily be avoided. In addition to poor training, the motivation to end a shift might also create a situation where the operator is rushing and ignores potential hazards.

Decision-making is always relevant but does not particularly fit any one subtask for routine shutdowns of ADS trucks (Figure 32). However, the timing at which ADS trucks are taken out of the yard, and the routes taken by the driver are influenced by decision-making. Some relevant examples of risks to decision-making from Table 5 are workload and experience. Depending on the demands at the end of a shift, such as backloading the barge (Figure 21), operators may wait to shut down the vehicles, impacting the truck's fuel use. Additionally, inexperience with the ADS and the end-of-shift activities may lead to poor route choices for operators driving the trucks to their storage locations, potentially leading to inefficiencies or safety-critical events.

Action is particularly relevant for disabling the ADS in the ADS trucks (see Figure 32). The "All Stop" button needs to be pressed for the safety of the operator approaching the vehicle. If the "All Stop" button is not pressed, the ADS truck can be commanded to move by lift operators, either by accident or purposefully. Some relevant examples of risks to action from Table 6 are fatigue and the HMI design. The HMI design needs to communicate the state of the vehicles and disable input at specific times. A fatigued lift operator may misunderstand a poorly designed HMI or even press the wrong button at the wrong time.

Coordination is relevant to all stages of the routine shutdown (Figure 32). Good coordination and communication ensure the ADS stays inactive during the approach and shutdown procedure. Additionally, good communication can ensure all other workers are aware that the trucks will be moving outside the prescribed route. Some relevant examples of risks to coordination from Table 7 are equipment failures, ambient noise, and role awareness. Like other coordination dangers discussed, typical operating noises can make the radio challenging to hear but can be worse when adding wind noises and potential equipment failures. An operator shutting down the system without an awareness of the dangers to other operators by violating ADS truck movement expectations could lead to further incidents.

3.3.2.5 Testable Metrics

The safe and efficient deployment of the ADS technologies warrants a comprehensive evaluation of the system during ADS-enabled barge operations. A sample of potential metrics are listed in Table 9 that capture various performative criteria by which the ADS deployment may be evaluated or tracked over time. Any comparisons of metrics across vehicle automation modality would need to be performed during both manual and automated modes. Comparisons of automation over time may highlight various elements of deployment (e.g., sensor degradation, weather or seasonal impacts, algorithmic improvements, training gaps, etc.) and systematic or unusual differences would need to be more carefully evaluated. A trip, for the purposes of the Port of Whittier, consists of one complete loop from the loading at the barge to the unloading onto the railcar, back to the barge awaiting another load.

Table 9. Potential metrics for ADS evaluation at the Port of Whittier.

Metric	Value	Exposure
Crash/Near-crash with another ADS-equipped vehicle	Safety	Per barge
Crash/Near-crash with Rover-equipped vehicle	Safety	Per barge
Crash/Near-crash with vehicle without Rover	Safety	Per barge
Crash/Near-crash with pedestrian	Safety	Per barge
Crash/Near-crash with object or animal	Safety	Per barge
GPS deviations from trail (count)	Safety	Per trip
GPS deviations from trail (maximum deviation)	Safety	Per trip
GPS deviations from trail (average deviation)	Safety	Per trip
Number of unique pedestrians detected (count)	Safety	Per trip

Metric	**Value**	**Exposure**
Distance to known objects (minimum distance per object)	Safety	Per trip
Vehicle speed (match to target speed)	Safety	Per trip
Vehicle acceleration (match to target acceleration parameters)	Safety	Per trip
Vehicle deceleration (match to target deceleration parameters)	Safety	Per trip
Accurate localization (matched to webapp)	Safety	Per second
Vehicle correct stops at locations within margin of error (percentage)	Safety	Per barge
Vehicle correctly responds to buffer override (percentage)	Safety	Per barge
Vehicle correctly responds to lift's automation engage command (percentage)	Safety	Per barge
Vehicle automation kickout due to pedestrian (count)	Safety Efficiency	Per barge
Vehicle automation kickout due to other error (count)	Safety Efficiency	Per barge
Emergency "All Stop" enacted (count)	Safety Efficiency	Per barge
Time in transit in automation mode (total)	Efficiency	Per barge
Number of trips taken	Efficiency	Per barge
Time in transit in automation mode (average)	Efficiency	Per barge
Time idle awaiting loading of cargo (static stop point at barge)	Efficiency	Per barge
Time idle awaiting unloading of cargo (dynamic stop point at barge)	Efficiency	Per barge
Time idle in queue (static stop points behind other ADS)	Efficiency	Per barge
Software errors establishing connectivity	Efficiency	Per barge
Software errors establishing automation	Efficiency	Per barge

4. CONOPS DATASET – DATAVERSE

4.1 IMPLEMENTATION

As part of this project, an open-source data repository, the VTTI CONOPS Dataverse, was developed to house the data from the CONOPS roadshows and deployments. The Dataverse, hosted by VTTI, serves as the interface for users accessing the data produced by this CONOPS study. The VTTI Dataverse has four separate collections consisting of 94 different datasets and 185 files. To ensure data privacy and security, VTTI drew on its own experience with naturalistic driving datasets and datasets containing sensitive information. A critical aspect to the success of the VTTI CONOPS Dataverse was its usability, easy access to background project information, and accessible documentation and training related to the website's query tool. The Dataverse features fields that provide an overview of the dataset, including a description of the project, subject, and keywords. The interface also provides information on the datasets, data directories, metadata, terms, and versions.

To complete data migration from the ADS deployments, data from the automated trucks were stored on an encrypted hard drive. The data were then removed from the automated truck by Pronto.ai and stored on its secure servers. Proprietary information was stripped from these data, and the remaining data were sent on an encrypted hard drive to VTTI. Upon arrival at VTTI, these data were first decrypted and stored on VTTI's secure server. Then, personally identifiable information (PII) was removed, and, if necessary, the data were filtered, smoothed, and uploaded to the VTTI CONOPS Dataverse for public access/viewing.

The Dataverse houses all the non-proprietary data collected over the course of the project:

- Data generated from the operation of the advanced driver assistance systems (ADAS)/ADS trucks (including video, kinematic, radar, GPS, and other sensors);

- Driver monitoring datasets from the ADS-equipped vehicles during the three deployments and use cases (port queueing, cross-country trips, and fleet integration); and

- Survey responses obtained from the public during the roadshows and the outreach events that gauge the perceptions and acceptance of ADAS/ADS technologies.

Researchers and decision-makers can access this data for their use.

4.2 DATA FROM ADS TECHNOLOGY ROADSHOWS

The VTTI team developed questionnaires that were used to investigate attitudes toward truck automation, use cases where automation will provide economic and/or safety benefits, and the ways in which truck drivers and the driving public can expect to interact with truck automation. The surveys also gathered demographic data to understand how different segments of truck fleets view ADS. The questionnaires were developed so they could be given at two different time points. In Chapter 2, the data were used to identify current gaps in the industry's understanding of truck ADS and how outreach activities can address this gap to improve attitudes toward truck ADS. Researchers also have access to this data on the Dataverse.

4.3 DATA FROM ADS TECHNOLOGY DEPLOYMENTS

This section provides details on the vehicle variables obtained from the three deployments. The data were collected and uploaded on the VTTI CONOPS Dataverse and can be directly accessed from the following link (https://dataverse.vtti.vt.edu/dataset.xhtml?persistentId=doi:10.15787/VTT1/ZYMSEM). Below is a brief description of the deployments and the data associated with each deployment use case. Figure 33 also summarizes datasets.

- Port Queuing: ADS-equipped trucks offer the potential to allow the vehicle to drive itself while queueing to be loaded or unloaded. The port queueing deployment included various use cases that involved interaction between an ADS and a driver at various stages of port operations. This involved: (1) a human driver manually driving the truck to the back of terminal's queue, (2) a driver engaging the ADS, and the truck automatically proceeding into the queue, through the terminal gate and inside the port, and (3) a driver disengaging the ADS and manually driving to the drop-off spot. Section 4.3.1 details the data collected during this deployment.
- Cross-Country: The purpose of this was to collect detailed inventories of ADS perception of sensory data on roadway features and the quality of supporting communications and location data. The intent was to develop a national dataset on the infrastructure and ADS performance metrics required for ADS operations. This data can be used to provide stakeholders and decision-makers on the infrastructure improvements required to support ADS integration into fleet operations. Section 4.3.2 details the data collected during this deployment.
- Fleet Integration: The Fleet Integration deployment focused on ADS state and safety metrics while being operated for revenue with a participating fleet on public/private roadways. The deployment use case provided video data and real-time vehicle information as an ADS-equipped truck navigated the unusual conditions at the port while also interacting with other vehicles and non-vehicular objects in its vicinity. Section 4.3.3 details the data collected during this deployment.

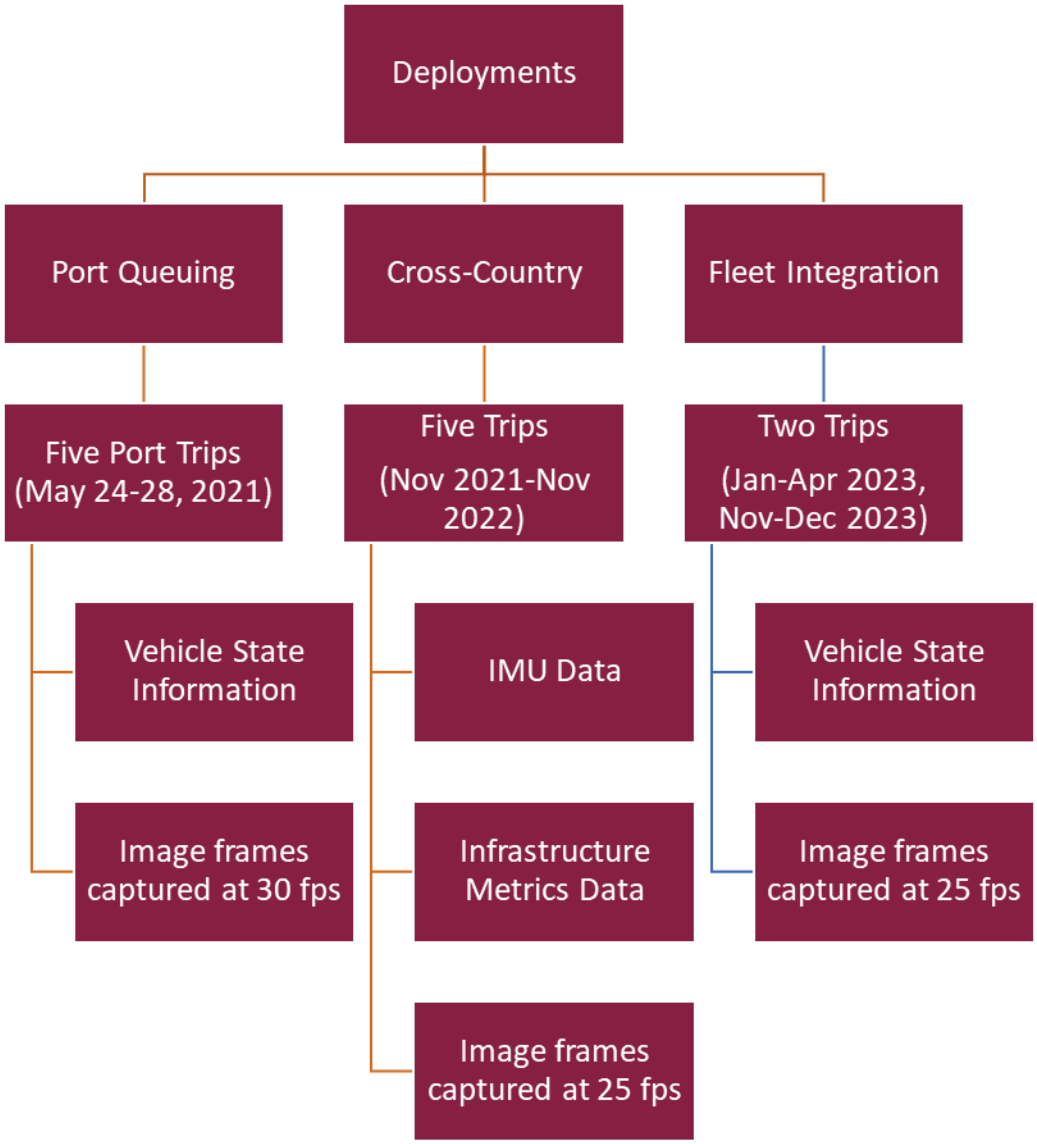


Figure 33. Diagram. High-level summary of data collected by Pronto during each operational use case deployment of ADS-equipped CMV available on the CONOPS Dataverse.

4.3.1 Port Queuing Deployment

The Port Queuing Deployment was conducted from May 24, 2021, to May 28, 2021. A total of 181 minutes of data was collected by the Pronto team from the five trips in Oakland, California. The data consists of vehicle state information, which is stored in CSV format. Images were also captured from the front-facing video stream during the port queueing. These frames are .jpeg format and have a uniquely identifiable name. Table 10–Table 14 provide the data collected at the port queueing deployment, including the information on the variables, the measurement unit, and the data type. The images were collected at a frequency of 30 frames per second (fps).

Table 10. File name: car state.

Variable Name	Measurement Unit	Possible values	Type
Applied Brake Pressure Primary	psi		Numeric
Brake	Percentage		Numeric
Drive State	Categorical	initializing-system booting, homing-Pronto DBW running calibration checks, not Ready-System booted, and calibration checks passed, ready to Engage- system ready for autonomous operation, engage-autonomous operation active, idling-Pronto system disabled	Text
Driver Brake	Categorical	True- safety driver pressed the brake pedal | False-safety driver did not press the brake pedal	Text
Driver Throttle	Categorical	True-safety driver requested throttle | False-safety driver did not request throttle	Text
Gear	Categorical		Numeric
PRNDL	Categorical		Text
Set Speed	m/s		Numeric
Steering Wheel Angle	Degrees		Numeric
System Engaged	Categorical	True- Autonomous system is engaged | False- Autonomous system is not engaged	Text
Throttle	Percentage		Numeric
Vehicle Speed (vEgo)	m/s		Numeric
Time Stamp	Time (in seconds)		Numeric

Table 11. File name: IMU.

Variable Name	Measurement Unit	Type
Accel X	m/s^2	Numeric
Accel Y	m/s^2	Numeric
Accel Z	m/s^2	Numeric
frame	north-east-down	
altitude	meters	Numeric
latitude	decimal degrees	Numeric
longitude	decimal degrees	Numeric
pitch	degrees/second	Numeric
roll	degrees/second	Numeric
yaw	degrees/second	Numeric
vx	m/s	Numeric
vy	m/s	Numeric
vz	m/s	Numeric

Table 12. File name: gpsRTK.

Variable Name	Measurement Unit	Type
altitude	meters	Numeric
latitude	decimal degrees	Numeric
longitude	decimal degrees	Numeric
status	Categorical	Text
frame	earth-centered earth-fixed	Text
x coordinate	decimal degrees	Numeric
y coordinate	decimal degrees	Numeric
z coordinate	decimal degrees	Numeric
Time Stamp	Time (in seconds)	Numeric

Table 13. File name: frames.

Variable Name	Measurement Unit	Type
Time Stamp	Time (in seconds)	Numeric
File name of the jpeg image captured	File name (text)	Text
Latitude	decimal degrees	Numeric
Longitude	decimal degrees	Numeric

4.3.2 Cross-Country Deployment

One of the objectives from the cross-country deployment is to collect, organize, and share data on infrastructure quality by driving an automated truck across various routes under a variety of conditions. Key infrastructure metrics include (1) cellular LTE connectivity, (2) lane marking quality, (3) road bumpiness, and (4) GPS satellite coverage. Based on the dictionary of the dataset collected from the cross-country drive, these infrastructure metrics were quantified by the following variables:

- Cellular LTE connectivity: *Signal Strength* (%)
- Lane marking quality: *Lane Score of Road* (%)
- Road bumpiness: *Road Condition* (Smooth or Bumpy)
- GPS satellite coverage: *GPS Satellites* (Count)

Table 15 summarizes the dataset collected and stored from the cross-country drive. In addition to the four infrastructure measures listed above, the dataset contains information on truck acceleration, motion basics (roll, pitch, and yaw), location, and speed. Table 16 and Table 17 provide more detail on the measurement units, the description, and the data type.

Table 14. Data from cross-country deployments.

Variable	Unit	Mean	Std Dev	Absmean
Acceleration X	m/s^2	✓	✓	✓
Acceleration Y	m/s^2	✓	✓	✓
Acceleration Z	m/s^2	✓	✓	✓
Roll	Deg	✓	✓	✓
Pitch	Deg	✓	✓	✓
Yaw	Deg	✓	✓	✓
Roll rate	Deg/s	✓	✓	
Pitch rate	Deg/s	✓	✓	
Yaw rate	Deg/s	✓	✓	
Latitude	Deg			
Longitude	Deg			
Signal Strength	%			
GPS Satellites	Count			
Speed	mph			
Time	ms			
Lane Score of Road	%			
Road Condition	Categorical			
State				

The Cross-Country deployment occurred in multiple trips. Table 15 shows the list of trips completed during the duration of the CONOPS projects.

Table 15. Five road trips that composed the cross-country deployment data collection.

Trip Name	Duration of the Trip
Nationwide Cross-Country Loop	October 25, 2021, to December 01, 2021
California – Texas (Round trip)	December 14, 2021, to December 21, 2021
Calgary, Canada – California (One way trip)	January 12, 2022, to February 06, 2022
California – Florida (Round trip)	February 28, 2022, to March 13, 2022
California – Oregon – Washington – Idaho – Montana – Wyoming – Utah – Arizona – Nevada – California	November 12, 2022, to November 17, 2022

The completed trips consist of IMU data and infrastructure metrics data. The data collected were stored in CSV format. Images were captured at a frequency of 25 fps from the front-facing camera. The image frames are in .jpeg format and have a uniquely identifiable name. The following variables were collected during the cross-country trips.

Table 16. Data type: IMU.

Variable Name	Measurement Unit	Description	Type
Accel X_Mean	m/s^2	Mean acceleration of the vehicle over 1 second in the x direction with respect to the vehicle body frame	Numeric
Accel Y_Mean	m/s^2	Mean acceleration of the vehicle over 1 second in the y direction with respect to the vehicle body frame	Numeric
Accel Z_Mean	m/s^2	Mean acceleration of the vehicle over 1 second in the z direction with respect to the vehicle body frame	
Roll_Mean	degrees	Mean roll angle of vehicle over 1 second	Numeric
Pitch_Mean	degrees	Mean pitch angle of vehicle over 1 second	Numeric
Yaw_Mean	degrees	Mean yaw angle of vehicle over 1 second	Numeric
Accel X_stddev	m/s^2	Standard deviation of acceleration of the vehicle over 1 second in the x direction with respect to the vehicle body frame	Numeric
Accel Y_stddev	m/s^2	Standard deviation of acceleration of the vehicle over 1 second in the y direction with respect to the vehicle body frame	Numeric
Accel Z_stddev	m/s^2	Standard deviation of acceleration of the vehicle over 1 second in the z direction with respect to the vehicle body frame	Numeric
Roll_stddev	degrees	Standard deviation of roll angle of vehicle over 1 second	Numeric
Pitch_stddev	degrees	Standard deviation of pitch angle of vehicle over 1 second	Numeric
Yaw_stddev	degrees	Standard deviation of yaw angle of vehicle over 1 second	Numeric
Accel X_absmean	m/s^2	Mean of absolute value of acceleration of the vehicle over 1 second in the x direction with respect to the vehicle body frame	Numeric
Accel Y_absmean	m/s^2	Mean of absolute value of acceleration of the vehicle over 1 second in the y direction with respect to the vehicle body frame	Numeric
Accel Z_absmean	m/s^2	Mean of absolute value of acceleration of the vehicle over 1 second in the z direction with respect to the vehicle body frame	Numeric
Roll_absmean	degrees	Mean of absolute value of roll angle of vehicle over 1 second	Numeric
Pitch_absmean	degrees	Mean of absolute value of pitch angle of vehicle over 1 second	Numeric
Yaw_absmean	degrees	Mean of absolute value of yaw angle of vehicle over 1 second	Numeric
Rollrate_mean	degrees/second	Mean roll angle rate of vehicle over 1 second	Numeric
Pitchrate_mean	degrees/second	Mean pitch angle rate of vehicle over 1 second	Numeric
Yawrate_mean	degrees/second	Mean yaw angle rate of vehicle over 1 second	Numeric
Rollrate_stddev	degrees/second	Standard deviation of roll angle rate of vehicle over 1 second	Numeric
Pitchrate_stddev	degrees/second	Standard deviation of pitch angle rate of vehicle over 1 second	Numeric
Yawrate_stddev	degrees/second	Standard deviation of yaw angle rate of vehicle over 1 second	Numeric

Table 17. Data type: infrastructure metrics.

Variable Name	Measurement Unit	Description	Type
Latitude	degrees	Latitude position	Numeric
Longitude	degrees	Longitude position	Numeric
Signal Strength	percentage	Received signal strength percentage for LTE Modem	Numeric
GPS Satellites	Count	Number of GPS satellites that are visible to vehicle	
Speed	mph	Vehicle speed	Numeric
Time	milliseconds	UTC time in milliseconds	
Lane Score of Road	percentage	Score between 0 and 1 indicating the ability to detect lane lines. 1 is the best score whereas 0 is the worst score.	Numeric
Road Condition	Categorical	Road condition of "Smooth" or "Bumpy" calculated over each second	Text
State		US State associated with reported position	Text

Road Lane Score

The dataset has lane scores between 0 and 1. The scores indicate the ability to detect lane lines. Here, a score of 1 or close to 1 is the best score, whereas a score of 0 is the worst score. The road lane score was calculated using Polyscore, which is shown below.

$$PS = 1 - \frac{\sum_{i=1}^{N} \left| |\hat{x}_S - \hat{x}| - \epsilon \right| / \epsilon -}{N} \begin{cases} 0 & if\ PS \leq 0 \\ PS & otherwise \end{cases}$$

$$\begin{cases} N = \text{number of keypoints} \\ \epsilon = \text{constant} \\ \hat{x}, \hat{x}_s = \text{coordinates of the predicted keypoints} \end{cases}$$

The Polyscore is a confidence estimation that is computed from test time augmentation of the image. The Polyscore requires an image and the inference from the PolyNet model. The process starts with a network that has an image and will predict the location of the lane lines in the image. It compares this to the lane line detection camera. This is an internally trained model created by Pronto. After, the confidence in the prediction is computed versus the actual image. A low score means that the prediction is less confident (between 0 and 1). The higher the score, the more confident the prediction is. A negative lane score is corrupted or not usable. The only gaps in Polyscore occur if there was no image collected to analyze, so a score of zero is still providing data.

Road Condition (Bumpy and Smooth)

Road condition was calculated using car state, such as acceleration, yaw, pitch, roll, and speed. The road condition is computed only when vehicle velocity is greater than 40 mph.

Model: Binary Support Vector Machine Classifier

Input features:

$$\begin{cases} \mu_{a_z} = \text{average acceleration} \\ \sigma_{a_z} = \text{standard deviation of the aceleration} \\ \mu_{\psi} = \text{average pitch} \\ \sigma_{\psi} = \text{standard deviation of the pitch} \end{cases}$$

Signal Strength

The raw signal strength is a value in the range [0, 31]. The signal strength as a percentage is computed as: "**percentage_SignalStrength" = "raw_SignalStrength" / 31.** The command AT+CSQ returns signal strength, and the returned values range between 0 and 31. The returned values are mapped to the received signal strength indicator, which is measured in dBm; it is a measure of received power.

4.3.3 Fleet Integration Deployment

The Fleet Integration Deployment was conducted from January–April and Nov–Dec of 2023 in Alaska. The data consists of vehicle state information which is stored in CSV format. Images were captured from the front-facing camera. The image frames are in .jpeg format and have a uniquely identifiable name. The images were collected at a frequency of 20–25 frames per second (fps). Table 18 lists the variables information was collected in car state files, and Table 19 lists the variables information was collected in frame files.

Table 18. File Name: car state

Variable Name	Measurement Unit	Possible values	Type
Brake	Percentage		Numeric
Drive State	Categorical	initializing-system booting, homing-Pronto DBW running calibration checks, not Ready-System booted, and calibration checks passed, ready to Engage- system ready for autonomous operation, engage-autonomous operation active, idling-Pronto system disabled	Text
Driver Brake	Categorical	True-safety driver pressed the brake pedal | False-safety driver did not press the brake pedal	Text
Driver Throttle	Categorical	True-safety driver requested throttle | False-safety driver did not request throttle	Text
Gear	Categorical		Numeric
PRNDL	Categorical		Text
Steering Wheel Angle	Degrees		Numeric
System Engaged	Categorical	True-Autonomous system is engaged | False-Autonomous system is not engaged	Text
Throttle	Percentage		Numeric
Time Stamp	Time (in seconds)		Numeric

Table 19. File name: frames.

Variable Name	Measurement Unit	Type
Time Stamp	Time (in seconds)	Numeric
File name of the jpeg image captured	File name (text)	Text
Latitude	decimal degrees	Numeric
Longitude	decimal degrees	Numeric

4.4 ACCESS AND USAGE

All the data collected by the CONOPS project are accessible via the VTTI CONOPS Dataverse. The datasets are minted with permanent digital object identifier (DOI) citations and published on the VTTI Dataverse. The datasets do not contain proprietary or confidential information, hence, there are no concerns regarding privacy, ethics, or confidentiality. The data management rights have been transferred to the curators of the VTTI CONOPS Dataverse. The data is available for open sharing under the Creative Commons Zero (CC0) universal public domain dedication. Under CC0, data and derivative products are available for reuse and redistribution without restriction. The VTTI CONOPS Dataverse meets the criteria outlined in the Guidelines for Evaluating Repositories for Conformance with the DOT Public Access Plan. The CONOPS Dataverse promotes an explicit mission of digital data archiving, which is described on the Dataverse website and is listed by the USDOT as a Data Repository Conformant with the DOT Public Access Plan at https://ntl.bts.gov/publicaccess/repositories.html.

4.4.1 Data Organization

Port Queuing: Pronto's logging system records data in 1-minute-long chunks. For each of the trips, Pronto provided CSV files and images. The data for Port Queuing were uploaded on Dataverse in two folders. One folder is dedicated to all the CSV files organized by trip. Each trip folder contains subfolders for each file name (such as carState, IMU, gpsRTK, frames) organized as file name-hr-min. The second folder will have all the images in .jpeg format. The images will also be organized by trip.

Cross-Country: As described for Port Queuing, Pronto's logging system records data in 1-minute-long chunks. A total of five cross-country trips were completed. The trips were as follows: (1) Nationwide Loop, (2) San Francisco–Texas–San Francisco, (3) San Francisco–Calgary–San Francisco, (4) San Francisco–Orlando–San Francisco, and (5) California–Montana–California. The data were uploaded on the Dataverse by State, followed by the trip name. Within the State folder, there are two folders. One folder has the CSV files containing the data that were collected on a particular day. The second folder has images in .jpeg format. The files in the image folder are organized as day-hr-min.

Fleet Integration: The Fleet Integration use case dataset is similar to the port queuing deployment dataset, with information on the vehicle state information stored in CSV and the front-facing images captured during the deployment. The data is also organized in a similar manner to the Port Queueing data organization.

5. GUIDELINES

This chapter provides guidance on a range of topics for fleets to consider and apply when preparing to deploy ADS-equipped CMVs in their fleet. The topics cover fleet-derived specifications, ADS installation and maintenance, ADS inspection procedures, driver-monitor alertness management, insuring ADS-equipped trucks, identification of ADS safety metrics/variables, ADS road assessment, and data security/transfer protocol and cybersecurity best practices.

5.1 FLEET SPECIFICATIONS

Early in the project the research team sought input from fleets through fleet manager questionnaires. Essentially, the research team identified potential early adoption uses cases for ADS including Exit-to-Exit, Yard-to-Exit, and Truck Queueing, and conducted research on what expectations stakeholder have of ADS technology in these use cases. This information served to inform the approach for developing guidelines. This is discussed in section 5.1.1. Then, using a literature search, various systems on existing trucks that may require special consideration towards the integration of ADS technology into CMVs generally, and for these use cases, were identified. These include the placement of safety equipment, electrical components, batteries, sensors, controls, displays, and other components for equipping CMVs with ADS as described in section 5.1.2.

5.1.1 Fleet Specifications for ADS-equipped CMV Use Cases

This project took an industry-first approach focused on how fleets will be able to integrate ADS-equipped trucks. In the near term, it is unlikely a company will have an entire fleet of ADS-equipped trucks to serve all possible freight operations. It is more likely that a segment of truck fleets will be ADS-equipped without a driver, but much of the fleet will remain conventional trucks and ADS-equipped trucks that require human driver involvement. The research team conducted discussions with truck industry partners regarding the use cases having the most appeal to truck fleets.

The goal of this activity was to outline a set of use case specifications, which were derived from fleet users, to support the development of the fleet ADS CONOPS. To support effective ADS deployment, input from fleet users is a critical step in the process. Participating truck fleets specified their needs as a function of their real-world operational experiences. Considering the needs of the end user is an important part of the design process. This user-centered design paradigm will help ensure that the needs of the end users (i.e., truck fleets) drive the ADS technology design.

This task was completed with discussions with the team’s truck industry partners. To meet the goals of this task, the VTTI team held discussions with fleets, yielding six respondents. The discussions were on (i) Functional, (ii) Non-Functional, and (iii) Contextual topics for each of the use cases: (1) Exit-to-Exit (e.g., highway), (2) Yard-to-Exit (e.g., origin to destination, such as regional and short haul), and (3) Truck Queuing. Functional discussions focused on specific functions/behaviors fleets expect of the ADS in each use case. Non-functional questions focused on general ADS performance/quality attributes in each use case, for example safety, security, usability, maintainability, scalability. Contextual questions focused on assumptions about the operating environment needed for the ADS to operate effectively in each use case. The research team developed a set of assumptions to bound the discussions and provide context to support fleet input. Three key assumptions were:

- The ADS will operate in a mixed environment (e.g., ADS-equipped trucks and human-operated trucks).
- The ADS will perform with a quality and success rate that is similar or better than an experienced truck driver.
- The ADS will be compliant within existing regulations and/or has an approved exemption to operate in the use case.

The following sections outline each of the three use case scenarios, list the questions/topics posed to fleet representatives, and summarize their responses. Each use case is presented in turn, along with the topics covered with the Functional, Non-Functional, and Contextual topics. Responses are in italics.

5.1.1.1 Exit-to-Exit (Highway)

It is expected that some of the earliest deployments of ADS-equipped trucks will occur on long, open stretches of highways (especially in the western and southern United States) rather than in urban areas. This use case studied the feasibility of operating an ADS-equipped truck from exit to exit on the U.S. highway system. A human driver operates the ADS-equipped truck until entering the U.S. highway system. The ADS-equipped truck will operate in automated mode once on the approved U.S. highway system. The human driver resumes control upon exiting the U.S. highway system or when the ADS-equipped truck requests the driver take over or any time the human driver desires to take control of the truck.

Functional Requirements: Please specify the services/abilities you expect from the ADS in this use case (i.e., what specific functions/behaviors do you expect of the ADS in this use case)? Answer this with respect to what the ADS must do in this use case (a specific function/behavior). Some key questions for this use case are:

(A) How does the role of the driver impact the utility of this use case (e.g., is it only useful when this use case can be driverless/unmanned)? Is there a business case for having a driver in the truck (but potentially sleeping or inattentive for some of the time)? Is there a business case when you always need a fully attentive driver, even though the ADS is doing all the driving?

Once ADS is fully operational, the true value will be when a truck can operate completely unmanned. Although L2 technology is of great assistance to drivers today, when L4 is available, having a driver onboard would likely be viewed as redundant and less cost-effective. Expectation is the driver to be attentive for a variety of reasons (e.g., unknown or sudden reaction to unknown road conditions, debris, animals, or possible ADS malfunction).

(B) How attractive is the “transfer hub” model?

Over the next few years, the transfer hub model is a reasonable way to pilot test and assess the benefits of L4 ADS. This model works well with operations in proximity to arterial highways. Longer term, for an over-the-road irregular route model, an end-to-end model would be most efficient.

(C) Do you need to operate your trucks for this use case (i.e., the ADS developer oversees the containers for a certain stretch of road)?

Once fully operational, the ADS developer could maintain primary oversight of L4 trucks (e.g., health checks, etc.). However, there would need to be ongoing interface with the carrier that would provide information, such as current location, delays in transit, updated time for departure for the customer, etc.

(D) Does there need to be an extensive exit-to-exit (interlinking) network already set up before you will start using this use case? Or, is just one or two “A to B” lines (possibly in the middle of nowhere) enough for you to start moving traffic to those nodes?

Just one or two A to B lines will be appropriate to get started for pilot testing purposes. As this process expands, additional sites will need to be established, especially for over-the-road carriers.

(E) How will you rebalance your logistics in a mixed-use environment once some routes are able to have driverless exit-to-exit? For example, Dallas to LA has a reliable driverless exit-to-exit operation and a container needs to go from Chicago to San Francisco. Will you now reroute the package to go from Chicago down to Dallas and then from LA to San Francisco (thereby increasing mileage and other logistical costs) to take advantage of that driverless Dallas to LA potential?

The decision would likely be dependent on the load, the customer needs, and efficiency of the transportation option (e.g., teams, intermodal, or L4/exit-to-exit). Ideally, a route will be mapped and certified; thus, a more direct, exit-to-exit approach can be used.

(F) What part of the “ideal” exit-to-exit ADS use case are you willing to give up in order to deploy the technology faster? For example, what’s a nice-to-have vs. a must-have to roll the technology out on an everyday basis?

An absolute “must have” is safety. The development of exit-to-exit hubs is not ideal and will likely require a degree of complexity to establish (locations, driver schedules, etc.), but this approach will be a reasonable trade-off to deploy the technology more quickly to assess the future benefits. Related to safety, an ideal ADS should be driverless.

Non-Functional Requirements: Please specify the performance/quality attributes of the ADS in this use case (i.e., what are the general ADS performance/quality attributes supposed to be in this use case)? Answer this with respect to what the ADS shall be in this use case (an overall property of the ADS, but not a specific function). Examples include safety, security, usability, testability, maintainability, extensibility, scalability, etc.

(A) How do you think about balancing the trade-offs between decreased costs vs. decreased efficiency (although it is often optimistically assumed that ADS, especially driverless, will both decrease costs and increase efficiency, in reality it is more likely that labor costs will be decreased, but operational complexity and efficiency might be adversely affected, especially in the early days).

Trade-offs (cost vs. complexity) are expected early in the development process. However, this will be necessary to learn and achieve true efficiency over time. Negative impacts to the service model would hinder use. Shippers would need to be agreeable to extended transit times unless the operating lanes fit in our existing network.

(B) Would you roll out the ADS for hazmat or high-value cargo? Why not, if, by definition, the ADS has as good or better performance than a human driver?

Long-term there would be no reason not to use ADS for hazmat or high-value loads. However, given the potential risks (and the sensitivity) associated with hazmat loads and the potential security questions that will arise with high-value loads, it's likely these load-types would be hauled via ADS after the technology has matured. Need to have enhanced security features.

(C) How do you believe this use case is affecting human driver recruitment? Driver retention? Dispatch logistics?

In the short-term, there will not be an impact on driver recruitment. Although the rate and pace of technology will continue to accelerate, drivers and prospective drivers will soon realize there will always be a need for skilled truck drivers in the immediate future. With respect to the dispatch process, there will be some complexity in pairing freight, equipment, and exit-to-exit schedules. However, these challenges will be confined to specific lanes designated for ADS in the short-term.

(D) How important is it for the ADS to be integrated and supported by an OEM (as opposed to an independent ADS tech vendor)?

For large carriers, the expectation will be that the ADS is purchased during regular cycles. ADS is installed and supported by the OEM, just as with any other tractor component. Although retro-fitting is feasible by an independent ADS technology vendor short-term, long-term independent ADS providers will likely need to align themselves with a specific OEM to enable system integration with OEM system components.

(E) What happens if the ADS is only available from a particular OEM? Will you only start purchasing the ADS-equipped trucks or wait until the ADS is available on your traditional OEMs?

Independent ADS retro-fitting will not be a barrier to using ADS technology. However, long-term carriers will expect their OEM of choice to provide ADS as an available spec.

Contextual Requirements: Within this use case, what assumptions about the operating environment are needed for the ADS to operate effectively (i.e., the traffic system in which the ADS operates is variable, what environmental/contextual variables should be considered)? This is a reciprocal relationship, so please consider how the environment/context impacts the ADS and vice versa.

(A) Should we expect the highways where exit-to-exit ADS becomes possible first to suddenly get much more congested? To what extent does that wash away the potential benefits?

Although it is certainly a consideration, other options could include the use of different exits or even co-location of "hubs" with other carriers. However, this is not viewed as a realistic outcome. Carriers move freight as commerce has a directional flow. There may be enough incentive to redirect freight in ADS lanes, but there are no advantages in additional time and mileage in most cases.

(B) Are there fears that if a competitor rolls out ADS on that stretch of road first, they will have a huge competitive advantage and take over the entire market for that road segment before others have a chance to respond?

Not necessarily. Given the number of different customers and the volume of freight in various regions of the country, early adopters are likely to see an initial benefit, but "fast-followers" will adopt a similar approach and over time experience similar benefits. However, it is possible that early adopters will control the technology and monitoring.

(C) Is it risky to be an early adopter (why would you want to be the first to roll this kind of service instead of waiting for it to be more proven first)? How do you balance those risks?

Early adopters will be able to understand the true benefits of ADS, where and how to apply these benefits, and, ultimately, have input on "the how" technology is developed and used. Additional benefits include the ability to provide insight to customers on the future use of ADS for freight-hauling efficiency, as well as the ability to provide input to regulators on how to best establish rules and regulations for ADS. Early adopters will also be able to determine which segments of trucking are not ready for ADS, which will allow for a more effective allocation of resources. Evolving technology typically hits the truckload sector first, but with exit-to-exit, it may be more beneficial to less-than-truckload rather than platooning.

(D) If a certain stretch of highway has reliable ADS for an exit-to-exit portion (especially a driverless one), how/why would you make sense on that segment of road? Even if the overall fleet operations remain mixed, why wouldn't you take full advantage and deploy only ADS-equipped trucks on that stretch of highway as soon as possible?

It would be dependent upon the flow of freight and lane density. These variables differ by carrier and are dependent upon their customer mix. However, if the equipment is available and drivers can be matched on each end of the load, the decision would be to determine if the "ADS" route would be offset by improved efficiencies (time, distance, fuel, etc.).

5.1.1.2 Yard-to-Exit

Many fleets report struggling with severe driver shortages and, as a result, long delays associated with deliveries where trucks run repetitive, predictable, and relatively short routes. For example, this is typical of the batch processing of intermodal containers that is required to quickly and efficiently load/unload trains and/or ships onto CMVs with intermodal trailer chasses. An ADS-equipped truck could fully automate a certain proportion of the trucks that drive such repetitive loops between loading and unloading locations. This use case identifies trucks running the same, fixed route all day, which would then enable the deployment of low-level and high-level automation in a mixed-fleet model. Because this operation may involve the use of driverless vehicles, for safety and regulatory reasons, one approach may be to test and validate the technologies with commercial truck fleets operating on private roads and/or very lightly trafficked roads before attempting to transfer them onto carriers operating on busier public highways.

Functional Requirements: Please specify the services/abilities you expect from the ADS in this use case (i.e., what specific functions/behaviors do you expect of the ADS in this use case)? Answer this with respect to what the ADS must do in this use case (a specific function/behavior).

(A) How does the role of the driver impact the utility of this use case (e.g., is it only useful when this use case can be driverless/unmanned)? Is there a business case for having a driver in the truck (but potentially sleeping or inattentive for some of the time)? Is there a business case when you always need a fully attentive driver, even though the ADS is doing all the driving?

Will be difficult to find drivers where the ADS does most of the work.

(B) Do you need to operate your trucks for this use case (i.e., the ADS developer oversees the containers for a certain stretch of road)?

Yes.

(C) What part of the "ideal" yard-to-exit use case are you willing to give up in order to deploy the technology faster? For example, what's a nice-to-have vs. a must-have to roll the technology out on an everyday basis?

Safety is the #1 factor.

(D) What happens if the ADS can only work for part of the year (say in summer when there is no rain), but is not reliable in the event of snow or heavy rain? Is that a dealbreaker and the ADS won't be adopted at all until it can work in all weather conditions that could reasonably be expected on the applicable route?

This is not a deal breaker. Integration will take time; hopefully, the ADS will increase in functionality in time for large-scale implementation. It would be difficult to get drivers for part of the year if this were not addressed relatively soon after implementation.

Non-Functional Requirements: Please specify the performance/quality attributes of the ADS in this use case (i.e., what are the general ADS performance/quality attributes supposed to be in this use case)? Answer this with respect to what the ADS shall be in this use case (an overall property of the ADS, but not a specific function). Examples include safety, security, usability, testability, maintainability, extensibility, scalability, etc.

(A) How do you think about balancing the trade-offs between decreased costs vs. decreased efficiency (although it is often optimistically assumed that ADS, especially driverless, will both decrease costs and increase efficiency, in reality it is more likely that labor costs will be decreased, but operational complexity and efficiency might be adversely affected, especially in the early days).

(B) Would you roll out the ADS for hazmat or high-value cargo? Why not, if, by definition, the ADS has as good or better performance than a human driver?

Yes, if safety is better than a safe human driver. If it also has security features.

(C) How do you believe this use case is affecting human driver recruitment? Driver retention? Dispatch logistics?

Why would you need to hire drivers if they are being phased out? Some drivers would leave. Logistics personnel will likely be the same, at least initially, but then they would leave as more ADS are integrated into the fleet.

(D) How important is it for the ADS to be integrated and supported by an OEM (as opposed to an independent ADS tech vendor)?

Would feel better if it comes from an OEM rather than retrofit, but not a deal breaker.

(E) What happens if the ADS is only available from a particular OEM? Will you only start purchasing the ADS-equipped trucks or wait until the ADS is available on your traditional OEMs?

Would purchase some portion of power units to start slow until available from an OEM.

Contextual Requirements: Within this use case, what assumptions about the operating environment are needed for the ADS to operate effectively (i.e., the traffic system in which the ADS operates is variable, what environmental/contextual variables should be considered)? This is a reciprocal relationship, so please consider how the environment/context impacts the ADS and vice versa.

(A) Are there fears that if a competitor rolls out ADS on that stretch of road first, they will have a huge competitive advantage and take over the entire market for that road segment before others have a chance to respond?

Yes.

(B) Is it risky to be an early adopter (why would you want to be the first to roll this kind of service instead of waiting for it to be more proven first)? How do you balance those risks?

Yes, and no. There is risk, but also reward. Will most likely use a small-scale implementation before ramping up.

(C) Do you believe the commercialization of this kind of use case encourages a greater shift to intermodal freight (at the expense of over-the-road or dedicated line haul)? Or could the opposite be true?

Believe this will increase intermodal freight unless transfer hubs are far from rail yards.

(D) How might the availability of ADS impact the important dynamic of a trucking fleet's key railroad relationships? Does the railroad end up with more (or less) power?

More difficult to implement at rail yards given their rules/regulations.

5.1.1.3 Truck Queuing

This use case would enable the truck to operate without a driver in the seat while queueing to be loaded or unloaded. With the ADS enabled, a driver could go off-duty and rest in a sleeper berth or even leave the vehicle and obtain rest in another location. Therefore, the waiting period could potentially be used for driver rest and not count against the driver's HOS, increasing the driver's overall productivity, the carrier's bottom line (more distance could be covered in the day), and safety (drivers would be better rested and less pressured by time).

Functional Requirements: Please specify the services/abilities you expect from the ADS in this use case (i.e., what specific functions/behaviors do you expect of the ADS in this use case)? Answer this with respect to what the ADS must do in this use case (a specific function/behavior).

(A) How does the role of the driver impact the utility of this use case (e.g., is it only useful when this use case can be driverless/unmanned)? Is there a business case for having a driver in the truck (but potentially sleeping or inattentive for some of the time)? Is there a business case when you always need a fully attentive driver, even though the ADS is doing all the driving?

The driver does not need to be attentive. Driver can take a nap. However, port terminal management may require a driver to be onboard and/or needs to be on standby.

(B) Do you need to operate your trucks for this use case (i.e., the ADS developer oversees the containers for a certain stretch of road)?

Truck fleet would like to have oversight of the vehicle.

Non-Functional Requirements: Please specify the performance/quality attributes of the ADS in this use case (i.e., what are the general ADS performance/quality attributes supposed to be in this use case)? Answer this with respect to what the ADS shall be in this use case (an overall property of the ADS, but not a specific function). Examples include safety, security, usability, testability, maintainability, extensibility, scalability, etc.

(A) How can this solution be balanced and/or integrated with other demand smoothing options ports may be considering (such as peak pricing or incentives to come during off-peak hours)?

The port terminal decides if these vehicles are allowed; fleet has little impact. No rights in the terminal.

(B) Is there a minimum queueing length/time that is required for this solution to make sense?

Rather have the ADS drive regardless of length in the queue.

(C) How should we think about the queue outside the port's gate vs. the queue once you are past the gate?

Limited rights once you pass the gate. Outside the gate is a less complex environment. Gate requires security checkpoint and different machinery.

(D) How do you think about balancing the trade-offs between decreased costs vs. decreased efficiency (although it is often optimistically assumed that ADS, especially driverless, will both decrease costs and increase efficiency, in reality it is more likely that labor costs will be decreased, but operational complexity and efficiency might be adversely affected, especially in the early days).

Decreased costs would be primary concern, efficiency will come later.

(E) Would you roll out the ADS for hazmat or high-value cargo? Why not, if, by definition, the ADS has as good or better performance than a human driver?

Not for hazmat.

(F) How do you believe this use case is affecting human driver recruitment? Driver retention? Dispatch logistics?

Make their job easier. Increase driver retention. Logistics would improve.

(G) How important is it for the ADS to be integrated and supported by an OEM (as opposed to an independent ADS tech vendor)?

Would want to be supported by an OEM eventually.

(H) What happens if the ADS is only available from a particular OEM? Will you only start purchasing the ADS-equipped trucks or wait until the ADS is available on your traditional OEMs?

Depends on the size of fleets. Lots of fleets in this space buy used trucks from larger carriers. If there is a mandate to buy electric vehicles such as proposed in California, that will require purchase of new vehicles.

Contextual Requirements: Within this use case, what assumptions about the operating environment are needed for the ADS to operate effectively (i.e., the traffic system in which the ADS operates is variable, what environmental/contextual variables should be considered)? This is a reciprocal relationship, so please consider how the environment/context impacts the ADS and vice versa.

(A) Are there fears that if a competitor rolls out ADS on that stretch of road first, they will have a huge competitive advantage and take over the entire market before others have a chance to respond?

Not in this use case; most are owner operators (90%).

(B) Is it risky to be an early adopter (why would you want to be the first to roll out this kind of service instead of waiting for it to be more proven first)? How do you balance those risks? How will the terminal and unions think about ADS?

This is always a risk. Do it now or you'll be behind the curve. This is a pivot point.

5.1.2 Industry Practices and References for ADS-equipped CMVs

The following information was collected during a literature search that identified subsystems and components on existing trucks that may need special consideration during the purchase and specification process when planning to equip a CMV with an ADS. A summary of each of the component areas is provided with descriptions of the guidance provided, how it applies to ADS operations, and the specific need for the specification consideration.

5.1.2.1 Placement of Safety Equipment

Scope: Guidelines for the placement of safety equipment including warning triangles (formerly referred to as flares) in heavy-duty commercial vehicle cabs.

Guidance: Guidance for safety equipment pertaining to Federal Motor Carrier Safety Regulations (FMCSR), 49 Code of Federal Regulations (CFR) 393.95, includes these considerations: amount of space, storage location for fire extinguishers for access from within the cab or for safety operator standing on the ground, location to avoid interference with other components in the cab, location of warning triangles, location of additional fire extinguishers, attachment strength to avoid cab damage, designation for safety equipment in manufacturer's owner manual, and mounting strength to last the life of the vehicle.

ADS Application: ADS-equipped CMVs carry components similar to conventionally operated CMVs on which FMCSR 49 CFR 393.95 safety equipment is required, and ADS-equipped CMVs also carry additional batteries and electronics that may require additional fire extinguishers. Warning triangles are an important consideration for ADS-equipped CMVs that are operated without onboard personnel.

Need: ADS-equipped CMVs will require a convenient and commonly understood location for safety equipment for onboard operators, as well as easy access to fire extinguishers for staff or emergency personnel supporting from outside an ADS-equipped CMV operating without onboard personnel. ADS-equipped CMVs that pull off onto the shoulder to arrive at a minimal risk condition (MRC) will need to set warning triangles when operating with or without onboard personnel. The process of setting warning triangles or similar flare-like technology may need to be innovated.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 403A: Placement of Safety Equipment, 10/2019. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

5.1.2.2 Electrical

Power Cable Assemblies

Scope: Power cable routing, cable gauge size, battery and power terminals.

Guidance: Minimum shielded and unshielded distance from hot components, cable size, terminal connection process, and parts specifications.

ADS Application: Specification and installation of ADS sensing and computing power cables.

Need: ADS-equipped CMVs have significant power demands for sensors, computing resources, and data collection and communication subsystems to support object, event, detection, and response ADS task.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 105D: Design and Installation of Copper Power Cable Assemblies, 10/2020. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Wiring Harness Protection

Scope: Minimum guidelines for protection of wiring harnesses from operational and environmental conditions.

Guidance: Guidance covers general function, conditions (i.e., abrasion, temperature, chemical resistance, cut resistance, and moisture), cable insulations, and harness coverings. Application guidelines include considerations for metal edges for routing, fastening structures, minimum distance between fasteners, clip types and coatings, flex between moving parts, and protection from operational and environmental hazards. Specifications are included for types of harness coverings: woven braid material, taping materials, plastic tubing, and heat-reflective wraps.

ADS Application: Wiring harness routing and clipping between components for ADS sensing and computing.

Need: ADS-equipped CMVs require durable and reliable bundled wiring harnesses to maintain functionality when exposed to extreme vibration in cab interior and exterior as well as survival from severe temperatures, snow/ice, and road debris during long trips between manual inspections. Harnesses are commonly located in areas that cannot be easily inspected visually without removing interior or exterior body panels or other substantial disassembly of non-interfacing parts.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 114B: Wiring Harness Protection, 10/2020. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Wiring Harness Routing, Clamping, and Protection

Scope: Routing, clamping, and protecting wiring harnesses used on 12- or 24-volt wiring systems in trucks, tractor trucks, trailers, and dollies among vehicle locations.

Guidance: Wiring harness routing and clipping between components for ADS sensing and computing. Environmental considerations include water, corrosion, chemicals, vibration, abrasion, impact, sand and dust, temperature extremes, electromagnetic interface/radio-frequency interface, tensile loads, and flexing (e.g., door hinges). Guidance includes description of the source of the issue, interacting factors that accelerate issues, and steps to mitigate or avoid the environmental issues are provided. Methods are provided to increase harness protection. Material guidelines provide information on types, temperature limits, and specific materials. Guidelines are also provided for mounting, routing, installing, and fastening.

ADS Application: ADS-equipped CMVs require durable and reliable bundled wiring harnesses to maintain functionality when exposed to extreme vibration in cab interior and exterior as well as survival from severe temperatures, snow/ice, and road debris during long trips between manual inspections.

Need: Harnesses are commonly located in areas that cannot be easily inspected visually without removing interior or exterior body panels or other substantial disassembly of non-interfacing parts.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 154A: Guidelines for Wiring Harness Routing, Clamping, and Protection, 3/2018. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Routing and Clipping

Scope: Additional and redesigned wires, cables, and connections are needed to engineer and install ADS on trucks, resulting in cable ties and mounts gaining popularity as hose, wire, and cable management solutions (Shalabi, 2014).

The SAE Heavy-Duty Electrical Connector Performance Standard (J2030_201506) encompasses connectors between two cables or between a cable and an electrical component and focuses on the connectors external to the electrical component (SAE, 2015).

The SAE Surface Vehicle Recommended Practice (J1742) provides suggested practices for connections for high voltage onboard vehicle electrical wiring harness, including test methods and general performance requirements (SAE, 2010).

The SAE Heavy-Duty Wiring Systems for On-Highway Trucks (J2202_201912) provides recommended practices and guidelines on the material selection, construction, and qualification of components and wiring systems used to construct nominal 12-volt direct current (VDC) and/or 24 VDC electrical wiring systems for heavy-duty vehicles (SAE, 2019).

Guidance: The SAE Duty-Vehicle Electrical Connector Performance Standard (2015) "provides environmental test requirements and acceptance criteria for the application of connectors for direct current electrical systems of 50 V or less in the majority of heavy-duty applications typically used in off-highway machinery. Severe applications can require higher test levels or field-testing on the intended application." The standard provides guidance on wire, cable, and connector assembly, test sequence, test methods, applications, and considerations. See J2030_201506 for detailed recommendations.

The SAE Surface Vehicle Recommended Practice (J1742) provides general equipment requirements and detailed test and acceptance requirements, including terminal and connector mechanical tests, terminal and connector electrical tests, environmental, special, and severe duty tests, and test sequences (SAE, 2010). See J1742 for detailed recommendations.

The future of commercial truck electrical systems will offer a multi-voltage electrical system, which will include voltages above a nominal system and new technologies and requirements not included in the current standards (SAE, 2019). The Recommended Practices detail test procedures, requirements, design requirements, and identify appropriate operating performance requirements. See J2202 for detailed recommendations (SAE, 2019).

ADS Applications: To accommodate new or redesigned wires, cables, and connection solutions on ADS CMVs, equipment such as cable ties and mounts are gaining popularity as hose, wire, and cable management solutions (Shalabi, 2014). Determining wire, cable, and hose routing is traditionally the last step in the design and development process, though this is changing as OEMs are finding that working with suppliers up front to address routing issues results in reduced routing and clipping warranty claims due to reduced wear and extended life of the equipment. Factors that can increase wear and tear on routing and clipping equipment include torque, strain, vibrations, repetitive stress, and extreme temperatures. Addressing these factors up front by manipulating equipment design, materials, and installation and mounting practices can reduce malfunction by extending the life and reliability of the equipment (Shalabi, 2014). This is especially practical for ADS CMVs, especially after-market equipment modifications, as there is an even greater need for planning and forethought on routing and clipping design and placement considerations to accommodate additional sensors, wires, cable management, and equipment access points discreetly and with limited space. Additionally, the serious concerns and consequences of equipment malfunctions and failures on ADS CMVs further support these changes in routing and clipping solutions.

Need: The future of commercial truck electrical systems will offer a multi-voltage electrical system, which will include voltages above a nominal system and new technologies and requirements not included in the current standards (Park, 2018). Standards for heavy-duty wiring systems and harnesses and electrical connector performance should include new technologies and considerations for higher voltage electrical systems.

References:

Park, J. (2018). The future of electrical systems on heavy duty trucks. *Heavy Duty Trucking*. Accessed from (https://tmcconnect.trucking.org/tmclibraries/newrplibrary).

SAE Surface Vehicle Recommended Practice. (2010). *Connections for high voltage on-board vehicle electrical wiring harnesses-Test methods and general performance requirements* (J1742). Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J1742_201003.

SAE Surface Vehicle Recommended Practice. (2019). *Heavy-duty wiring systems for on-highway trucks (J2202)*. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J2202_201912/

SAE Surface Vehicle Standard. (2015). *Heavy-duty electrical connector performance standard (J2030)*. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J2030_201506/

Shalabi, L. (2014). Routing and clipping. *OEM Off Highway*. Accessed from https://www.oemoffhighway.com/home/article/10166645/routing-and-clipping.

Wiring System Identification

Scope: Minimum requirements are provided for wiring system identification.

Guidance: Electrical circuit wires should be readily identifiable by technicians (e.g., color, number, letters, symbols). A wiring diagram should be provided for each vehicle, and it should comply with SAE J2191, SAE EA-1128, and TMC RP 146.

ADS Application: Circuits and wires may be added to the vehicle during installation and/or integration activities.

Need: New circuits and wires on ADS-equipped CMVs should be identified to increase troubleshooting and maintenance ease and to support safe maintenance practices.

References:

Technology & Maintenance Council. TMC Recommended Practice RP 120B: Wiring System Identification, 04/2021. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Electrical Circuits Identification

Scope: Standard circuit identification for heavy vehicle electrical circuit diagrams specified in SAE J2191.

Guidance: Endorsement of common methods to organize and identify circuits on heavy vehicles to increase understanding among technicians, assist in use of the service manual, and reduce vehicle downtime as specified by SAE J2191. A list of circuits and subsystems is provided to promote consistency by developers and manufacturers. An identification method is provided including primary circuit identifier, separator, and supplemental suffix.

ADS Application: During design and development of new electrical ADS subsystems, alignment with common assembly categories can be implemented.

Need: Complex electrical and electronic subsystems are added to ADS-equipped CMVs. Applying pre-existing and consistent categories during design may improve development, integration, and maintenance activities.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 146: Identification of Standardized Electrical Circuits for Class 8 Vehicles, 10/2020. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Electrical Circuit Diagrams

Scope: Standard graphic symbology for heavy vehicle electrical circuit diagrams specified in SAE J2221.

Guidance: SAE J2221 as applied to heavy vehicles when developing a building-block circuit diagram. The benefits of symbols include universality, providing enhanced communication, technician recognition, avoiding design over-specification, and clear visual display information.

ADS Application: Diagrams developed during design and development of new electrical ADS subsystems that are added to ADS-equipped CMVs from the point of interface with existing or other developers/manufacturers specified in other product materials.

Need: Complex electrical and electronic subsystems are added to ADS-equipped CMVs. Planning for the consistent communication and layout of circuits during design can improve efficiency and safety of human interactions by making diagrams of complex systems available during the purchase specification, installation, and repair and maintenance performed by developers and fleets. These diagrams also support roadside enforcement and emergency first responder interactions.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 145: Symbols for Electrical Circuit Diagrams, 10/2020. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Circuit Protection

Scope: Covers circuit protection of D.C. wiring systems due to exposure to high current levels.

Guidance: Guidelines for primary and secondary protection devices with electrical and physical considerations for design of power feed circuits excluding batteries, starter motors, and generator/alternator circuits.

ADS Application: Specification and installation of circuit protection for components for ADS sensing and computing subsystems.

Need: ADS-equipped CMVs require circuit protection across sensors, computing resources, and data collection and communication subsystems.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 111C: Circuit Protection, 10/2021. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Electrical Circuit Protection Components and Fuses

Scope: Heavy-duty commercial vehicle circuit protection component types, descriptions, functional explanation, and information for proper replacement.

Guidance: Circuit protection devices serve to protect circuits from thermal damage caused by current that exceeds the circuit's design specifications by opening the circuit. The range of devices includes mini fuse and breaker, automatic transfer case (ATC; closed blade), fuse and breaker, maxi fuse and breaker, glass fuse, and polymeric positive temperature coefficient (PPTC) and fusible link wire. Consider SAE J156 for further detail on fusible links. Consider SAE J1284 for ATC/ATO (closed and open) type fuses. Recommendations are provided, including that a circuit protector be operated at no more than 75%–80% of its rating, as well as safety factors to avoid tripping induced by surge. Characteristics and images of the circuit protection devices are provided.

ADS Application: Specification and installation of circuit protection for components for ADS sensing and computing subsystems.

Need: ADS-equipped CMVs require circuit protection across sensors, computing resources, and data collection and communication subsystems.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 156A: Electrical Circuit Protection Components, 5/2016. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Fuses

The functional safety of AVs starts with the electrical power supply that feeds into all of the safety-relevant components. The wiring system is the vehicle's central nervous system and must be designed to ensure that the system is functional under all conditions and scenarios. The electrical wiring system includes all cables and wiring, connectors and terminations, coverings, seals, other incorporated items to maintain the integrity and performance of the electrical system, and the connectors to mating devices (see SAE J2174).

Scope: SAE J2174 establishes the minimum performance requirements for electrical distribution systems for use in dollies and trailers in single or multiple configurations for 12-VDC nominal applications (SAE, 2020). The SAE Recommended Practices (J2202) provide guidelines on materials, construction, and qualification of components and wiring systems used to construct electrical wiring systems for heavy-duty vehicles, as well as requirements for operating performance (SAE, 2019).

Guidance: The wiring industry is no different post-ADS than it was pre-ADS. Automotive wiring harnesses are still manually built by people who individually attach thousands of components. General guidance should follow SAE J2174, which covers guidelines, requirements, assembly, installation, and testing and SAE Recommended Practices J2202, which covers wiring system construction and operating performance.

ADS Applications: How companies design, engineer, manufacture, and deliver vehicle wiring harnesses has completely changed with the growth of automated systems. Automotive OEMs are looking at new electrical architectures to simplify harness designs so they can minimize wiring complexity and cost. For the Tier 1 OEMs, wiring harnesses are a very labor-intensive product with thousands of part numbers going into making each vehicle's wiring harness, and the finished product weighing 150 pounds or more (Morrison, 2019). OEMs have to coordinate all the materials and components for these products and ship them from all around the world. This creates an incredibly long, complex supply chain with hundreds of design changes occurring along the way, all of which need to be individually tracked, implemented, and validated.

The variation in automotive wiring harnesses is extremely vast with optimized architectures, especially for cost and weight (Morrison, 2019). Many different architectures have risen to meet the needs of individual vehicle designs and are going to continue to evolve as vehicles continue to leverage new, next-generation technologies. For example, AVs will have to implement centralized data storage and scalable, modular system architectures, and the wiring and networking components will have to evolve to support them. A question for next generation wiring challenges is optical or wireless instead of copper. A variety of parameters will factor into these decisions, extending from the vehicle's network and software considerations to their physical wiring and electrical performance specifications.

Needs: Simplified automotive wiring harness designs will lend themselves to more automated assembly and delivery processes and allow OEMs to implement changes more quickly, which will reduce costs across the entire chain (Morrison, 2019). In addition to the raw materials required to build wiring harnesses, including connectors, terminals, wire, tape, and various other components, OEMs have to store a certain amount of inventory to prevent potential supply disruptions.

There is no standard to guide OEMs on an approach to meet the high-speed network needs of ADS vehicles. Ethernet, CAN, and local interconnect network (LIN) approaches are available, each with pros and cons, but the proprietary and application-specific protocol make it difficult to identify a standard (Morrison, 2019).

As vehicles become more software-driven, there will be a greater need for diagnostics to ensure that critical systems are functioning properly (Morrison, 2019). Hardware, data, communications, back-up and fail-safe mechanisms, and diagnostic capabilities will need to be ramped up.

References:

Morrison, G. (2019). *Automotive wiring undergoes an architectural revolution*. Accessed: https://www.connectorsupplier.com/automotive-wire-harness-content-increasing/

SAE Surface Vehicle Standard. (2019). *Heavy-duty wiring systems for on-highway trucks* (J2202). SAE International. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J2202_201912/

SAE Surface Vehicle Standard. *Heavy-duty wiring systems for trailers 2032 mm or more in width* (J2174). (2020). SAE International. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J2174_202002/

Electrical Systems Connectors

Scope: Minimum guidelines for design, performance, and application of connectors for heavy-duty vehicles.

Guidance: General connector guidance on soft mold-over, locking features, friction type, and environmental protection. Provides connector design minimum pull force recommendations to ensure proper connector mating based on cable size (gauge). Also provides guidance on corrosion preventative compound application.

ADS Application: Specification of connectors between ADS components.

Need: ADS-equipped CMVs require durable and reliable connections to maintain functionality when exposed to extreme vibration in cab interior and exterior as well as survival from severe temperatures, snow/ice, and road debris during long trips between manual inspections.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 113B: Electrical Systems Connectors, 4/2020. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Plug and Receptacle Wire-to-Terminal Interface

Scope: Performance standard for wire-to-terminal connections.

Guidance: The performance guideline provides current, cycling, and aging standards per SAE J560 for plugs and receptacles. Failure mechanisms are specified, including relaxation of the materials, corrosion of the wire-to-terminal, overheating, chemical changes, and loose/improper/fractured terminal screw. Environmental exposure test descriptions, procedures, and pass/fail criteria are described. The guideline covers thermal aging, temperature/humidity cycling, and current cycling.

ADS Application: Specification of connectors between ADS components and between ADS and other vehicle hardware interfaces.

Need: ADS-equipped CMVs require durable and reliable connections to maintain functionality when exposed to extreme vibration in cab interior and exterior, as well as survival from severe temperatures, snow/ice, and road debris during long trips between manual inspections. According to Naval Research Laboratory environmental laboratory test results, internal corrosion in the plug and socket is the primary cause of J560 coupler electrical failures.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 147: J560 Plug and Receptacle Wire-to-Terminal Interface Performance Guidelines, 10/2020. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Electrical Terminals and Connectors Corrosion

Scope: Guidance for truck, tractor truck, and trailer manufacturers, and fleet maintenance to specify products for electrical terminals and connector products that can withstand high temperatures, be compatible with plastic materials, reduce insertion and withdrawal forces, reduce fretting corrosion, and provide a barrier for environmental corrosion.

Guidance: The benefits of connection lubricants are discussed, and resistive criteria are provided. The advantages and disadvantages when applying lubricants to the electrical wiring harness connection system are listed. The types of lubricants and factors to consider when selecting a lubricant include operating temperature, lubricant compatibility, performance, application, and life.

ADS Application: Specification of connectors between ADS components and between ADS and other vehicle hardware interfaces.

Need: ADS-equipped CMVs require durable and reliable connections to maintain functionality when exposed to extreme vibration in cab interior and exterior, as well as survival from severe temperatures, snow/ice, and road debris during long trips between manual inspections.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 155A: Selection and Application of Corrosion-Preventing Materials for Sealed and Unsealed Electrical Components, 5/2021. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Design for Preventing Vehicle Electrical Fires

Scope: Recommendations to prevent Class 7–8 heavy-duty commercial vehicle electrical fires.

Guidance: Recommendations are a result of TMC’s Electrical Thermal Events Solutions Task Force and with input from the ATA’s Technical Advisory Group and the Truck Manufacturers’ Association. Recommendations for developers and equipment users include these topics: battery cable routing, circuit protection, power supply fuses, limits to use of Type 1 circuit breakers, design of branch circuits, starting motor design, lamp installation, electrical cables and harness routing, environmental protection of circuit protection distribution centers, and circuit protection for directional and emergency flashers.

ADS Application: Circuits and wires may be added to the vehicle during installation and/or integration activities.

Need: When adding new circuits and wires to ADS-equipped CMVs, protective measures should be taken by selecting, locating, and routing wires and components to mitigate the risk of vehicle electrical fires.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 168: Design Recommendations for Preventing Vehicle Electrical Fires, 10/2020. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

5.1.2.3 Batteries

Battery Considerations for Engine Cranking

Scope: Provides battery specifications for cold cranking ampere and reserve capacity ratings.

Guidance: 12-volt and 24-volt battery cold cramp amperes (CCA) at engine oil viscosity and remote capacity, which is the number of minutes a battery can supply 25 amperes of current at 80 °F (27 °C) while maintaining a minimum of 1.75 volts per cell.

ADS Application: Specification and installation of batteries to support ADS sensing and computing subsystems.

Need: ADS-equipped CMVs introduce new loads on batteries to meet the demands of sensors, computing resources, and data collection and communication subsystems. These new loads may affect traditional battery cold-start and spare capacity.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 109A: Battery Ratings and Engine Cranking Requirements, 3/2003. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Battery Vibration

Scope: Survival of batteries to excessive heavy-vehicle vibration.

Guidance: Based on OEM bench tests and field evaluations of vibration, it has been concluded that "a vibration resistant battery was just as important as proper battery mounting procedures" (TMC RP 125A). Must comply with TMC RP 125, SAE J3060, and SAE J537. Specific parts of the SAE testing protocol and criteria are provided for Class 6–8 applications. OEM recommendations are provided for battery location, battery carrier, and hold down. Recommendations are also provided for fleets to support battery life.

ADS Application: Specification and installation of batteries to support ADS sensing and computing subsystems.

Need: ADS-equipped CMVs may introduce additional batteries to meet the demands of sensors, computing resources, and data collection and communication subsystems. The specifications and mounting of additional batteries may affect ADS operations.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 125A: Battery Vibration Standards, 4/2019. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Managed/Isolated Battery Systems

Scope: Considerations when isolating or managing vehicle subsystem or device demands on vehicle batteries.

Guidance: Battery isolation system functionality is defined; for example, isolation when the engine is OFF while allowing dual charging while the engine is ON. Battery management system functionality is defined, for example, disconnection or prioritization of auxiliary and parasitic loads. Other practices are referenced: TMC RP 109, TMC RP 139, RP 140, and SAE J2185. Guidance is provided on management mechanisms, signaling devices, fusing, and wiring, as well as items that should (e.g., radio, dome, cigar/auxiliary power outlet) and should not be managed (e.g., electronic engine control, safety lighting, anti-lock brake system [ABS], and medical A/B/C-positive airway pressure [PAP] devices [TMC RP 445]).

ADS Application: ADS-equipped CMVs require power to meet the demands of sensors, computing resources, and data collection and communication subsystems.

Need: ADS-equipped CMVs may require the introduction of additional batteries to the vehicle. Some critical functions may need to be managed if not isolated from other high-priority vehicle powertrain demands or low-priority convenience devices when the vehicle is operational.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 136C: Managed/Isolated Battery Systems for Electric Start Systems, 5/2021. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

5.1.2.4 Controls, Displays, and Instruments

Location and Operation of Instruments and Controls in Cabs

Scope: Recommendations for controls and displays in the cab of heavy-duty commercial vehicles.

Guidance: Recommendations promote consistency of controls and displays for onboard vehicle operators. The primary function and location are organized based on classically understood human factors and ergonomics performance criteria. The location and orientation are specified for these controls: lamp switches, gauges, wiper controls, tractor-trailer and trailer parking brake controls, engine/emission switches, indicators and telltales and warning lights, object detection displays, rearview mirrors, door controls, steering wheel and stalks, manual and automatic shift controls, seat setting controls, and accessory and secondary instruments.

ADS Application: Consistency in the design and location of controls and displays on ADS-equipped CMVs can support activities by operators who engage in continuous or intermittent control and monitoring of the vehicle depending on the intentions of the onboard operator and depending on the location and state of the vehicle and weather compared to the ADS ODD.

Need: Depending on the status of the vehicle operation with the ADS ODD and the status of the ADS, onboard operators may need to engage with the vehicle through manually operated driving controls and displays to take over control when exiting the ODD or in the event of ADS failures leading to minimal risk events.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 401D: Location and Operation of Instruments and Controls in Motor Truck Cabs, 10/2020. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Location and Operation of Instruments in Sleepers

Scope: Recommendations for displays used to check status of heavy-duty commercial vehicles in the sleeper of heavy-duty commercial vehicles.

Guidance: No guidance discovered.

ADS Application: Consistency in the design and location of displays in sleepers on ADS-equipped CMVs can support the needs of onboard operators to check the status of the ADS.

Need: Onboard operators may need to check the status of the ADS operation through displays from the sleeper area before an ADS-equipped CMV reaches the boundaries of its ODD in normal operations and before receiving warnings in the event of ADS failures leading to MRCs.

Reference: Unspecified

In-Cab Trailer ABS Malfunction Lamps

Scope: Minimum performance for in-cab trailer/dolly ABS malfunction lamps.

Guidance: The guidance includes a description of function, color, labeling, mounting position, and states of the malfunction lamp used for combination vehicles to communicate trailer and trailer converter dolly ABS messages into the cab. Environment specifications reference SAE J1455. Electric and electronic systems should coexist with J1939 and J1587 and require no unique equipment for servicing.

ADS Application: Guidance for in-cab ABS lamp could be considered for application to ADS status lamp in-cab to onboard operator or on the exterior of the truck or tractor-trailer to other vehicle operators. Federal Motor Vehicle Safety Standard (FMVSS) No. 121 requirements for power vehicles (tractor-truck) and trailers and dollies are referenced and quoted.

Need: Similar to the high-priority communication of ABS malfunction to human drivers, ADS-equipped CMVs should communicate indication and warning status of ADS to onboard operators. Additionally, this element may inform design considerations for over-the-air communication to inspectors, law enforcement, and operators of other vehicles that may benefit from a lamp that communicates ADS status on the exterior of each vehicle and combination vehicle.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 144: Minimum Performance Requirements for In-Cab Trailer ABS Malfunction Lamps, 4/2019. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Interior Displays

Scope: OEMs and display manufacturers are introducing innovative display designs and layouts to address current ADS concepts, as well as mapping out steps and plans for future designs and display needs (Pawsey, 2018). OEMs are competing to produce the most aesthetically pleasing, personalized, and functional HMI systems.

The FMVSS (36 FR 22902) "specifies performance requirements for the location, identification, color, and illumination of motor vehicle controls, telltales, and indicators" (ECFR, 2021).

The FMVSS No. 101 Ground Vehicle Standard, "Controls and Displays," specifies requirements for the location, identification, and illumination of motor vehicle controls and displays for commercial vehicles (National Highway Transportation System Administration [NHTSA], 1971).

The ISO 2575.2010 standard, "Road Vehicles-Symbols for controls, indicators, and telltales," specifies symbols and display colors for use on controls, indicators, and telltales applying to passenger cars, light and heavy commercial vehicles, and buses to ensure identification and facilitate use (ISO, 2010).

Guidance: Safety standards for motor vehicles assume that a human occupant will be able to control the operation of the vehicle, and many standards incorporate performance requirements and test procedures geared toward ensuring safe operation by a human driver. Some standards focus on the safety of drivers and occupants, in particular seating arrangements. Standards impose specific requirements for the visibility to a human driver of instrument displays, vehicle status indicators, mirrors, and other driving information (NHTSA, 2018).

Standards, regulations, and requirements for interior displays, including location, identification, illumination, brightness, color, messaging space, and conditions for controls, telltales, and indicators, and displays are detailed in the FMVSS (36 FR 22902) §571.101 Standard No. 101: Controls and displays (ECFR, 2021). This standard also facilitates the proper selection of controls under day and night lighting conditions in order to reduce the diversion of the driver's attention from the driving task and mistakes in selecting controls.

Standards to ensure the accessibility and visibility of controls and displays to reduce safety hazards caused by diversion of driver attention from the driving task and mistakes in selecting controls, under all lighting conditions, are outlined and detailed in the FMVSS No. 101 Ground Vehicle Standard, "Controls and Displays" (NHTSA, 1971).

Standards for vehicle controls, indicators, and telltales specify symbols used on controls and displays to ensure proper identification and use, as well as indicate the display colors of optical telltales, which inform the driver of operation and malfunction status (ISO, 2010).

ADS Applications: OEMs are focusing on developing and improving HMIs and providing driver information in a quick and easy format to improve reaction time, decrease eyes off road, and support a vehicle environment that offers a seamless transition between automated and manual driving modes (Pawsey, 2018). Interactive displays that are highly responsive to touch and visual stimulus are a key feature of ADS interior displays (Bepari, 2019). Near-future innovations such as augmented reality and 3D displays will facilitate ADS display functionality and the HMI experience. Longer term future vehicle displays will be non-driving task centric, freeing up the driver to concentrate on tasks other than driving, via the interior display.

OEMs are currently developing and refining fully reconfigurable instrument clusters with advanced digital display technologies, driver monitoring features, and ADS integration. Driven by the need to conserve cost, space, and power consumption, OEMs are designing domain controllers that integrate the instrument cluster, infotainment, and heads-up displays into one electronic control unit (ECU).

Digital solution displays with embedded functionality, including camera systems and ambient lighting, are being developed (Pawsey, 2018). Integrated infrared driver monitoring cameras designed for facial recognition, head, and eye-gaze tracking are important technologies to determine driver alertness and preparedness to take over vehicle control when needed. Windshield solutions for heads-up displays and augmented reality solutions that can be integrated into ECUs are also being developed (Bepari, 2019).

Multi-layered display systems that provide a 3D display of the instrument panel will be a safety feature in ADS vehicles that provide information to the driver in a way to facilitate quicker understanding and information processing and reduce eyes-off-road time (Pawsey, 2018). The 3D designs are also supposed to alleviate headaches, eye strain, and fatigue.

Need: NHTSA’s current safety standards do not prevent the development, testing, sale, or use of ADS built into vehicles that maintain the traditional control features of human-operated vehicles. However, some Level 4 and Level 5 AVs may be designed to be controlled entirely by an ADS, and the interior of the vehicle may be configured without human controls (i.e., no information displays). For such ADS-equipped vehicles, NHTSA’s current safety standards constitute an unintended regulatory barrier to innovation (NHTSA, 2018).

References:

Bepari, S.A. (2019). What’s trending in the automotive display market? *Electronic Design*. Accessed from: https://www.electronicdesign.com/markets/automotive/article/21807933/whats-trending-in-the-automotive-display-market.

Electronic Code of Federal Regulations. (2021). Part 571-Federal Motor Vehicle Safety Standards. Subpart B-Federal Motor Vehicle Safety Standards. §571.101. Standard No. 101; Controls and displays. Accessed from https://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=635b08ab5e31e3bf86ebf4cb93c6aecb&mc=true&n=pt49.6.571&r=PART&ty=HTML#se49.6.571_1101

ISO. (2010). *ISO 2575:2010 – Road Vehicles-Symbols for Controls, Indicator, and Tell-tales*. Accessed from https://www.iso.org/standard/54513.html

National Highway Transportation System Administration. (1971). *Controls and displays*. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/FMVSS100/

National Highway Transportation System Administration. (2018). *Preparing for the future of transportation: Automated Vehicles 3.0.* Accessed from: https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf

Pawsey, C. (2018). Displays and autonomous driving challenges and solutions in the US. *Automotive IQ*. Accessed from https://www.automotive-iq.com/electrics-electronics/articles/displays-and-autonomous-driving-challenges-and-solutions-us.

Interior Controls

Engineering and installation standards and recommendations for Level 1 to Level 3 ADS will not functionally change for interior controls, as drivers will be responsible for manually manipulating these controls. However, in more advanced ADS (primarily Level 4 and Level 5), the majority of interior controls that are traditionally manipulated by the driver will be controlled by the ADS ECU.

Scope: FMVSS No. 101 (36 FR 22902) "specifies performance requirements for location, identification, color, and illumination of motor vehicle controls, telltales and indicators" (ECFR, 2021).

FMVSS No. 101 Ground Vehicle Standard, "Controls and Displays," specifies requirements for the location, identification, and illumination of motor vehicle controls and displays for commercial vehicles (NHTSA, 1971).

The ISO 2575.2010 standard, "Road Vehicles-Symbols for controls, indicators, and telltales," specifies symbols for use on controls, indicators, and telltales applying to passenger cars, light and heavy commercial vehicles, and buses to ensure identification and facilitate use (ISO, 2010).

Guidance: Current safety standards for motor vehicles assume a human occupant will be able to control the operation of the vehicle, and many standards incorporate performance requirements and test procedures geared toward ensuring safe operation by a human driver. Standards impose specific requirements for the visibility for a human driver of instrument displays, vehicle controls and status indicators, mirrors, and other driving information (NHTSA, 2018).

Standards, regulations, and requirements for interior displays, including conditions for controls, telltales and indicators, and displays are detailed in the FMVSS (36 FR 22902) §571.101 Standard No. 101: Controls and displays (ECFR, 2021). This standard also provides guidance on facilitating the proper selection of controls under day and night lighting conditions in order to reduce the diversion of the driver's attention from the driving task and mistakes in selecting controls.

Standards for controls to ensure the accessibility and visibility of controls and displays, under all lighting conditions, in order to reduce safety hazards caused by diversion of driver attention from the driving task and mistakes in selecting controls, are outlined and detailed in the FMVSS 101 Ground Vehicle Standard, "Controls and Displays" (NHTSA, 1971).

Standards for vehicle controls, indicators, and telltales specify symbols used on controls and displays to ensure proper identification and use, as well as indicate the display colors of optical telltales, which inform the driver of operation and malfunction status (ISO, 2010).

ADS Applications: With respect to currently available Level 1 and Level 2 automation technologies and Level 3 technologies under development, drivers must understand the capabilities and limitations of the technology, when human monitoring of the system is needed, and where it should be operated (NHTSA, 2018). OEMs may need to consider new approaches for providing information so that drivers can use the technology safely and effectively. In Level 4 and Level 5 trucks, the majority of interior controls traditionally manipulated by the driver will be controlled by the ADS ECU. As part of driver education and training programs, OEMs and AV dealers and distributors may consider including an on-road or on-track experience demonstrating AV operations and how humans interact with redesigned vehicle controls (NHTSA, 2018).

Need: NHTSA's current safety standards do not prevent the development, testing, sale, or use of ADS built into vehicles that maintain the traditional control features of human-operated vehicles. However, some Level 4 and Level 5 AVs may be designed to be controlled entirely by an ADS, and the interior of the vehicle may be configured without manual controls for human manipulation. For such ADS-equipped vehicles, NHTSA's current safety standards constitute an unintended regulatory barrier to innovation (NHTSA, 2018).

A concern is that as ADS and computer technology become more capable and complex, it will be more challenging for drivers and safety monitors to understand what the ADS is doing and how the vehicle is functioning; yet the driver/safety monitor is still responsible to take over manual control when needed. In Level 4 and Level 5 ADS vehicles, manual driving controls will be replaced by automation, potentially degrading manual driving, and vehicle performance and diagnostic monitoring skills currently ingrained in CMV drivers.

References:

Electronic Code of Federal Regulations. (2021). Part 571-Federal Motor Vehicle Safety Standards. Subpart B-Federal Motor Vehicle Safety Standards. §571.101. Standard No. 101; Controls and displays. Accessed from https://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=635b08ab5e31e3bf86ebf4cb93c6aecb&mc=true&n=pt49.6.571&r=PART&ty=HTML#se49.6.571_1101

ISO. (2010). *ISO 2575:2010 – Road Vehicles-Symbols for Controls, Indicator, and Tell-tales*. Accessed from https://www.iso.org/standard/54513.html

National Highway Transportation System Administration. (1971). *Controls and displays*. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/FMVSS100/

National Highway Transportation System Administration. (2018). *Preparing for the future of transportation: Automated Vehicles 3.0*. Accessed from: https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf

5.1.2.5 Sensors

Radar

Scope: The scope of the SAE Surface Vehicle Information Report is to (1) identify the expected functionality and performance from active safety sensors, and (2) detail a basic understanding of how sensors work. Radar, an active object detection system, uses radio waves to determine the range, direction, and speed of objects. Radar transmits pulses of radio waves or microwaves, which bounce off any object in their path, and then reflect the wave's energy back to a dish or antenna, where it is sensed.

Guidance: Two general methods of measuring distance using radar are direct and indirect propagation methods. Types of automotive radar systems include pulsed, continuous wave, frequency-modulated continuous wave, and radar sensor architectures. Every radar system is divided into two categories: small-angle bi-static radars and mono-static radars. Radar frequency (wavelength) directly influences design and the performance of radar systems. Higher frequency/shorter wavelengths allow for better spatial resolution of the sensor, allow more compact design, and are less susceptible to interference. Two different frequency bands are currently being used in industry (see SAE J3088 for short- and long-range specifications). Radar has some limitations. Due to the low resolution and the lack of semantic features, radar-related technologies for object detection and map updating are still insufficient compared with other perception sensors in high automated driving (Zhou et al., 2020). Radar can be limited by resolution specifications, such as angular, distance, and Doppler resolutions, in addition to obscuration (see SAE J3088). Finally, while most radar sensors react well to adverse weather, there are reported cases where radar functions can be disabled by obscurities, such as the accumulation of ice in front of the sensor. Modern radar sensor returns range, velocity (including sign), angle (typically azimuth but sometimes elevation as well), and signal-to-noise ratio. They may update this information at rates significantly faster than camera systems. Given that radar systems can provide distance, speed, azimuth angle, and signal-to-noise ratio information, a reliable feature extraction and classification process has to be implemented either at the sensor level or the ECU level. To classify objects such as pedestrians and vehicles, the velocity profile and range profile signal features are used, along with other available parameters (size of the object, variations of the Doppler shift, etc.). Since radar is based on the use of radio frequencies, the design of radar solutions is heavily regulated by national organizations, such as the Federal Communications Commission (FCC) in the United States. These regulations define the frequencies that can be used and limit the output power of the devices. For example, at the date of publication, the 77- to 81-GHz band is not yet authorized by the FCC. This band has been approved by the European Union (EU) and Japan.

ADS Application: For high-level automated driving, radar data is used in object detection, object tracking, motion prediction, and self-localization. Because of the limited spatial resolution of radar, radar sensors are often used with vision sensors in applications that require precise shape recognition or object classification. For lane change assistance applications, radar can identify approaching vehicles, and can localize to which lane the vehicle is in. This is true as long as either the target vehicle's range or velocity is different than the surrounding vehicles. If the ranges and velocities of the target vehicles are identical, vision systems can be used to augment the lane information.

Millimeter-wave (MMW) radar is low cost and enables long measuring distance range, dynamic target detection capacity, and environmental adaptability to enhance the stability, security, and reliability of the vehicle (Zhou et al., 2020). MMW has been widely applied on Level 1 and Level 2 ADAS. MMW helps ADAS to find and avoid driving risks and has functionality in frontal collision warning, lane change warning, and automatic emergency braking (AEB). MMWs can be used to control vehicle longitudinal and lateral dynamic and following distance, and therefore have practical application in adaptive cruise control. Finally, MMW radar can adapt to weather conditions and can directly measure objects' speed for a long range.

Need: ADS-equipped CMVs need to be able to sense conditions farther in advance to allow for longer stopping distances (Ackerman, 2021). Sensors should be able to detect other vehicles and calculate trajectories at distances twice that of CMV drivers. Increased accuracy of classifying objects and object size, and better detection and precision for small objects are needed for radar capabilities in ADS, both light and heavy vehicle (Bigelow, 2019). Ground penetrating radar, a promising emerging technology that could help with localization in poor weather conditions, is being monitored by companies as a potentially important sensor modality in the future (Rangwala, 2020).

References:

Ackerman, E. (2021). *This year, autonomous trucks will take to the road with no one on board*. Accessed from: IEEE Spectrum. https://spectrum.ieee.org/transportation/self-driving/this-year-autonomous-trucks-will-take-to-the-road-with-no-one-on-board

Bigelow, P. (2019). Radar finds new place in self-driving technology. *Automotive News.* Accessed from: https://www.autonews.com/technology/radar-finds-new-place-self-driving-technology.

Rangwala, S. (2020). LiDAR vision-helping bring autonomous trucks to your neighborhood. *Forbes*. Accessed from https://www.forbes.com/sites/sabbirrangwala/2020/12/17/lidar-visionhelping-bring-autonomous-trucks-to-your-neighborhood/?sh=4215531073f7

SAE Surface Vehicle Information Report-Active Safety System Sensors (J3088). (2017). SAE International. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J3088_201711/

Zhou, T., Yang, M., Jiang, K., Wong, H., & Yang, D. (2020). MMW radar-based technologies in autonomous driving: A review. *Sensors (Basel, Switzerland)*, *20*(24), 7283. https://doi.org/10.3390/s20247283

Cameras

Scope: The scope of the SAE Surface Vehicle Information Report is to (1) identify the expected functionality and performance from active safety sensors, and (2) detail a basic understanding of how sensors work.

Guidance: Vision sensors are used in a wide range of applications, capturing the light intensity and color (if applicable) of the surrounding environment in arrays of varying resolution and density. Vision sensors are passive, relying on ambient lighting as a light source, and information can be directly displayed and comprehended by humans without minimal processing, or overlayed with complementary information. Information obtained from vision sensors on an object typically relies on a supplementary form of processing of the acquired image. Vision sensors used in active safety applications use charge coupled device sensors and active pixel sensors for acquiring the image. Advantages and disadvantages of each are further discussed in SAE J3088. The primary technical features of cameras for automotive applications are dynamic range, imaging sensitivity, spectral range sensitivity, resolutions, frame rate, and light-emitting diode (LED) flicker.

The vision sensor is usually incorporated into a camera that includes lenses, power supply, and housing. Some include high-end image processing functions specific to the applications supported, such as sign and lane recognition and distance estimation. Monocular and stereo cameras are further discussed in SAE J3088. Vision sensors generate a very large quantity of data, and therefore the transport of the image data between the sensor and the processing unit can be based on a different protocol that must be considered when selecting a sensor.

Cameras that serve as sensors have some limitations. Algorithms performing feature extraction from images rely on contrast of either color or intensity between objects and their background. In situations where the camera system may not be able to extract key features (e.g., detecting a pedestrian dressed in white against a white snowbank), it is critical to assess the failure potential of identifying the desired features and include safeties in the processing chain. It is important for vision systems to be evaluated under conditions that create a degradation of performance in addition to optimal performance conditions.

ADS Applications: Vision sensors have a wide range of uses in detecting and classifying objects based on visible qualities, such as intensity, color, and shape. They are also used to estimate distance to objects and provide visual feedback information to the driver. Vision sensors are used in collision warning/mitigation applications, adaptive cruise control, lane detection, lane assist, and lane departure warning, sign recognition, obstacle classification (i.e., pedestrian, vehicle recognition), vision enhancement (i.e., night vision, backup camera, blind spot viewing, backseat passenger viewing, etc.), accident recorder, and adaptive headlamp control. Vision sensors are also found inside the vehicle to estimate occupant position, driver pose, and gaze estimation for driver vigilance monitoring.

Of particular interest for CMV applications are visual sensors used in CMV driver monitoring video platforms. These systems have advanced machine vision to capture and categorize risky driving behaviors for CMV driver feedback and training; driver recognition and identification (for multiple drivers operating a tractor); cameras with wide-angle dual lens for better picture quality and accuracy; continual video to capture real-time driving behaviors; and infrared light to provide clear visibility at low light and night. Visual sensors used in CMV driver monitoring video platforms provide reliable video evidence for occasions when fleets need information about an event, or to verify service or ensure driver compliance. Visual data can help to exonerate drivers regarding crash fault and prevention, ultimately saving money, insurance claims, and lives.

Needs: Practical solutions are needed to address lighting, contrast, and depth data, which are fundamental limitations of camera technologies. Top technology challenges facing AV image sensors include compact and durable sensor packaging and thermal stability (Smithers, n.d.). Building a sensor into a camera housing is a challenge for developers. The size is crucial for the camera and, ultimately, pixel size and count determine the optical diagonal. Additionally, the temperature has a significant impact on the life expectancy of the camera system, and thus the failure rate of the overall camera system. Image sensors on a vehicle must be able to function across a range of challenging environmental conditions; not to mention, the sensor itself is a source of heat. Image sensors deliver the best quality image at a given temperature and read speed, but when outside this range the sensor is functional but with limited image quality or visible artifacts in the picture. Extreme temperatures, especially heat, can distort the image by bright pixilation. Outside-mounted cameras are especially challenging as they are more affected by temperature fluctuations. For example, direct sunlight generates temperatures over 100 degrees Celsius in an active camera. The primary concern is to determine the intrinsic heat in the sensor and ensure there are no mechanical shifts in the optical path.

References:

SAE Surface Vehicle Information Report-Active Safety System Sensors (J3088). (2017). SAE International. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J3088_201711/

Smithers. (N.D.) *Top technology challenges for autonomous vehicle image sensors*. Accessed from https://www.smithers.com/resources/2019/mar/challenges-for-autonomous-vehicle-image-sensors

LIDAR

Scope: The scope of the SAE *Surface Vehicle Information Report* is to (1) identify the expected functionality and performance from active safety sensors, and (2) detail a basic understanding of how sensors work.

Guidance: Light Detection and Ranging (lidar), an active sensing technology, can measure the distance to targets by illuminating them with light and analyzing the backscattered light. The majority of lidar sensors use ion laser light sources, though LEDs and lasers are also used. Most automotive commercial lidar systems use infrared light wavelengths, though a wide range of light wavelengths can be used, including ultraviolet, visible, and infrared. In automotive applications, the backscattering of light is caused by simple reflection, or Raleigh scattering. Three general methods of measuring distance using lidar include incoherent or direct energy detection (also known as pulsed lidar), coherent energy detection, and structured light method. Pulsed lidar is commonly used in automotive technologies. See SAE J3088 for details on specifications, sensor detection and processes, and uses.

Lidar has a higher frequency and shorter wavelength compared to radar. Unlike radar, commercial light-based sensors do not estimate an object's speed in real time but rather rely on acquisition of the distance differential between two acquisitions to estimate speed. Lidar has a much higher spatial resolution than radar, enabling more precision and management of interference in a more constrained manner. The reflectivity of an object is the major external factor influencing the performance of lidar sensors. Many factors can influence reflectivity, and therefore lidar performance (see SAE J3088).

Variants of lidar sensor architecture include light source, wavelength, photodetector type, and scanned vs. flash lidar. See SAE J3088 for details on each type, including properties, specifications, uses, and applications.

Lidar lasers can burn the retina of the eye; therefore, automotive lidars must be designed for eye safety. U.S. and European regulations exist for eye safety, and the Maximum Permissible Exposure is the key indicator to evaluate safety (see J3088 for detailed specifications). The limitations of lidar include angular resolution, distance resolution, obscuration of small particles, field of view or illumination, mounting location, and range or distance profile of the scene (see SAE J3088).

A key challenge with current lidar in trucking is the ability to handle a large field of vision at low ranges and a smaller field of vision at high ranges with accurate resolution. A stepped field of vision in both directions would be helpful to the perception suite (Rangwala, 2020). Additionally, performance, durability, and reliability under more extreme conditions of shock and vibration need to be addressed. Flash lidar solutions could be advantageous for trucking applications due to improved reliability, though such lidars do not currently provide the required range, resolution, and field-of-view performance for trucking automation. Since lidar is immature compared to other sensors, improvements can be instilled quickly and often; therefore, the perception stack needs to be able to accommodate these improvements seamlessly.

ADS Applications: Lidar sensors are distance and range profile determination sensors and can serve applications similar to those of radar sensors. Lidar resolution is directly related to sensor cost; therefore, determining the sensor resolution requirements is important to consider. Lidar sensors are monochromatic and cannot sense color and thus cannot be used in applications that require color information to inform precise shape recognition or object classification. Camera sensors must accompany lidar for these applications. Lidar is appropriate in complex urban situations where multiple objects or dense range profiles must be acquired, due to the higher spatial resolutions and reduced sensitivity to interference. Additionally, the structured light sensors of lidar have in-cabin applications to determine occupant position and driver attentiveness.

Applications of lidar sensors include parking assistance and backup parking aid, adaptive cruise control, collision warning, collision mitigation, blind spot detection, lane change assist, and rear crash avoidance.

Need: For lidar requirements, the perception range for a front-facing unit with high resolution and field of view is critical, as are the capabilities of the sensor stack to reliably work in all weather conditions (Rangwala, 2020). Since lidar performance is impacted by weather, trucking companies often rely on radar and cameras to perform under bad weather conditions. Sensor mounting is also key; specially designed mounts ensure that higher shock loads minimize impacts on performance and reliability. Lidar systems that maintain reliability in harsh environmental conditions are also key. To help with roadway debris, higher resolution lidar within a specified field of view near the horizon could help find debris earlier. Finally, fleets also cite the importance of close relationships with lidar suppliers so that as the capabilities of the technology and needs of the drivers evolve, and new sensors become available, they can seamlessly be integrated into operations (Rangwala, 2020).

References:

Rangwala, S. (2020). *LIDAR vision-helping bring autonomous trucks to your neighborhood*. Accessed from https://www.forbes.com/sites/sabbirrangwala/2020/12/17/lidar-visionhelping-bring-autonomous-trucks-to-your-neighborhood/?sh=41da300873f7

SAE Surface Vehicle Information Report-Active Safety System Sensors (J3088). (2017). SAE International. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J3088_201711/

GPS/Other Antennas

Scope: Identify the functionality and performance to be expected from GPS sensors. Establish a basic understanding of how sensors work regarding GPS (see SAE J3088).

Guidance: GPS is a space-based satellite navigation system that provides information on location and time, in all weather conditions, anywhere on Earth. GPS requires an unobstructed line of sight to four or more GPS satellites. Advancing technologies and new demands on the existing GPS system have led to efforts to update and modernize the GPS system.

The design and installation of GPS systems into the vehicle must account for some common GPS signal degradations, including ionosphere and troposphere delays, signal multipath, receiver clock errors, orbital errors, number of visible satellites, satellite geometry, and internal degradation of the satellite signal (see SAE J3088).

ADS Applications: Originally developed for mapping and navigation systems, GPS has been employed to use vehicle location data to aid active safety systems. It can provide location and speed data to warn the driver of speeding or upcoming road delays and hazards. GPS can also be used in vehicle-to-vehicle communication (see SAE J3088).

Needs: Multi-frequency receivers are recommended to reduce errors, such as signal delay, which can come from atmospheric interference. The most commonly used frequency combination is L1/L2, but L5 is being used for more modern GPS units.

Precise Point Positioning or Kinematic Positioning may be used to aid in finding the precise location of the vehicle. These programs and services may often be used for free, or for a nominal membership fee (Hexagon).

References:

Hexagon/NovAtel. *Applications of High-Precision GNS*S. https://novatel.com/industries/autonomous-vehicles

SAE Surface Vehicle Information Report-Active Safety System Sensors (J3088). (2017). SAE International. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J3088_201711/

Camera and Sensor Connectors/Cabling

Scope: Camera/monitor/sensor connector and cabling guidance for heavy-duty commercial vehicles.

Guidance: The various types of connectors and cables are described. Images of connectors and pinouts are provided. The connectors described include these analog types: Bayonet-Neil-Concelman (BNC) video coaxial, Deustsches Institut fur Normung (DIN) connector, Radio Corporation of America (RCA), and Fachkreis Automobil (FAKRA). The connectors described include these digital types: low-voltage differential signal (LVDS) high-speed data and S-video, Ethernet, Digital Visual Interface (DVI), High-Definition Multimedia Interface (HDMI), and USB. Installation guidelines are also provided, including vehicle interfacing, power and ground connections, routing and clipping, and slack and bundling.

ADS Application: Multiple types of sensors, including cameras, are installed and connected on ADS-equipped CMVs to support detection and perception capabilities.

Need: When designing and installing ADSs on heavy-duty vehicles, a list of connector and cable types can improve implementation. Proper installation can ensure durable performance and communication of sensors to the ADS.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 183: Video Camera and Sensor Connector and Cabling Guidelines, 3/2019. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

5.1.2.6 Body Exterior

Headlamps

Scope: Specifications for headlamps to be equipped on heavy and commercial vehicles.

Guidance: Should comply with RP 111, 112, 113, 114, 120, 127B, FMVSS No. 108, FMVSS 108, SAE J575. Headlamps (halogen/non-halogen sealed beam, 2-lamp replacement bulb) are identified by automotive trade number and expected life at design (assumes 12 V nominal) and accelerated voltages. Guidance is provided on vibration resistance, system operating voltage, voltage surge suppression, and field verification.

ADS Application: Headlamps provide visibility for human operators of vehicles. However, headlamps also increase conspicuity of the vehicle to other vehicles both operated by humans and ADS. Headlamps also assist cameras as sensors.

Need: New lamp output levels may be developed and varied dynamically to accommodate optimal conspicuity and human operational control, while also supporting ADS sensing on ADS-equipped CMVs.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 124B: Heavy-Duty Headlamp Design Specifications, 5/2021. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Exterior Lighting Systems

Scope: Guidelines for the design and installation of exterior lighting systems on Class 7–8 combination vehicles.

Guidance: Considerations are provided for signal, marker, clearance, and identification lamps. The guidelines are intended to improve safety and maintenance while reducing downtime and the cost of ownership. System design priorities include motor vehicle safety standards (e.g., FMVSS 108), feature benefits, and application (i.e., on- versus off-highway). Power requirements are addressed because voltages that are too high reduce lamp life and voltages that are too low reduce lighting effectiveness. Some States have made it a requirement that a minimum of 85% of the design voltage must be supplied to exterior lamps. A priority for installation is location. The location of lamps should meet the requirements of FMVSS No. 108, and other components mounted around the lamps should not interfere with the visibility of the lamps.

ADS Application: ADS-equipped vehicles may have additional components mounted on the exterior of the tractor truck or trailer. Similar considerations for these components (e.g., sensors) may benefit from understanding the wiring, mounting, durability, and visibility requirements of exterior lighting systems.

Need: New components mounted in or on the exterior body of tractor-trailers should not interfere with the visibility by and communication to other vehicle operators through the use of exterior lighting systems.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 148: Exterior Lighting Systems for Signaling, Marker, Clearance and Identification Lamps. 4/2019. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Lenses and Glass

Scope: Refers to exterior components on the tractor or trailer body with ADS function, including cameras and other sensor that have lenses, and windshields that serve as the physical support for mounted ADS cameras and sensors or housing for built-in sensors. The scope of the SAE Surface Vehicle Information Report (J3088) is to (1) identify the expected functionality and performance from active safety sensors, including exterior cameras, and (2) detail a basic understanding of how these cameras work. This SAE Recommended Practice (J381) details uniform test procedures and performance requirements for the defrosting system of enclosed cab trucks, buses, and other vehicles.

Guidance: Design and installation of exterior cameras and lenses on ADS vehicles must consider proper protection from the external environment, elements, weather, and debris. In order for sensors and cameras mounted on the windshield to function properly, performance of the CMV’s defrosting system must be capable of maintaining a cleared viewing area. See SAE Recommended Practices J381 for test procedures and performance requirements (SAE, 2000).

ADS Applications: Exterior cameras have a wide range of uses in detecting and classifying objects based on visible qualities, such as intensity, color, and shape (SAE, 2017). They are also used to estimate distance to objects and provide visual feedback information to the driver. Cameras are used in collision warning/mitigation applications, adaptive cruise control, lane detection, lane assist, lane departure warning, sign recognition, obstacle classification (i.e., pedestrian, vehicle recognition), vision enhancement (i.e., night vision, backup camera, blind spot viewing, backseat passenger viewing, etc.), accident recorder, and adaptive headlamp control.

Windshields are the physical mounting mechanisms for ADS cameras and sensors, in addition to housing built-in sensors, special positioned areas of tint/no tint, heaters, and noise reduction layers, among others (Snow, 2017). The location and position on the windshield of these attached and built-in sensors are extremely precise. For example, lane departure warning systems have precise areas of the windshield that the lens sees through; therefore, great care must be taken during installation to ensure everything is fitted and lined up properly.

Needs: Exterior cameras and lenses that are susceptible to harsh elements and debris can be easily obscured or blocked, which can completely undermine the safety system. To address this from an installation perspective, some OEMs have moved exterior cameras and sensors to behind the windshield (Linkov, 2018). Great care must be taken during installation to ensure that the windshield is fitted and lined up properly due to the precise location and position of attached and built-in ADS sensors (Snow, 2017).

References:

Linkov, J. (2018). The big race to protect car sensors from their biggest foes: Dirt and weather. *Consumer Reports*. Accessed from https://www.consumerreports.org/car-maintenance/protect-car-sensors-from-dirt-and-weather/

SAE Surface Vehicle Information Report. (2017). *Active safety system sensors* (J3088). SAE International. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J3088_201711/

SAE Surface Vehicle Recommended Practice (J381). (2020). *Windshield defrosting systems test procedure and performance requirements-Trucks, buses, and multipurpose vehicles.* SAE International. Accessed from https://saemobilus-sae-org.ezproxy.lib.vt.edu/content/J381_200009/.

Snow, D. (2017). *Windshield replacement calibration with ADAS: What you need to know*. Accessed from https://info.glass.com/windshield-replacement-calibration-adas/

Brackets and Mounts

Scope: The SAE “Recommended Practice Truck and Bus Aerodynamic Device and Concept Terminology” document (J2971) describes devices and technologies used to control aerodynamic forces on heavy trucks and buses.

Guidance: J2971 describes the mounted devices common on trucks and buses that aid in aerodynamics. They are aerodynamic bumper, mirror, visor/slat, dam, cab edge radius, cab roof fairing, cab roof deflector, side edge turning vane, cab side fairing, cab side flex extender, chassis skirt, chassis skirt ground seal, undercarriage axle fairing, undercarriage fairing, undercarriage bogie fairing, and fender lips. It also lists aerodynamic mounts for trailers/freight boxes and buses. (J2971)

ADS Applications: While aerodynamics may not impact ADS, it does reduce vehicle fuel consumption, which frees up more resources for other systems.

Needs: All mounted parts must be installed properly to achieve aerodynamic benefits. Manufacturers of these products should have training or diagrams to explain how to properly install all mounted aerodynamic parts. (J2971)

References:

SAE J2971, *Recommended Practice Truck and Bus Aerodynamic Device and Concept Terminology*

5.1.2.7 Chassis, Tires, and Wheels

Wireless Tire Pressure Monitoring Systems

Scope: Guidance for heavy-duty commercial vehicle Tire Pressure Monitoring Systems (TPMS) and radio frequency identification (RFID) devices and processing modules used to measure tire inflation and temperature.

Guidance: Guidance and minimum requirements to support interoperability and performance criteria. TPMS sensors and RFID collect tire identification, installation, and pressure and temperature data and communicate to the vehicle's onboard processing unit, where the data can be stored for viewing through in-cab displays or transmitted from the vehicle to dispatch and operations centers.

ADS Application: ADS-equipped CMVs may also be equipped with TPMS and onboard processing units that communicate the status of the tires to onboard data loggers or off the vehicle and over-the-air to roadside inspectors and fleet dispatch or operation centers.

Need: ADS-equipped CMVs may operate for hours without onboard observation or inspection by human operators. Continuous monitoring of each tractor truck and trailer tire's inflation and temperature status during driverless operations can support safe and efficient transportation of goods. Tire performance can be an important indicator of vehicle, roadway, and environmental status.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 228C: Guidelines for Wireless Tire Pressure Monitoring Systems (TPMS) for Medium- and Heavy-Duty Truck Tires, 3/2018. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Considerations for Splash and Spray Suppression

Scope: Recommended practices for specifying equipment and evaluation methods to reduce road spray at highway speeds in inclement weather for heavy-duty commercial vehicles. This recommended practice is connected to "Trailers, Bodies, and Material Handling," section S.7 of the manual.

Guidance: "Spray is defined as the projection of standing water from a road surface as vehicles pass through that water at speeds greater than 30 mph" (TMC RP 759). Spray can take the forms of water jets, spray, and mist. Locations for heavy spray include tires, tractor-trailer gap, obstructions to air flow in the undercarriage, and around the rear of the vehicle. Road salts in the spray can increase the problem of obstructing glass, sensors, and lamps. Road surfaces such as non-porous asphalt can increase road spray issues compared to channeled concrete or porous asphalt. Steer tires play an important role in the problem of road spray. Proper selection and maintenance of steer tires to reduce spray include proper inflation, tread depth, and chine—a bead detail available on some steer tires that redirects water back to the paved surface. Some types of trailers, such as flatbed and car carriers, increase road spray. Components that are mounted perpendicular to the direction of travel create spray. Aerodynamically designed body components and elements that reduce drag can reduce road spray.

ADS Application: The performance of sensors mounted on the interior and exterior of ADS-equipped CMVs may be reduced by road spray and splash.

Need: Specifying aerodynamic body components and tires carefully could impact the amount of road spray that may cause ADS-equipped CMV sensors such as cameras and lidar to have reduced performance. The shape and location of sensors mounted on the cabs may increase the road spray and obstructions for other vehicles.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 759: Splash and Spray Suppression Guidelines, 4/2015. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

5.1.2.8 Trailer Interfaces

Truck-Trailer/Converter Dolly Jumper Cable, Line, and Connectors

Scope: Selection of trailer hook-up lines.

Guidance: Connector design for securing trailers to truck-tractors; cable length and suspension practices to ensure sufficient cable length and to avoid sagging, abrasion, and snagging during trailer turns.

ADS Application: ADS-equipped CMVs that are connected to trailers, which are equipped with sensors on the trailer.

Need: ADS-equipped CMVs seek additional data from trailers to improve detection around the combination vehicle.

Reference:

Technology & Maintenance Council. TMC Recommended Practice RP 107C: Seven Conductor Truck-Trailer/Converter Dolly Jumper Cable and Connector Selection, 5/2014. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Technology & Maintenance Council. TMC Recommended Practice RP 417B: Selection Guidelines for Pneumatic Tractor-Trailer Hookup Lines, 5/2023. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Technology & Maintenance Council. TMC Recommended Practice RP 435A: Installation and Inspection Guidelines for Pneumatic Tractor-Trailer Hookup Lines, 5/2023. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Tractor Truck ABS Power Supply

Scope: Considerations when interfacing with tractor truck ABS.

Guidance: Performance recommendations and test method for tractor truck power available for stop lamp circuits (SAE J560 seven-pin) and dedicated power circuit. Because circuit designs should account for the use of long seven-conductor electrical cords among some tractor trucks, approximate voltage drops in seven conductor cords by length (i.e., 10–22 ft) are provided. Guidance should be combined with TMC RP 141A.

ADS Application: Per SAE J3016 JUN2018, “crash avoidance features, including intervention-type active safety systems, may be included in vehicles equipped with driving automation systems at any level. For ADS features (i.e., Levels 3–5) that perform the complete dynamic driving task (DDT), crash avoidance capability is part of ADS functionality.”

Need: ADS-equipped CMVs may apply existing active safety systems such as ABS; therefore, consideration of vehicle network and tractor truck to trailer communication of ABS and interfaces with ADS equipment is important.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 137D: Antilock Electrical Supply from Tractors through the SAE J560 Seven-Pin Connector, 5/2017. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

Trailer ABS Power Supply

Scope: Considerations when interfacing with trailer ABS.

Guidance: Performance recommendations and test method for trailer electrical systems and maximum circuit resistances for stop lamp circuits (SAE J560 seven-pin) and continuous power circuits. Recommendations for minimum voltages to support trailer equipment that vary in length, wiring gauge sizes, lighting technology, ABS power consumption, and ground methods. Guidance considers single, double, and triple trailer combinations. Guidance should be combined with TMC RP 137D.

ADS Application: Per SAE J3016 JUN2018, "crash avoidance features, including intervention-type active safety systems, may be included in vehicles equipped with driving automation systems at any level. For ADS features (i.e., levels 3–5) that perform the complete DDT, crash avoidance capability is part of ADS functionality."

Need: ADS-equipped CMVs may apply existing active safety systems such as ABS; therefore, consideration of vehicle network and tractor truck to trailer communication of ABS and interfaces with ADS equipment is important.

Reference: Technology & Maintenance Council. TMC Recommended Practice RP 141A: Trailer ABS Power Supply Requirements, 5/2017. Washington, D.C. (https://tmcconnect.trucking.org/tmclibraries/newrplibrary)

5.2 ADS INSTALLATION AND MAINTENACE GUIDE

Maintenance and documentation of ADS will be a critical issue once these systems are introduced in the truck market. The VTTI team developed this guide for fleets to support the installation and maintenance of ADS equipment. One of the goals of this CONOPS is to prove the viability of an ADS in mixed fleets composed of trucks from a variety of OEM makes, models, and years equipped with a range of driving automation systems that assist drivers or carry full responsibility for sustained control and monitoring.

The ADS used during the project varied based on the operational use case for deployment. These systems are examples demonstrating how ADS technologies and their assembly with the vehicle can vary based on the ODD and automation functions required for operation. The first system was developed to support operations on public highways between hubs and exits. The second system was developed to support operations in limited geofence private yards or ports. Two separate installation guides and related maintenance practices are provided for each system.

5.2.1 Highway and Port Queueing ADS

In this section, we provide a product-focused overview of the installation process of Pronto's ADS on CMVs. The installation practices are heavily guided by Pronto's goal to provide an ADS that can be installed in a straightforward manner and swiftly validated in different CMV makes and models. Following this principle, the ADS can be conceptualized as being divided into three layers that guide the installation process:

1. Drive-by-wire (DBW)
2. ADS hardware
3. ADS software

The DBW encompasses all the electrical and electromechanical subsystems (including the ECUs required to achieve full vehicle control). These include steer-by-wire, brake-by-wire, throttle control, transmission control, and instrument cluster functions (e.g., turn signals, warning lights, headlights).

ADS hardware encompasses all essential components and sensors that the ADS software requires to run and communicate with the DBW in order to operate the CMV (for both the port queuing and highway demos of this project). Assembly and installation of Pronto's ADS hardware was designed to take advantage of modularization. Different groups of components and assemblies can be built and validated in parallel even before their installation on the target vehicle. This approach reduces CMV downtime for commercial fleets. Installation on the CMV requires minimal electrical and mechanical modifications that do not impede vehicle operations in the event that the hardware is later uninstalled.

Pronto's ADS software has three primary functions: (1) aggregate information from the vehicle sensors about the vehicle's surroundings, (2) extract contextual and semantic meaning from the environment/surroundings, and (3) make driving decisions within a predefined scope of operations (Level 2 or Level 4 driving) that then translate to actuation commands like braking, steering, and throttle via the DBW. Installing and delivering software is relatively simple because modern software engineering provides highly reliable and scalable tools to load validated, stable versions of ADS software (more commonly known as “releases”) to the artificial intelligence (AI) AV computer.

This section details the ADS hardware and software components, installation, and validation to provide a holistic understanding of the convergence required to deliver a fully functional ADS-equipped CMV. The information on DBW installation and validation is the same as that provided earlier in section 3.3 for the fleet integration use case and also in the next subsection 5.2.2 for the Port ADS. Additional information is also provided in Appendix C. Pronto’s longer term goal is to deliver a fully functional system in 4 days.

- Day 1: DBW installation and validation
- Day 2: ADS hardware installation and validation
- Day 3: ADS software configuration and validation
- Day 4: Initial operational integration test

5.2.1.1 ADS Installation Guide – Hardware

ADS hardware encompasses all the necessary components, sensors, and connectivity devices that the ADS software requires to run. It was designed and built with a modular approach that packages most components in a single assembly referred to as the “Longhorn” to facilitate propagating the technology to many CMVs. The Longhorn is a roof rack attachment that can be installed with minimal engineering and can be quickly modified to meet any height or width restrictions. To deliver a holistic understanding of ADS hardware installation practices, this section will cover the components of the Longhorn and its ancillaries, sensors, and HMIs, as well as their installation and validation processes.

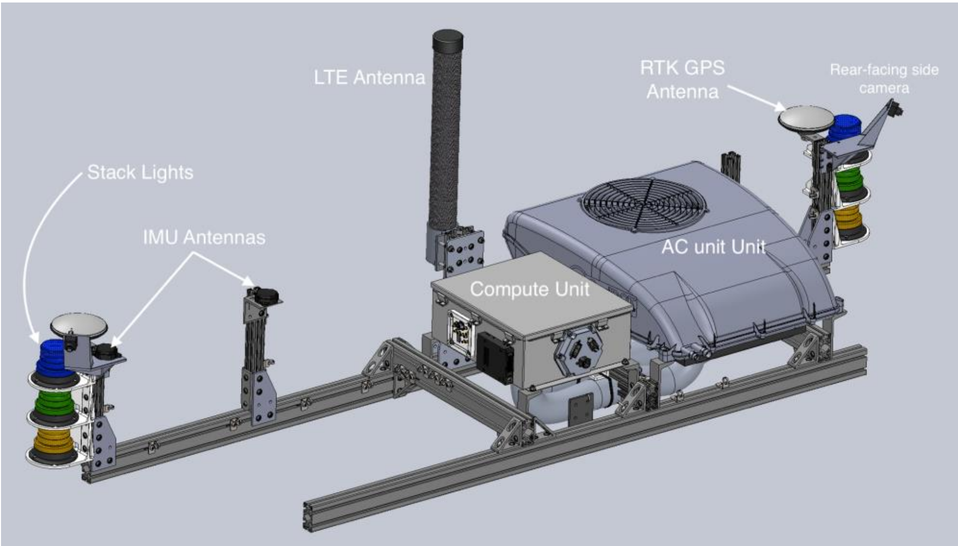


Figure 34. Diagram. Longhorn assembly.

Figure 35. Photo. Longhorn mounted on roof rack.

Longhorn: The core of the Pronto's ADS hardware is the Longhorn assembly pictured in Figure 34 and Figure 35. The Longhorn is built with an 80/20 T-slot system that provides incredible flexibility for installation onto different models of CMVs and adding new components. It contains the compute unit, the compute unit cooling system, antennas, rear-facing cameras, and antennas. The compute unit (Figure 34) is a shoebox-sized National Electrical Manufacturers Association-rated enclosure that contains the "brain" of Pronto's ADS:

- AI-ready compute module
- IMU
- Real-time kinematic (RTK) Global Navigation Satellite System (GNSS)/GPS modules
- LTE module
- Dedicated Short Range Communications (DSRC) module
- Camera processing module – supports up to six cameras via Gigabit Multimedia Serial Link (GMSL)
- Integrated CAN bus
- General purpose Input/Output (IO)
- Power conditioning and management unit
- 4-TB logging hard drive

The compute unit also contains two plates from which connections for antennas, CAN, power management, and cameras are aggregated and managed (Figure 36 and Figure 37).

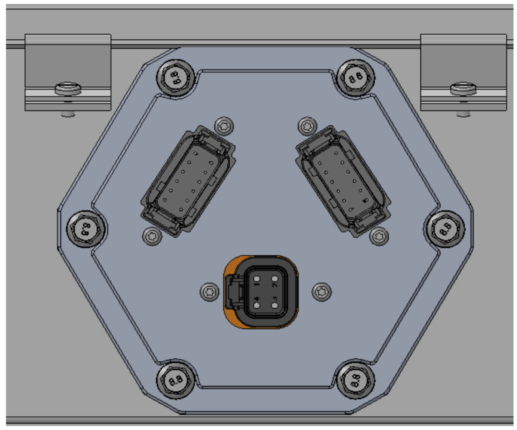


Figure 36. Diagram. Power and CAN Interface Plate.

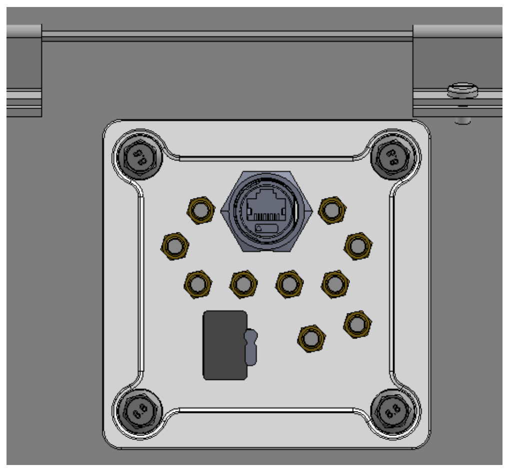


Figure 37. Diagram. Communications Interface Plate.

The Power and CAN Interface Plate is composed of two Deutsch DTM 12-way connectors and one Deutsch DTP 4-way connector. The DTM connector at the top left manages the Pronto DBW CAN bus, radar CAN bus and power, and SAE vehicle J1939 bus. The DTM connector at the top right manages IO for the stack lights (discussed in a further section), HMI CAN bus, and power control for the air conditioning (AC) unit fan and clutch. The DTM connectors are keyed to prevent installation errors. The DTP connector supplies power to the power conditioning and management unit inside the compute unit.

The Communications Interface Plate is composed of five pairs of SMA connectors for antennas, an all-weather Ethernet port for engineering and troubleshooting, and a key-shaped hole where camera GMSL cables are routed. Although not visible in Figure 37, the SMA connector pairs correspond to the antennas for the following devices:

- IMU GNSS/GPS – for accurate positioning of the vehicle using RTK
- RTK GNSS/GPS
- LTE – for vehicle-to-vehicle and vehicle-to-server/cloud communication
- DSRC

All the antennas, with the exception of the DSRCs, are labeled in Figure 34.

The AI-ready computer can generate significant heat when running the multiple neural networks at the core of the ADS software. In order to keep the unit running at safe temperatures, an after-market AC unit, labeled in Figure 34, was integrated to circulate air from the bottom of the compute unit. The AC unit contains all components for an entire AC system loop except for the compressor.

In the most up-to-date revision of the Longhorn, stack lights and two wide-angle cameras pointing backwards, have been added for port queueing operations (Figure 38).

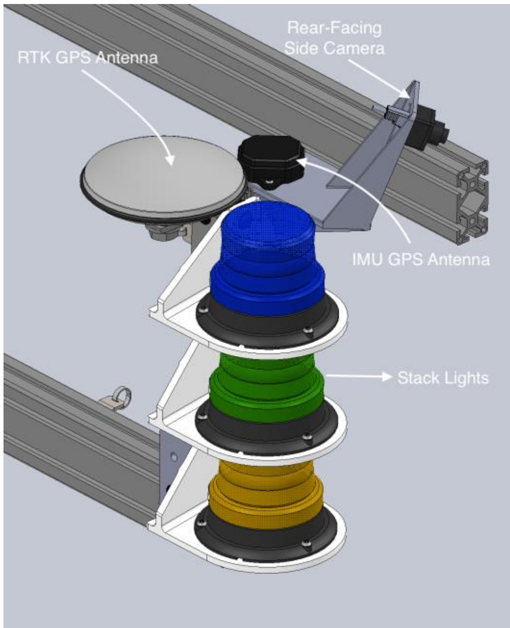


Figure 38. Diagram. Stack light and side cameras.

The stack light is composed of three colors:

- Blue when the CMV operates in automated operation.
- Green when the CMV operates in manual operation.
- Orange when the parking brake is applied.

Operators should not approach the vehicle unless they are following proper lockout procedures.

Longhorn Ancillaries: Although the Longhorn packages most of the ADS hardware, additional components are needed to securely mount it to the vehicle, power it, and connect it to the Pronto DBW and vehicle CAN buses. These can be grouped in the following categories:

- Mechanical mounts
- Power components

- Wire harnesses
- Cooling components

The Longhorn requires a series of mounting brackets attached to the vehicle's body to secure it in place. The goal was to make the Longhorn quickly removable for maintenance and repairs. Engineering work specific to the CMV is done to build and install mounting brackets.

Power for the Longhorn and all other components is sourced from the vehicle's 12-V system. The components to supply power safely and reliably are:

- ~10 AWG wire
- Battery disconnect switch
- Ignition switch contactor
- Fuse sized for expected current draw
- Power distribution wiring harness connector

Power flows from the 12-V battery through the battery disconnect switch into a fuse and ignition switch contactor. The contactor supplies power to the rest of the system through the power distribution wiring harness when the ignition switch is in the ON position.

Wiring harnesses supply power and data connections between the vehicle and the Longhorn. Power is sourced from the vehicle's 12-V battery system to the compute unit through the Deutsch DTP connector and to the AC unit's power supply. Data connections link CAN bus lines, Ethernet, and GMSL camera cables from the compute unit's Deutsch DTMS 12-way connectors to the vehicle's cabin where the front-facing camera, ECUs, and CAN bus devices live. A short list of components includes:

- Power distribution wiring harness
- Data wiring harness
- Radar wiring harness extension

Wiring harnesses are secured to the vehicle's cab and routed to the exterior components through a single through hole. Depending on the model of the CMV, a through hole must be created for the wiring harnesses.

The AC unit mounted on the Longhorn needs to be tied to the truck's AC compressor. This needs to be done both electrically, by wiring the AC compressor clutch to the compute unit's power conditioning and management board, and mechanically, by connecting the refrigerant lines to the compressor. The list of components to support this includes:

- AC compressor hoses – from compressor to AC unit
- AC hose fittings – compressor

- Refrigerant
- Relay sized for the current draw of the truck's compressor

Cameras and Radar: The Pronto ADS's primary sensors are the forward-facing camera and the front-facing radar. More details about these can be found in Appendix C. The front-facing camera is mounted inside the cabin and attached to the windshield. The radar is typically mounted at the center of the front bumper. The mount for each sensor was designed and manufactured in-house by Pronto to be versatile across CMVs. An additional driver-facing camera can be installed for driver monitoring functions. Figure 39 and Figure 40 show the front-facing camera and radar mounted onto one of the CMVs in the project's test fleet. Note that in Figure 39 there are two camera mounts (for testing), but operation of the ADS only requires one.

Figure 39. Photo. Front-facing camera.

Figure 40. Photo. Front-facing radar.

HMI: Pronto has developed its own human-machine hardware to operate the vehicle in both queueing and highway operations. A prototype version of the HMI box, pictured in Figure 41, provides tactile and responsive feedback to safety operators. It is the primary form of ADS control used during testing. The HMI is mounted to an easily accessible location on the vehicle fascia and communicates with the ADS software through the CAN bus. In addition, there is also a companion phone app that provides more detailed information and control of the vehicle with the intention to be the primary form of operator-to-vehicle communication during unmanned operations.

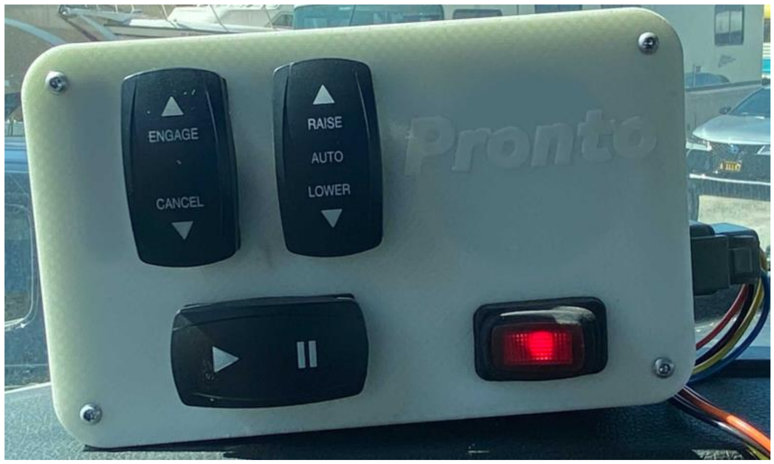


Figure 41. Photo. Cabin HMI prototype.

Installation and Validation: Pronto's goal is to deliver an ADS that can be installed with minimal support. All components and assemblies are validated at Pronto's facilities in San Francisco, California.

The installation of the ADS hardware can be divided into three phases:

1. Mechanical installation and validation
2. Electrical installation and validation
3. ADS hardware/software cross-validation

The mechanical installation requires mounting and securing the components to the vehicle's body and connecting the AC unit to the vehicle's compressor. The electrical installation involves wiring harnesses and all other modifications to connect the compute unit (which distributes power to most of the components) to the vehicle's 12-V power system and route and connect all data wiring harnesses to their endpoints. It is important to note the interdependence between the ADS software and the hardware. The ADS hardware/software cross-validation is performed by executing a series of tools developed by Pronto. Those custom tools are installed on the onboard computer and check that all ADS hardware components and Pronto's DBW communicate and behave as expected. These checks are discussed further in section 5.2.1.2 (Software and Hardware Cross Validation).

5.2.1.2 ADS Installation Guide – Software

The installation procedure for the ADS software is relatively simple and straightforward. Modern software engineering best practices provide highly reliable and repeatable tools to load stable and validated versions of the software (a.k.a. “releases”) over-the-air (wirelessly) to the AI-ready computer. In this iteration of the document, the firmware will be excluded, as it pertains to the Pronto DBW system. For robotics systems like the Pronto ADS, software installation includes additional steps because the ADS software is highly interdependent with the hardware platform and, as a result, must be fully integrated with the operations of the target customer. These additional steps can be summarized as follows:

- Software and hardware cross-validation
- Configuration
- Camera calibration
- Controls tuning
- Connectivity
- Operational validation

Software and Hardware Cross Validation: Once the ADS hardware is installed, the Pronto ADS can be turned on by switching the battery disconnect and ignition switch to ON. The onboard computer, already preloaded with the latest release of ADS software, has built-in diagnostic tools that are used to check that it is communicating correctly with all the necessary hardware components. The built-in software checks include:

- Antenna installation (correctly connected to their corresponding SMA connector)
- LTE connectivity
- Radar configuration and output
- Camera streams
- IMU initialization
- Stack lights
- HMI buttons (correctly mapped to their corresponding actions)
- Communications with the DBW
- J1939 bus information
- Camera intrinsics (correctly loaded)
- Logging system

To supplement these tools, the phone app developed by Pronto can also be used to check the results of the diagnostics. In addition, the app can be used to visualize all video streams to confirm correct placement of the cameras.

Configuration: Before the Pronto ADS-equipped vehicle can start driving, the operational mode and lever arms have to be configured and validated by a qualified technician or engineer. Operational mode refers to the ADS’s two functional modes: highway mode and port queueing operations. Lever arms are measurements of the sensor locations relative to a predefined coordinate system.

Operational mode is an important feature to highlight, as the two functional modes of Pronto ADS-equipped trucks have two fundamentally different safety recovery mechanisms. The e-stop system, part of the Pronto DBW, is able to switch between the modes in an assured and reliable way. When in queueing operation with a remote operator, an emergency stop must disable actuation to the truck while also ensuring that the brakes come on to prevent a runaway vehicle. However, in highway operation with a safety operator, it is critical that the truck remain in motion.

Lever arms are a fundamental part of the configuration because all vehicles share the same sensors and components but with varying placements. In order to construct a unified and accurate geometrical representation of what the perception stack "sees," a coordinate system must be defined from which each sensor location is measured. It is highly important for these to be right for correct placement of objects relative to the vehicle and accurate localization for path navigation. For the Pronto ADS, the origin of the coordinate system is at the bottom center of the compute unit installed on the Longhorn, which is also the location of the IMU. This was chosen intentionally to hedge measurement errors. The following lever arms must be measured before the ADS software is ready to operate:

- Front radar
- Front camera
- RTK GPS antenna receivers
- IMU GPS antenna receivers

At the moment, an engineer must input and validate those measurements. These lever arms are tightly coupled with vehicle controls. More details about validating these will be provided in the following subsections.

Calibration: Pronto's ADS core technology is powered by vision-based machine learning algorithms, making cameras the primary mode of perception. Just as the lever arms must be measured, camera extrinsic and intrinsic parameters must be obtained to understand the placement of objects relative to the vehicle position. Extrinsic camera parameters describe where the camera is located relative to a predefined coordinate frame (level arm from section 5.2.1.2 [Configuration]) as well as its orientation (yaw-pitch-roll). Camera intrinsic parameters describe how world points map to the image plane and also describe distortion introduced by camera lenses.

The intrinsic calibration procedure of each camera installed in a system occurs at Pronto's facility in San Francisco, and values are loaded onto the ADS onboard computer. If the calibration has not already happened at Pronto's offices, it can be done on-site. Camera extrinsic parameters are measured along with the lever arms of other sensors and antennas. The initial orientation measurement is obtained by manually driving the vehicle and using the built-in calibration tool, which uses computer vision techniques, to derive them from motion. The ADS software periodically checks and updates the orientation of the camera. No human intervention is required unless the camera has been drastically displaced from its initial location.

Controls Tuning and Validation

The Pronto ADS controls were designed to function with CMVs of different makes and models, each with its own vehicle dynamics. To quickly fine-tune the algorithms to the specific vehicle, each can be described by a set of discrete characteristics that can be measured and loaded into the ADS software. These include:

- Vehicle wheelbase
- Steering ratio
- Maximum steering wheel angle
- Compute unit location relative to the first non-steering axle
- Brake pressure calibration

All of these are part of the Pronto DBW, and these parameters will live in the ADS software and ECU firmware. More details will be provided in later revisions of this document.

Once all of these have been configured, a safety operator and an engineer will perform a closed-circuit test to confirm that the controls are behaving as intended and refine them as needed. In addition, safety failure cases will be tested to validate safety systems and procedures. Once completed for both operational modes, it is safe for the safety operator to test the system in a real-world environment.

Connectivity and Operational Validation: Once control tuning and validation have been completed for the ADS-equipped CMV, it is ready for operation. The ADS-equipped CMV will most likely be integrated into fleet management and dispatch software and will enter a regular maintenance schedule. The goal is to provide an easy-to-manage asset with high uptime and low maintenance requirements. In order to achieve this, connectivity and operational flexibility are of the utmost importance.

Connectivity is highly important for both maintenance and productivity; therefore, part of the validation process is to make sure that communications—LTE, Wi-Fi mesh networking, radio, and DSRC—are stable and highly reliable across the intended operation zone. This ensures that the individual in charge of managing the assets can quickly react to business and maintenance needs. The ADS software diagnostics (currently under development) can alert different stakeholders to evolving issues in real time, which we anticipate will prove to be key to realistic operations.

In addition, the ADS companion phone app can be used to manage the truck from any location, and technicians can use it to perform diagnostics. Part of the validation process includes verifying that the local Wi-Fi and local area networks are working, as they provide redundancy for quickly accessing and diagnosing the CMV if the primary form of communication were to fail.

5.2.1.3 ADS Maintenance Guide

Properly maintaining and routinely inspecting ADS-equipped vehicles is an important part of a fleet's ADS adoption process and is key to preventing crashes and related losses. Pronto has, from the outset of their vehicle testing program, defined and updated maintenance guidelines for ADS use that build upon the Driver Pre-trip Inspection Checklists required by the FMCSA for CMVs. Pronto has expanded these checklists to include the practical realities of operating Pronto ADS-equipped vehicles (for both highway and port queueing operations). This section summarizes the maintenance practices used in Pronto's Fleet Safety Program. This information is an example of the maintenance information that is constantly being updated to remain current with periodic changes in hardware and software.

Pronto focuses on three distinct maintenance programs: preventative maintenance, demand maintenance, and crisis maintenance. While all three have an important role in a fleet safety program, the most cost-effective is preventative maintenance. Before defining the scope of each, it is important to discuss the pillars of an effective maintenance program.

An effective and well-rounded maintenance program for ADS-equipped CMVs should include the following:

- A review of the manufacturer's specifications and recommendations for periodic preventative maintenance integrated with the actual experience of the vehicles;
- Clearly defined mileage-based service intervals consistent with manufacturer's recommendations;
- Thorough quarterly inspection by a Pronto-trained ADS technician;
- Robust analog and digital documentation practices; and
- A culture of accountability.

Pronto is committed to following a rigid, daily inspection program carried out by the drivers of highway products and vehicle operators for port queueing applications. Any losses resulting from a failure to inspect the equipment are considered grounds for disciplinary action, including termination. Mandatory inspections occur at the beginning and end of each shift. All drivers/operators must perform a pre-trip inspection prior to ADS-equipped vehicle operations.

Inspection and maintenance programs are only as good as record-keeping procedures. Drivers, operators, mechanics, and technicians need to forward all vehicle maintenance and repair records for record-keeping. Vehicle service history and inspection documentation will be stored electronically using fleet management software.

Preventative Maintenance: Preventative maintenance (PM) is performed daily and on a mileage and time basis. Typical PM inspections and services are the same for an ADS-equipped vehicle as a manual one and include fluids, filters, brakes, tires, suspension, general powertrain, and drivetrain. All regular vehicle maintenance is performed by a Pronto-trained professional mechanic or Pronto's Vehicle Maintenance Team. This includes oil changes, suspension alignment, brake service, tire service, OEM parts replacement, plus any component related to the ADS DBW and hardware platform. Only Automotive Service Excellence (ASE)-certified technicians may perform engine or transmission repair work. Only Pronto-approved technicians can perform work to the ADS DBW and hardware. The maintenance manager ensures that all technicians hold current valid ASE certifications. In addition, the maintenance manager will track manufacturer Technical Service Bulletins (TSBs) and recalls, including those issued by NHTSA. TSB and recall service is performed by the applicable manufacturer dealership or authorized service center.

Pronto drivers/operators are the first line of defense for any vehicle defects. Maintenance concerns are to be reported directly to the assigned program administrator. Drivers use a third-party app at the beginning and end of their driving shift to inspect the vehicle. Drivers also use Pronto's phone app to get feedback from the ADS's system diagnostics tools. Each vehicle has a maintenance schedule based on the manufacturer's guidelines. These intervals are traced electronically through third-party management software. In short, the PM for an ADS-equipped vehicle is almost identical to that for a traditional vehicle, and the ADS DBW and hardware do not require any specialized skills to be inspected (although they do require Pronto-approved technicians to perform maintenance work on those components). This is key for commercial fleets to be able to readily adopt ADS trucks in a mixed-fleet environment without requiring burdensome additional manpower or employee training.

Driver Pre-trip Inspection: A properly performed and thorough pre-trip inspection must be conducted by each driver/operator prior to operating an ADS-equipped CMV. For port queuing operations, the inspection should occur before the vehicle is set to autonomous mode and marked as available for work in the fleet management software. The pre-trip inspection is the same for highway and port queuing modes, as they currently use the same hardware platform. Any mode-specific item will be clearly noted in the pre-trip inspection checklist. The following steps must be completed for each pre-trip inspection. If anything potentially unsafe is discovered during the inspection, it must be fixed immediately and verified by the assigned authority.

1. **Review Last Vehicle Inspection Report** – The driver must review the last DVIR to verify that any needed repairs were made to the vehicle. If an authorized signature certifies that defects were corrected or that correction was unnecessary, the driver may continue with the pre-trip inspection. If the defects noted were not acknowledged by an authorized signature, the driver shall not drive the vehicle until the defects are corrected.
2. **Vehicle Documentation** – The driver must verify that vehicle registration, insurance cards, and the emergency procedures document are in his or her possession (if applicable). These are to be stored in the center console.
3. **Vehicle Overview** – A general condition review of the vehicle is required. The driver will:
   - Look for damage or unusual wear to the vehicle.
   - Look under the vehicle for fresh oil, coolant, grease, or fuel leaks.
   - Check the tires for punctures, pressure leaks, and damage.
   - Verify that illumination and signal lights function as intended.
   - Verify that the fuel level is above one-quarter of a tank.

- Verify that sensors are securely fastened.
- Verify that the exterior is reasonably clean.

4. **ADS Hardware Overview** – A general condition review of the accessible ADS hardware components. The driver will check that:
   - The front radar is securely in place with no obvious damage.
   - The front-facing camera is still securely attached to the windshield.
   - The Longhorn and its components are securely attached and with no obvious damage.
   - The wire harnesses (from Longhorn to the interior of the cab) show no obvious damage.
   - All antennas are still in place:
     - 1 × LTE
     - 2 × RTK GNSS
     - 2 × IMU GPS
   - Stack lights are secured and show no obvious damage.
   - The rear-facing cameras are still in place with no damage.
   - The compressor hoses to the Longhorn's AC unit are connected and free of visible damage.
   - The vehicle is clean, especially since there is no buildup of excessive grime on components and sensors.
5. **Start Engine and Inspect Inside the Vehicle** – The driver will verify that the parking brake is set, start the engine, listen for unusual noises, and then check the following:
   - Gauges (oil, ammeter/voltmeter, coolant temperature, engine oil temperature, warning lights and buzzers).
   - Condition of controls. Look for looseness, sticking, damage, or improper settings (steering wheel, accelerator, brake controls windshield wiper/washer, and lights [headlights, turn signals, emergency flashers, and brake lights].
   - Condition of mirrors, the windshield, and windows.
   - Location of emergency equipment (three red triangles, first aid kit, emergency phone number list, and emergency procedures).
   - Maintenance required and check engine light.
   - Vehicle cleanliness:
     - Sensor surfaces are clean.
     - The driver will clean all lights, reflectors, and glass as needed.
6. **ADS Software Verification** – The driver will use the Pronto-supplied phone application to initiate diagnostic checks. The diagnostics run software/hardware cross-validation and report if the system is ready for operation. Any critical system that does not pass diagnostics will have to be verified by a qualified technician before the system is unblocked for use. The granularity of the diagnostics information will

be filtered based on the role of the person running the inspection. The ADS software diagnostics tool will check that:

- All required sensors and antennas are connected and in optimal condition.
- The AC unit is running and keeping the system at a safe operating temperature.
- All software subsystems (as described in the ADS Technology Specification document) are running.
- The system is logging data.
- (*In Development*) J1939 is being used to report OEM diagnostics information.
- Connectivity is established with Pronto's servers (only required for the port queueing operations).
- While the system is locked out and the parking brake is applied, the stack lights illuminate properly.

7. **Test Methods of ADS Disengagement** – While the vehicle is stopped, the driver will engage and then disengage the ADS using each method of disengagement and verify that the e-stop mechanism of the intended mode of operation is executed.
8. **During a Trip** – Once on the road for highway operations, the driver must examine the vehicle:
   - Before they begin driving after any stop
   - After driving for 3 hours
   - After driving 250 miles

If a problem is found, the driver must either have the necessary repairs or adjustments made prior to operating the vehicle or safely travel to the nearest repair facility. During each stop, the driver will check the following items:

- Tires, wheels, and rims
- External mounted sensors (if any)
- Lights and reflectors

For port queueing operations, the ADS will self-report problems to the fleet management system. Depending on the issue, the vehicle will stop or return to the maintenance area. If the vehicle cannot safely proceed, the appropriate person will have to be alerted and will have to lock out the vehicle, enter and disengage the system, and drive it manually to the maintenance area to be diagnosed, fixed, and validated before returning to operation.

9. **Post-Trip Inspection and Report –** Each driver is required to complete a written report on each vehicle's condition at the end of the day, or when they finish driving the vehicle for that day. The report must be completed in its entirety and the driver must note any defects to the following:
   - Parking brake
   - Steering mechanism

- Lighting devices
- Tires
- Horn
- Windshield wipers
- Windshield and windows
- Rear-view mirrors
- Wheels and rims
- Brakes and throttle
- Emergency equipment
- ADS hardware

The driver must also note any other defects that could affect the safe operation of the vehicle or result in its mechanical breakdown. The report must also indicate whether no defects are found. A copy of the inspection report and certification of repairs will be retained electronically. The inspection reports on which defects were noted and the certification of repairs will be retained for 3 months.

Quarterly Assessments: In addition to the periodic maintenance assessments dictated by the OEM, Pronto requires an in-depth inspection of all DBW and ADS hardware components on a quarterly schedule. The quarterly ADS hardware assessment includes the following tasks:

- Check that the bolts and screws holding the Longhorn assembly and mounts together are present and properly torqued.
- Replace the Longhorn AC unit air filter.
- Check that the compute unit is properly secured.
- Check antennas for wear and tear.
- Check that all antenna cables and connections are secure.
- Inspect the inside of the compute unit for any loose or broken parts.
- Verify the health of all data and power harnesses.
- Inspect connections to the vehicle's 12-V system for corrosion or damage.
- Verify that all camera mounts have not been damaged or displaced. If damage is found, the mount has to be replaced and the camera has to be recalibrated.
- Run built-in hardware diagnostic checks included with the ADS software.

Once the assessment is complete. The operator must test that the ADS engagement works and complete a test lap. Documentation records must be kept, and a service sticker must be placed on the vehicle's windshield with the date of the next assessment.

Demand Maintenance: Demand maintenance is performed only when the need arises. Some vehicle parts are replaced only when they actually fail. These include light bulbs, window glass, wiring, etc. Other "demand maintenance" items involve vehicle components that are worn based on information from the vehicle condition report. These include tires, engines, transmissions, universal joints, bushings, batteries, etc. Since these situations are identified through periodic vehicle inspection, they can actually be classified within the PM program. All ADS hardware components will follow the same guidelines and there is nothing unique about an ADS-equipped vehicle from a maintenance perspective.

Crisis Maintenance: Crisis maintenance involves a vehicle breakdown while on the road. While situations of this type may happen regardless of the quality of a PM program, it is an expensive alternative to not having an effective PM program at all. Crisis maintenance situations should be minimized through proper PM procedures.

In the event of a vehicle breakdown, the driver is to park the vehicle in a safe location and notify the fleet dispatcher immediately. The dispatcher and driver will coordinate with the maintenance manager to determine if a tow truck should be dispatched, if it is safe to drive the vehicle to a repair facility, or if the vehicle can be driven back to base. In the event of a vehicle breakdown, the ADS must no longer be used until the problem is fixed even if the breakdown is wholly unrelated to the ADS features.

Software Maintenance: To ensure proper ADS operation, a series of tests are performed to ensure that the ADS software is operating and updated properly.

5.2.1.4 Initial Operation at a New Deployment

After the ADS is set up, tuned and calibrated for a new deployment for the first time (see section 5.2.1.2 of this guide), the ADS must pass a series of commissioning tests to ensure that the software is performing as expected before it can be put into operation for a customer. Pronto's practices are to first complete the commissioning tests "internally," meaning that only Pronto personnel are involved with the tests. After successful completion, the tests are then repeated with the customer representative present. During the "customer commissioning" tests, a representative of the ADS end-user fills out test notes, observations, results, and signs confirmations that the commissioning tests were successfully completed.

Pronto's commissioning tests focus on safety-critical operations of the software. They cover, among other things:

- Camera-based tests
  - Detection and proper interaction with other vehicles at different view angles for both front- and rear-facing cameras
  - Correct detection and projection of the intended path of travel for the ADS-equipped vehicle (both forward and reverse)
- Safety-system tests
  - Ensure that a command to stop ADS operations works and that the ADS cannot re-engage. This test also covers tests to ensure that the ADS-equipped vehicle is "safe to approach" by drivers or other personnel.

- Check emergency stop operations by injecting faults into the software and ensuring the system stops properly.
- Check a series of fault conditions (by disengaging/crashing certain software functions, hardware connections, and CAN interfaces) to ensure that the ADS properly responds to each "failure." The failures tested include, among others, a loss of GPS precision, loss of computer power, loss of camera feed(s), driving off the intended path of travel, loss of communications with a device that can order an emergency stop remotely, and broader loss of communications.

- Driving tests
  - Brake commands tests (service brakes)
  - Steer command tests
  - Path tracking tests
  - Parking brake tests
  - AEB tests

5.2.1.5 Software Updates and New Releases

Like all other software, the ADS software needs to occasionally be updated to improve performance or patch vulnerabilities. Before new versions are rolled out to ADS-equipped vehicles operated by customers, the Pronto software team first compiles all the changes/updates to be rolled out into internal release notes. The engineering team reviews the release notes and the new/updated features. They then discuss any additional tests that may be needed for this software update specifically or more generally for all future releases.

The Pronto engineering team then completes a full software "release test" at its private truck testing grounds. Notes and results are compiled in internally managed release test reports. This ensures that the new (or improved) functionality of the ADS works as intended and, just as importantly, that the new release has not somehow unintentionally degraded other performance/functionality of the prior software release. The release tests are similar to the commissioning tests described above and have an additional focus on the newly updated features.

After successful internal completion of the release tests, the software is updated at each customer site and all of the ADS-equipped trucks operating at customer sites undergo release update testing. These are a subset of the internal release tests that cover the core safety features of the ADS software.

Although there are not yet industry-standard tests that cover ADS software performance, there are more general automotive safety system tests that can be referenced and leveraged to validate ADS performance. In developing its internal commissioning and software release/update tests, Pronto referenced and adapted several such industry standards and tests, including:

- ISO 3450, part 6, performance tests of brakes
- ISO 5010, part 6, performance tests for steering

- The United Nations Economic Commission for Europe (UNECE) and International Organization of Motor Vehicle Manufacturers (OICA) working group on advanced and autonomous emergency braking (AEB) standards and test protocols
- The European New Car Assessment Program (Euro NCAP) Test Protocols for AEB
- The Euro NCAP Test Protocols for AEB for Vulnerable Road User (VRU) protection
- The New Car Assessment Program for Southeast Asian Countries (ASEAN NCAP) Test Protocol for AEB Systems
- The Insurance Institute for Highway Safety (IIHS) Pedestrian Autonomous Emergency Braking Test Protocol (Version II)

5.2.2 Port ADS

The installation and maintenance guide in the previous section gives an overview of Pronto's approach to installing and maintaining ADS on their trucks specifically for highway systems. Considering that vehicle operations at ports can differ significantly from those on typical highways (for example, port operations may involve more queueing conditions, more turning movements, lower speed, vehicle cut-ins, more reverse maneuvers, and more interaction with non-vehicular objects), Pronto's ADS equipment was first refined to match these conditions before deployment. This ensures equipment integrity, as there are potentially more moving parts and more demand on the equipment due to the tougher or irregular operating conditions at ports. The refinement also facilitates traceability when troubleshooting, service, or repair is needed at ports. This section covers the installation and maintenance of ADS equipment including the DBW system, the RF cables and connections, cameras, seals, harness, steering, and braking systems, specifically for port operations.

5.2.2.1 Port ADS Installation Guide

Before the installation begins, the entire kit is fully bench-tested. The kit is assembled on a rolling cart with each part that will eventually be installed on the truck, including RF cables and harnesses. This allows the bring-up time for each truck to be much faster than previous installations as full system checks can be completed except for anything that requires communication with the base truck. The steps for the installation of the Pronto kit have been broken down into 18 installation guides plus a master guide, the "Global Installation Instructions." A different set of guides is required for each supported truck. These guides cover the entire installation and are as decoupled as possible, meaning that jumping between guides is kept to an absolute minimum. However, due to the current design and the nature of the complex systems that are installed, some sections require jumping between guides. A summary of the installation follows.

The DBW can be broken down into two categories. Included in the first category are actions that are only actuatable with a physical signal. That is, they are not controllable with an electronic signal. For example, the brake pedal pushes on a pneumatic valve. The pneumatic valve controls the air pressure to the braking system. There are no electronics in the loop. The second category includes everything that is controllable with an electrical signal. For example, the throttle pedal is connected to a sensor that outputs the position. This position signal is what the engine responds to. The Pronto kit needs to control things in both categories. The steering, service braking, parking, and parking brake all fall into the first category and therefore need a physical actuator added. The throttle, gear shifter, and horn are in the second category and can be controlled by the electronic signal, without the need for a mechanical actuator.

Steer-by-wire: The steer-by-wire kit affects the steering system by actuating the hydraulic steering gear. Critically, this system does not break the physical link between the steering wheel and the wheels on the ground, allowing for normal operation whenever the Pronto system is disconnected. Relevant installation guides are “2: Pronto Steer-by-wire Installation,” “4: Floor Pass Through Installation,” “5: Exterior Harness Installation,” and “13: Internal Harness Installation.”

Brake-by-wire: The brake-by-wire kit actuates a second treadle valve in parallel with the manufacturer’s brakes, which, similarly to the steering kit, does not interrupt the normal operation of the truck. The brake-by-wire kit is installed inside the cab on a Pronto-designed bracket. Relevant installation guides are “4: Floor Pass Through Installation,” “6: Exterior Brake Hose Installation,” “16: Parking Brake Installation,” and “18: Brake Box Installation.”

Squid : The electronically controllable signals are intercepted by the Pronto system through the Squid, a custom ECU with a tentacle-like topology. The installation consists of mounting the ECU to a Pronto-designed bracket in the cab, routing the wiring harness to each system that is controlled, and then connecting to the base truck at each of those systems. Relevant installation guides are “4: Floor Pass Through Installation,” “5: Exterior Harness Installation,” “13: Internal Harness Installation,” and “18: Brake Box Installation.”

5.2.2.2 Port ADS Maintenance Guide

After the Installation: To facilitate traceability, we implemented as-built forms. This form documents each installation with very specific photos. It will be designed to capture any deviation from the standard procedure to inform any future maintenance or troubleshooting. The system is designed to reduce the regular maintenance that is required. For instance, thread locker and proper torque for screws are called for in the initial installation. However, there are a few items that should be serviced regularly.

RF Connections: Over time, the RF connections may come loose even though they have been installed with thread locker and torqued appropriately. Check these connections every shift by hand. If any have become loose, retighten to the recommended torque (0.6 Nm for SMA connections, 2.2 Nm for N-type connections). Note that a special torque screwdriver and crows foot attachment must be used. Overtightening can permanently damage the connector and therefore the cable. Note that the RF connections at the GPS cable should also be checked. Relevant installation guides are “8: Front Camera Installation,” “9: Rear Camera Installation,” “12: RF Harness Installation,” and “17: Compute Box And Mount Installation.”

Cameras: The front camera is placed such that the windshield wipers will clean the glass in front of the camera lens. However, the rear camera is not. The rear windshield should be cleaned as often as needed to keep a clear view in front of the camera. This should happen at least once a shift but as often as necessary. If the front camera design does not have a baffle, then the glass on the lens itself should be cleaned periodically. For example, the front camera on the day cab trucks does not have a baffle. To clean the lens, use any glass cleaning wipe. Relevant installation guides are “8: Front Camera Installation” and “9: Rear Camera Installation.”

Seals: The polymer seals that are used should be checked every 6 months. For example, on the GPS and LTE antenna installation on the 579 Day Cabs, sealant is required on some of the bolts into the roof of the cab. Relevant installation guides are “10: GPS & LTE Mount Installation” and “11: Snorkel Installation.”

Harness Routing: With proper installation, the harnesses should be relatively maintenance free. To ensure proper installation, after 4 weeks of operation, the harness routing should be checked for any signs of damage from rubbing components, heat, or exposure. Replace, reroute, and protect as necessary. There are a couple of items which may need replacing after 6–12 months of operation. Specifically, check the adhesive zip tie mounts on the roof and back of the cab used to secure the RF and SVD cables respectively. Relevant installation guides are “5: Exterior Harness Installation,” “12: RF Harness Installation,” and “13: Internal Harness Installation.”

Steering: As part of the installation, wedgelock washers (name brand Nordlock) are used on safety-critical and/or high-vibration bolted connections. The steer-by-wire installation uses these washers on the mounting points to the bracket. As part of the pre-trip inspection, the pinch bolts on the shaft (using deformed thread lock nuts) and the bolts connecting the actuator to the bracket should be visually inspected. Torque stripe is used after torquing the bolt to the appropriate torque. This allows for a quick visual inspection to see if any bolts have loosened. Relevant installation guide is “2: Pronto Steer-By-Wire Installation.”

Braking: The brake-by-wire system requires greasing at two different locations inside the brake-by-wire enclosure. The plunger that contacts the treadle valve slides through a bronze bearing. White lithium grease should be used every 3 months on this sliding joint. With the plunger fully retracted, apply a pea-sized amount of grease (Loctite® LB 8042 White Lithium Grease) to the plunger with a gloved finger. Smooth out over the cylindrical surface. Additionally, the ball screw jack also requires regular greasing. There is a zerk fitting accessible once the brake enclosure is opened. Use Mobilgrease XHP222 every 6 months. The maintenance intervals for this item are still being fine-tuned, so this may change. Relevant installation guides are “6: Exterior Brake Hose Installation,” “16: Parking Brake Installation,” and “18: Brake Box Installation.”

RF Cables: RF cables are used in some of the most critical components of the Pronto system. Care must be taken during the installation process to not kink any of the cables. If any cable is suspected to have been damaged during operation (pinched, kinked, abraded, etc.) then the cable must be replaced. Regular maintenance is not required. Relevant installation guide is “12: RF Harness Installation.”

5.3 ADS INSPECTION PROCEDURE

5.3.1 Background

FMCSA is charged with the responsibility of reducing "crashes, injuries, and fatalities involving large trucks and buses."[30] To accomplish this safety mission, FMCSA establishes and enforces the FMCSRs. Truck inspections are a key element of Federal and State commercial vehicle safety programs. They are designed to ensure compliance with Federal and State safety, credentialing, and administrative (e.g., weight) regulations.

The FMCSRs require various types of inspections of commercial vehicles (large trucks, commercial buses, and hazardous materials vehicles).[31] Each commercial vehicle must be inspected at the beginning of the work shift. The driver is responsible for conducting this pre-trip inspection to ensure that major vehicle components are in good condition, and that the vehicle can be operated safely. Also, the driver, who has experienced the vehicle's handling, sounds, scents, and viewed the status of dashboard indicators, is in the best position to assess major vehicle components at the end of a work shift. Therefore, the driver has the responsibility for completing the DVIR at the end of the work shift. The motor carrier is responsible for complying with the FMCSR requirements for a periodic inspection. The motor carrier or third party is also responsible for a more thorough annual or periodic inspection.

Additionally, FMCSA provides support to its State partners to conduct roadside inspections of elements called out in the FMCSRs. FMCSA's State partners, located on major highways, conduct roadside inspections at fixed or mobile facilities. Roadside inspections focus on driver or vehicle inspection elements and are typically conducted when the commercial vehicle is en route to its destination. Violations found during a roadside inspection fall into two categories: (1) non-critical defects and (2) out-of-service (OOS). Typically, non-critical defects are those that pose little to no safety risk, and the commercial vehicle can return to the road even before the violation has been corrected. OOS violations, on the other hand, must be corrected before a commercial vehicle can return to service. OOS orders ensure that a commercial vehicle and/or its driver cannot proceed on the road until the conditions are corrected and the vehicle is safe to operate.

FMCSA has established several tools to support its enforcement efforts, including the Compliance, Safety, Accountability (CSA) Program and the Safety Measurement System (SMS). SMS ranks motor carriers based on their safety performance. The ranking is based on a function of data collected during roadside inspections (e.g., the frequency of different types of violations and the frequency of crashes that a carrier has had). The SMS was developed to prioritize unsafe, high-risk motor carriers for targeted interventions.

5.3.1.1 Problem

The development of vehicle automation and ADS provide tremendous potential for significant safety improvements. However, there will be a need to inspect the vehicle and its systems that operate without a driver onboard to ensure proper performance and safety. This creates a challenge for NHTSA, FMCSA, and the CVSA to create policy and inspection procedures to ensure the safety of both CMVs and the motoring public.

Except for ADS components and software, the FMCSRs regarding the various requirements for truck inspections can continue without modification as long as a driver or safety operator is present. Once trucks are operating at SAE Level 4 and above, without a driver or safety operator, there is a need to modify the procedures that account for tasks that the driver and roadside inspector would normally be responsible for during each of the required truck inspections.

5.3.2 Literature Review

VTTI reviewed the FMCSRs and the existing research literature to better understand the current state of practice regarding truck inspections and the implications of driverless vehicles. Additionally, the VTTI study team interviewed nine experts involved in motor carrier enforcement, motor carrier safety, and ADS technology development to better understand the challenges that ADS-equipped vehicles pose to existing truck inspection processes, to identify the changes needed in the FMCSRs, and to identify alternative truck inspection procedures. This section summarizes findings from the literature review.

In conducting the literature review, the study team searched various terms related to truck inspections—roadside, pre-trip, DVIR, periodic, and the link between mechanical failures and truck crashes. While there is considerable research that supports the connection between truck mechanical failures and crashes and the impact of roadside inspections, the study team found only one study regarding the impact of periodic inspections and the two driver inspections (pre-trip and post-trip with DVIR).

5.3.2.1 Mechanical Failures and Truck Crashes

There have been many different approaches to studying the impact of mechanical failures and whether they contribute to truck crashes. Most seem to underreport the problem. Some of the early research (dating back to 1976) has suggested that mechanical failures in trucks are rare, as are failures in environmental components, such as the road system.[(32)]

In a 1989 study, researchers from the IIHS investigated the role of defective equipment in large truck crashes in a case-control study design. They found that 77% of tractor-trailers in crashes and 66% of those not involved in crashes had defective equipment warranting a citation. Brake defects were the most common type, found in 56% of tractor-trailers in crashes, followed by steering equipment defects (found in 21% of tractor-trailers in crashes).[(33)]

In a 1996 analysis of national crash data, researchers found very low rates of reported mechanical defects. For instance, only 2.8% of the trucks involved in crashes had mechanical defects. Of the defects noted, brakes were the most frequent, followed by wheels and tires, and steering.[(34)] Among fatal crashes, the authors found that brake defects were recorded for only 2%–3% of cases. The authors noted that "one obstacle in assessing the role of vehicle defects in accidents is the lack of systematic, post-collision vehicle inspections." They concluded that reported vehicle defects were low and that it was difficult to determine whether this was due to the rarity of defects themselves or underreporting.

Some researchers have analyzed Police Accident Reports (PARs) to determine how frequently mechanical factors were cited. In a 1998 study that used this approach, researchers found that brake malfunctions were most frequently cited but were only found in 1.7% of crash involvements. Other cited defects related to tires, wheels, coupling, and load securement, all cited in about 0.4% of crashes.[35]

Other research approaches tend to find higher rates of vehicle defects. Researchers in Quebec used a case-control approach to study mechanical failures and truck crashes.[36] Their study team included three mechanical engineers who were trained in crash investigations. This team evaluated each crash and classified the crashes according to the role of mechanical defects. They found that only 11% of the trucks had no defects, 49.2% had minor defects, and 39.5% had serious defects. They found that heavy-vehicle mechanical condition was responsible for 10%–20% of crashes in Quebec. Like many other studies, they found that the most common defects related to truck brakes, followed by defects related to tires, chassis, and steering systems.

Because of the lack of consistency in research findings regarding the impact of mechanical failures on CMV crashes, Congress provided funding through the Motor Carrier Safety Improvement Act of 1999 to conduct a Large Truck Crash Causation Study (LTCCS) to determine contributing factors and causes of crashes involving CMVs. From 2001 to 2003, FMCSA collected a nationally representative sample of large-truck fatal and injury crashes at 24 sites in 17 States. FMCSA collected up to 1,000 data elements on each crash. The total sample involved 967 crashes, which included 1,127 large trucks, 959 non-truck motor vehicles, 251 fatalities, and 1,408 injuries. This was, by all accounts, the largest study ever conducted on commercial vehicle crashes. FMCSA concluded that 87% of crash involvements were related to driver error, followed by vehicle factors at slightly over 10%, and environmental and other factors at approximately 3%.[37]

The lack of consistency in the research regarding mechanical failure and truck crashes is primarily due to the evaluation methods used. PARs—and the national databases that are informed by PARs—tend to underreport the impact of mechanical failures on crashes. Studies with professionals trained to evaluate mechanical defects tend to suggest that the impact of mechanical failures is much more significant.[38,39,40] The Quebec study[41] and the landmark LTCCS[42] found that mechanical failure is a contributing factor in at least 10% of truck crashes.

5.3.2.2 Research on Roadside Inspections

To help achieve the Agency's safety mission of reducing crashes involving CMVs, FMCSA provides support for States to perform roadside inspections of large trucks, commercial buses, and hazardous materials vehicles.[43] Roadside inspections are typically conducted at fixed and mobile sites located along major highways when a CMV is traveling to its destination. There are multiple levels of inspections, which focus on the driver, the vehicle, or both.

Violations found during roadside inspections fall into two categories: (1) non-critical defects and (2) OOS. Typically, non-critical defects pose little to no safety risk. When issued a violation for a non-critical defect, the commercial vehicle can return to the road before the violation has been corrected. OOS violations, however, indicate a safety risk. OOS violations must be corrected before a commercial vehicle or driver can return to service. OOS orders can decrease the incidence of crashes caused by mechanical defects and/or problems with driver credentials or HOS.[44]

Roadside inspections also inform other FMCSA enforcement initiatives, including the CSA program and the SMS. The SMS ranks motor carriers based on their safety performance, which is informed by data collected during roadside inspections (e.g., the frequency of different types of violations and the frequency of crashes that a carrier has had). The SMS was developed to prioritize unsafe, high-risk motor carriers for targeted interventions. Many researchers have found that roadside inspections are useful to remove unsafe commercial vehicles from the highway and have helped reduce commercial vehicle crash rates. [45, 46, 47, 48, 49, 50]

5.3.2.3 Research on Periodic Inspections

The main objective of FMCSA's periodic inspection requirement (49 CFR section 396.9) is to help ensure that the mechanical condition of certain vehicle components is acceptable. The concern is that without such a program, as vehicles get older and acquire greater mileage and wear and tear, their mechanical condition will deteriorate, and the risk of crashes caused by mechanical defects will increase. However, research results on the efficacy of periodic inspections of all vehicles are mixed, and the study team was only able to find one research study that examined periodic inspections of commercial vehicles.

In a 1999 study of the effects of commercial vehicle mechanical condition on road safety in Quebec, researchers found that Quebec's Mandatory Mechanical Inspection Program (MMIP) was not achieving its stated objective of keeping vehicles with the potential for mechanical failure—particularly vehicles greater than 10 years old—off the road. If the older vehicles were removed, then there was evidence that the MMIP did help to identify vehicles that had mechanical failures. However, the effectiveness of the periodic inspections for newer vehicles lasted for only 3 months. Brakes need to be checked more frequently than annually. The study concluded the whole inspection regimen—including pre-trip inspection and frequent roadside inspections—should help keep noncompliant vehicles off the roads. The authors suggested that drivers should be better trained on how to conduct inspections and should use visual indicators to verify the adjustment of brake-cylinder push rods.[51]

The study team also reviewed the research on light vehicles. It is important to note that there are considerable differences between light and heavy vehicles regarding miles traveled per year. In 2019, the FHWA determined that the average light duty vehicle travels 11,500 miles per year, whereas the average combination truck travels 59,900 miles per year.[52] Some researchers have shown that periodic inspections have positive safety impacts, while others have not found safety benefits. A 1982 study showed that random safety inspections were as effective as periodic inspections in preventing crashes and deaths.[53]

A 1985 study that applied an econometric model to data from New Jersey determined that the State's inspection program had positive safety effectiveness in terms of reducing fatalities and injuries.[54] In another study, researchers found that States with a vehicle safety inspection program can prevent one to two safety-related fatalities per billion vehicle miles traveled, when compared to States without such a program.[55] This study projected that Pennsylvania would experience 127 to 187 fewer fatalities each year because of its inspection program. Another study that evaluated Pennsylvania vehicle safety inspection data from 2008 to 2012 found that the State safety inspection failure rate for passenger vehicles was 12%–18%.[56]

In a 2008 study, researchers compared crash data from Nebraska before and after the discontinuation of the State safety inspection program and concluded that the program did not reduce fatalities.[57] Similarly, a 1994 study on vehicle safety inspection laws and highway facilities[58] and a 1999 study on the effectiveness of safety inspections[59] found no evidence that inspections significantly reduce fatality or injury rates. A 2002 study found that inspections had no significant impact on the number of older cars on the road.[60] Another study published in 2013 showed that periodic safety inspections can bring some safety benefits, but more frequent inspections (more than once per year) are not justified.[61] Finally, in a 2018 study that utilized a synthetic controls approach to examine traffic fatality data from 2000 to 2015 in New Jersey (which ended safety inspection requirements in 2010), researchers concluded that ending the mandatory inspection program did not result in a significant increase in the frequency or intensity of crashes resulting from car failure.[62]

5.3.2.4 Summary of Review Findings

Research on the effects of roadside inspections has shown a strong relationship between quality maintenance and inspection procedures and a decline in crashes related to vehicle defects. Mechanical failures appear to be a contributing factor in at least 10% of truck crashes. Failures most likely to cause crashes were those associated with brakes, tires/wheels, and lights. Additionally, research has found that roadside inspections and application of the OOS criteria have significantly decreased the rate of truck crashes in which mechanical or safety defects were cited as a primary contributing factor. The efficacy of the periodic annual inspection is more uncertain. One study of CMVs suggested that the annual inspection was important with older vehicles and for identification of vehicles that were likely to have mechanical failures. This research suggested the need for more frequent inspections and that the frequency of the periodic inspection needed to be increased, particularly for those systems (brakes, tires/wheels, and lights) that are more likely to contribute to crashes.

5.3.2.5 Summary of the ADS Enhanced CMV Inspection Program Documentation

The CVSA Enhanced Commercial Motor Vehicle Inspection Standard (for motor carrier operations) December 2022 Edition is a comprehensive book detailing all the requirements for the inspection, including illustrations and diagrams as well as checklists and charts. It includes sections on inspection procedures, cargo securement, operational policies, inspection bulletins, training aids, and the inspection standard.

Also available is the CVSA Enhanced Commercial Motor Vehicle Inspection (for motor carrier operations) Course Participant Manual December 2022 Edition. This abbreviated manual is for classroom use and includes worksheets. The sections of the inspection are broken down into categories, including introduction, initial tractor inspection, mid-section inspection, trailer and wheel inspection, subsequent tractor inspection, axle inspection, brake inspection, and tractor interior inspection. This book is designed to be used during training and retained by the trainee after the course. Both resources are available in print and electronic form.

5.3.3 Existing Truck Inspection Requirements

ADS-equipped trucks may be subject to different types of inspection requirements than existing, non-ADS trucks. There are five existing truck inspection requirements:

1. Pre-trip Inspection
2. DVIR
3. Roadside Inspection/Post-crash Inspection
4. Periodic Inspection – Annual Maintenance
5. Law Enforcement Stops – Safety Inspections

Table 20 summarizes key characteristics of each type of inspection requirement (e.g., frequency, who conducts the work, and elements inspected).

Table 20. Inspection requirements for CMVs.

Truck Inspection Requirements	Pre-trip Inspection	Roadside Inspection/Post-Crash Inspection (Fixed & Mobile Sites)	DVIR	Periodic Inspection: Annual Maintenance	Law Enforcement Safety Inspections
Frequency	Daily	Possibly Daily	Daily	Annual	Infrequent
Conducted by:	Driver	State Inspector	Driver	Motor Carrier or Third-party Maintenance	Law Enforcement
Special Credentials	CDL holder	FMCSA/CVSA-trained	CDL holder	Experience, training, or both	
Inspection Elements	Pre-trip inspection to ensure that all DVIR elements are functioning correctly.	Thorough inspection of the DVIR elements: • Suspension • Open-top trailer and van bodies • Emergency exit • Driveshaft • Cargo securement • Hazardous materials and cargo tank driver inspection items	Minimum Elements 1. Service brakes and connections 2. Parking brake 3. Steering mechanism 4. Lights and reflectors 5. Tires 6. Horn 7. Windshield wipers 8. Rear vision mirrors 9. Coupling devices 10. Wheels and rims 11. Emergency equipment	• Inspect for defects • Brakes • Coupling devices • Exhaust system • Fuel system • Lighting device • Safe loading • Steering, suspension, and frame • Tires, wheels, and rims • Windshield glazing and wipers • Driver seat	Ad hoc safety inspection

5.3.3.1 Pre-trip Inspections

The primary goal of the pre-trip inspection is to ensure that all vehicle components are in good working order. As shown in Table 20, the FMCSRs specify the minimum elements that drivers are required to inspect prior to beginning a trip. Some motor carriers may require drivers to inspect more elements than the minimum specified by FMCSA.

Summary of the Requirements – Pre-trip Inspections: Per 49 CFR 396.13, *Driver inspection*, before operating a CMV, a driver must inspect the vehicle and be satisfied that it is in safe operating condition. During the pre-trip inspection, the driver should check to ensure all the elements included in the DVIR are functioning properly. If the last vehicle inspection report notes any deficiencies, the driver must sign the report to acknowledge (1) that the driver has reviewed it, and (2) that there is a certification that the required repairs have been performed. The signature requirement does not apply to listed defects on a towed unit that is no longer part of the vehicle combination.

Pre-trip Inspection Considerations for ADS-equipped CMVs: As indicated above, 49 CFR 396.13 specifically requires the driver to complete a series of inspection tasks. Table 21 presents the challenges that 49 CFR 396.13 may pose to ADS-equipped vehicles, potential changes that may need to be applied to the regulation to enable safe deployment of ADS-equipped vehicles, and some potential pre-inspection alternatives.

Table 21. Summary of considerations around 49 CFR 396.13 (pre-trip inspection).

Challenges and Considerations for ADS-equipped Vehicles	FMCSR Changes and Considerations	Inspection Alternatives and Considerations
1. The driver is responsible for inspections, recognition, and decision-making tasks. 2. The pre-trip inspection itself is not a complex task; it is a series of go/no-go decisions.	1. The FMCSRs may require modification to allow carrier personnel (not necessarily drivers) to conduct inspections or to allow electronic checks of inspections elements. 2. Some inspection elements may need to be added or removed from the list of elements to be covered on the DVIR.	1. **Alternative Carrier Inspection.** Allowing other carrier personnel to conduct the pre-trip inspection. Are special credentials needed for "carrier inspectors"? 2. **Electronic Inspection.** What inspection elements can be conducted electronically? To whom should they be communicated? 3. **Hybrid Inspection.** Electronic and carrier check of inspection elements.

Expert Opinions on Pre-trip Inspections for ADS-equipped CMVs: Inspectors suggested that the pre-trip inspection is an important part of the overall truck inspection regime and, if done properly, it ensures that trucks on the roadway are mechanically fit for U.S. highways. There were some concerns raised that truck drivers may not be adequately trained to conduct a thorough inspection or that they do not take the time to do an adequate pre-trip inspection. Some were also concerned that electronic systems have made it too easy for drivers to sign-off that the inspection was conducted. One inspector pointed out that he has put trucks OOS for inspection elements that were very visible and that should not have gone undetected. He also pointed out that, nationwide, roughly 20% of the trucks inspected at roadside are put OOS; if the pre-trip inspection was done properly, he felt that the percentage would not be that high.

The CVSA's recommended inspection protocol limits the roadside inspection of an ADS-equipped vehicle operating without a driver or safety operator to situations where an imminent hazard is observed or during a post-crash investigation. Rather, the protocol focuses on an origin/destination (terminal) inspection model, and the vehicle would be required to communicate to enforcement while in motion that it had passed the origin/destination inspection, that its ADS were functioning, and that it is operating within its ODD.

CVSA and ATA Recommendations: CVSA has made several recommendations for inspecting ADS-equipped vehicles that are operating at SAE Level 4 and above. CVSA and the American Trucking Associations (ATA) task force have both supported an enhanced pre-trip inspection model like the trip inspection outlined in the Canadian National Safety Code (NSC) #13. Members of the Canadian Council of Motor Transport Administrators (CCMTA), with the help of the motor carrier industry, developed a set of 16 safety standards. The goal of these standards was to improve highway safety and the efficient movement of people and goods across Canada. The NSC is somewhat like the U.S. FMCSRs in that it provides a general federal framework that each of the provinces and territories can adopt to regulate their motor carrier industry.

NCS #13 specifies a daily trip inspection. The goal of the daily trip inspection is to provide early detection of vehicle problems, malfunctions, and defects, thereby reducing the possibility of mechanical breakdown or collision. This is similar to the U.S. pre-trip inspection, but instead of prescribing only 11 DVIR inspection items, it requires the inspection of 23 items on the vehicle every 24 hours, as shown in Table 22. After the trip inspection is conducted, non-critical defects are noted on a report for the vehicle, and major issues need to be fixed by the motor carrier before the vehicle can be driven. An example of the U.S. DVIR is provided in Figure 42.[(63)]

Driver's Vehicle Inspection Report

Check ANY Defective Item and Give Details under "Remarks."

DATE: ____________________

TRUCK/TRACTOR NO. _________________

- ❑ Air Compressor
- ❑ Air Lines
- ❑ Battery
- ❑ Brake Accessories
- ❑ Brakes
- ❑ Carburetor
- ❑ Clutch
- ❑ Defroster
- ❑ Drive Line
- ❑ Engine
- ❑ Fifth Wheel
- ❑ Front Axle
- ❑ Fuel Tanks
- ❑ Heater
- ❑ Horn
- ❑ Lights
  - Head – Stop
  - Tail – Dash
  - Turn Indicators
- ❑ Mirrors
- ❑ Muffler
- ❑ Oil Pressure
- ❑ On-Board Recorder
- ❑ Radiator
- ❑ Rear End
- ❑ Reflectors
- ❑ Safety Equipment
  - Fire Extinguisher
  - Flags – Flares – Fuses
  - Spare Bulbs & Fuses
  - Spare Seal Beam
- ❑ Springs
- ❑ Starter
- ❑ Steering
- ❑ Tachograph
- ❑ Tires
- ❑ Transmission
- ❑ Wheels
- ❑ Windows
- ❑ Windshield Wipers
- ❑ Other

TRAILER(S) NO (S). ____________________

- ❑ Brake Connections
- ❑ Brakes
- ❑ Coupling Chains
- ❑ Coupling (King) Pin
- ❑ Doors
- ❑ Hitch
- ❑ Landing Gear
- ❑ Lights – All
- ❑ Roof
- ❑ Springs
- ❑ Tarpaulin
- ❑ Tires
- ❑ Wheels
- ❑ Other

Remarks: ____

____

____

____

____

____

____

❑ Condition of the above vehicle is satisfactory

Driver's Signature ____

❑ Above Defects Corrected

❑ Above Defects Need NOT Be Corrected For Safe Operation Of Vehicle

Mechanic's Signature ________________________________ Date ________________

Driver's Signature __________________________________ Date ________________

Figure 42. Illustration. U.S. DVIR.

Table 22. Comparison between U.S. pre-trip and Canadian trip inspection elements.

U.S. Pre-trip Inspection Items	Canadian Trip Inspection NSC#13
Service brakes and connections	Brake system defect(s)
Parking brake	
	Electric brake system defect(s)
	Hydraulic brake system defect(s)
Coupling devices	Coupling devices defect(s)
Emergency equipment	Emergency equipment & safety devices defect(s)
Rear vision mirrors	Glass and mirrors defect(s)
Horn	Horn defect(s) 1
Lights and reflectors	Lamps and reflectors defect(s)
Steering mechanism	Steering defect(s)
Tires	Tires defect(s)
Wheels and rims	Wheels, hubs and fasteners defect(s)
Windshield wipers	Windshield wiper/washer defect(s)
	Cab defect(s)
	Cargo securement defect(s)
	Dangerous goods major defect(s)
	Driver controls defect(s)
	Driver seat defect(s)
	Exhaust system defect(s)
	Frame and cargo body defect(s)
	Fuel system defect(s)
	General defect(s)
	Heater/defroster defect(s)
	Suspension system defect(s)

The team interviewed a CCMTA official who felt that the big difference between the U.S. and Canadian trip inspections was that NSC #13 specifies "Schedule 1," which clearly lays out defects that a driver is expected to find during their daily vehicle inspection. The schedule also indicates (1) that the non-critical defects that do not prohibit the vehicle from being driven provided they are recorded on the daily vehicle inspection report and (2) that the major defects have to be repaired before continuing.

Alongside enhanced pre-trip inspections, Level 4 and above ADS are expected to have access to self-diagnostic capabilities exceeding those of traditional trucks. In this scenario, if the ADS is unable to pass the self-diagnostics, then the ADS would not allow the system to be switched into automated driving mode.

Evidence suggests that the Canadian trip inspection identifies faults and defects more effectively than the U.S. pre-trip inspection. With the assistance of the Analysis Division of the FMCSA, the VTTI team obtained data on U.S. roadside inspections. Table 23 shows the results of three inspection types (vehicle, driver, and HAZMAT) for U.S.-domiciled motor carriers versus Canadian-domiciled motor carriers. The data is from FMCSA's Motor Carrier Management Information System (MCMIS) data snapshot as of May 28, 2021, including current year-to-date information for fiscal year (FY) 2021. Of the three inspection types, vehicle OOS rates were considerably higher (nearly 10%) for U.S.- versus Canadian-domiciled carriers. The difference in OOS rates for driver and HAZMAT inspections was much smaller. Interviews with Canadian officials suggested that the Canadian regimen of inspections (daily and periodic) provides better detection of mechanical failures.

Table 23. OOS rates for U.S.- and Canadian-domiciled carriers.

	FY 2017		FY 2018		FY 2019		FY 2020		FY 2021	
Vehicle Inspections	Number of Inspections	OOS Rate	Number of Inspections	OOS Rate	Number of Inspections	OOS Rate	Number of Inspections	OOS Rate	Number of Inspections	OOS Rate
U.S.	1,988,450	21.6%	2,049,341	21.9%	2,042,419	21.7%	1,619,369	21.8%	1,107,030	22.0%
Canadian	46,531	12.4%	46,011	12.1%	45,643	11.4%	38,191	11.0%	29,844	12.1%
Difference		9.2%		9.8%		10.3%		10.8%		9.9%
Driver Inspections										
U.S.	2,927,147	5.5%	3,035,975	5.2%	3,000,996	5.4%	2,382,237	5.6%	1,621,217	6.0%
Canadian	83,760	3.3%	83,798	2.2%	85,086	2.1%	67,414	2.3%	50,555	2.1%
Difference		2.2%		2.9%		3.3%		3.3%		3.9%
HAZMAT Inspections										
U.S.	187,168	4.0%	188,565	4.2%	193,297	4.5%	144,439	4.6%	101,850	4.2%
Canadian	2,968	2.8%	2,799	3.0%	2,723	3.8%	2,001	3.9%	1,491	3.8%
Difference		1.2%		1.2%		0.8%		0.7%		0.5%

CCMTA officials felt that the difference between the U.S. and Canadian vehicle OOS rates was more likely due to the Canadian inspection regime as compared to the U.S. inspection regime. The Canadian inspection regime can include the daily trip inspection, which includes more inspection elements, and a periodic inspection that, depending on the province, can be required twice per year.

5.3.3.2 Post-trip Inspections–DVIR

In addition to a pre-trip inspection (required by 49 CFR 396.13), drivers are also required to conduct a post-trip inspection. The rationale for the post-trip inspection is that the driver, who has experienced the vehicle's handling, sounds, scents, and changes in various dashboard indicators, is in the best position to assess major vehicle components at the end of the work shift. Therefore, the driver is responsible for completing the DVIR at the end of the work shift.

Summary of the Requirements–Post-trip Inspection/DVIR: Per 49 CFR 396.11, "Every motor carrier shall require its drivers to report, and every driver shall prepare a report in writing at the completion of each day's work on each vehicle operated, except for intermodal equipment tendered by an intermodal equipment provider." Like the pre-trip inspection, the post-trip inspection must cover the following minimum elements:

- Service brakes including trailer brake connections
- Parking brake
- Steering mechanism
- Lighting devices and reflectors

- Tires
- Horn
- Windshield wipers
- Rear vision mirrors
- Coupling devices
- Wheels and rims
- Emergency equipment

A CMV driver is only required to prepare a post-inspection DVIR if the driver discovers a defect or deficiency during the inspection (or if a defect or deficiency is reported to the driver).[1] When a report is required, the report must identify the vehicle and list any defect or deficiency discovered by or reported to the driver that would affect the safe operation of the vehicle or result in a mechanical breakdown. If a driver operates more than one vehicle during the day, a report must be prepared for each vehicle operated. The driver is required to sign the report.

If a driver identifies and records defects or deficiencies during a post-crash inspection, the motor carrier or its agent must repair the listed defects or deficiencies before the driver operates the vehicle again. Once the repairs are completed, the motor carrier or agent must certify on the DVIR that the required repairs have been made (or that the repairs are not necessary before the vehicle is operated again). The motor carrier must maintain the DVIR, certification of repairs, and certification of the driver's review (at the next pre-trip inspection) for 3 months from the reporting date.

Drivers and/or motor carriers must also conduct post-trip inspections of any equipment provided by intermodal equipment providers (IEPs). Drivers and motor carriers must report to the IEP (or its designated agent) any known damage, defects, or deficiencies in the intermodal equipment at the time the equipment is returned to the IEP (or its designated agent). The report must include the following minimum parts and accessories:

- Brakes
- Lighting devices, lamps, markers, and conspicuity marking material
- Wheels, rims, lugs, tires
- Air line connections, hoses, and couplers
- King pin upper coupling device
- Rails or support frames
- Tie down bolsters
- Locking pins, clevises, clamps, or hooks
- Sliders or sliding frame lock

[1] Exception: drivers of for-hire passenger CMVs are required to prepare this report whether any defects/deficiencies are detected or not.

In addition to a description of the identified damage, defects, or deficiencies that would affect the safe operation of the intermodal equipment or cause its mechanical breakdown while in transport, the intermodal equipment report must include the name and USDOT number of the motor carrier responsible for operating the intermodal equipment at the time the issue(s) were identified. The report must also include the IEP's USDOT number and a unique identifying number for the item of intermodal equipment, the signature of the driver who prepared the report, and the date and time the report was submitted.

The IEP is responsible for repairing the reported damage, defects, or deficiencies on a piece of intermodal equipment before allowing the motor carrier to transport that piece of equipment again. The IEP or designated agent must certify on the original driver's report that the damage, defects, or deficiencies have been repaired (or that the repairs are not necessary before the equipment is operated again). For each intermodal equipment report, the IEP must maintain the original driver report and the certification of repairs for a period of 3 months from the date that a motor carrier or driver submits the original report to the IEP or its designated agent.

Post-trip Inspection/DVIR Considerations for ADS-equipped CMVs: Drivers play a significant role in post-trip inspections, not only in conducting the inspection itself, but also in preparing the DVIR and reviewing the motor carrier's certification that the necessary repairs were made prior to the next trip. Besides the pre-trip inspection, the post-trip inspection is the most driver-centric inspection requirement. Table 24 summarizes the challenges that existing post-inspection requirements may pose to ADS-equipped vehicles, along with potential changes that may need to be applied to the regulations to enable safe deployment of ADS-equipped vehicles. The table also outlines potential roadside inspection alternatives.

Table 24. Summary of considerations around 49 CFR 396.11 (post-trip inspections).

Challenges and Considerations for ADS-equipped Vehicles	FMCSR Changes and Considerations	Inspection Alternatives and Considerations
1. The driver is responsible for inspections, recognition, and decision-making tasks. 2. The post-trip inspection itself is not a complex task; it is a series of go/no-go decisions.	1. The FMCSRs may need to be modified to allow carrier personnel (not necessarily drivers) to conduct inspections or to allow electronic checks of inspection elements. 2. With ADS-equipped trucks that are likely dispatched upon arrival to a depot, the post-trip inspection may no longer be needed or practical (i.e., no need for two inspections on quick turnarounds). 3. Some inspection elements may need to be added or removed from the list of elements to be covered on the DVIR.	1. **Alternative Carrier Inspection.** Allowing other carrier personnel to conduct the post-trip inspection. Are special credentials needed for "carrier inspectors"? 2. **Electronic Inspection.** What inspection elements can be conducted electronically? To whom should they be communicated? 3. **Hybrid Inspection.** Electronic and carrier check of inspection elements. **4. Eliminate the Post-trip Inspection.**

The purpose of the post-trip inspection is to get driver input into the operations of the commercial vehicle. The driver has driven the vehicle for as long as 11 hours and should be aware of any vehicle components that appear to be malfunctioning. This provides a carrier with useful information on the repairs that may be needed prior to the start of the vehicle's next shift.

DVIR Considerations for ADS-equipped CMVs: Currently the DVIR is the responsibility of the driver. For scenarios in which a driver or safety operator is not required, the FMCSRs may need to be modified to allow carrier personnel (not necessarily drivers) to conduct inspections or to allow electronic checks of inspection elements. Additionally, ADS-equipped trucks will likely be highly utilized by motor carriers since they will no longer be constrained by HOS limitations. Therefore, they will likely be dispatched upon arrival to a depot or transfer station. The post-trip inspection may no longer be needed or practical, i.e., there may be no need for both pre- and post-trip inspections for quick turnarounds. Additionally, some inspection elements may need to be added or removed from the list of elements to be covered on the DVIR.

Expert Opinion Regarding the DVIR for ADS-equipped CMVs: The study team interviewed Federal and State officials, including CVSA inspectors. The consensus of this group was that the post-trip inspection would no longer be needed. Given the many possible utilization scenarios, this group felt that these vehicles will likely be highly used to increase vehicle productivity and that these vehicles will not be limited to the current driver's HOS constraints. Therefore, the inspectors that we interviewed felt that these vehicles would be dispatched in a way that would require quick turnarounds and that there is no need for both the pre-trip inspection and post-trip DVIR.

5.3.3.3 Roadside Inspections/Post-crash Inspections

Inspectors conducting roadside inspections are working to ensure that motor carriers operating on the Nation's roadways are adhering to the safety standards established by Congress and the USDOT. The purpose of the roadside inspection is to provide an unscheduled "spot check" examining a carrier's and driver's compliance.

Summary of the Requirements – Roadside Inspections: CMV roadside inspections are costly to conduct in terms of both time and human resources. A Level I inspection takes 30 minutes to an hour to complete, not including the amount of time trucks wait in the queue for a manual roadside inspection. Highly trained inspectors in each State inspect CMVs using inspection procedures developed by CVSA. These procedures and criteria are part of the North American Standard (NAS) Inspection Program and currently include eight levels of inspection, which are summarized in Table 25.

Table 25. CVSA levels of inspections and procedures.

Level	Description
Level I: NAS Inspection	An examination of the carrier's and driver's credentials, record of duty status (RODS), the mechanical condition of the vehicle, and any hazardous materials/dangerous goods that may be present.
Level II: Walk-Around Driver/Vehicle Inspection	A driver and walk-around vehicle inspection, involving the inspection of items that can be checked without physically getting under the vehicle.

Level	Description
Level III: Driver/Credential/ Administrative Inspection	A driver-only inspection that includes examination of the driver’s credentials and documents.
Level IV: Special Inspections	Special inspections are a one-time examination of a particular item. These examinations are normally made in support of a study or to verify or refute a suspected trend.
Level V: Vehicle Only Inspection	A vehicle-only inspection, which may be performed without a driver present, at any location.
Level VI: NAS Inspection for Transuranic Waste and Highway Route Controlled Quantities of Radioactive Material	An inspection of transuranic waste and route-controlled quantities of radioactive material.
Level VII: Jurisdictional Mandated Commercial Vehicle Inspection	A jurisdictionally mandated inspection.
Level VIII: NAS Electronic Inspection	An inspection conducted electronically while the vehicle is in motion, without direct interaction. At the time of this report, this inspection is driver focused.

The Level I inspection—the most common and most comprehensive of all the inspection types—involves the examination of the driver’s credentials and RODS along with a detailed inspection of the mechanical condition of the vehicle. It is a 37-step procedure that addresses the following items:

Vehicle:

- Suspension, tire, rim, hub, wheel assemblies
- Open-top trailer and van bodies
- Windshield wiper operations
- Emergency exit
- Steering mechanisms
- Driveline/driveshaft mechanisms
- Lightning device and coupling operations
- Cargo securement
- Hazardous material and cargo tank specification compliance
- Braking systems
- Electrical systems
- Exhaust system
- Fuel systems

Driver:

- Seatbelt usage

- Possible drug and alcohol usage
- Medical Examiner's Certificate
- Skill Performance Evaluation certificate
- Commercial Driver's License
- HOS or HOS compliance
- RODS or RODS compliance

Violations from these inspections are recorded in the MCMIS. FMCSA uses data in the MCMIS to identify carriers that are out of compliance with Federal regulations and good candidates for targeted safety interventions. The MCMIS contains carrier registration details, information from inspections and interventions, and violation and crash data. All these data is used in FMCSA's SMS.

One of the challenges in the United States with the existing roadside inspection program is that there are currently approximately 5 million CMVs, and only up to 3.5 million inspections are conducted each year. This means that a CMV could go several years without being inspected. Many carriers have complained that SMS does not contain enough inspection data to prioritize safety interventions. In addition, many large carriers participate in bypass programs and thus do not get credit for operating safe vehicles.

Per 49 CFR 396.9, *Inspection of motor vehicles and intermodal equipment in operation*, special agents of FMCSA are authorized to conduct inspections of a motor carrier's vehicles and/or intermodal equipment in operation. Inspectors use the Driver Vehicle Examination Report to record inspection results. Inspectors are responsible for declaring motor vehicles or intermodal equipment OOS if its mechanical condition would likely cause an accident or breakdown. Motor carriers, IEPs, and their staff (including drivers) are prohibited from operating OOS vehicles or equipment until all necessary repairs have been made. This includes towing the vehicle, except under certain circumstances (e.g., with a crane or hoist).

Inspectors provide a completed inspection report to the driver of any inspected motor vehicle (or vehicle transporting intermodal equipment). The driver is then required to deliver a copy of that report to the motor carrier (and if applicable, the IEP) upon arrival at the next terminal or facility. If the driver is not scheduled to arrive at the terminal or facility within the next 24 hours, the driver is required to mail, fax, or otherwise transmit the report to the motor carrier or IEP.

Upon receipt of the inspection report, motor carriers and IEPs are required to examine the report and correct any noted violations or defects, documenting repairs to OOS intermodal equipment in associated maintenance records. Within 15 days of the inspection, the motor carrier or IEP must (1) certify that all noted violations were corrected, and (2) return the completed roadside inspection form to the issuing agency. The motor carrier or IEP must also maintain a copy of the completed form for at least 1 year.

Roadside Inspection Considerations for ADS-equipped CMVs: As described above, several CVSA inspection levels (see Table 25) and 49 CFR 396.9, specifically, require the driver to interact with the inspector and complete a series of tasks. Table 26 summarizes the challenges the existing requirements may pose to ADS-equipped vehicles, along with potential changes that may need to be applied to the regulation to enable safe deployment of ADS-equipped vehicles. The table also outlines potential roadside inspection alternatives.

Table 26. Summary of considerations around 49 CFR 396.9 and the existing CVSA inspection levels.

Challenges and Considerations for ADS-equipped Vehicles	FMCSR Changes and Considerations	Inspection Alternatives and Considerations
1. In a CVSA Level I, II, or III inspection, the driver must provide credentials and other information (e.g., RODS or HOS logs). 2. Per 49 CFR 396.9(d), any driver who receives an inspection report must subsequently deliver it to the motor carrier and/or IEP within 24 hours. 3. In a CVSA Level I, II, or V inspection, the inspector must examine a number of vehicle components, some of which may have different specifications in ADS-equipped vehicles (compared to non-ADS-equipped vehicles).	1. The FMCSRs may need to be modified to allow inspectors to transmit inspection reports directly to motor carriers or IEPs (instead of the driver delivering the report). 2. Some of CVSA's required inspection elements may need to be modified for Level I, II, and V inspections of ADS-equipped vehicles.	1. **Electronic Inspection.** What inspection elements can be conducted electronically? To whom should results be communicated? 2. **Hybrid Inspection.** Electronic and inspector check of inspection elements.

Expert Opinion Regarding Roadside Inspections of ADS-equipped CMVs: Inspectors were split on the idea of whether to conduct a Level 1 inspection at roadside or a Level 5 inspection at an alternative site (i.e., carrier's terminal or transfer center). The inspectors who felt it would be necessary to inspect vehicles roadside commented that ADS-equipped trucks must have the capability of responding to communications from roadside inspectors. These vehicles would need to take direction on where to stop, where to go, and when to park so that CVSA personnel could inspect the vehicle. They further commented that there will always be the possibility that inspectors would pull the ADS-equipped vehicle in either because of a visible safety concern or if the vehicle did not strictly respond to a system-generated request to pull over for inspection. Some inspectors randomly pull vehicles in for inspection. It was also suggested that it may be difficult to differentiate an ADS-equipped truck from other trucks, particularly at highway speeds.

Some inspectors raised safety concerns about inspecting ADS-equipped trucks without a safety operator or driver. They were concerned about inspecting a vehicle without the ability to communicate with it or control its movement. The ADS-equipped truck would have to maneuver over an inspection pit and remain in place until the truck was inspected. In the absence of an inspection pit, the ADS-equipped vehicle would need to remain parked until the underside of the vehicle was inspected. The experts felt that inspectors would not feel safe under an ADS-equipped vehicle even with appropriate safety procedures (i.e., wheel chocks were in place). Inspectors felt there was a need to be able to contact and talk directly to either a carrier's dispatch or the technology developer monitoring the vehicle to perform a Level 1 inspection at roadside.

On the issue of whether the vehicle should be inspected at roadside, one inspector thought that ADS-equipped trucks should be inspected like any other vehicle. His concern with exempting these vehicles from inspection was that criminal elements might then use these types of vehicles in human trafficking or to transport illegal cargo such as illicit drugs.

One inspector felt that CVSA might consider a phased approach, involving Level 5 inspections for the next 5 years. His thoughts were that only a relatively small number of vehicles would be operating without a driver or a safety operator in that period. In the next phase, all vehicles would be required to have the capacity to be inspected roadside either physically or electronically. This would give technology developers time to transition from developing their ADSs to building out the electronic communications controlling the ADS-equipped vehicle. Electronic communications will be important not only for government systems at roadside but for communicating with the ADS-equipped truck when picking up and dropping off loads at a terminal or port facility.

Post-crash Inspections of ADS-equipped CMVs: FMCSA has the authority to inspect CMVs that have been involved in a crash. Typically, this is a Level I NAS Inspection that includes driver's license, Medical Examiner's Certificate, medical waiver, alcohol and drug testing, driver's RODS, HOS, seat belt, vehicle inspection report, and critical vehicle items such as the brake system, coupling devices, exhaust system, frame, fuel system, lights and turn signals, safe loading, steering mechanism, suspension, tires, van and open-top trailer bodies, wheels and rims, and windshield wipers. If some of the parts and accessories are damaged due to the crash, the officer may document any defects that need to be repaired before the vehicle can go back on the road.

Expert Opinion Regarding Post-crash Inspections of ADS-equipped CMVs: The study team asked inspectors to comment on changes needed to the FMCSRs regarding post-crash inspections. Inspectors did not feel that any changes were necessary for the mechanical side of an ADS-equipped vehicle. They did, however, feel that a whole new set of inspection criteria would be needed to evaluate whether the ADS contributed to the crash. They felt that ADS developers should be required to save and surrender video and data collected from the ADS. By using that data, a crash investigator should be able to determine whether the system itself was operating properly or whether it contributed to the crash. Inspectors felt that all ADS-equipped trucks involved in crashes should be inspected to determine whether mechanical components of the truck or the ADS contributed to the crash. They felt that the public would expect that each crash involving an ADS-equipped vehicle would be thoroughly investigated, which would include video and other data stored by the ADS.

5.3.3.4 Periodic Inspection—Annual Maintenance

Motor carriers are required to inspect each CMV at least once every 12 months. Some States require other periods for these inspections, such as every 6 months.

Summary of the Requirements – Periodic Inspections: The inspection must include all of the parts and accessories outlined in 49 CFR Chapter III, Subchapter B, Appendix G, *Minimum*

Periodic Inspection Standards.[(64)] The regulation specifies that the term "CMV" includes each vehicle in a combination vehicle. For example, for a tractor semitrailer, full trailer combination, the tractor, semitrailer, and the full trailer (including the converter dolly if so equipped) must each be inspected. Motor carriers must inspect all motor vehicles subject to their control, while IEPs must inspect intermodal equipment that is interchanged (or intended for interchange) to motor carriers in intermodal transportation.

A motor carrier must not use a CMV, and an IEP must not tender equipment to a motor carrier for interchange, unless each component identified in the Minimum Period Inspection Standards has passed an inspection during the preceding 12 months and documentation of the periodic inspection is on the vehicle. The documentation may be the inspection report or some other form of documentation based on the inspection report (e.g., a sticker or decal with the date of the inspection, the name/address of the entity where the inspection report is maintained, information uniquely identifying the vehicle inspected, and a certification that the vehicle passed the inspection).

A motor carrier or IEP may self-inspect vehicles or equipment under their control that are not subject to an inspection under 49 CFR 396.23(a)(1). In lieu of a self-inspection, a motor carrier or IEP may choose to have a commercial garage, fleet leasing company, truck stop, or other similar commercial business perform the inspection as its agent, provided the business operates and maintains facilities appropriate for commercial vehicle inspections and it employs qualified inspectors.

Periodic Inspection Considerations for ADS-equipped CMVs: Table 27 summarizes the challenges that existing requirements may pose to ADS-equipped vehicles, along with any potential changes to the regulations that may be needed to enable safe deployment of ADS-equipped vehicles. Once the safety operator and/or driver role is removed, the ADS-equipped vehicle will be unrestrained in terms of the miles or hours it can operate. As a result, it is believed that motor carriers will employ these vehicles 24 hours a day, 365 days a year, if they have freight that needs to be moved. As noted earlier in this report, in 2021, FHWA determined that the average combination truck travels 59,900 miles per year.[(65)] Without the constraints of a CMV driver's HOS, these vehicles could operate 24 hours a day minus the time for pre-trip inspections, dropping and picking up trailers, and refueling. All totaled, the vehicle miles per year could go from 59,500 miles per year to more than 350,000 miles per year (a possible scenario based on 20 hours a day at 50 miles an hour on average for 355 days a year). An ADS-equipped truck could travel more than 5 times the number of miles that a typical truck with a driver does today, which means it could transport 5 times the amount of freight that an average truck transports today.

Table 27. Summary of considerations around 49 CFR 396.17 (periodic inspections).

Challenges and Considerations for ADS-equipped Vehicles	FMCSR Changes and Considerations	Inspection Alternatives and Considerations
1. Inspection not done by the driver – no difference in inspection requirement for mechanical systems. 2. High operational mileage would suggest the need for increasing the frequency of the periodic inspection; instead of annually, inspections should be conducted once a quarter.	1. Need to add the external inspection of ADS sensors and computer diagnostics. 2. Need to change the frequency of the inspections and who should conduct the inspection.	1. Some vehicles may have limited usage during certain periods; therefore, time-based inspections for ADS-equipped trucks may not be optimal. An alternative is a mileage-based inspections requirement with a minimum time basis. 2. Consideration should be given to having a third party conduct at least one of the periodic inspections.

As previously stated in the literature review, researchers found that the Quebec mandatory mechanical inspection program, which amounts to their annual inspection of commercial vehicles, was only effective for 3 months, and that the periodic inspection was really not frequent enough to keep trucks that had developed mechanical problems off the road. The authors recommended more frequent inspection of vehicles coupled with an enhanced pre-trip inspection. Therefore, more frequent periodic inspection is needed, no matter whether the truck is a new or older model vehicle. The engineers in this study stated that "more frequent checks were needed particularly for brakes and tires" because of wear and tear from the roadway. This recommendation was for standard vehicles, and some Canadian provinces began a biannual program of inspecting vehicles based on the findings of this study.

Expert Opinion Regarding Periodic Inspections of ADS-equipped CMVs: There is almost universal agreement among inspectors that the periodic inspection of ADS-equipped trucks would not be that much different from the inspections that are currently being conducted on similar vehicle classes today. The driver is generally not present during these inspections. What will be different is the operating environment and, more generally, the number of miles that a truck will operate in a particular year. Inspectors felt that ADS-equipped trucks were likely to be driven more miles per year and therefore should be inspected more frequently. Most inspectors felt that the frequency of inspection should be conducted at a minimum of at least once a quarter. If a vehicle is driven 350,000 miles per year, a quarterly inspection would equate to about 87,500 miles between inspections. This would mean that there would be more miles between inspections compared to the FHWA-determined annual average of 59,900 miles for combination truck CMVs.

One inspector suggested that an alternative inspection regime could be tied to vehicle mileage. Perhaps some motor carriers will not operate at a high operating tempo as projected. In this case, one alternative would be for motor carriers to opt into a mileage-based inspection schedule. For example, when reaching out to one of the leading fleet maintenance organizations, the study team learned that this organization inspects its vehicles every 40,000 miles.

Additionally, one inspector suggested that at least one of the inspections should be conducted by a third party certified to conduct these types of mechanical inspections—basically, a certified organization that does not benefit from the results of the inspection.

5.3.3.5 Law Enforcement—Safety Inspections

The National Institute of Justice, working with the RAND Corporation and the Police Executive Research Forum, developed an expert panel report on policing AVs.[(66)] This report identified four likely scenarios in which law enforcement would likely interact with autonomous trucks:

1. Traffic Stops. While it is unlikely that ADS-equipped trucks will violate traffic laws, traffic stops may arise from visible safety concerns (unsecure doors or straps, smoke, improper vehicle parking, etc.).
2. Collisions. Inevitably there will be crashes between ADS-equipped trucks and other vehicles operating in their vicinity.
3. Emergencies. ADS trucks will have to take law enforcement direction for evacuation and detours.
4. Tangential Interactions. Law enforcement may want to use information obtained from an ADS-equipped vehicle as evidence in investigations.

The expert panel report concluded that communications with ADS-equipped trucks will be one of the most important capabilities that largely does not exist today. Law enforcement will need the ability to interface with the vehicle and vehicle owner. The vehicle must be able to take direction from law enforcement. ADS technology will need to recognize law enforcement signals such as lights, sirens, and basic hand signals from officers. Law enforcement needs a means to know whether a vehicle is operating without a driver or safety operator. Additionally, law enforcement needs a means to communicate with the vehicle and/or the vehicle owner. The expert panel report concluded that there was a need for "research on developing a standard electronic means for law enforcement to communicate securely with autonomous vehicles on the road."

Universal Electronic Vehicle Identification (EVI) may provide a means of communicating between law enforcement and the ADS-equipped truck. This technology could identify a CMV electronically while the vehicle is in motion and convey to law enforcement that the vehicle has and is being driven by ADS. Universal EVI does not provide the ability for law enforcement and the motor carrier to interact so that law enforcement can have some control over vehicle movement.

The concept of ADS remote operation originated with the U.S. Army and drone management on the battlefield. One soldier can operate multiple drones and fly them into battle space. When a drone arrives at its destination, the operator will remotely connect to it to see the video from the drone and then make battlefield decisions.

Remote assistance for ADS-equipped trucks can be similar. The role of the dispatcher within a motor carrier could be expanded from controlling 50–100 drivers to 10–20 trucks that are operating autonomously. The dispatcher could be provided a warning of a possible operational concern and then remotely connect to the vehicle, thereby providing direction to the truck when it either loses situational awareness or has some sort of mechanical issue. Once the vehicle detects law enforcement, the dispatcher could take over control of the vehicle and take direction from police officers to stop or follow hand signals for detours or for truck inspections. Adding remote assistance roles to a dispatcher could result in a need for further regulations qualifying the dispatcher to operate a CMV, possibly including certifications and HOS requirements.

The concept of remote assistance could work well with regard to pickup and delivery of trailers/containers at a motor carrier's depot. Several organizations have been working to develop remote assistance capabilities that could be utilized within the commercial trucking industry. Fully functional remote assistance would help the deployment of ADS-equipped trucks on public roads, as remote human intervention can overcome critical situations that the ADS-equipped vehicle cannot handle by itself. One of the technical challenges of remote assistance is the lack of network coverage along major freight corridors. The deployment of 5G is not expected to be complete before 2025, and current network capabilities cannot always guarantee the bandwidth and latency requirements of remote assistance. Dynamic video compression technology delivers a continuous video feed to the teleoperator. Funding for U.S. infrastructure should help to expedite network coverage to rural America, particularly along highways.

Law Enforcement/Safety Inspection Considerations for ADS-equipped CMVs: Table 28 summarizes the challenges that existing requirements may pose to ADS-equipped vehicles, along with any potential changes that may need to be applied to regulations to enable safe deployment of ADS-equipped vehicles.

Table 28. Summary of considerations around 49 CFR 350 & 368.7 (interactions with law enforcement/inspection personnel).

Challenges and Considerations for ADS-equipped Vehicles	FMCSR Changes and Considerations	Inspection Alternatives and Considerations
1. There are a number of scenarios where enforcement and the ADS vehicle will need to interact: traffic stops, collisions, emergencies, and to assist in investigations. 2. Law enforcement will need to be able to communicate with the vehicle/motor carrier in real time.	1. Traffic stops are generally governed by the Fourth Amendment of the U.S. Constitution and State and Local statutes. 49 CFR 350.103, 350.111, and 350.201 state that traffic enforcement agencies and political jurisdictions partner to establish programs to improve carrier, CMV, and driver safety, which includes stopping vehicles on highways, streets, or roads for moving violations and safety inspections. 49 CFR 368.7 states that certificates of registration must be maintained in all vehicles and made available	1. Universal EVI should help provide information to law enforcement that the vehicle is operating in autonomous mode. 2. Remote assistance could provide the interface for communication between law

Challenges and Considerations for ADS-equipped Vehicles	FMCSR Changes and Considerations	Inspection Alternatives and Considerations
	upon request to authorized inspectors and enforcement officers.[67]	enforcement and the vehicle/motor carrier.

5.3.4 Enhanced CMV Inspection Program

While the Enhanced CMV Inspection Program is not a regulatory requirement, it is already becoming a common practice within the industry. This section will provide both a high-level overview of the enhanced inspection process and an overview of the required training currently offered to become certified to perform an enhanced inspection of an ADS-equipped CMV.

When does an enhanced inspection occur, and is it relevant for all CMVs?

The CVSA Enhanced CMV Inspection Standard was designed specifically with ADS-equipped trucks in mind. Inspections are to be performed by trained and certified individuals who are not necessarily drivers. These inspections will occur at various points during the deployment of the ADS-equipped vehicle.

- The initial inspection shall be performed at the point of origin prior to allowing the vehicle to be placed into service on the highway. To pass this level of inspection, the vehicle and any attached trailer must be found to be "defect free."
- Additionally, these ADS-equipped vehicles will be subject to additional "in transit" inspections or an inspection at least once every 24 hours. During this level of inspection, certain non-safety critical defects will be noted for repair, but the vehicle can still be allowed to proceed to its destination. Upon arrival at its destination point, these defects must be corrected prior to returning the equipment to service.
- If at any time during the 24-hour period the ADS-equipped vehicle is connected to a different trailer, a new initial inspection shall be required to once again ensure all equipment is defect free prior to being placed into service on the highway.

5.3.4.1 ADS Working Group

FMCSA has actively supported the development of initial recommendations for inspecting ADS-equipped CMVs. In September 2018, CVSA's Enforcement and Industry Modernization Committee, in cooperation with FMCSA, established an Automated CMV Working Group (with diverse representation across CVSA's membership types)[2] to address the inspection process for ADS-equipped trucks. The Automated CMV Working Group has:

- Assessed the latest advances in CMV automation and developed recommended approaches for inspecting ADS-equipped vehicles based on stakeholder interviews;

[2] CVSA membership types include Class I (State/provincial/territorial), Class II (local enforcement), Class III (associate), and Class IV (Federal).

performed research into best practices, current deployment, and testing trends; and gathered input from CVSA members.

- Completed a Phase 1 report, which provided recommendations for inspection requirements and procedures for ADS-equipped CMVs.
- Developed a matrix of ADS-equipped truck inspection procedures for each of the SAE levels of automation.
- Made initial recommendations regarding possible changes to FMCSA and NHTSA regulations and CVSA policies and training (in the context of ADS-equipped CMVs).

A few issues identified by the working group are still "unresolved," particularly regarding safety standards and the data that ADS-equipped trucks need to transmit to the roadside.

In March 2020, the ATA proposed the creation of a new task force to examine the inspection of ADS-equipped vehicles. This task force was drawn from the fleet maintenance, component supplier, and ADS provider communities within ATA's Technology and Maintenance Council and partnered with CVSA's Automated CMV Working Group to create an information report exploring consensus-based approaches to inspection and enforcement for SAE Levels 4 and 5 ADS-equipped trucks. Kodiak Robotics, Embark, Ike, and TuSimple are examples of ADS trucking developers that have supported the task force in developing consensus-based standards for ADS-equipped vehicles.

5.3.4.2 Training

As of the writing of this report, training for the enhanced inspection program has been made available to both industry partners and law enforcement, with only a small number of trained and certified inspectors having completed it. This 5-day training course took place in Grapevine, Texas, in February 2023. Attendees included representatives from "self-driving" developers, assorted trucking companies exploring their future options of adding ADS-equipped vehicles to their fleets, law enforcement (roadside inspectors), and VTTI staff to both participate in the training and better understand how this process will integrate into the combined fleet operations that will make their way to highways across North America in the coming years. These classes will be ongoing.

Classroom: The classroom training portion of the enhanced inspection course was presented by experienced former roadside inspectors from the United States and Canada who currently worked for CVSA. Classroom training spanned a period of 3 days, with each class day ending outside working with instructors to identify and discuss topics from the training. Each afternoon, an instructor worked with students using equipment provided by FedEx and Kodiak Robotics. This approach allowed all attendees, including those with no prior mechanical or inspection experience, to better understand and identify individual parts and systems on the trucks and seek help from an instructor on an individual level.

As covered previously in section 5.3.2.5, each student was provided with both a participant manual and an even more in-depth resource that included the current (as of 2023) *Roadside Inspections Handbook* for inspectors. In addition to the manuals, CVSA instructors provided numerous example parts and other items, which were passed around the class for students to better understand how the various truck parts and sub-parts work and provide visible examples of defects, etc.

The Handbook provided to all participants included the following breakdown of categories of instruction and required inspection:

- Power Train
- Suspension
- Brakes (Air)
- Steering
- Instruments and Auxiliary Equipment
- Lamps
- Electrical System
- Body
- Tires and Wheels
- Coupling Devices

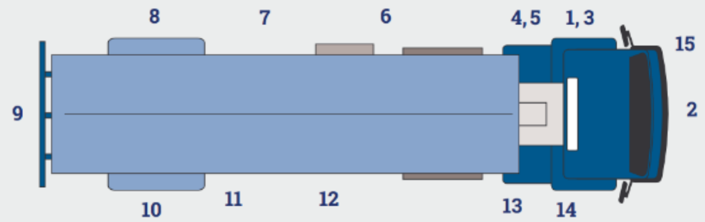
During the classroom portion of the training, students received detailed insight into each of the categories and their subcategories. The subcategories allowed both instructors and trainees to further identify and explore individual parts and systems that a certified Enhanced Inspector would be required to examine. Beyond gaining an understanding of and familiarity with these systems and parts, each student received training on what would or would not be considered a defect during an inspection.

CVSA provided this information via illustrations, a glossary of terms, and easy-to-read/interpret charts for each system and individual item that required inspection. These tables were broken down further into columns for "Dispatch" inspections and "In-Transit" inspections. As referenced previously, the enhanced inspection training made it clear that any ADS-equipped vehicle and attached trailer must be defect free to be cleared and released for service on a public highway. The training, and by extension the CVSA manual, used clear and unambiguous wording, descriptions, and illustrations as to what is or is not a defect.

The enhanced inspection manual also provides both a step-by-step inspection procedure form as well as an Enhanced CMV Inspection Vehicle Report for the inspector. Copies of these current two-page forms (as of September 28, 2023) are included as Figure 43 and Figure 44.

Inspection Procedure

Enhanced CMV Inspection *(for motor carrier operations)*



1 Prepare the Vehicle for Inspection

- Check the periodic inspection(s) for validity.
- Check the license plate, DOT number and carrier name.
- Place the chock blocks, put the vehicle transmission in neutral, release all the brakes, ensure the air pressure is at maximum, turn engine off and ensure the key is in the "on" position.
- Inspect the "ABS" malfunction lamp(s) on the dash for the tractor and trailer.

2 Inspect Front of Tractor
(and the rear for lighting)

- Check headlamps (low and high beam), ID, clearance, turn signals, and any other required lamps for improper color, operation, mounting and visibility.
- Ensure the ABS lamp on the trailer is marked and not activated.
- Inspect the bumper for security.
- Inspect ADS sensors (camera, lidar, radar)

3 Inspect Left Front Side of Tractor

- Inspect the hood and latch.
- Check front wheel, rim, hub and tire.
- Inspect visible portions of the frame.
- Inspection the door for operation.
- Check the side windows and rearview mirror.

4 Inspect Left Saddle Tank Area

- Check fuel tank area.
- Check exhaust system, if applicable.
- Inspect the battery for security and leaks, if visible.
- Inspect visible portions of the frame and mounts.

5 Inspect Trailer Front/Rear of Tractor

- Check air and electrical lines.
- Inspect the cab air suspension, shocks and reefer, if applicable.
- Inspect the cab reflective markings
- Inspect the headache rack or bulkhead of trailer.
- Inspect the fenders for security.

6 Inspect Left Rear Tractor Area

- Check wheels, rims, hubs and tires
- Check the lower, upper and slider components of the fifth wheel assembly.
- Check all required lamps and reflective tape.
- Inspect the rear window, if applicable.
- Check the condition of the mudflaps/ fenders.
- Inspect the reefer, if applicable.

7 Inspect Left Side of Trailer

- Inspect the landing gear.
- Check frame and body (upper/lower rails/ crossmembers of trailer).
- Check the condition of the aerodynamic device, if applicable.
- Check the reflective tape along the side of the trailer.

8 Inspect Left Rear Trailer Wheels

- Check wheels, rims, hubs and tires.
- Check the frame and visible suspension components.
- Ensure the sliding subframe is secured and the pins, guides and handle are in place.
- Inspect the condition of the mudflaps.

9 Inspect Rear of Trailer

- Inspect the reflective markings.
- Inspect the rear impact guard, if applicable.
- Inspect the aerodynamic device, if applicable.
- Check the condition of the cargo doors and the security of the cargo.
- Check the tail lamps, license plate lamp and lamp on projected load.

10 Inspect Right Rear Trailer Wheels

- Check as in step 8.

11 Inspect Right Side of Trailer

- Check as in step 7.
- Check the spare tire security, if applicable.

12 Inspect Right Rear Tractor Area

- Check as in step 6.

13 Inspect Right Saddle Tank Area

- Check as in step 4.

14 Inspect Right Front Side of Tractor

- Check as in step 3.

15 Inspect Steering Axle
(activate hazard lamps)

- Inspect hazard lamps.

Pull the hood of the tractor to get a better view of components.

- Check steering system (power steering fluid), front suspension and front brake components.
- Scribe the brakes, if necessary and determine chamber size.
- Check the front axle, frame and crossmembers.
- Inspect visible inside sidewall tire condition.

over

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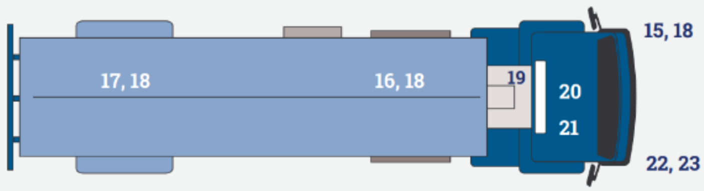
Inspection Procedure: Enhanced CMV Inspection *(for motor carrier operations)*



16 Inspect Axles 2 and/or 3

- Check driveline/driveshaft.
- Inspect the exhaust system for security and leaks.
- Check the suspension, brake components and tires on both sides.
- Check the air tanks for security and condition.
- Scribe the brakes, if necessary and determine chamber size.
- Inspect the axles, frame members and crossmembers.
- Check the hazard lamps at rear of tractor for operation.

17 Inspect Axles 4 and/or 5

- Check the suspension, brake components and tires on both sides.
- Scribe the brakes, if necessary and determine chamber size.
- Inspect the axles, frame members and crossmembers.
- Check the hazards lamps at rear of trailer.

18 Check Brake Adjustment

- Ensure air pressure is 90-100 psi (620-690 kPa).
- Apply the service brakes fully (person or device).
- Measure and record the pushrod travel (if applicable) and ensure brake lining to drum contact.
- Listen for air leaks.
- Inspect the brake lamps on the tractor and trailer.

19 Inspect the Tractor Protection System

Note: This procedure tests both the tractor protection system and the emergency brakes.

- Ensure the emergency brakes are still released and then disconnect both brake lines from the trailer. Ensure the air stops leaking from the supply line before 20 psi (138 kPa). Inspect for bleedback from the trailer.
- Apply a full brake application.
- Listen for air leaking from the service/ supply gladhands.
- Reconnect the lines.

20 Inspect In-Cab Area

- Inspect the driver's seat and seatbelt.
- Inspect the interior and exterior sun visor condition.
- Check windshield for damage, wipers and washers for proper operation.
- Check the function of the horn.
- Record the odometer and check the speedometer.
- Check for a fault on the ESC or RSS for trailer.
- Inspect the ADS fault system.
- With air pressure at 80 psi (551 kPa), apply the service brake and conduct the air pressure loss rate test. (combination - loss of more than 4 psi (28 kPa) in one minute/ tractor only - loss of 1 psi (7 kPa) in one minute)

Start the tractor and push in the dash valves (parking brakes released). While engine is at idle (600 – 800 rpms):

- Ensure that the low air pressure warning device activates by pumping the foot valve to exhaust air.
- Build air up to 80 psi (551 kPa) and check the function of the air gauge(s).
- Conduct the air pressure buildup test (builds from 85-100 psi (587-690 kPa) within two minutes).
- Ensure the governor cuts out before 145 psi (1000 kPa).
- Ensure the pressure does not drop more than 20 psi (138 kPa) on brake application.
- With the engine running, measure steering wheel lash while wheels are straight.
- Check the telescopic/tilt steering, steering wheel and column.
- Inspect the fire extinguisher and hazard warning devices.
- Check the defroster/heater/brake pedal and accelerator pedal.
- Check the floor and condition of the cab for holes, etc.

21 Check Fifth Wheel/Tractor Parking Brakes

Caution: If conducted improperly, this method of checking for fifth wheel movement can result in serious damage to the vehicle.

- Remove the chock blocks and apply the spring brakes on the trailer.
- Put the tractor in drive/reverse and feel for excessive play in the fifth wheel.
- Apply the tractor spring brakes only and conduct the parking brake test.

22 Inspect Cargo Securement

- Ensure the cargo is secured, blocked or tied down, as required.

23 Complete the Vehicle Inspection Report

- Complete a trip inspection report.
- Record and repair any defects that are found during a dispatch inspection OR record defects that do not require immediate attention during an in-transit inspection.

Note: Fifth wheel movement, ABS malfunction lamp operation on trailer and reverse lamp cannot be adequately inspected in a one-person inspection – it is recommended that if there is another person available to get assistance for these items.

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Figure 43. Illustration. Enhanced CMV Inspection procedure form.

Enhanced CMV Inspection Report – Tractor/Semitrailer (Air Brakes)

Refer to the Enhanced Commercial Motor Vehicle Inspection Standard for Defect Criteria

Inspection Date/Time:____________________ Location:____________________ Odometer Reading:____________________

Plate/Unit Number(s): ____________________ Dispatch/In-Transit (Circle applicable inspection) Name/Signature: ____________________ (Printed name and signature of inspector)

I – Inspection Component (Mark "X", if Defective) / E – Enhanced CMV Inspection Standard Reference

Inspection Step	I	E
2 – Front of Tractor	**X**	**E**
• Periodic Inspection Decal/Document		Valid for 3 months
• Headlamp		6.1.a/b
• Turn Signal		6.1.a/e
• Hazard Warning Lamp		6.1.a/f
• Clearance Lamp		6.1.a/h
• Identification Lamp		6.1.a/i
• Bumper		8.10.a-b
• ADS System		5.10.a
3 – Left Front Side of Tractor	**I**	**E**
• Hood or Engine Enclosure		8.1.a-d
• Front fender		8.3.d
• Cab and Passenger Vehicle Body		8.3.a-c
• Frame, Rails and Mounts		8.5.a-b
• Cab Door		8.7.a-b
• Side Windows		8.12.a-b
• Rear-view Mirror		8.16.a-d
• Tires - Tread Depth		9.1.a
• Tires - Tread/Sidewall Condition		9.2.a-d
• Tires - Sidewall Markings		9.3.a-b
• Tires - Inflation		9.4.a-c
• Wheels - Hub		9.5.a-e
• Wheels - Rim		9.6.a
• Wheels - Spoke		9.7.a-c
• Wheels - Disc		9.8.a
• Wheels - Fasteners		9.9.a-b
4 – Left Saddle Tank Area	**I**	**E**
• Exhaust System		1.2.a-g
• Fuel System		1.4.a-e
• Battery		7.2.a-d
• Frame, Rails and Mounts		8.5.a-b
5 – Trailer Front	**I**	**E**
• Air System (Gladhands/Fittings/Leaks)		3.11.a-c
• Headache Rack, if applicable		5.9.a
• Wiring		7.1.a-c
• Trailer Cord		7.3.a-b
• Air Suspended Cab		8.2.a-d
• Unitized Body Elements (bulkhead)		8.6.a
• Reefer or Auxiliary Power Unit		8.9.a
6 – Left Rear Tractor Area	**I**	**E**
• Tail Lamp		6.1.a/c
• Stop (Brake Lamp)		6.1.a/d
• Turn Signals		6.1.a/e
• Hazard Warning Lamps		6.1.a/f
• Back up/Reverse Lamp		6.1.a/j
• License Plate Lamp		6.1.a/k
• Reflex Reflector		6.2.a-c
• Retro-Reflective Marking		6.3.a-d
• Rear Window		8.13.a
• Fender/Mudflap		8.19.a
• Tire Tread Depth		9.1.b
• Tires - Tread/Sidewall Condition		9.2.a-d
• Tires - Sidewall Markings		9.3.a-b
• Tires - Inflation		9.4.a-c
• Wheels - Hub		9.5.a-e
• Wheels - Rim		9.6.a
• Wheels - Spoke		9.7.a-c
• Wheels - Disc		9.8.a
• Wheels - Fasteners		9.9.a-b
• Automated Coupling Device		10.2.a
• Fifth Wheel Coupler		10.3.a-f

Inspection Step	I	E
7 – Left Side of Trailer	**X**	
• Left Side Marker Lamp		6.1a/g
• Retro-Reflective Marking		6.3.a-d
• Cargo Body		8.4.a-i
• Frame, Rails and Mounts		8.5.a-b
• Landing Gear on Trailer		8.20.a-c
• Sliding Axle Assembly		8.21.a-c
• Aerodynamic Device		8.22.a
8 – Left Rear of Trailer	**I**	**E**
• Tires - Tread Depth		9.1.b
• Tires - Tread/Sidewall Condition		9.2.a-d
• Tires - Sidewall Markings		9.3.a-b
• Tires - Inflation		9.4.a-c
• Wheels - Hub		9.5.a-e
• Wheels - Rim		9.6.a
• Wheels - Spoke		9.7.a-c
• Wheels - Disc		9.8.a
• Wheels - Fasteners		9.9.a-b
9 – Rear of Trailer	**I**	**E**
• ABS Malfunction Lamp		3.19.a
• Tail Lamp		6.1.a/c
• Stop (Brake Lamp)		6.1.a/d
• Turn Signals		6.1.a/e
• Hazard Warning Lamp		6.1.a/f
• Clearance Lamp		6.1.a/h
• Identification Lamp		6.1.a/i
• License Plate Lamp		6.1.a/k
• Projecting Load Lamp, if equipped		6.1.l
• Reflex Reflector		6.2.a-c
• Retro-Reflective Marking		6.3.a-d
• Cargo Door		8.7.a-b
• Aerodynamic Device		8.22.a
• Rear Impact Guard		8.23.a-b
10 – Right Rear of Trailer	**I**	**E**
• Frame, Rails and Mounts		8.5.a-b
• Tire Tread Depth		9.1.b
• Tires - Tread/Sidewall Condition		9.2.a-d
• Tires - Sidewall Markings		9.3.a-b
• Tires - Inflation		9.4.a-c
• Wheels - Hub		9.5.a-e
• Wheels - Rim		9.6.a
• Wheels - Spoke		9.7.a-c
• Wheels - Disc		9.8.a.
• Wheels - Fasteners		9.9.a-b
11 – Right Side of Trailer	**I**	**E**
• Right Side Marker Lamp		6.1.a/g
• Retro-Reflective Marking		6.3.a-d
• Cargo Body		8.4.a-i
• Frame, Rails and Mounts		8.5.a-b
• Landing Gear on Trailer		8.20.a-c
• Sliding Axle Assembly		8.21.a-c
• Aerodynamic Device		8.22.a
12 – Right Rear Tractor Area	**I**	**E**
• Retro-Reflective Marking		6.3.a-d
• Air Suspended Cab		8.2.a-d
• Frame, Rails and Mounts		8.5.a-b
• Fender/Mudflap		8.19.a
• Tire Tread Depth		9.1.b
• Tires - Tread/Sidewall Condition		9.2.a-d
• Tires - Sidewall Markings		9.3.a-b
• Tires - Inflation		9.4.a-c

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Inspection Step	I	E
• 12 – Right Rear Tractor Area (cont'd)	**X**	
• Wheels - Hub		9.5.a-e
• Wheels - Rim		9.6.a
• Wheels - Spoke		9.7.a-c
• Wheels - Disc		9.8.a
• Wheels - Fasteners		9.9.a-b
• Fifth Wheel Coupler		10.3.a-f
13 – Right Saddle Tank Area	**I**	**E**
• Exhaust System		1.2.a-g
• Fuel System		1.4.a-e
14 – Right Front Side of Tractorr	**I**	**E**
• Hood or Engine Enclosure		8.1.a-d
• Cab and Passenger Vehicle Body		8.3.a-c
• Cab Door		8.7.a-b
• Fender		8.3.d
• Frame, Rails and Mounts		8.5.a-b
• Side Windows		8.12.a-b
• Rear-view Mirror		8.16.a-d
• Tire Tread Depth		9.1.a
• Tires - Tread/Sidewall Condition		9.2.a-d
• Tires - Sidewall Markings		9.3.a-b
• Tires - Inflation		9.4.a-c
• Wheels - Hub		9.5.a-e
• Wheels - Rim		9.6.a
• Wheels - Spoke		9.7.a-c
• Wheels - Disc		9.8.a
• Wheels - Fasteners		9.9.a-b
15 – Steering Axle	**I**	**E**
• Spring Hangers		2.1.a-b
• Axle Tracking Components		2.2.a-e
• Axle and Axle Assembly		2.3.a
• Spring and Spring Attachment		2.4.a-h
• Shock Absorber		2.6.a-c
• Air Compressor		3.1.a-c
• Air System (Fittings/Leaks)		3.11.a-c
• Brake Chambers		3.12.a-c
• Brake Drums/Shoes/Linings/Seals		3.13.a-e
• S-Cam/pushrod/clevis/adjuster/etc.		3.14.a-e
• Disc Brakes (calipers/rotors/pads)		3.17.a-e
• Steering control and linkage		4.1.a-i
• Power Steering System		4.2.a-f
16 – Axle 2 and 3 Undercarriage	**I**	**E**
• Drive Shaft and Differential		1.3.a-e
• Spring Hangers		2.1.a-b
• Axle Tracking Components		2.2.a-e
• Axle and Axle Assembly		2.3.a
• Spring and Spring Attachment		2.4.a-h
• Air Suspension		2.5.a-d
• Shock Absorber		2.6.a-c
• Air Tanks/Reservoirs		3.4.a-c
• Air System (Fittings/Leaks)		3.11.a-c
• Brake Chambers		3.12.a-c
• Brake Drums/Shoes/Linings/Seals		3.13.a-e
• S-Cam/pushrod/clevis/adjuster/etc.		3.14.a-e
• Disc Brakes (calipers/rotors/pads)		3.17.a-e
• Frame, Rails and Mounts		8.5.a-b
17 – Axle 4 and 5 Undercarriage	**I**	**E**
• Spring Hangers		2.1.a-b
• Axle Tracking Components		2.2.a-e
• Axle and Axle Assembly		2.3.a
• Spring and Spring Attachment		2.4.a-h
• Air Suspension		2.5.a-d
• Shock Absorber		2.6.a-c
• Air System Leakage		3.3.a-b
• Air Tanks/Reservoirs		3.4.a-c
• Air System (Fittings/Leaks)		3.11.a-c
• Brake Chambers		3.12.a-c
• Brake Drums/Shoes/Linings/Seals		3.13.a-e
• S-Cam/pushrod/clevis/adjuster/etc.		3.14.a-e
• Disc Brakes (calipers/rotors/pads)		3.17.a-e
• Frame, Rails and Mounts		8.5.a-b

Inspection Step	I	E
18 – Brake Adjustment	**X**	
• S-Cam Brake Adjustment		3.15.a
• Wedge Brake Adjustment		3.16.a
19 – Tractor Protection System	**I**	**E**
• Tractor Protection Valve		3.8.a
• Trailer Supply Valve		3.8.b
• Bleedback Valve (Trailer)		3.8.c.
20 – In Cab Inspection	**I**	**E**
• Accelerator Pedal		1.1.a-d
• Air Pressure Build-up/Loss Rate		3.2.a-b/g
• Low Pressure Warning		3.2.c
• Air Pressure Gauge		3.2.d
• Air Pressure Drop/Reserve		3.2.e
• Air Leakage		3.2.f./3.3.a
• Brake Pedal/Actuator		3.5.a-c
• Treadle Valve		3.6.a-b
• Brake Valves and Controls		3.7.a
• Parking/Emergency Brake Tractor		3.9.a-b
• Parking/Emergency Brake Trailer		3.10.a-b
• ABS Malfunction Lamp(s) on Dash		3.18.a-b
• Stability Control on Truck		3.20.a
• ESC/RSS on Trailer		3.21.a
• Steering Operation		4.3.a-d
• Fire Extinguisher		5.1.a-b
• Hazard Warning Kit		5.2.a
• Horn		5.3.a-b
• Speedometer/Odometer		5.4.a/5.5.a
• Windshield Wiper/Washer		5.6.a-d
• Heater/Defroster		5.7.a-b
• Auxiliary Heater		5.8.a
• Automated Driving System (ADS)		5.10.a
• Windshield		8.11.a-f
• Interior Sun Visor		8.14.a-c
• Exterior Windshield Sun Visor		8.15.a
• Seat		8.17.a-b
• Seatbelt		8.18.a-d
21 – Fifth Wheel Movement	**I**	**E**
• Excessive Play Between Parts		10.1.a/10.3.c-e
22 – Cargo Securement	**I**	**E**
• Equipment Mounted on Vehicle		8.9.a
• Inadequate blocking and bracing		393.100/NSC 10
• Inadequate number of tiedowns		393.110/NSC 10

X = Item is a defect in the Standard

Periodic Inspection – Tractor ______________________ **(date)**

Trailer ______________________ **(date)**

Brake Measurements

Chamber Size/Type					
Axle	**Axle 1**	**Axle 2**	**Axle 3**	**Axle 4**	**Axle 5**
Right Side					
Left Side					

Comments:

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Figure 44. Illustration. Enhanced CMV Inspection Report – Tractor/Semitrailer (Air Brakes), procedure form.

In addition to the inspection process for the trucks and trailers themselves, the trainees also received a course of instruction on how to properly inspect the cargo for securement. During this block of instruction, the students learned about differing securement requirements based on load types. This included such things as inspecting load locks, straps, and chain thickness. In addition to the securement devices themselves, students also learned about secondary items that should be used to properly secure various loads. Examples include learning about attachment points, blocking, bracing, dunnage, edge protectors, friction mats, void fillers, and understanding the Working Load Limit when using these items in combination with the securement devices themselves.

Hands-on Vehicle Inspection: Training for the enhanced inspection procedure went beyond the classroom to include a hands-on demonstration of knowledge. During this phase of training, instructors prepared a group of trucks with a series of "defects" that the students were expected to locate and identify while performing a full enhanced inspection on a non-ADS-equipped truck and trailer set. As part of the training process, these defects were consistent across the trucks used during this class. These defects were not, however, the only ones that may be used in future training classes. This was by design in order to prevent complacency on the part of students who, for whatever reason, need to repeat the class, as well as for the purpose of recertification. The complete list of potential defects is maintained by CVSA instructor staff and is not intended to be released in order to maintain the integrity of the program.

Step 1: Following the inspection form in Figure 43, the students began their inspections by approaching their assigned vehicle. Students checked for a current annual inspection decal, license plate, DOT number, and carrier name. With the engine running, the students placed chock blocks around the tractor's drive wheels, placed the vehicle in neutral, released the brakes, ensured the air supply pressure was at maximum, and then turned the engine off and placed the ignition key in the "on" position. Students verified that the ABS malfunction lamps properly illuminated on the dashboard and the trailer.

Step 2: Students then moved to the front of the tractor to verify the headlights (low and high beam) worked properly and that all clearance, signal, and other required lamps worked, were the proper color, and were clearly visible. Rear tractor lights were also checked at this time. In this step, students were also expected to inspect the front bumper and ensure that all ADS sensors (e.g., cameras, radar, lidar) were properly and securely mounted and that the ABS light on the trailer had not remained illuminated.

Step 3: Students were then expected to check the left front side of the tractor to include the hood latch, front wheel, rim, hub, and tire as well as visible portions of the frame. The driver's door, side mirrors, and windows were checked for proper operation.

Step 4: Next, the left saddle tank area was inspected. This included tank securement, leakage, cap presence, batteries confirmed free of leaks, and, if applicable, confirming the exhaust was properly mounted and free of damage.

Step 5: Students moved on to inspect the front of the trailer and rear area of the tractor. In this step, the students checked the condition of the air and electrical lines, cab air suspension shocks, and refrigeration unit, if present. The cab was inspected to ensure the presence of the required reflective material and rear fenders. If present, the headache rack or bulkhead was inspected for proper mounting, to include any improperly secured materials.

Step 6: Students inspected the left rear area of the tractor to include the wheels, rims, hubs, and tires. Visible portions of the frame were inspected for damage, cracks, or excessive rust. In addition, the fifth wheel assembly and upper and lower slider components were inspected. Students also checked the condition of any rear windows, if present, and confirmed the presence (if required) and condition of the mud flaps.

Step 7: Students next inspected the left (driver's) side of the trailer, checking the frame and body for corrosion fatigue, damage to the upper and lower rails, and cracked, broken, or missing crossmembers or other defective body parts. As part of the inspection of the trailer body, all panels were checked for loose or missing rivets or bolts. The landing gear was inspected to confirm no parts were loose or missing and that the handle could be properly stowed. If present, any aerodynamic devices were inspected for damage and loose or improper mounting. All required reflective markers were inspected to confirm proper placement and that minimum requirements were met.

Step 8: While still inspecting the left side of the trailer, students moved on to the left side hubs, wheels, tires, brakes, suspension, sliding subframe, and mudflaps. Students checked items such as tread depth, tire pressure, properly functioning slack adjusters, and brake pad thickness, as well as any visible issues with air or electrical lines under the trailer. Additionally, all locking pins and slider guides were inspected during this step.

Step 9: Students next moved on to the rear of the trailer, where they inspected the reflective material, aerodynamic devices (if present), and all rear-facing lights (marker, signal, brake, flashers, and tag). Cargo doors were inspected for proper working condition and attachment and ensured that the cargo was properly secured. The rear impact guard was also inspected to confirm it was within the more stringent enhanced inspection criteria:

- Not missing, loose, or broken.
- No cracked welds in the horizontal or vertical member or supporting structure or any attachment to vehicle structure.
- **The horizontal member is not bent inwards, downward, upward, or outward beyond 3 inches.** [Emphasis from original document.]
- The vertical supports and/or supporting structure is not weakened, bent, or distorted.

Step 10: Students performed an inspection of right trailer wheels, etc., following the same procedures as in Step 8.

Step 11: Students performed an inspection of the right side of the trailer body, etc. The procedure was the same as in Step 7 and added, if present, inspection of the spare tire storage device and that the tire is properly secured.

Step 12: Students performed an inspection of the rear tractor area, following the same procedure as in Step 6.

Step 13: Students performed an inspection of the right saddle tank (if present), following the same process as in Step 4.

Step 14: Students performed an inspection of the right front side of the tractor, with the same procedure as in Step 3.

Step 15: Students performed an inspection of the steering axle and surrounding components. This part of the inspection began with activating and confirming proper function of emergency flashers prior to opening the hood. Once the hood was open, students inspected several systems and components from both above and underneath via a creeper. These systems included:

- The steering system. This inspection included checks of the steering box and shaft, all nuts, bolts, clevis pins, fluid level, etc.
- The suspension system. This included nuts, U-bolts, shocks, shackles, leaf springs (none missing, cracked, or broken), airbags, etc.
- The front brake components. This included verification of brake chamber size, proper pad thickness, condition of the drums or rotors, etc.
- The front tires. This included a check of sidewall condition, tread depth (minimum of 4/32 in.), verification that no retreads were present, etc.

Step 16: Students (while still under the vehicle) moved on to inspect the drivetrain and axles 2 and/or 3. During this part of the inspection, they checked:

- The drive shaft, exhaust system, and air tanks to ensure all were in good condition and properly secured.
- The suspension and related components.
- The brake components (if needed; this includes scribing to determine chamber size).
- The frame condition and all items attached to it.
- Hazard lamps on the rear of the tractor.

Step 17: Students continued inspecting under the trailer (floor, frame, crossmembers, etc.) via a creeper as they worked their way back to axles 4 and/or 5. This included brake and suspension components and tire sidewall inspections, ending with the student exiting from under the rear of the trailer to confirm all hazard lights were properly functioning.

Step 18: During this step, students were required to demonstrate the ability to properly check brake adjustment. This began with the students ensuring air pressure was 90 to 120 psi. Students then used a supplied device (called a brake buddy) to apply and hold the service brakes. They then measured and recorded the pushrod travel (where applicable) and verified proper pad-to-drum contact. Students also listened for and identified the location/source of any air leaks and inspected the brake lamps on the tractor and trailer.

Step 19: Students next inspected the tractor protection system to ensure it worked properly. With the emergency brakes still released, the students disconnected both air lines from the trailer to ensure air stopped leaking from the lines before reaching 20 psi. Students also checked for any air pressure bleeding from the trailer itself. Students then fully applied the brakes to listen for any leakage from the gladhands prior to reconnecting them to the trailer.

Step 20: During this step of the inspection, students moved to the interior of the cab and inspected items such as the seat belts, sun visors, windshield, wipers (looking for damage or improper operation), and horn function. In addition to these items, the students checked the dashboard for warning lights, fault indicators for the ABS, and, if present, the electronic stability control. During the training class, all trucks were non-ADS-equipped vehicles; however, each student was trained that this would also be the point in the inspection when they would look for and indicate faults in the ADS if one were present. While in the cab, students also performed an air brake test. With the air pressure at 80 psi, students would apply the foot brake and look for air pressure loss. There could be losses of no more than 4 psi in the period of 1 minute or it would be considered a defect requiring repair.

Once the leak down test was completed, students then learned to start the tractor and push in the dash valves (wheel chocks were still in place for safety), and with the engine at idle, students would:

- Ensure the low-pressure warning activates by pumping the brake pedal to exhaust air.
- Build air up to 80 psi and verify gauge function. Continue building pressure to confirm it builds from 85 to 100 psi within 2 minutes and ensure the governor cuts out before 145 psi.
- Ensure brake pressure does not drop more than 20 psi per foot application.

Once the brake testing was completed, students moved on to checking for proper steering wheel lash, properly working tilt and telescopic features, and for damage to or improper function of the steering column. Students also verified the presence of safety triangles and fire extinguishers, the condition of the floor (free from holes), and finally, that the throttle, brake pedal defrosters, and heater all functioned properly.

Step 21: During Step 21, students demonstrated the ability to inspect both the fifth wheel and tractor parking brakes. Students removed the wheel chocks with the spring brakes set on the trailer. Students then placed the transmission in both drive and reverse to check for excessive play between the fifth wheel and the king pin. Students learned to properly mark and measure these components as needed to confirm excessive play. Students also released the trailer brakes and set the tractor parking brakes to confirm they properly worked as well.

Step 22: Students applied what they had learned in the classroom to properly verify that the trailer's payload was properly secured, blocked, and/or tied down as required.

Step 23: Students concluded the inspection process by properly completing the trip inspection report. For a "Dispatch Inspection," ALL defects are required to be both documented and fixed prior to the vehicle being released onto public highways. For "In-Transit Inspections," all defects must be documented, and any qualifying defect that requires repair must be correct prior to release. All other lesser or non-safety critical defects that can be allowed to continue without immediate repair must be documented for repair prior to once again being "dispatched."

Hands-on training completion requires that the students achieve a minimum of 85% accuracy at the end of the inspection. Failure to locate, properly identify, and document at least 85% of the defects placed by instructor staff results in not completing the course and not receiving an inspector certification. Any student who is unable to pass would be required to complete the course again in its entirety and score 85% or higher. In addition to the inspector certification, CVSA does offer a certificate of course completion for those members of industry who wish to have a better understanding of the process from a more administrative perspective. This does not require a successful (or any) completion of the hands-on portion of the training. People who only obtain a certificate of course completion will not be permitted to perform a CMV enhanced inspections.

5.3.4.3 Electronic Communication of ADS Enhanced Inspection

As of August 2023, the following represents the current state of the electronic communication of an ADS enhanced inspection:

Electronic verification attached to the CVSA Enhanced CMV Inspection Program stands apart from other proposed and existing vehicle bypass and driver-focused messages such as a unique electronic identification (UEI) for CMVs and CVSA's Level VIII Electronic Inspection. UEI does not include information such as status of ADS equipment or ODD. UEI could serve a different function more akin to a vehicle registration for CMVs, whether operated by an ADS or human drivers. The CVSA Enhanced CMV Inspection is also not the same as CVSA's Level VIII Electronic Inspection, though the two could potentially be integrated in the future. Level VIII Inspections, as currently defined, focus on the status of human drivers and do not include hands-on vehicle inspection data.

During the summer of 2023, the Texas Department of Public Safety worked in partnership with Kodiak Robotics and Drivewyze to run a pilot of this program in order to learn more about the practicality and reliability of transmitting data between an ADS in motion and roadside monitoring stations.

During the test pilot, a series of trips were completed by ADS-equipped Kodiak Robotics trucks. As these trucks encountered designated inspection stations the following information was both transmitted and successfully received:

- Automated vehicle identification (identifies the vehicle as an AV)
- Inspection date
- Inspection time
- Inspection location
- Odometer reading
- Truck plate and jurisdiction on the enhanced inspection form

- Unit number
- Trailer license plate and jurisdiction
- Inspector name
- Defect status (whether the inspection was defect-free)

Per Drivewyze, and without disclosing proprietary information, "the screening aspects of the program, applied as the vehicle approaches the site, fall under the State Bypass Program." This is an important piece of key information as it makes it clear to both industry and enforcement that while there is a new level of inspection, at its most basic level it remains standardized and conforms to existing practices. As of this writing, the final data points to be transmitted have not been established.

5.3.5 Key Findings and Recommendations

Research on the effects of roadside inspections has shown a strong relationship between quality maintenance and inspection procedures and a decline in crashes related to vehicle defects. Mechanical failures appear to be a contributing factor in at least 10% of truck crashes. The failures most likely to cause crashes were those associated with brakes, tires/wheels, and lights. Additionally, research found that roadside inspections and application of the OOS criteria have significantly decreased the rate of truck crashes in which mechanical or safety defects were cited as a primary contributing factor. The efficacy of the periodic annual inspection is a little more uncertain. One study of CMVs suggested that the annual inspection was important for older vehicles and for identification of vehicles that were likely to have mechanical failures. This research suggested that the frequency of the periodic inspection needs to be increased, particularly for those systems (brakes, tires/wheels, and lights) that are more likely to contribute to crashes. ADS-equipped trucks may be subject to different types of inspection requirements than existing (non-ADS) trucks.

There are six existing truck inspection requirements: Pre-trip Inspection, Post-trip Inspection/DVIR, Roadside Inspection, Post-crash Inspection, Periodic Inspection, and Law Enforcement Inspection. In the pre-trip inspection, the driver is responsible for inspections, recognition, and decision-making tasks. Working with government and industry stakeholders, CVSA has developed an enhanced pre-trip inspection for ADS-equipped trucks. There is considerable support for an enhanced pre-trip inspection that considers both U.S. and Canadian inspection models. CVSA has determined that special credentials and training are needed for carrier inspectors of ADS-equipped CMVs. A determination on electronic communication of inspection elements is ongoing.

Currently, post-trip inspections are required. The basis for the DVIR is sound: the driver, who has driven the vehicle for as much as 11 hours, should be aware of any part of the vehicle that appears to be malfunctioning. The consensus of the interview with Federal and State employees was that the post-trip inspection/DVIR would no longer be needed for ADS-equipped CMVs. Given that an ADS-equipped truck is likely to be dispatched with "quick turnarounds," there is no need for both the pre-trip inspection and post-trip DVIR.

Inspectors were split on the idea of whether to conduct a Level I inspection roadside or a Level V inspection at an alternative site (i.e., carrier's terminal or transfer center). The inspectors who wanted to inspect ADS trucks at roadside felt that an ADS-equipped truck would have to be capable of responding to communications from roadside inspectors (where to stop, go, and park). Some inspectors raised safety concerns about inspecting ADS-equipped trucks without a safety operator or driver. Electronic communications will be important not only for government systems at roadside but for communicating between the ADS-equipped truck when picking up and dropping off loads at terminals or port facilities to verify the status of repair and maintenance at dispatch and in-transit locations.

Inspectors did not feel that any changes were necessary for the mechanical side of an ADS-equipped vehicle for post-crash inspections. They did, however, feel that a whole new set of inspection criteria would be needed to evaluate whether the ADS contributed to the crash. There was broad agreement among inspectors that the periodic inspection of ADS-equipped trucks would not be that much different than the inspections that are currently being conducted on similar vehicle classes today. Inspectors felt that ADS-equipped trucks were likely to be driven more miles per year and therefore should be inspected more frequently, possibly tying the periodic inspection to vehicle mileage. Additionally, inspectors suggested that at least one of the inspections should be conducted by a third party certified to conduct these types of mechanical inspections (i.e., a certified organization that does not benefit from the results of the inspection).

The National Institute of Justice, working with the RAND Corporation and the Police Executive Research Forum, developed an expert panel report on policing regarding ADS-equipped vehicles. This report identified four likely scenarios where law enforcement would likely interact with ADS-equipped trucks: traffic stops, collisions, emergencies, and tangential interactions. The expert panel report concluded that communications with the ADS-equipped truck will be one of the most important capabilities that largely does not exist today. One of the technical challenges of remote assistance is the lack of network coverage along major freight corridors. The deployment of 5G is not expected to be completed before 2025, and current network capabilities cannot always guarantee the bandwidth and latency requirements of remote assistance. Funding for U.S. infrastructure should help to expedite network coverage to rural America, particularly along highways.

In addition to these requirements, there is an Enhanced CMV Inspection that is not yet a requirement but is being accepted as a voluntary policy. It was designed with broad industry participation specifically for ADS-equipped trucks and addresses many of the considerations brought up in this paper. It is one significant part of the answer to the question of how to ensure the safety of ADS CMV operations. It is possible that this enhanced inspection will become a standard or requirement in the future.

The Enhanced CMV Inspection Program was designed to encompass requirements from both the U.S. and Canadian Inspection (Standard 13 of the NSC), and therefore it is already a strong candidate for a larger North American standard if that is something that is desired in the future. Many CMVs operate across borders, and, especially in a future with driverless trucks, there may be real benefit in implementing the Enhanced CMV Inspection Program across the entire North American continent.

5.3.5.1 *Next Steps and Opportunities*

Although there have been numerous advancements in the process to bring ADS technology to America's highways as highlighted throughout this document, there are still many more aspects of this process that must be determined. Some examples of discussions still ahead for the CVSA Enforcement and Industry Modernization committee are:

- Inspector Certifications
  - How frequently will classes need to be held in both the short and long term (initial rollout/long-term implementation)?
  - What will be the process for both recertifying as well as decertifying inspectors?
  - Would a "Train the Trainer" model be an acceptable option for recertifications?
- Enhanced Inspection Process
  - How will the Enhanced CMV Inspection Program Process impact the existing DVIR process for all inspections?
  - What changes to Federal regulations must be considered and how complicated might those changes be?
  - The current program works around a 24-hour clock:
    - When does the clock begin?
    - What happens should the vehicle be delayed due to traffic congestion, weather issues and compliance beyond the 24-hour window, and how should these delays be documented?
    - Would longer periods than 24 hours be accepted in special circumstances?
    - Can vehicles be inspected in advance and then staged in advance of an upcoming departure?
    - Is the vehicle still defect free if that inspection was greater than 24 hours prior to departure?
    - Can trucks and trailers be inspected separately as part of a staging process?
  - Record Keeping for Law Enforcement Inspections of Terminals.
    - A key component in the successful deployment and inspection of ADS commercial vehicles may include law enforcement in some form of accountability at the carrier or operator level.
    - Who maintains the records for review? How long? In what format/media?
    - Should there be a crosscheck or database established so that trends or common sources can be identified regarding failed enhanced inspections?
      - This trend analysis may be valuable, for example, not only in identifying common points of failure on ADS-equipped CMVs, but also identifying inspection stations that have an elevated number of failed inspections.
      - This trend analysis could also identify issues such as the need for remedial training or potentially identify inspectors or stations not following the enhanced inspection process in general. This could then relate back to the above work group question regarding decertification of an inspector as well as potential legal liability.

- Establishing criteria for both voluntary and random inspections of ADS-equipped vehicles by Law Enforcement.
- Determination of the weight of an unmanned ADS-equipped truck.
  - Will ports potentially be required to have a method of weighing trucks and trailers prior to releasing them to the highway?
  - Will CMV weight be transmitted to roadside monitors as part of an in-motion "inspection?"
  - Will CMV weight be accepted as the true and accurate weight, and what if there is a discrepancy during a weigh-in-motion screening?

These questions are a few key considerations that are active at the time of this report. As the industry continues to advance towards live integration of ADS-equipped CMVs into fleets and onto public highways, more challenges and discussions will be discovered.

5.4 TEST DRIVER STATE MONITORING

On April 6, 2022, a CMV operating with automation active while being monitored by a test driver or safety operator veered left into a median.[68] The safety operator was able to regain control of the vehicle, and the CMV suffered only minor scrapes. However, the integrity of testing prototypical ADS on public roadways was again brought into question.

The Automated Vehicle Safety Consortium (AVSC) is considered the guiding body for developing principles to lead industry-wide standards for ADSs. The AVSC[69] published a "best practices" report for in-vehicle fallback test drivers, or safety operators. These terms are considered synonymous, but this section will refer to these drivers as safety operators. The role of a safety operator is to "supervise the performance of prototype Level 4 (L4) ADS-operated vehicles in on-road traffic for testing purposes."[70] The safety operator is responsible for responding to unexpected scenarios where the ADS acts incorrectly or even hazardously; however, these failure events are not frequent. Therefore, these drivers are highly trained in vigilance maintenance and uphold strict selection criteria. In addition to taking frequent breaks to maintain vigilance, drivers are prohibited from tasks that may impede their ability to drive a vehicle. These tasks include using personal electronic device use, eating, smoking, vaping, and alcohol or drug use. Unique to safety operators, an attentive driver is discouraged from engaging in conversation irrelevant to the driving task and is encouraged to always maintain hand position on or near the steering wheel.

The necessity for these operators is evidenced by the April 6 incident in which an ADS-equipped CMV executed a dangerous maneuver on a public roadway. The attentive safety operator reacted swiftly and correctly to prevent a potentially more serious crash. A similar incident detailed in a 2019 National Transportation Safety Board Accident Report[71] involved a light-vehicle safety operator driving an Uber equipped with Uber's ATG Developmental ADS. Unlike the attentive safety operator who had both hands on the wheel and was constantly monitoring the roadway to anticipate a takeover, this operator was interacting with a personal device when the system transferred emergency control due to a foreign object detected in the roadway. Due to several factors, including the driver's inattention, the safety operator did not assume control of the vehicle and it fatally collided with a pedestrian.

These cases exemplify the need for an actively engaged and attentive safety operator when operating L4 ADS-equipped vehicles. The AVSC report[72] defines criteria for safety operator selection, training, and expectations and recommends equipping ADS test vehicles with a driver state monitoring (DSM) system to ensure the driver is fit to assume control during an emergency takeover request. DSM systems are designed to track metrics (i.e., physical, physiological, psychological, and/or behavioral variables) that may be indicative of driver inattention or inability to react appropriately. There are many applications of DSM, including those for ADS-equipped vehicles. Although there are many recommendations from the AVSC, there are no standardized requirements for individual fleets. This means each ADS developer is responsible for assigning specific tasks to the safety operators. Therefore, it is unknown exactly what a safety operator's responsibility is to ensure the vehicle is operating appropriately.

The purpose of this investigation of DSM technology and practices was to compile available information through a detailed literature review and outreach about DSM and compare commercially available systems on the market through a technology scan and exploratory evaluation. The following sections outline the findings from each of these collection techniques.

5.4.1 Information Collection

The literature review sought to establish information about specific driver state metrics and thresholds for takeover ability relevant to a CMV safety operator. For example, it was unclear which physiological or behavioral metrics (e.g., heart rate [HR], eye-glance behavior, posture, hand position) translate to specific driver capacity. Specifically, this literature review determined specific driver characteristics that may impact readiness to take control of an ADS vehicle and the metrics or thresholds indicative of a driver's state. Additionally, the review considered the differences in thresholds of driver states necessary for a safety operator who is highly trained as an ADS-equipped CMV safety operator versus a typical CDL holder operating an ADS-equipped CMV. For example, a safety operator may be held to a higher attentional standard due to the unpredictability of an ADS malfunction. For the benefit of future research, the results from this literature review provided insight into the types of DSM technologies (i.e., sensors) that warrant specific testing in an ADS-equipped CMV to monitor the safety operator appropriately.

5.4.1.1 Literature Review Methodology

The initial literature search involved reviewing databases in the transportation industry such as the Transportation Research Information Services & Documentation Database (TRID), the Repository & Open Science Access Portal (ROSAP), and the Virginia Transportation Research Council (VTRC) database. The search was expanded to target publications from the Institute of Electrical and Electronics Engineers (IEEE), ResearchGate, ScienceDirect, and PubMed to consider physiological measures of human state not yet introduced to the transportation industry. The query terms used for each database included *driver monitoring* and *state detection*, and more specific searches for each individual driver state included *distraction detection*, *drowsiness detection*, etc. The resulting literature consisted of 91 papers detailing DSM research and criteria for defining various human states. Several papers were excluded from the final review due to (1) irrelevance to the driving context such as blood work or other invasive medical devices, (2) a lack of converging evidence, and (3) investigating irrelevant features of DSM relative to the scope of this literature review such as light-vehicle applications or vehicle-based metrics. Eighty-one papers remained for inclusion in the final literature scan. These papers were selected based on their relevance to DSM in the context of ADS-equipped CMVs or their contribution to understanding how to define and monitor a driver's state while in a vehicle. The following sections detail the results of the literature review and provide an understanding of how to effectively monitor a safety operator using DSM technology.

5.4.1.2 Driver Sate Monitoring

Halin et al.[(73)] conducted the most comprehensive review to date of DSM literature and relevant concepts. This review builds on Halin et al. by considering the unique perspective of the safety operator and adding updated technology, but the current review is narrower in scope due to solely addressing DSM in the context of safety operators of prototype ADS-equipped CMVs. The five important driver states discussed in this paper are drowsiness, mental workload, distraction, emotions, and driving under the influence. The following sections outline (1) how the literature defines these respective states, (2) the behavioral and physiological metrics used to indicate the respective states, (3) sensors that can be used to assess the metrics in a driving context, and (4) considerations for safety operators.

The most common and accurate identifiers of a degraded driver state are driver performance variables determined by vehicle-based metrics.(74,75) Vehicle-based metrics include following distance, lane deviation, and speed variability that can indicate diminished driving ability. However, Leicht et al.(76) pointed out that vehicle-based metrics only change once a driver's state begins to impact performance of the vehicle. Thus, a more proactive detection method is needed to effectively prevent performance degradation. Additionally, ADS-equipped CMVs are designed to maintain control of the vehicle, so vehicle-based metrics are irrelevant measures for safety operators who are monitoring the ADS for malfunctions. For the successful integration of DSM systems into ADS-equipped CMVs, the determination of driver state should be done proactively and through measures that do not require a driver's influence on the vehicle. For these reasons, all indicators discussed in this paper are driver-based. Driver-based metrics include behavioral indicators (i.e., yawning, holding a phone, eye position) and physiological indicators (i.e., HR, pupil dilation) that monitor a human's level of awareness regardless of the ADS operating performance.

5.4.1.3 Driver State: Distraction

Driver distraction is defined as a mismatch between a driver's attention and the attention needed to safely perform the tasks required to operate the vehicle.(77) These "activities" fall into four main categories based on the source of distraction: visual, manual, auditory, and cognitive. Visual resources are needed for most driving tasks, while the remaining tasks are allocated to auditory, tactile, and haptic resources.(78) Therefore, visual distraction is one of the most frequently studied forms of distraction and is caused by activities such as reading a text message or any activity that causes the eyes to look away from driving-relevant information. Safety operators are prohibited from using cell phones, but cell phones are only one cause of visual distraction. Manual distraction occurs when the hands, body, or feet required for the driving task are performing irrelevant activities such as reaching for a purse or adjusting the air conditioning. Cognitive distraction, such as being lost in thought or problem solving, is one of the most elusive forms of distraction because it is difficult to observe. The final category is auditory distraction, which can occur when a driving-irrelevant sound (e.g., radio, music) masks a driving-critical sound (car horn, emergency vehicle) or when an auditory input such as speech uses cognitive resources that diminish performance on a driving task.(79) A task may result in one or some combination of all these forms of distraction. For example, texting while driving is considered a visual-manual distraction due to the use of both the hands and eyes to complete the task, but it also requires cognitive resources. Although many researchers have defined distracted driving, few have defined the parameters of an attentive driver. Kircher and Ahlstrom(80) defined an attentive driver as one who sufficiently samples enough information to meet the demands of the driving task. Therefore, an effective DSM system should be able to accurately identify each form of distraction to alert the ADS of possible inattention.

Gaze patterns are one of the best behavioral indicators for determining manual and visual distractions. There are different ways to characterize gaze behavior. One method is Percent Road Centre (PRC), or the percentage of gaze points that fall within the road center. If a driver is not looking at the road center for the majority of the time interval collected, they are considered distracted. The average PRC of a baseline driver is 70% to 80%. PRC above 92% is considered cognitive distraction and below 58% is considered visual distraction.[81] This method fails to consider other areas of the vehicle where a driver may look to assess safety-relevant information such as mirrors or cross traffic. Therefore, a more popular method used to determine gaze behavior is gaze duration, which assesses whether a driver is actively looking in a direction relevant to the driving task. Two methods are commonly used to identify gaze behavior: eye/facial landmark detection or head position. The driver's head position and eye pose are determined by using computer vision detection of major facial landmarks and pupil detection. An algorithm then classifies the positions of these features using decision pruning. Fridman et al.[82] considered six major "driving-relevant" regions: road, center stack, instrument cluster, rear-view mirror, and left and right mirrors. One issue with this method is that it fails to account for driving-relevant tasks outside these specific gaze zones, such as cross traffic when entering an intersection. A proposed method to account for this issue is the attentional buffer technique. Ahlstrom et al.[83] used an attentional buffer of 2 seconds in any gaze direction to define "situational awareness" as opposed to attention. These authors asserted that if the driver looks too long in any one direction, they are not gathering and searching for more information relevant to the driving task. Several studies support the attentional buffer due to findings indicating that longer fixations denote cognitive distraction and shorter fixations denote visual distraction, regardless of direction.[84,85,86]

Another method used to detect driver distraction is monitoring the driver's positions and interactions with other objects in the vehicle. Yan et al.[87] used hand monitoring and driver position algorithms to assess six categories of behavior: talking on the cell phone, eating while driving, shifting gears, hands on wheel, phone use, and smoking. Due to the lack of standardization of safety operator tasks, it is unclear what secondary tasks a safety operator may be able to perform when monitoring the ADS-equipped CMV. Zhao et al.[88] and C. Yang et al.[89] outlined the benefit of monitoring posture and foot position as a way of determining whether a driver is ready to take over a vehicle. If a driver's feet are not near the pedals, nor their hands near the steering wheel, they cannot be expected to react to an emergency takeover request in a timely manner. Safety operators are encouraged to keep their hands near the wheel at all times, yet each fleet can individually decide the extent to which they do so. Therefore, a DSM system specific to safety operators should assess whether a driver is abiding by this practice.

Researchers have mostly used camera-based systems to monitor observable behaviors because computer vision and AI can be used to extract information from the driving scene. Several studies used infrared light (IR) cameras to record video from participants due to their ability to capture changes in facial landmarks in complete darkness. The cameras were all mounted on the dashboard pointed at the driver's face.[90,91,92] Other researchers used an eye tracking software that combined information about head movement, eye opening, pupil activity, and blink behavior to understand distraction in two different camera-based studies.[93,94] All aforementioned studies commented on the difficulty of using camera-based detection due to the interference of the driving environment. For example, varying levels of illumination, vibration, and items that can block the sensors are typical challenges in determining the type of sensors to use. IR lights or cameras with IR technology help with nighttime driving because they illuminate the human's face even in complete darkness, but they are sometimes impeded by drastic variations in lighting such as broad daylight.[95]

One unique exception to the benefit of observational measures of distraction is cognitive distraction. It is difficult to outwardly observe cognitive distraction, so a few researchers have investigated the value of physiological measures such as brain activity and attempted to assess this type of distraction.(96,97) These studies suggest that arithmetic and conversational loads cause the focal points of the eyes to narrow and overall gaze direction to become concentrated to a particular range. Therefore, by combining pupil diameter, gaze direction, and HR, these studies were able to improve the detection rate over simply using gaze behavior. McDonald et al.(98) concluded that perinasal perspiration, palm electrodermal activity (EDA), HR, and breathing rate were effective in distinguishing an attentive driver from a cognitively distracted one. Although it may be difficult to assess the masking qualities of sounds in the vehicle to safety critical sounds in the environment, auditory distraction that induces cognitive distraction elicits similar behavior in drivers.(99) However, these metrics were combined as one illustration of driver state, so it is difficult to say if one of these measures alone was the contributing factor or if using all metrics combined produced the most accurate results. Similarly, although these metrics were seen as valuable contributors to the picture of driver state, it is questionable how feasible it is to put these sensors in a driving environment or implement them in an ADS-equipped CMV. Safety operators are banned or strongly discouraged from most visual-manual distraction activities (cell phone use, eating, smoking, etc.), so they are most susceptible to cognitive distraction. Therefore, extra care should be taken to find effective methods for detecting cognitive distraction.

5.4.1.4 Driver State: Drowsiness

Drowsiness is the physiological desire to fall asleep.(100) This is not to be confused with fatigue, however, which is the feeling of exhaustion or tiredness that occurs after mental and physical over- or under-exertion.(101) Although the motivations and variables that influence each of these states should be differentiated, their effect on driver safety is similar. Both states are characterized by mood alteration, impairments of psychomotor performance, poor decision-making, reduced reaction time, and other attentional issues that all increase performance errors and crash risk.(102,103) Drowsiness and fatigue are major concerns for CMV drivers, as the demands of a professional driving career often involve irregular sleep hours, long periods of hypovigilance, and highly demanding tasks.(104,105) In this report, drowsiness monitoring will be covered in this section, while fatigue, which is typically indicated by mental workload, will be discussed in the following section.

Because drowsiness is a physiological impulse similar to hunger or thirst, it is most accurately measured through physiological indicators. The most researched physiological indicators for drowsiness are heart rate variability (HRV), skin conductance, breathing rate, pupil response, and brain waves.(106) Sahayadhas et al.(107) illustrated that HRV can be a valid physiological measure of drowsiness. An electrocardiogram (ECG) is a common method used to measure HRV. However, direct contact with skin is necessary, which causes issues for use while driving or discourages people from using it consistently. There are some watch models, finger rings, and patches available on the market,(108) but these devices require the user to put them on, keep them charged, or keep them clean; therefore, the feasibility of implementing these devices into ADS-equipped CMVs is questionable. Similarly, CMV drivers frequently enter and exit the vehicle to unload cargo and interact with customers, so any device that requires constant removal or adjustment would be especially bothersome. Another valid measurement of drowsiness, often used in the medical field, is monitoring electrical brain activity.(109) Using an electroencephalogram (EEG), the activity of theta band (4–8 Hz), which is associated with drowsiness, can be compared to the beta band (13–25 Hz), which is associated with alertness, to measure drowsiness. Awais et al.(110) combined an EEG sensor that measured brain activity and an ECG sensor that measured HRV and achieved a 90% accuracy rate for detecting drowsiness, which illustrates a common understanding that combining methods is more effective than using a single indicator. However, EEG and ECG devices are highly invasive when considering the driving environment. Some research has investigated the effectiveness of wearable technology or sensors that are integrated into steering wheels, seat belts, or seats, but the motion artifacts from wearable technology testing can decrease the clarity of the signals.(111, 112, 113, 114) Jeanne et al.(115) investigated the use of a camera-based HR monitoring system in the variable lighting conditions that characterize the driving environment. An IR-based remote photoplethysmography (PPG) camera system was used to detect micro-blushes in the skin of a driver to measure the HR and HRV. The authors achieved a 99% accuracy rate when comparing this with ground truth metrics. Another study achieved similar results by using PPG imaging.(116) Although HR has shown less correlation with drowsiness than HRV, there are studies that have shown correlation between decreased HR and self-rated sleepiness.(117) Considering the improvements from combining multiple metrics, a case can be made for improving the validity of HR as a measure of drowsiness by combining it with other camera-based indicators.

Behavioral indicators of drowsiness are more easily identified using camera-based methods. Wierwille and Ellsworth(118) developed a continuum of rating drowsy behaviors called the Observer Rating of Drowsiness (ORD). This continuum defines the stages of drowsiness by observable mannerisms such as rubbing the face or eyes, scratching, glassy-appearance, fixed gazes, and eventually prolonged eye closures, lack of activity, and microsleeps. These observations were made by human raters, and the study concluded that rater assessment is a viable method of drowsiness assessment using video images of the vehicle operator. In an experiment reviewing naturalistic driving data, drowsy drivers were classified based on similar observable behaviors such as blink rate, yawning, stretching, and heaviness of the eyelids.(119) Barr et al.(120) used a computer vision algorithm that tracks facial features and body movements to identify instances of drowsiness. Considering the results from Wierwille and Ellsworth, future machine learning algorithms may act as “raters” to provide drowsiness measures in real time. Several eye-based metrics have shown potential in drowsiness monitoring due to the relationship between eye movements and sleep stages.(121) Hanowski et al.(122) referred to the percent of eye closure (PERCLOS) as the “gold standard” of drowsiness detection and argued that it is the most valid driver-based drowsiness measure. PERCLOS is the percentage of eye closures over the pupil over time where drowsiness is defined as the amount of time in 1 minute that the eyes are at least 80% closed. This measure describes eye behavior as “droops,” as opposed to blinks, to characterize the slower movement of the eyes as a human becomes drowsy.(123) Dinges et al.(124) found that PERCLOS was the only drowsiness metric evaluated that consistently covaried with the validation criterion for drowsiness. Hanowski et al. mentioned that although PERCLOS is a highly valid measure for drowsiness, the limiting factor is the quality of the sensor used to measure PERCLOS due to the highly dynamic driving environment (e.g., lighting variation) and driver variability (glasses, hats, etc.). Therefore, the DSM effectiveness can only be as strong as the technology being used, and the strongest technologies are those that account for this dynamic driving environment.

Meyer and Llaneras[125] recognized that using more "gross level" behavior such as head position, mirror checks, yawning, or stretching may be supplementary information that can corroborate the decision to classify a driver as drowsy. Several studies have used drivers' facial expressions (e.g., brow raising, yawning, jaw drop) gathered from IR-camera video recordings to classify a driver as drowsy.[126,127,128] Lew et al.[129] found that drivers actually yawned less in the moments leading to critical drowsiness, not more; therefore, yawning may only be indicative of the earlier stages of drowsiness and not a reliable indicator of late-stage drowsiness. This study also supported the conclusion that blink rates such as PERCLOS and slow blinking were the most accurate determinants of drowsiness across all participants.

Overall, it seems the least invasive method for determining drowsiness is using an IR camera to capture PERCLOS, HRV, or facial movements. However, further innovation in less intrusive technology such as wearables or integration into steering wheels, seats, or seat belts may put EEG, ECG, and other physiological measures at the forefront of drowsiness detection in DSM systems.

5.4.1.5 Driver State Mental Workload and Fatigue

As mentioned previously, drowsiness and fatigue are not synonymous in this paper. Much of the literature on fatigue is really referencing drowsiness, or the physiological urge to fall asleep. This section defines fatigue as it is related to cognitive load, or mental workload. Williamson et al.[130] defined fatigue as the state of reduced mental alertness that impairs performance of cognitive and psychomotor tasks, including driving. According to the Yerkes–Dodson law (Figure 45), the optimal state of an operator is enough stimulation to stay engaged in the driving task without being bored or over-stressed.[131]

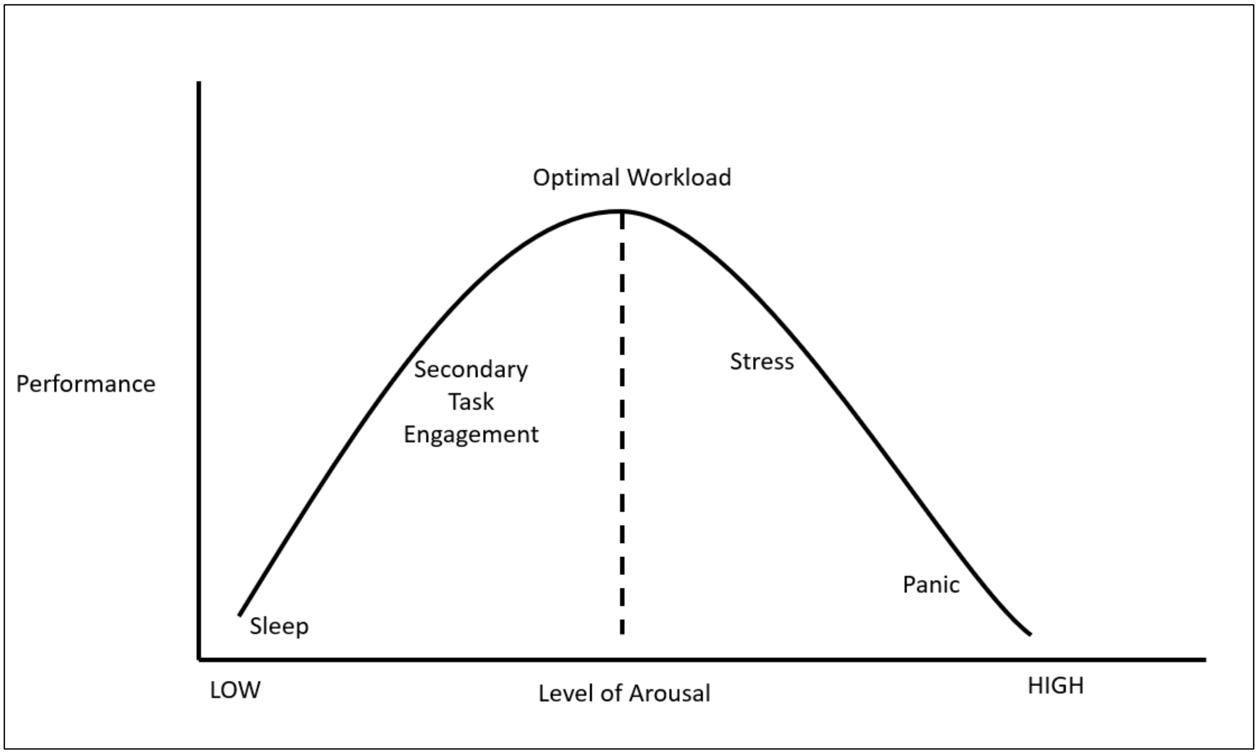

Figure 45. Diagram. Illustration of the Yerkes-Dodson Law of Arousal. As arousal level increases from sleep, the performance level increases until it reaches an optimal state. As arousal increases past this optimal state, performance decreases due to overloading of limited resources.

Therefore, with high-level automation, one of the main concerns for safety operators is the monotony of monitoring an ADS-equipped CMV without really "driving." Low vigilance can impact a driver's reaction time, efficiency, decision-making capabilities, situational awareness, and, therefore, safety.(132,133) Additionally, to mitigate fatigue and drowsiness, drivers naturally tend to engage in secondary tasks to generate stimulation, potentially leading to distraction-related inattention errors that further decrease safety.(134) However, protective effects of hands-free phone use and CB radio use have been reported with CMV drivers.(135) These tasks may stimulate the driver enough to mitigate the effects of fatigue without adding to visual-manual distraction. It is important to note that safety operators are prohibited from common in-vehicle distractors such as cell phones and are even prohibited from non-task-related conversation with other passengers. Therefore, the current regulations on safety operators may be so stringent that they add to the performance decrement experienced by prolonged periods of vigilance. Statistics show that between 10% and 20% of all traffic crashes are due to drivers with a diminished vigilance level.(136) Protective effects of secondary task engagement specific to safety operators should be investigated, which may lead to alternative standards for safety operator behaviors.

The status of a human's cognitive workload is best assessed using physiological techniques. EEG results show that changes in alpha and theta waves indicate high cognitive load.(137) Yamamoto and Matsuoka(138) showed decreases in performance occur when long-lasting theta waves are present in EEG results. HR and HRV are also shown to increase with higher driver workload, and decreased HR and HRV are correlated with low driver workload.(139,140,141) Although physiological indicators are highly indicative of fatigue, there is still an issue with the intrusiveness of the technology that make it unrealistic in real-world driving environments. Wierwille[142] suggested that computer vision is the most promising noninvasive driver monitoring technology for monitoring driver alertness. Rahman[143] used a video-based computer vision system and IR cameras to achieve a correlation of 0.96 between HR, saturation of peripheral oxygen (SpO2) monitoring, and fatigue measures. Eye-based metrics are also highly correlated with fatigue and mental workload. Barr et al.[144] used computer vision to assess PERCLOS with an IR camera. Wang et al.[145] used an IR-illuminated space with a high-definition camera to track eye blinking and closures, the 3D gaze of the eyes, and head/facial feature positions even under highly variable lighting conditions characteristic of a driving environment. Nakano et al.[146] illustrated that eye blink frequency increases as cognitive load increases. The study found that the average person spontaneously blinks at a rate of 15 to 20 times per minute, so an increase in this rate is usually an indicator of increased cognitive load. Another important consideration of fatigue is that the likelihood of experiencing fatigue increases with task time.[147] Therefore, the machine learning algorithms assessing the state of the driver should consider the length of time the driver has been on the road.

5.4.1.6 Driver State: Emotions

There is not a common definition of emotion in the literature. Many authors have recognized the difficulty in producing a consistent definition of emotion due to the subjective and multifaceted nature of human beings.[148] Young[149] argued that the reasons for this difficulty are the variations in perspectives and the idea that emotions are individually experienced. For the purposes of this paper, emotion is defined as the “mood” of a driver, or the arousal of a driver based on external or internal circumstances. The four most commonly researched driving-related emotions are happy, sad, angry, and neutral.[150,151] Zimasa[152] emphasized the relationship between mood and attention. The author argued that as mood changes, the attention placed on the driving task is diminished as the person diverts attention to the cause of the mood-altering event. The impacts of aggressive driving and road rage are well-established effects of negative moods.[153] Knapton[154] stated that the risk of a crash is increased by 14% when a driver is experiencing emotions such as sadness or anger, which is correlated with effects such as aggressive driving and road rage. Dingus et al.[155] analyzed naturalistic driving data and found that drivers exhibiting clearly negative emotions such as anger, sadness, crying, or emotional agitation increased crash risk by 9.8 times. Techer et al.[156] showed that drivers of higher levels of ADS-equipped vehicles tended to grow frustrated with the “cautious” driving style of the vehicle and lack of control. Van Huysduynen et al.[157] supported this idea by adding that drivers of lower-level ADS-equipped vehicles take control when they feel the driving style of the vehicle is disrupting the flow of driving. This is of particular interest to safety operators due to the novelty of the vehicles being tested. These drivers may grow frustrated with the behaviors of drivers around the vehicle and the subject vehicle’s ADS.

Anger and stress cause a high arousal state for the body and are well monitored through physiological metrics.[158] HR and electrodermal activity are the indicators with the highest correlations to high-arousal emotions.[159,160] As mentioned previously, the limiting factor in using devices measuring HR and electrodermal activity is the sensor, as it must (1) accommodate the variability in the driving environment, (2) not impede the movement or visibility of the driver, and (3) be comfortable to wear in real-world working conditions. For these reasons, emotion detection currently relies on the idea that facial expressions are an outward display of a driver's emotions.[161] Gao et al.[162] proposed a real-time driver emotion monitoring system using a camera-based method and a highly trained convolutional neural network to analyze facial expressions. Kowalczuk et al.[163] used a similar method by exploiting the facial emotion recognition (FER) algorithm that assesses a person's emotional state by collecting facial landmark information. This study pointed out that the detection accuracy and classification of emotional state based on facial features is only as capable as the machine learning algorithm being used to assess it. Similarly, the driver's head position can decrease the accuracy of the computer vision information acquisition. Therefore, when considering which method to use in a DSM application, technology is the limiting factor. Tavakoli et al.[164] noted an interesting caveat in the capability of emotion detection using facial features. The authors emphasized the individual nature of human expression and illustrated that natural face states may mimic expressions of anger when the person is actually experiencing a neutral state. Similarly, some authors argued that there are cultural variations in the appearance of basic facial expressions of emotion between Western and Eastern cultures.[165,166,167] These findings support the need for combined data sources such as physiological measures with diversely trained facial detection algorithms to classify a driver's emotional state more accurately across all driver types.

5.4.1.7 Driver State: Under the Influence

Halin et al.[168] defined driving under the influence (DUI) or driving while intoxicated (DWI) as the operation of a vehicle by a driver who has consumed alcohol or drugs to the point where their performance is significantly impaired compared to someone who had not consumed alcohol or drugs. In 2018, 25% of fatal motorcycle crashes and 21% of fatal light-vehicle crashes involved a blood alcohol concentration (BAC) of 0.08.[169] The prevalence of DUI among CMV drivers is lower, as 3% of CMV drivers involved in fatal crashes had a BAC of 0.08 or higher.[170] This may be because CMV drivers are considered to be professional drivers and their legal BAC limit is 0.04. However, in a study conducted by Crouch et al.,[171] fatal CMV driver crashes were analyzed in eight states over a 1-year period. One or more drugs were detected in 67% of the drivers, and 33% had detectable blood concentrations of psychoactive drugs/alcohol. The most commonly found drugs were alcohol followed by cannabinoids. If the delta-9 concentration of 1.0 ng/mL and/or a BAC of 0.04 or higher were present, the impairment of the driver was found to be the cause of the crash.

The majority of drug- and alcohol-related traffic incidents are found after the fact. A proactive, real-time approach to monitoring the drug and alcohol use of a driver should be considered. The current standard for preventing drunk driving is using an alcohol interlock device (AID) on a vehicle. The driver is expected to provide a deep-lung breath sample by blowing into a plastic tube before starting the vehicle. Ferguson and Draisin[172] pointed out that this process, although highly effective and accurate, takes time and is difficult for some drivers due to the volume, flow, and exhalation time. Similarly, they commented that these systems need frequent calibration and constant maintenance due to the condensation of breath. Fournier et al.[173] proposed a driver alcohol detection system for safety (DADSS) that measures a driver's BAC non-invasively through either tissue spectrometry or distant spectrometry. This solution does not, however, allow for the real-time monitoring of the state of the driver and does not prevent the driver from drinking alcohol after starting the engine. Celaya-Padilla et al.[174] created a continuous monitoring device by using a metal oxide semiconductor that detects the presence of alcohol vapor in a driver's breath. This method achieved an accuracy of 0.989, but the authors mentioned that improvements could be made by moving the sensors closer to the driver. Several studies have investigated camera-based methods that identify saccadic eye movements and gaze position of the driver.[175,176] Sussman[177] found success using eye unsteadiness as a method for alcohol detection. Identifying an intoxicated driver can also be achieved by using an IR camera that capitalizes on the expansion of blood vessels in the forehead when a person is under the influence of alcohol, the pupil dilation of the driver, and differences in body temperature.[178,179,180] Most research has been conducted in the context of alcohol impairment; monitoring the impacts of over-the-counter drugs and drugs in general is not well understood in the driving context.

5.4.1.8 Summary of Literature

Table 29 summarizes the indicators and sensors used in DSM literature to define each of the five driver states. The indicators are characteristics of humans (behavioral or physiological) that can be used to signify a driver's state. The metrics are the specific trends or methods used to determine whether the indicator is signifying a negative or neutral state. Sensors are the technology used to capture or assess the information.

Table 29. Summary of findings.

Driver State	Indicators	Metrics	Sensors
Distraction	Head Position	Looking at driving-relevant information	IR Camera + Computer Vision
Distraction	Gaze Behavior	PRC	IR Camera + Computer Vision
Distraction	Gaze Behavior	PRC	Eye Tracking
Distraction	Gaze Behavior	Gaze Duration	IR Camera + Computer Vision
Distraction	Gaze Behavior	Gaze Duration	Eye Tracking
Distraction	Gaze Behavior	Attentional Buffer	IR Camera + Computer Vision
Distraction	Gaze Behavior	Attentional Buffer	Eye Tracking
Distraction	Posture	Hand & Feet Position	IR Camera + Computer Vision
Distraction	Posture	Hand & Feet Position	IR Camera + Computer Vision
Distraction	Posture	Hand & Feet Position	Seat Monitor
Distraction	Object Detection	Cell Phone, Food/Drink, Cigarette, Purse, etc.	IR Camera + Computer Vision
Distraction	Pupil Diameter	Increase/Decreased Size	IR Camera + Computer Vision
Distraction	Pupil Diameter	Increase/Decreased Size	Eye Tracking
Distraction	HRV	Increase/Decrease	IR Camera + RGB Camera + Computer Vision
Distraction	HRV	Increase/Decrease	Wearable Monitor (Watch, Ring, etc.)
Distraction	HRV	Increase/Decrease	ECG Electrodes on Body
Distraction	HRV	Increase/Decrease	Integrated Sensor (Steering Wheel, Seat Belt, Seat)
Drowsiness	Posture	Slouching, Stretching, Touching Face, Slapping Face	IR Camera + Computer Vision
Drowsiness	Facial Features	Droopy Eyes, Mouth Open, Brow Angle, Eyes Open/Closed	IR Camera + Computer Vision

Driver State	Indicators	Metrics	Sensors
Drowsiness	PERCLOS	Slow Eye Closure Rate	Eye Tracking
Drowsiness	PERCLOS	Slow Eye Closure Rate	IR Camera + Computer Vision
Drowsiness	HR	Decrease	IR Camera + RGB Camera + Computer Vision
Drowsiness	HR	Decrease	Wearable Monitor (Watch, Ring, etc.)
Drowsiness	HR	Decrease	ECG Electrodes on Body
Drowsiness	HR	Decrease	Integrated Sensor (Steering Wheel, Seat Belt, Seat)
Drowsiness	HRV	Decrease/Increase	IR Camera + RGB Camera + Computer Vision
Drowsiness	HRV	Decrease/Increase	Wearable Monitor (Watch, Ring, etc.)
Drowsiness	HRV	Decrease/Increase	ECG Electrodes on Body
Drowsiness	HRV	Decrease/Increase	Integrated Sensor (Steering Wheel, Seat Belt, Seat)
Drowsiness	Brain Activity	Theta & Beta Wave Activity	EEG Electrodes on Body
Drowsiness	Brain Activity	Theta & Beta Wave Activity	EEG Headband/Hat
Drowsiness	SpO2 level	Decreases	IR Camera + RGB Camera + Computer Vision
Mental Workload	PERCLOS	Slow Eye Closure Rate	Eye Tracking
Mental Workload	PERCLOS	Slow Eye Closure Rate	IR Camera + Computer Vision
Mental Workload	HR	Increase	IR Camera + RGB Camera + Computer Vision
Mental Workload	HR	Increase	Wearable Monitor (Watch, Ring, etc.)
Mental Workload	HR	Increase	ECG Electrodes on Body
Mental Workload	HR	Increase	Integrated Sensor (Steering Wheel, Seat Belt, Seat)
Mental Workload	HRV	Increase/Decrease	IR Camera + RGB Camera + Computer Vision
Mental Workload	HRV	Increase/Decrease	Wearable Monitor (Watch, Ring, etc.)
Mental Workload	HRV	Increase/Decrease	ECG Electrodes on Body
Mental Workload	HRV	Increase/Decrease	Integrated Sensor (Steering Wheel, Seat Belt, Seat)
Emotions	Facial Expressions	Happiness, Neutral, Anger, Sadness	FER Algorithm & IR Camera + Computer Vision
Emotions	HR	Increase/Decrease	IR Camera + RGB Camera + Computer Vision
Emotions	HR	Increase/Decrease	Wearable Monitor (Watch, Ring, etc.)
Emotions	HR	Increase/Decrease	ECG Electrodes on Body
Emotions	Electrodermal Activity	Increase for Negative Emotions	Electrodermal Electrodes on Body
Emotions	Electrodermal Activity	Increase for Negative Emotions	Integrated Steering Wheel
Under the Influence	Gaze Behavior	Erratic Eye Movements, Unsteadiness of Eyes	Eye Tracking

Driver State	Indicators	Metrics	Sensors
Under the Influence	Gaze Behavior	Erratic Eye Movements, Unsteadiness of Eyes	IR Camera + RGB Camera + Computer Vision
Under the Influence	Pupil Dilation	Pupil Size Increases w/ Drugs & Alcohol	IR Camera + Computer Vision
Under the Influence	Pupil Dilation	Pupil Size Increases w/ Drugs & Alcohol	Eye Tracking
Under the Influence	Tissue Spectrometry	Imaging of Micro-blushes	High-resolution Imaging + Computer Vision
Under the Influence	Air Vapor Analysis	Alcohol Vapors Present in Air	Semiconductor Vapor Sensors
Under the Influence	Blood Vessel Dilation	Blood Vessels Increase in Size	IR Camera + RGB Camera + Computer Vision
Under the Influence	Blood Vessel Dilation	Blood Vessels Increase in Size	IR Camera + Computer Vision
Under the Influence	Blood Temperature	Blood Temperature Increases w/Alcohol	Temperature Camera + High-resolution Imaging + Computer Vision

5.4.1.9 Evaluating the Driver Monitoring System

Halin et al.[(181)] divided driver monitoring into two components: (1) characterizing the state of the driver and (2) deciding what action to take based on this assessment. The focus of this paper was only on the first piece. The second component delves into the study of providing feedback to the driver. Boyle et al.[(182)] asserted that the main goal of the DSM is to improve driver performance and safety on roadways. This sentiment falls under the second piece of driver monitoring, for performance and safety cannot be impacted unless the driver is aware of his or her degraded performance. Therefore, when considering the evaluation of DSM systems, this paper looked exclusively at metrics involving the assessment of technology, not the behavior of the driver after receiving feedback. Although the reaction of the ADS is important, it is considered out of scope as the purpose of this report guideline is to understand DSM technologies.

Bowman et al.[(183)] compiled a list of several specifications a DSM system must meet to be assessed appropriately. First, the DSM system must be robust or adaptable to the various environmental conditions in a vehicle such as illumination levels, different operators, driver characteristics (e.g., skin color, glasses), driver behaviors, vehicle vibrations, and temperatures. Second, the technology must hold high construct validity and accuracy of the real-time driving environment. The device should accurately, continuously, and in real-time measure the intended state(s) by minimizing the disparities between the estimated state and the true state of the operator while simultaneously minimizing the prevalence of false alarms and misses. Third, the technology must meet a human's interface needs. For example, the device should not distract from the driving task or impede the driver's vision of the roadway or mobility and must also be easy for an operator to interact. Fourth, the device should not be cumbersome to calibrate or maintain, nor should it require high costs to maintain. Barr et al.[(184)] added to this list by including three more valuable design requirements. The monitoring system should consider the security of the driver in terms of protecting sensitive information that may be captured by the system. The device itself should preferably be automatically activated and deactivated when the vehicle is powered on and off. However, if manual activation and deactivation are necessary, it should not be cumbersome for the driver. Similarly, it should not allow intentional or unintentional misuse of the system. Finally, the authors stressed the importance of driver acceptance and stakeholder buy-in. They asserted that regardless of the safety benefits of the system, successful deployment is unlikely if the users do not deem the device acceptable.

Combining works from Dinges and Mallis,[(185)] Whitlock,[(186)] Bekiaris et al.[(187)], and Barr et al.[(188)] conceptualized a methodology using five criteria to assess user acceptance of new and emerging technologies. The two most relevant to DSM are perceived value and advocacy. Perceived value is the extent to which drivers view the benefit of the technology as outweighing possible costs. It is important for drivers to understand the safety benefits of monitoring and the data confidentiality of the information being collected about their driving behavior. Advocacy is the desire to endorse their fleet's purchase of the new technology. Advocacy is important because although perceived value may be high, the willingness of drivers to support the process of obtaining it is just as important. Peng et al.[(189)] investigated the perception and attitudes of 37 CMV drivers towards DSM systems. Over half of the participants viewed the DSM as improving safety and regarded the system in a mostly positive light. Six of the participants were classified as overly trusting of the DSM system and were strong proponents of its implementation. Eight of the participants viewed the system negatively and were concerned with the privacy issue of being continuously monitored. Ghazizadeh et al.[(190)], Greenfield et al.[(191)], and Camden et al.[(192)] found similar results with issues of privacy. Therefore, it is recommended that fleets educate their drivers on privacy protection, their role in safety, and the functions of the system in detail before implementing this new technology.

5.4.1.10 Literature Review Conclusions

The purpose of this literature review was to determine thresholds of driver characteristics such as fatigue, drowsiness, distraction, negative emotions, or impairment that may impact a safety operator's readiness to take over an ADS-equipped CMV. Additionally, the review considered the differences in thresholds of driver states necessary for a safety operator who is presumed to be a highly trained individual versus a typical CDL holder supporting operations onboard an ADS-equipped CMV.

Considering the complexity of the driving environment, many technologies measuring physiological indicators are currently too invasive to monitor driver state in real-world, everyday driving environments. For example, some of the most accurate indicators of driver state such as EEG or ECG require skin contact or other invasive eyewear/headwear. The least invasive indicator is a wearable watch or ring to monitor HRV, yet the compliance rate of these devices has not been investigated with safety operators. Safety operators have been distinguished from the general CMV professional driving population due to their rigorous training on vigilance and ADS technology, so it is unclear whether wearable technology would have higher compliance rates with this population. Despite the difficulties with physiological measures, IR camera-based systems show great potential for their ability to monitor a wide range of driver states, including some physiological measures, in a robust and adaptive manner. These camera-based sensors rely on computer vision to classify objects, facial features, or body posture, and a machine learning algorithm determines whether the characteristics of the driver represent an impaired state. Therefore, the DSM systems with the most potential use deep learning algorithms to classify data captured by advanced external sensors in real time and in highly variable conditions.

Overall, there are gaps in the literature for understanding DSM as it applies to safety operators; however, DSM systems show promise for integration with ADS-equipped CMVs. As developers of ADS-equipped CMVs continue to seek safety assurance for their vehicles with new features and operational design domains, the role and standards for safety operators will continue to evolve through iterative testing and deployment. Similarly, different ADS fleets have individual standards for their safety operators, which may not be reflected in the AVSC standards. For example, the AVSC[(193)] recommends certain driver behaviors such as keeping hands on the wheel or taking frequent breaks, yet individual fleets choose the exact rules for their drivers. Moving forward, investigating currently available DSM systems for their applicability to safety operators is necessary to understand how these defining metrics of driver state support the safe driving of safety operators in the future. Additionally, gaining an understanding of the exact responsibilities of a safety operator across various fleets through a task analysis or function allocation should be done to correctly design a DSM system for this population.

5.4.2 Technology Scan

The purpose of this technology scan was to identify commercially available DSM technologies that can be applied to and inform the safe operation of ADS-equipped CMVs. The scope of the scan is limited to technologies that monitor driver characteristics identified by the literature review (i.e., distraction, impairment, drowsiness, mental workload, and emotions) and technologies that could be used to assess the ability of a safety operator to take over control of an ADS-equipped CMV during a planned or unplanned ADS disengagement. For example, monitoring HR alone may not provide a full understanding of driver state; however, combining video monitoring, HR, and manual control checks may accurately illustrate the condition of the driver and their ability to take over driving tasks. This technology scan established what DSM technologies and systems are available and their functions, capabilities, limitations, and use cases when integrated and applied with ADS operations.

5.4.2.1 Technology Scan Results

An initial internet search was conducted using various publicly available search engines. The following keywords were used to find company websites mentioning DSM systems: *driver monitoring system*, *driver monitoring*, *video-based monitoring*, *commercial vehicle driver monitoring*, *driver impairment monitoring*, *fleet camera systems*, *driver alcohol sensors*, *in-vehicle alcohol sensor*, and *in-vehicle drug sensor*. Each website that mentioned DSM systems or some form of monitoring system was included in a document along with a link to the site. The results from this initial scan are shown in Table 30.

Table 30. Full list of providers and technologies from the initial results of the technology scan.

Vendor	DSM Technology
Aptiv	Driver Monitoring System
AT&T	FleetComplete Vision
Azuga	SafetyCam
BlackVue	BlackVue AI-powered Driver Monitoring System
BlueArrow Telematics	SurfSight
Brickhouse Security	Driver-facing Camera

Vendor	DSM Technology
CalAMP	Vision AI-driven dash video and analytics
Cambridge Mobile Telematics	Driver Monitoring System
Clearpath GPS	Driver Facing Camera
Coretex	Driver Facing Camera
Denso	Driver Monitoring System
E-Drive Technology	E-Driver Facing Camera
Faurecia	Active Wellness
FieldLogix	Wireless Dash Cam
Fleet Complete	Driver Facing Camera
FleetCam	FleetCam
FleetHoster	FleetFlix AI + Pro Dash Cam
FleetOptix	Driver Facing Camera
Forward Thinking	Fleetcam 3.0
Garmin	Garmin Instinct Watch
Geotab	Third-party Dash Cams
GPS Insight	Driveri
GPSTrackit	VidFleet
GreenRoads	VideoSense
Harman	Ready Care
HD Fleet	GOS Tracking Cam (Same as FleetOptix)
Insight Mobile Data	Driver Facing Camera
ISR Tech	Driver Facing Camera
JJKeller	Driver Facing Camera
Linxup	Dashcam
Lytx	DriveCam
Lytx	SurfSight
MixTelematics	Mix Vision
Motive	AI Dash Cam
Nauto	AI Cam
Netradyne	Driveri
NexTraQ	Driver Facing Camera
Orbcomm	Driver Facing Camera
Orion Fleet Intelligence	Orion Vision: AI Dashcam
Pedigree Technologies	Driver Facing Camera

Vendor	DSM Technology
Rand McNally	Driver Facing Camera
RoadHawk	Driver Facing Camera
Rosco Vision Systems	DV6 “Dual Vision”
Samsara	AI Dash Cam
Seeing Machines	Guardian
SkEYEwatch	SkEYEvue AI-powered smart dash cam
SmartCap	LifeBand
SmartEye	SmartEye Driver Monitoring
SmartWitness	KP2: Modular Dual Camera Solution
Solera	SmartDrive
Spireon FleetLocate	FL360 Camera
SureCam	SureCam
Teletrac Navman	Driver Facing Camera
TitanGPS	AI Fleet Smart Camera System or In-CAB
Trac Star International	SmartWitness
TrackNet	Truck Dash Cam (Same as FleetOptix)
Trimble	Cabin Intelligence Monitor (CIM)
Verizon Connect	Intelligent AI Dashcam
Vision Track	VT3000-AI
Zenduit	Zenducam AD Plus
Zen-tinel	Surveillance Cam
Zonar System	Zonar Coach
Zonepro	Zonepro ADAS And Driver’s Camera

Ineligible technologies were those that could not be integrated or applied to a SAE L4 ADS. For example, technologies were removed from the list if they used only vehicle-based metrics (e.g., lane departures, speed) to determine driver state. In an SAE L4 AV, the vehicle is assumed to have control over longitudinal and lateral functions; therefore, these functions would not be influenced by driver state. Additionally, technology was removed if it did not assess the state of a driver continuously and in real time. Some technologies merely record events for later review, which would not proactively determine a driver’s state before an incident. Lastly, technologies were removed if they used invasive sensors to measure driver state. Excessively invasive designs included headbands/caps with electrodes, sensors that covered the fingers, wires that extended from the hand, wrist, or body, and glasses or headwear. These technologies were excluded because they rely on the drivers to properly calibrate and adjust the devices, which may negatively impact the compliance rate. Furthermore, these technologies may cause discomfort for the driver or fail to address the individual differences in drivers’ characteristics. The remaining companies were categorized based on the items in Table 31.

Table 31. Description of each of the metrics collected from the DSM technologies.

Characteristic	Definition	Examples
1. Driver State Metrics	The data collected about the physical condition of the driver that can be used to determine state	HR, head position, eye glances, etc.
2. Driver State Evaluation	The states of the driver that can be classified by the system	Visual distraction, manual distraction, drowsiness, intoxication, etc.
3. Sensors	The method for collecting driver state metrics data	Cameras, IR lights, HR monitor, etc.
4. Driver Involvement	Yes/No – Does the technology require driver involvement?	Frequent calibration, turning the system on/off each drive, wearing a device, etc.
5. Stand-alone or Combined	The capability of the identified technology to assess DSM independently and effectively or the need to be used in conjunction with another technology	HR monitor – must be combined Video-based monitoring – stand-alone

Each remaining technology was assessed based on these characteristics. Table 32 shows the results from the final technology scan. Each column in Table 32 represents a different metric collected from each of the DSM technologies identified in each row. The results from this table were identified using public websites belonging to each of the technology developers listed in the rows of the table. The wording used in each category is standardized due to the variability in terminology from each of the DSM companies. For example, some DSM companies used the term “fatigued” to describe the stages leading to falling asleep; however, the term “drowsy” is used to describe that state here. In the Driver Involvement column, the term “unknown” is used when a company’s website failed to mention the maintenance or driver action required. The term “unknown – assumed minimal requirements” is used when the company’s website mentioned “easy maintenance” or otherwise indirectly mentioned simple driver involvement but did not detail the exact requirements. Otherwise, the driver involvement is described. Overall, the term “unknown” is used when a company’s website did not provide enough information to make a conclusion about the capability of the DSM technology in the respective category.

Table 32. Final technology scan results.

Technology	Driver State Metrics	Driver State Evaluation	Sensors	Driver Involvement	Stand-Alone/Combined
BlackVue AI-powered Driver Monitoring System	Head Position	Visual Distraction Hand-Held Cell Phone Distraction Drowsy	Camera AI Infrared LEDs	Unknown – Assumed Minimal Requirements	Combined
DriveCam	Head Position	Visual Distraction Manual Distraction	Camera AI Infrared	No	Combined
Driveri	Facial Recognition	Distraction Drowsy	Camera AI	Unknown – Assumed Minimal Requirements	Combined
Field Logix Wireless Driver Cam	Unknown	Visual Distraction Manual Distraction	Camera AI Infrared	No	Combined
FleetCam	Eye Movement Head Position	Visual Distraction Manual Distraction Drowsy	Camera AI	Unknown – Assumed Minimal Requirements	Combined
FleetCam 3.0	Eye Movement Head Position	Visual Distraction Manual Distraction Drowsy	Camera AI Infrared	Unknown – Assumed Minimal Requirements	Combined
FleetComplete Vision	Head Position	Visual Distraction	Camera AI	Unknown	Combined
FleetFlix AI + Pro Dash Cam	Unknown	Visual Distraction Hand-Held Cell Phone Distraction Drowsy Cell Phone Use	Camera AI Infrared	Unknown – Assumed Minimal Requirements	Combined

Technology	Driver State Metrics	Driver State Evaluation	Sensors	Driver Involvement	Stand-Alone/Combined
FleetOptix Driver Facing Camera	Head Position Facial Landmarks Eye Movement	Visual Distraction Manual Distraction Drowsy	Camera AI Infrared	Unknown – Assumed Minimal Requirements	Combined
Garmin Instinct Trucker Watch	HR Respiration Rate Pulse Oxygen Energy Monitor Stress Monitor Sleep Monitor	Stress	Wearable Watch	Yes	Combined
JJ Keller Dash Cam PRO advanced	Unknown	Visual Distraction Drowsy	Camera AI	No	Combined
Motive AI Dual-Facing Dash Cam	Head Position	Visual Distraction	Camera AI Infrared	No	Combined
Orion Vision AI Dashcam	Eye Movement Head Position Facial Recognition	Visual Distraction Hand-Held Cell Phone Distraction	Camera AI Infrared	Unknown – Assumed Minimal Requirements	Combined
Rosco DV6	Eye Movement Head Position Facial Landmarks	Visual Distraction Drowsy Hand-Held Cell Phone Distraction	Camera AI Infrared	No Manual Updates	Combined
Samsara AI Dashcam	Head Position	Visual Distraction	Camera AI Infrared	No	Combined
Guardian	Eye Movement Head Position	Visual Distraction Drowsy	Camera AI	No	Combined

Technology	Driver State Metrics	Driver State Evaluation	Sensors	Driver Involvement	Stand-Alone/Combined
SkEYEvue AI Powered Smart Dash Cam	Unknown	Visual Distraction Drowsy Manual Distraction	Camera AI Infrared	Unknown	Combined
Smart Drive	Eye Movement Head Position	Visual Distraction Drowsy	Camera AI Infrared	Unknown	Combined
Smart Witness KP2: Modular Dual Camera Solution	Head Position	Visual Distraction Drowsy	Camera AI Infrared	Unknown	Combined
SmartEye Driver Monitoring	Eye Movement Head Position Body Posture	Visual Distraction Manual Distraction Drowsiness	Camera AI Infrared	Yes	Combined
SurfSight	Head Position Facial Landmarks	Visual Distraction Drowsy	Camera AI Infrared	No	Combined
Trimble Cabin Intelligence Monitor (CIM)	Unknown	Visual Distraction Drowsy	Camera AI Infrared	Unknown	Combined
Verizon Intelligent AI Dashcam	Unknown	Visual Distraction	Camera AI Infrared	Unknown	Combined
VideoSense	Unknown	Visual Distraction Manual Distraction Drowsy	Camera AI	No	Combined
VidFleet	Eye Movement Head Position	Visual Distraction Manual Distraction	Camera AI Infrared	Unknown	Combined

Technology	Driver State Metrics	Driver State Evaluation	Sensors	Driver Involvement	Stand-Alone/Combined
Vision Track VT3000-AI	Unknown	Visual Distraction Manual Distraction Drowsy	Camera AI Infrared	Unknown	Combined
Zenduit Zenducam AD Plus	Head Position Facial Landmarks	Visual Distraction Manual Distraction Drowsy	Camera AI Infrared	Unknown	Combined

5.4.2.2 Selection Criteria

To determine the most appropriate DSM for safety operators, the various technologies were assessed based on their ability to meet the criteria defining an ideal DSM system. These criteria were adapted from the evaluation standards for DSM systems defined by Bowman et al.(194) and the AVSC's(195) description of safety operators. The DSM technology should:

1. Assess a safety operator's level of drowsiness, level of distraction (cognitive, visual, manual, and auditory), emotional state, level of intoxication, and mental workload.
2. Be robust to the dynamic driving environment consisting of temperature changes, vibration, illumination changes, and varying safety operator characteristics (e.g., skin color, glasses, eye shape).
3. Assess the state of the safety operator continuously, in real time, and with high accuracy.
4. Not be cumbersome to calibrate or maintain, nor should it require high costs to maintain.

5.4.2.3 Technology Scan Conclusions

Currently, no commercially available DSM system meets all criteria for an ideal DSM system for a safety operator. First, none of the technologies capture all driver states. Most systems assess whether a driver is distracted visually or manually but fail to consider cognitive and auditory distraction. Most systems assess driver drowsiness using eye behavior or head position but do not attempt to measure physiological signs of drowsiness. No DSM systems currently offer alcohol/drug detection or mental workload assessments. HRV monitors and alcohol/drug monitors are available separately, but few companies consider their products in the driving context; therefore, many of the devices are cumbersome or require the user to engage with the device, which they could not do while driving.

To measure all driver states with the available DSM systems, a combination of technologies is needed. For example, a DSM system measuring distraction, drowsiness, and emotions can be combined with an external alcohol monitor and wearable watch that measures workload to capture all aspects of the driver's state. Second, most companies offering DSM systems mention robustness to temperature variation and vibration and include an infrared light for night driving, yet they fail to discuss variability in operator characteristics. Third, all the DSM systems in this review monitor the safety operator continuously and in real time; however, it is difficult to understand the accuracy of each of the technologies without a standardized comparison criterion. This aspect of the technologies would need to be tested further in an experimental design or more detailed analysis. Lastly, it is assumed that most camera-based DSM systems activate when the vehicle starts and deactivate when the vehicle is off, which would require no involvement from the driver. However, the websites rarely mention maintenance requirements or frequency of updating the AI algorithms.

Based on the evaluation criteria defined above, the Smart Eye Driver Monitoring System was used for testing in the next phase of research(196) in parallel with the Empatica smart watch.(197) This DSM system currently captures the states of drowsiness and both visual and manual distraction. Additionally, Smart Eye claims their DSM system stands up to vibration and difficult lighting conditions found in heavy vehicles. The Smart Eye system also uses gaze position, eye movement, and pupil size to determine a driver's state, which is a more robust measure of distraction and drowsiness than head position alone, which several companies use. Lastly, the Smart Eye website mentions easy installation, allowing drivers to install and interact with the system using a tablet.

The Empatica watch was selected to fit the needs of the study as well. When considering physiological measures, the selected device needed to be a non-intrusive item, such as a wearable smart watch device. Additionally, most smart watches currently available are designed for messaging and internet access; however, for data security during research, the watch selected needed to have a dedicated platform for data analytics and ensured security. Lastly, the Empatica watch has great battery life, measures several crucial data points such as HRV and EDA, and it is FDA approved. Although the Smart Eye and Empatica devices were used in testing, this selection does not imply endorsement of any Smart Eye or Empatica products mentioned in this report. Other systems may be desired for reasons not prioritized in this study.

The Smart Eye DSM system and Empatica device meet several criteria relevant to human drivers; however, it is unclear whether the exact needs of safety operator monitoring are being met. This is due to a lack of information on the tasks a safety operator performs during their ADS duties. This gap in knowledge illustrates the need for a task analysis of safety operator responsibilities across various ADS fleets. This task analysis would establish the exact states and activities a DSM system would need to monitor relevant to a safety operator.

5.4.3 Driver State Monitoring Industry Interviews

Currently, the AVSC recommends including a DSM system in ADS-equipped test vehicles to ensure a safety operator is fit to assume control during an emergency takeover request.(198) This requires DSM technology to accurately identify inappropriate driving behaviors and correct them in real time. As stated earlier, a literature review and technology scan were conducted to compile available information about state-of-the-art DSM systems. From these results, it is evident that the technology required to integrate DSM systems and ADS-equipped vehicles and to accurately monitor a safety operator is still developing. Additionally, it is unclear exactly what responsibilities a safety operator has at the wheel given the additional monitoring requirements of ADS technology with the rarity of failure events. In other words, it is unclear if the features of current DSM technologies are sufficient to monitor a safety operator given that DSM systems are designed for regular CMV drivers.

During this effort the research team sought to understand the role of safety operators and the present gaps in the technology used to monitor them. The objective of this phase was to connect research with industry practices by interviewing representatives from two critical sectors: ADS developers and DSM technology providers. The interviews gathered information about the integration of DSM into ADS-equipped CMVs through questions about barriers to integration, roles of a safety operator, and current use of DSM technology. The following section presents the processes and results of the interviews with DSM technology providers and ADS developers about DSM systems being integrated in ADS-equipped CMVs.

5.4.3.1 Interview Methodology

The team planned to interview up to nine representatives from each group using existing relationships with industry contacts. Many companies chose not to participate due to proprietary concerns. A total of seven representatives from DSM providers and three representatives from ADS developers agreed to participate in the interview process. All interviews lasted 30 minutes and were conducted via an online video platform.

The DSM providers were asked seven questions about their efforts to improve and integrate DSM technology. The ADS developers were asked 13 questions about safety operators and the possibility of DSM integration with their systems. The results from those questions are grouped by theme and presented below.

5.4.3.2 DSM Technology Providers

Terminology: To understand terminology used by individual companies, participants were asked if their company referred to their system as “DSM,” and if they did not, they were asked what they called the video technology used to assess driver state while driving. Only one of the seven participants said that their company specifically called their system DSM (14%). Two of the participants said that they called it a driver monitoring system, and another two said that they had different names for the system but would agree the capabilities were similar. All companies agreed that calling the technology a DSM system was appropriate. The exact names of the alternative technologies have been left out to protect the anonymity of the companies, but they all referenced specific features of the technology as opposed to the general term DSM.

Integrating DSM with ADS-equipped CMVs: Regarding DSM, the participants were asked whether their companies were exploring ways to integrate their systems with ADS-equipped vehicles. The responses to this question are shown in Figure 46. As shown in Figure 46, the majority (57%) of the participants indicated that their companies are not exploring ways to integrate with ADS-equipped vehicles. The main reason that these participants said they were not interested in integrating their systems with ADS-equipped vehicles was that it was not their business focus. They were primarily focused on providing aftermarket solutions for vehicles that are currently on the road.

As a follow-up question, the participants were then asked why they have or have not considered ways to integrate their systems into AVs. Many participants again cited the need to cater their systems to their current customers who drive non ADS-equipped CMVs and did not find it advantageous to explore AVs. Another participant claimed they were not exploring integration because their company focuses heavily on driver behavior coaching, which may become obsolete in the field of ADS-equipped CMVs, as the industry is moving towards driverless trucks. Other participants cited the desire to improve the depth of the current technology as opposed to the breadth of their operations.

For participants who indicated their companies were considering integration, the reasons for doing so varied. One reason was the upcoming European requirement of DSM in all new vehicles.[199] The other two reasons were more focused on the goal of DSM technology to improve safety: DSM systems could optimize the relationship between human drivers and ADSs by predicting when the human may need a break from the driving task to help prevent collisions, and DSM systems could help prevent human drivers from becoming complacent with ADS technology in their vehicles.

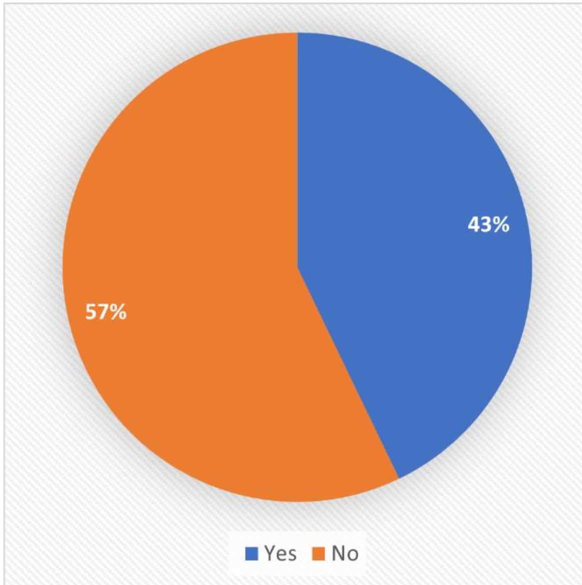

Figure 46. Chart. Percentage of responses to the question, "Is your company currently exploring ways to integrate driver state monitoring with autonomous vehicles?"

Barriers to Integration: Next, participants were asked about current barriers their company is facing in the efforts to improve DSM technology. There were two major trends in the answers to this question. The largest barrier that the participants mentioned was access to the right data to make improvements, which was indicated as a barrier by four of the participants. One participant mentioned the major trade-offs of making an aftermarket solution that is affordable while being small enough to fit on a windshield and processing enough data to make it accurate. Billions of data points are needed to understand the edge cases in human behavior that the providers need to detect, so large processors are needed to run through this data. Additionally, one provider mentioned there are issues with sensors on the vehicles being insufficient for collecting data and that some of the available data is proprietary. The participant emphasized that not only are the sensors insufficient, but many do not communicate properly with each other, especially with an aftermarket solution. These factors make using vehicle data for improvement difficult. Another barrier that participants noted was privacy laws, which were brought up by three of the participants. There is an issue with drivers not wanting the technology in their vehicles, so the providers need to try to gather data while protecting driver privacy.

Methods of Improvement: Participants were also asked what methods their company uses to improve DSM technology. The most common response to this question (57%) was using customer feedback to make improvements to their technology. The providers want to use information from customers to make sure they are targeting the most relevant improvements. Several companies utilize human review to check the decisions made by the software. The reviewers use customer feedback to flag the most relevant issues from reviews. Along with this, another method of improvement mentioned by one of the participants included scanning data for near misses and using this to look for early warning indications and patterns of behavior to improve precision for detecting certain behaviors. For example, if many drivers nod their head before falling asleep, instead of triggering an alert when the driver is fully asleep, alerts can begin when the driver first shows signs of drowsiness. A final method of improvement identified by one of the participants was using data from other DSM system providers, released research, and white papers to validate their findings and make sure they are moving in the right direction.

Methods for Testing Effectiveness: In addition to methods of improvement, the participants were asked what methods their companies are using to test DSM technology effectiveness. Most of the participants (86%) said that customer feedback was a method their company was using to test effectiveness. For example, if they notice a high level of negative feedback from their customers, this may indicate a need to adjust the algorithm or to do further testing. The second most common method among the participants (57%) was using large datasets to test their system's effectiveness. The new datasets help train their algorithms on edge cases, which helps improve effectiveness and accuracy. Then, along with these methods, participants also mentioned using live testing with drivers and simulations such as installing the systems in employee's vehicles.

Other Monitoring Factors: The last question participants were asked was whether their company had considered monitoring for other factors like emotions, alcohol use, or drug use. For alcohol and drug monitoring, 57% of the participants said that their companies are considering this type of monitoring. However, the other participants said that their companies are more focused on monitoring behaviors instead. Across the board, emotion monitoring was not an interesting factor to the companies. There was concern among the participants that it would be difficult to detect emotions, and that there would not be much that the system could do to try to change an operator's emotions. Additionally, emotional aspects could likely be identified through driving behavior, so there would not be much need for the DSM to look for emotional factors.

5.4.3.3 ADS Developers

Terminology: To ensure they understood the terminology being used in the interview, the first question ADS developers were asked was whether their company agreed with the name "safety operator" as someone who monitors an AV for possible failure. All three of the developers that were interviewed agreed with that naming convention.

Once the terminology was established, the developers were asked if they used safety operators in their fleets, and if so, they were asked how many safety operators were employed at their fleet. All three developers said they did use safety operators. All the companies shared the number of safety operators in their fleet; however, they did not feel comfortable with us publishing the number of safety operators, as this may reduce their anonymity. All companies had over five safety operators.

Team Driving: Next, the participants were asked if their safety operators operate in teams. Two of the three developers responded that their safety operators do not drive in teams, but they have a remote operator or dispatcher to interact with the safety operator. The last developer stated that their safety operators operate alone most of the time, but occasionally have a co-pilot or ride-along depending on the task.

Safety operator Training: The following question pertained to the type of training the safety operators received. Developers were asked where their safety operators were trained and whether they refer to the AVSC guidelines in training. All three of the developers indicated that they do their safety operator training in-house. One participant specifically noted that they do both an in-classroom training and road testing, where safety operators demonstrate their ability to do maneuvers. Only two of the developers said that they refer to the AVSC guidelines specifically. These two companies stated that they use these guidelines to see where the safety emphasis is identified.

Safety Operator Responsibilities: The next four questions that the developers were asked all related to the specific responsibilities of the safety operators and what actions they are prohibited from doing. The responses to these questions for all three developers are displayed in Table 33.

Table 33. Responses for all ADS developers about safety operator responsibilities and prohibited actions.

Responsibility or Prohibited Action	Yes (All Companies)	No (All Companies)
Monitor roadway and vehicle behavior	✓	
Disengage if necessary	✓	
Keep hands on wheel (or hover)	✓	
Screen/Phone use prohibited	✓	
Drinking prohibited		✓
Eating prohibited	✓	
Talking prohibited		✓

In general, safety operators are expected to always remain alert to the roadway and vehicle behavior with their hands on or near the wheel so they would be capable of taking control of the vehicle in a failure case. One company required that the safety operator always keep their hands on the wheel, while the other two companies required their safety operators to hover their hands over the wheel and feet over the pedals. Respondents emphasized that safety operators are expected to perform all the roles of an ordinary driver while behind the wheel.

Many of the checks the safety operators perform on the vehicle are communicated via laptop to the passenger or via in-cab alerts to the safety operator. For example, one company stated they use a combination of simple visual, verbal, and auditory alerts to communicate the state of the vehicle to reduce distraction for the safety operator.

As the table above shows, the main actions that are prohibited for safety operators are eating and using a phone or some other screen. If an operator must drink water, they are expected to disengage from ADS mode. Secondary tasks performed by the safety operator should be kept to a minimum. One company stated that they have zero tolerance for electronics and if a safety operator uses an electronic device while driving, they are immediately terminated. The AVSC guidelines discourage conversation between safety operator and co-pilot unless it is about work-related matters; however, none of the companies claimed to adhere strictly to this suggestion, as they feel light conversation helps reduce the safety operator's cognitive load. Two companies mentioned that their safety operators often communicate with dispatchers via verbal interaction as well.

DSM Use and Integration: The last three questions that developers were asked involved whether DSM technologies are currently in use in test vehicles and what the possibilities of DSM integration would be in the future. All three of the developers said that they do use some type of third-party DSM in their test vehicles. Two companies discussed using multiple different DSM systems and testing multiple types of DSM technology. However, they all noted that there are significant issues with false positives for the behaviors they claim to assess. One company provided further insight by stating they do not think DSM technology is feature deficient, as it does monitor for the correct behaviors, but that it is rather capability deficient, as it does not accurately detect behaviors. As a result of these issues with available DSM technologies, only one ADS developer said that their company is interested in integrating a DSM system with ADS-equipped vehicles. In addition to the efficacy issues of DSM technologies, some of the other barriers to integration that developers identified included the following: apprehension of safety operators to have inward-facing cameras, limits to installation locations given other cameras in the vehicle, and lack of DSM system predictive capabilities. Two of the companies claimed they are looking into developing their own DSM system, as the technology between ADSs and DSMs are similar.

5.4.3.4 Industry Interview Conclusions

These conversations provided valuable insights into DSM and ADS technologies. ADS developers recognize the utility of DSM systems for monitoring their safety operators, acknowledging their importance in ensuring safe operation. However, the path to seamless operation will require further refinement of DSM technologies before ADS developers can confidently integrate these systems into their vehicles. False positives and efficacy concerns are among the challenges that need to be addressed. DSM providers must continue to enhance the technology's accuracy and reliability. Other barriers to integration include data access limitations and driver apprehension about inward-facing cameras. Without further technological innovation, DSM developers may struggle to find the tedious balance between affordability, size of the device, and computing power sufficient to improve accuracy. The barriers to DSM use are not insurmountable but require concentrated efforts to overcome.

The evolving landscape of ADS-equipped CMVs requires ongoing dedication to ensure the safe and effective deployment of ADS technology on U.S. roadways. As ADS-equipped CMVs become an integral part of the transportation environment and demands on drivers become more complicated, addressing the challenges associated with DSM integration becomes critical. These interviews highlight areas for future research in enhancing the accuracy of DSM technologies, exploring innovative approaches to reducing false positives for safety operators, and devising methods to gain driver buy-in for the use of driver-facing cameras while considering privacy law concerns. Overall, there is a clear need for collaboration between stakeholders in this field to improve DSM technology so that it can be integrated into ADS-equipped CMVs.

5.4.4 Exploratory Technology Evaluation

As made evident from the previous two sections of this report, ADS developers desire to have DSM systems in their vehicles to monitor their safety operators for inattention, fatigue, and other safety measures like seat belt use. However, each of the developers commented on the inaccuracies and false alarms present in the aftermarket technologies currently available for purchase. When considering integration, the ideal DSM technology would communicate with the ADS and remote assistants about driver state and take corrective action based on the operator's degraded takeover ability. Developers that are interested in future integration of DSM systems with their ADS-equipped CMVs must consider the efficacy of these systems. Successful integration of DSM technologies in an ADS-equipped CMV is only possible if those technologies overcome the barriers of inaccuracy. Other barriers to integration include establishing valuable training datasets, sensor limitations, and affordability of aftermarket solutions. The purpose of this data collection was to explore the capabilities of two DSM systems by documenting possible shortcomings and by exploring how effectively a state-of-the-art DSM system meets the needs of safety operator monitoring. Additionally, this report serves to recommend future research opportunities that can build upon these findings.

This evaluation used two testing environments. The first part of testing occurred on a controlled test-track where the DSM system was installed in a CMV and the driver performed various behaviors relevant to a safety operator. Recent developments in DSM systems point towards a research need in testing DSM systems in naturalistic driving settings without manipulating operator state triggering.[200] Therefore, the second part involved collecting naturalistic data from a DSM system installed in an ADS-equipped CMV with a safety operator.

5.4.4.1 Methods

This testing included two monitoring technologies. The first technology was the Smart Eye Aftermarket Installation System (AIS) (Figure 47).

Figure 47. Photo. Smart Eye AIS hardware.

This technology was selected based on the criteria listed earlier. This technology represents a video-based monitoring system that tracks the driver's eye and head positions to determine driver states such as drowsiness and distraction. Material in the literature review noted that future research with DSM systems should consider integrating different state indicators such as video-based and physiological indicators.[201] Two separate DSM systems were used in parallel during testing to begin addressing this research need. In addition to the video-based system, a smart wearable device called Empatica (Figure 48) was included in the data collection. This technology represents a wearable physiological data sensor.

Figure 48. Photo. Empatica smart wearable device.

The two DSM systems were evaluated using two driving contexts: (1) a naturalistic automated driving in a port and (2) a controlled test track experiment using emulated driver states. In the first evaluation, the systems were installed in a CMV owned by a participating fleet with the ADS provided by Pronto integrated into the CMV. The driver of the truck was a safety operator. The ODD for the Pronto truck was a breadcrumb trail around a shipyard in Alaska. The truck was practicing moving freight across the yard to prepare for active barge operations. The safety operator was tasked with monitoring the system during this 2-hour practice in the ODD, which is part of their regular job duties. The system was installed in the fleet's ADS-equipped CMV according to the Smart Eye AIS installation procedures documented both on their website and in the mobile app by a VTTI installer. The Smart Eye system was set to default system settings for all behaviors and the speed limit was set to "simulated" so that driving tasks could be performed at any speed. Images of the Smart Eye system installed in the Pronto truck and the driver are not included for privacy reasons. Video recording of the vehicle operation was collected, but no footage of the driver was taken during the practice due to privacy concerns. The driver was interviewed after the drive to inquire about tasks completed during monitoring and general fatigue level. The driver wore the Empatica watch on the left wrist (non-dominant). Both systems were checked to ensure they were collecting data properly before testing was initiated.

In the second evaluation, the systems were installed in a conventional semi-truck provided by VTTI. The driver of the truck was a Class A CDL holder employed by VTTI. Testing took place on the Virginia Smart Roads for 2 hours during daylight. The same Smart Eye system used in Alaska was installed in the VTTI truck by the same VTTI installer. The installation position is included in Figure 49.

Figure 49. Photo. Installation position for Smart Eye.

The driver also wore the Empatica watch on the left wrist (non-dominant), as shown in Figure 50.

Figure 50. Photo. Empatica watch on driver.

Both systems were checked to ensure they were collecting data properly before the driver started piloting the CMV. The two systems were evaluated by having the driver emulate three common driver states: drowsiness, distraction, and high mental workload. Additionally, since ADS developers often mentioned false alarms for their DSM systems during the interviews, quasi-distraction behaviors were also included to test the system's discernment of distraction. For example, testing included whether or not looking in the side mirrors was categorized as distraction. Each task was standardized to ensure the driver performed similarly across each trial. Additionally, timers and audio cues were used to ensure the timing of each task matched the protocol. The protocol for each task is listed below.

To emulate a state of distraction, the driver texted multiple messages on a smartphone and held a phone to their ear as if taking a phone call. For the phone call task, the following protocol was used to test the device’s ability to identify the behavior:

1. The driver looked down at the cup holder, where the phone was sitting, once.
2. The driver reached for the smartphone in the cup holder with their right hand.
3. The driver looked at the phone as if to unlock it.
4. The driver held the phone to their ear for 30 seconds while looking at the road.

Figure 51 illustrates how the driver held the phone during testing.

Figure 51. Photo. Phone call.

For the texting task, the following protocol was used to test the device’s ability to identify the behavior:

1. The driver looked down at the cup holder, where the phone was sitting, once.
2. The driver reached for the smartphone in the cup holder with their right hand.
3. The driver held the phone in their right hand at an elbow bend of 45 degrees within view of the camera.
4. The driver looked up and down at the phone for 2 seconds with eyes off road and 1 second with eyes on road twice, for a total of 6 seconds, based on Olson et al., which found that drivers dialing their phone tended to look down for an average of 3.8 seconds over a 6-second period.(202)

Figure 52 illustrates the driver following the procedure for sending an outgoing text message.

Figure 52. Photo. Texting behavior

To emulate a state of drowsiness, the driver performed several behaviors that characterize symptoms of a sleepy driver, as well as pretending to fall asleep. The driver blinked slowly, drooped his head, closed his eyes, and yawned. For the yawning task, the driver simply yawned three times per trial by opening his mouth wide. The driver attempted to stifle any yawns that occurred outside of the trial. Figure 53 illustrates how the driver followed the yawning procedure.

Figure 53. Photo. Yawning

For the slow blinking task, the following procedure was used to test the device’s ability to identify the behavior:

5. The driver slowly closed his eyes over the course of 3 seconds until they were shut.
6. The driver held his eyes shut for 1 second, then opened them.
7. The driver held his eyes open for 3 seconds.
8. The driver blinked slowly five times.

Figure 54 illustrates the driver following the procedure for the slow blinking.

Figure 54. Photo. Blinking slowly.

For the closing eyes task, the driver emulated a microsleep with eyes closed and head up. In terms of procedure, the driver simply closed his eyes for 5 seconds per trial. Figure 55 illustrates the driver following the procedure for closing eyes.

Figure 55. Photo. Closing eyes.

For the drooping head task, the driver emulated a microsleep with eyes closed and head down. The following procedure was used to test the device's ability to identify the behavior:

1. The driver slowly drooped his head down towards his chest over the course of 5 seconds.
2. The driver lifted his head quickly and opened his eyes.
3. The driver repeated this three times per trial.

Figure 56 illustrates the driver following the procedure for drooping head.

Figure 56. Photo. Drooping head

To induce a state of mental workload, the driver was asked to count backwards from 1,000 by 3, 7, and 13, once per trial. The driver maintained his gaze on the road during this task.

To understand how normal driving behaviors could be confused for improper driver state, the driver was instructed to check his mirrors, look at the dashboard, and focus on pedestrians outside of the vehicle. For the mirrors and dashboard tasks, the driver looked at the object for a total of 3 seconds. For the pedestrian task, the driver was asked to follow the pedestrians with his gaze until they were out of comfortable view. The setups for the pedestrians are included in Figure 57 and Figure 58.

Figure 57. Photo. Motorcycle and bicyclist road users positioned at intersection.

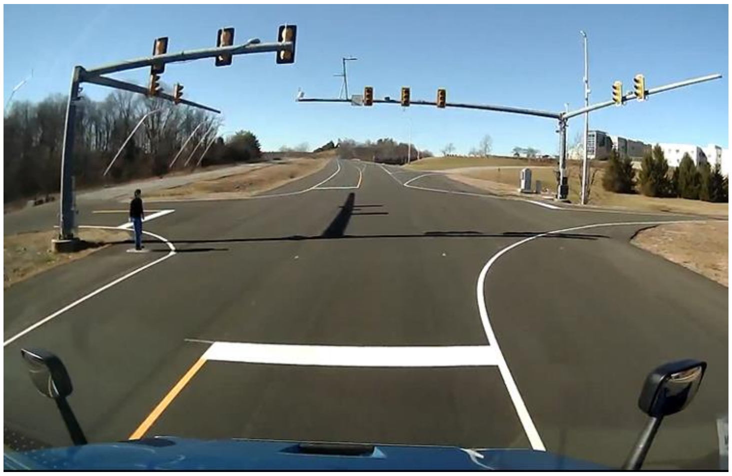

Figure 58. Photo. Adult, male pedestrian positioned at intersection.

The analysis of the results differed for each testing environment. For the observational data collected in the shipyard, the frequency of alerts was taken for each of the collected behaviors to understand how often the driver was notified of improper behavior. Each count corresponds to an in-cab alert delivered to the driver over the course of the 90-minute drive. The number of false alarms was not collected during this drive, as in-cab video was not recorded due to privacy concerns. Summary statistics received from the Empatica watch, such as HR, HRV, and EDA, were gathered for each of the metrics collected.

For the Smart Roads testing, the number of successful alerts was determined for each category (i.e., texting, phone call, etc.). In the event there were multiple successful alerts for the same behavior, only the first behavior was included in the count. Although the number of false alarms could be totaled, this metric is considered outside the scope of this exploratory effort. Instead, it was noted whether there was at least one false alarm in each category and whether the system incorrectly identified at least one behavior. This decision was made because this project is not a benchmarking effort to understand the exact capabilities of two particular driver monitoring systems, but rather an attempt to understand possible shortcomings of all DSM systems when integrated with an ADS-equipped CMV.

5.4.4.2 Results

The following section presents the results obtained from the exploratory data collected in this study, which aimed to investigate the general success of a DSM system to monitor a safety operator during both naturalistic driving and closed test track driving.

Smart Roads Testing

For Smart Roads testing, the driver was instructed to emulate 11 driving behaviors, or tasks. The number of alerts during each trial was documented for each of the 11 tasks. The results are included in Table 34.

Table 34. Emulated driving behaviors and tasks.

State	Task	Number of alerts	Number of Trials
Distraction	Phone Call	3	3
	Texting	3	3
Drowsiness	Yawning	1	3
	Blinking Slowly	3	3
	Drooping Head	3	3
	Close Eyes	3	3
Mental Workload	Counting Backwards	0	3
Other	Looking at Instrument Panel	3	3
	Looking at Pedestrian Crossing	2	9
	Looking at Left Mirror	3	3
	Looking at Right Mirror	3	3

It is important to note that the number of trials for all tasks is three, except for the pedestrian tasks, which had nine trials. The pedestrian task had nine trials because three configurations of pedestrians were used with three trials in each configuration (Motorcycle & Bicycle, Adult Male Pedestrian, and Child Male Pedestrian). The number of alerts represents the number of alerts that went off during testing for that task. This did not capture whether the alert was incorrectly assigned to the task, nor if there were multiple alerts for the same behavior, as only the first alert was counted. During testing, at least one false alarm was produced, and at least one false categorization occurred.

From the Empatica watch, beats per minute (BPM) over the trip time was graphed to understand how the driver’s HR changed during the trip (Figure 59).

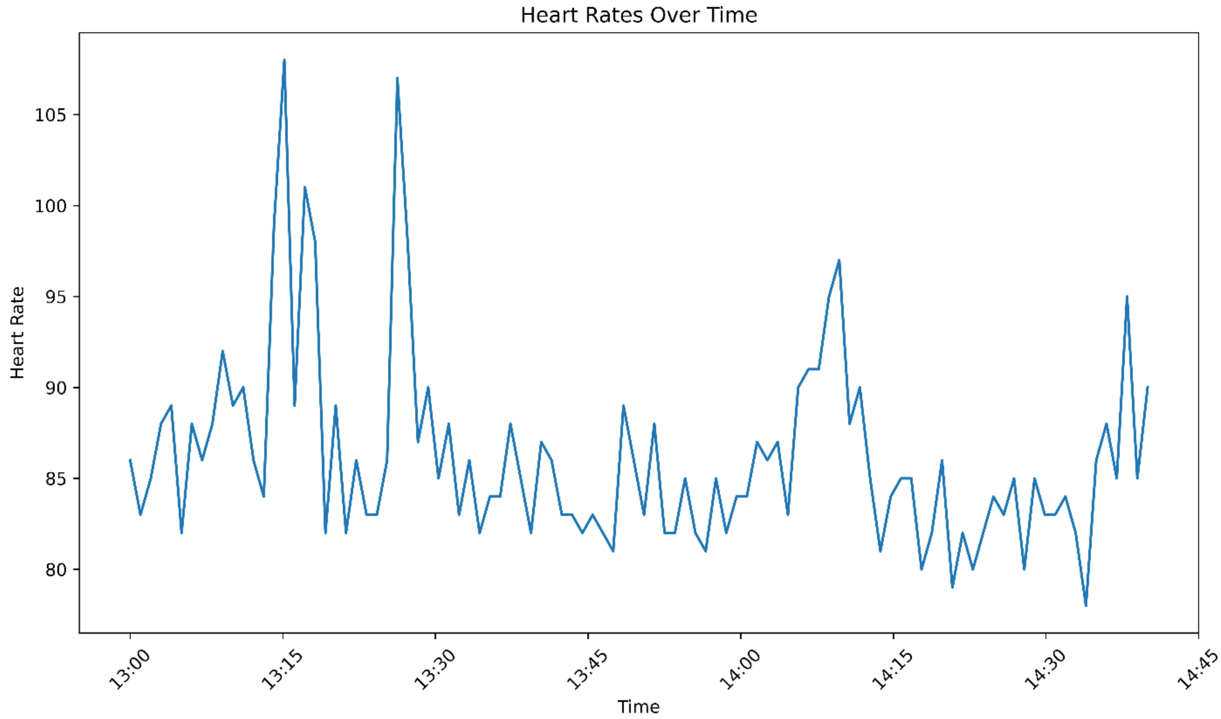

Figure 59. Changes in HR (in BPM) over time for the Smart Roads driver.

The points of interest in the HR graph are the four peaks. The times of these peaks were compared to footage of the driver to understand possible causes. From 13:14 to 13:17, the driver was outside the vehicle helping with the setup for the pedestrian models. The driver was standing, moving, and lifting heavy mannequins during this period, which was likely responsible for the first peak. During the second peak around 13:30, the driver was again outside the vehicle aiding with breakdown for the pedestrian setup. From 14:06 to 14:10, the driver and researcher took a stretch break outside of the vehicle. The mental math trials occurred from 14:20 to 14:29. There were no obvious spikes in the HR during this time that would indicate the driver was experiencing heightened mental workload. The final, fourth, peak is interesting, although it is outside of the testing window. From 14:35 to 14:40, the driver was moving the truck from the closed test track to a facility further down the road. He encountered live traffic during this time, which seems to account for the spike in HR. Although this is outside the scope of this project, it is an interesting data point.

The EDA amplitude collected from the Empatica watch over the trip time was graphed to understand how the driver's EDA changed during the trip (Figure 60).

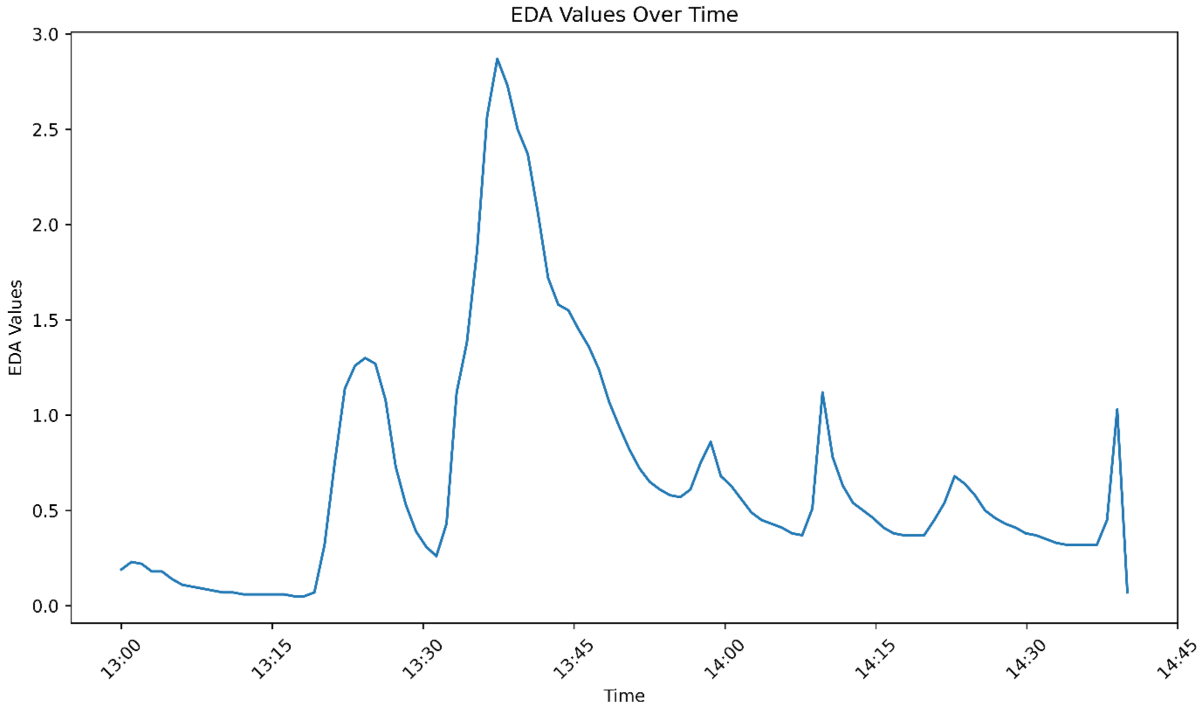

Figure 60. Photo. Changes in EDA over time for the Smart Roads driver.

The points of interest in the EDA graph are the six peaks in phasic skin conductance response, or the faster varying process that fluctuates within seconds and minutes and the general shift of the tonic skin conductance level, or the slower varying process that fluctuates more slowly across time. The first three peaks and the general increase in EDA amplitude line up with the times where the driver was outside of the vehicle helping with the pedestrian setup (13:14 to 13:17; 13:30 to 13:40; 13:50 to 14:00). The fourth peak around 14:10 corresponds with the stretch break the driver took outside of the vehicle, which may be responsible for the peak in EDA amplitude. Interestingly, the mental math trials occurred from 14:20–14:29, which corresponds with the fifth peak. Although there was no indication of increased mental workload on the HR graph, there is an indicator on the EDA graph of increased arousal. The final, sixth, peak lines up with the time where the driver left the closed test track and encountered live traffic while dropping the truck off at another location.

Port Testing: During shipyard testing, the driver was not instructed to complete specific behaviors. Instead, the driver was monitored while working as a safety operator. The behaviors listed in Table 35 are self-reported behaviors the driver completed during the drive. These were reported in an interview after the drive.

Table 35. Driver self-reported behaviors during drive.

Behaviors reported by driver during drive	Collective time spent on task
Talking on a walkie-talkie	10 minutes
Looking at forward roadway	30 minutes
Drinking water	3 minutes
Looking at cellular device	10 minutes
Checking mirrors	30 minutes

The context of the drive is important for interpreting these results. The vehicle had a top speed of 12 mph around the yard. Additionally, the vehicle alternated between stop and movement during the loading and unloading procedures. The driver would often be sitting in the truck waiting to be loaded or unloaded, where they would look for nearby vehicles, which did not involve looking at the forward roadway. The driver also used a walkie-talkie instead of a handheld cell phone device for communications with other yard operators such as forklift drivers. The operator explained that the cellular device use was because the truck was controlled partially by an app on the mobile device.

The number of alerts is documented for each of the 11 tasks listed in Table 34. The results are included in Table 36.

Table 36. Number of alerts for each of the 11 tasks.

Smoking Detected	Distraction Detected	Microsleep
1	89	39

The device alerted once to smoking; however, the driver did not smoke during the drive. There were 89 instances of distraction detected during the drive and 39 instances of microsleep detected. The driver reported a high level of distraction during the drive but did not report feeling tired.

From the Empatica watch, the BPM over the trip time was graphed to understand how the driver’s heart rate changed during the trip (Figure 61).

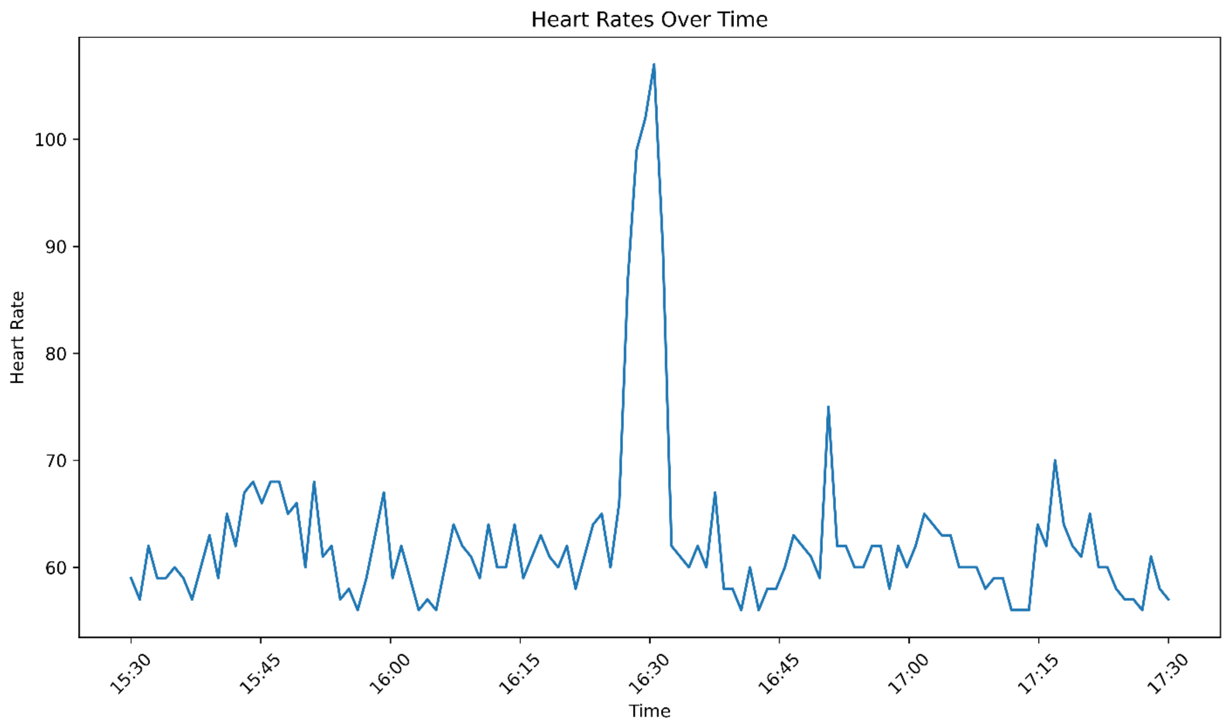

Figure 61. Graph. HR in BPM for during the shipyard trip.

The points of interest on the BPM graph are the two spikes in HR. Unfortunately, due to privacy concerns, the driver was not recorded during the drive, so it is unclear exactly what caused the two spikes. However, the research team was present in the yard in a separate vehicle during the drive and was able to listen to the walkie-talkie communication between the yard operators. During the drive, there were several times where the truck got stuck on the ice and needed to be put in manual mode to be driven. Speculatively, the spikes in HR could be caused by the shift from monitoring to manual driving.

The EDA amplitude from the Empatica watch over the trip time was graphed to understand how the driver's EDA changed during the trip (Figure 62).

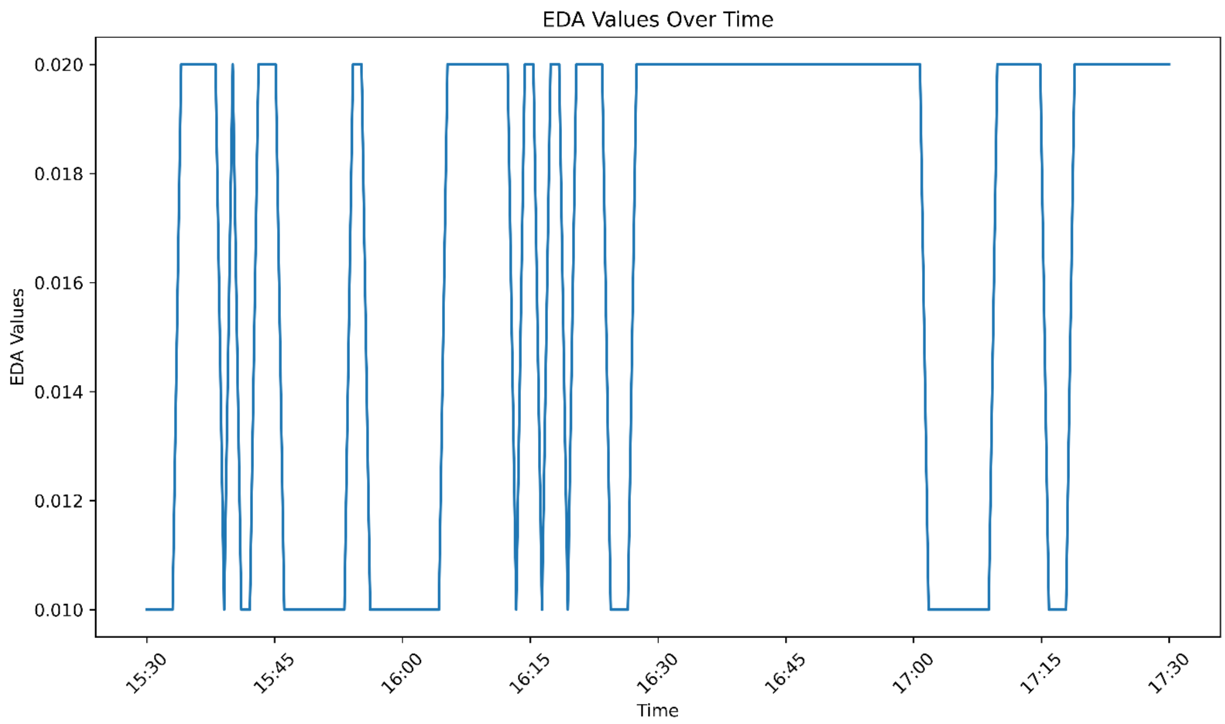

Figure 62. Graph. Empatica EDA amplitudes over trip duration.

Compared to Figure 60, the Figure 62 graph has a much smaller vertical range. External factors such as temperature and humidity can make EDA results inconsistent. In Alaska, the temperature was very cold, and the humidity level was very dry, which may have impacted the driver's EDA amplitude. Based on the lack of baseline and no video, it is difficult to produce meaningful results from this graph.

5.4.4.3 Exploratory Conclusions

Overall, this exploratory research aimed to investigate the capabilities and shortcomings of DSM systems and understand how effectively a state-of-the-art DSM system meets the needs of safety operator monitoring. Interviews with ADS developers indicated that DSM systems are feature sufficient but accuracy deficient, meaning they can detect the desired behaviors, such as distraction, but the accuracy of this detection is questionable.

The results from testing support these anecdotal reports. The device was able to detect distraction, drowsiness, and policy violations such as smoking, but these specific testing environments produced at least one false alarm and at least one false categorization, which threatens accuracy. If these systems are to be integrated into ADS-equipped CMVs, then accuracy is paramount to correctly inform the system and protect drivers. For example, in one interview with an ADS developer, the representative stated the company has a zero-tolerance policy for cell phone use. With this DSM system, there was no way to verify the validity of alerts with recorded footage. If a driver was falsely reported to be distracted, this could have negative implications for their career. This points towards the necessity for footage review of DSM systems or, at a minimum, image captures of instances where the driver is categorized as distracted. Another important aspect of inaccurate alerts is false categorization. When a DSM system is integrated into a vehicle, if the system inaccurately labels drowsiness as distraction, the decision-making vehicle needs to be able to accurately respond to the driver's state. If the driver is categorized as distracted, the system may only provide an alert, whereas if the driver is identified as being drowsy, it may trigger the vehicle to pull over. This indicates the need for highly accurate monitoring prior to integration.

The results also underscore the criticality of maintaining context of the DSM systems for interpreting results. When comparing testing at the port and on the test track, the vehicle environments were completely different. In Alaska, the ADS-equipped CMV drove at a top speed of 12 mph with icy road conditions. One of the driver's duties was to monitor the environment for other yard operators getting near the truck. The driver needed to look in many directions, which may have increased the number of distraction alerts even though the driver was successfully completing his job. On the test track, the driver maintained a speed of 25 mph to 45 mph on a relatively straight road with clear conditions. When turning the vehicle around, the driver looked in the direction of the turn, which was the forward roadway, but the systems often alerted to this as being distraction. Meaning, even though the driver was looking where the vehicle was going, the device categorized these instances as distraction because the driver was not looking "straight." These types of false alerts may discourage drivers from accepting DSM systems because they may feel they are doing their job correctly, while the alerts indicate otherwise. Adjusting the alert sensitivity may help alleviate the onslaught of alerts. If the device were integrated into the vehicle and received information about the external context of the vehicle, then the DSM system could adjust categorization more effectively.

The collected physiological data was best interpreted with video context. Without knowledge of driver's activities and timing, there was no real way to decipher the EDA and HR data. In the future, if DSM systems intend to integrate physiological data, a way to contextualize the information with video is worthwhile. Another consideration of physiological data is the cost. Several DSM system manufacturers commented that one major barrier to integration is cost, as they are trying to keep aftermarket products scalable to large fleets. When considering the added cost of current wearable technologies, this may be economically out of reach for large fleets. This points to the differences in OEM versus aftermarket technologies. Although there are benefits to including DSM systems as aftermarket products in terms of cost, effectiveness may be severely limited without full integration with the vehicle.

5.4.4.4 Limitations and Future Needs

As this was an exploratory study, there are several limitations to consider. First, the decision to assess a single video-based DSM system, while based on pre-established criteria, does not consider the diverse landscape of available DSM technologies. Many DSM technologies available require a minimum number of devices to be purchased, which was not cost-effective for the project. Additionally, many platforms have a subscription-based service that must be purchased to access the dashboard data. By excluding consideration for system carriers that mandated minimum purchases or subscription services, the study's outcomes may not holistically reflect the efficacy and applicability of DSM systems across different market offerings. Consequently, the findings derived from this study may not be generalizable to other DSM systems, potentially limiting their broader relevance and applicability within the field.

However, the results emphasize the importance of continued research in this field before DSM systems can be fully integrated into and trusted to manage ADS-equipped CMV testing operations. Additionally, given the rapid evolution of technology, the information collected in the technology scan and literature review in October 2022 may not accurately reflect the current state-of-the-art in DSM technology.

The study’s sample size, comprising only two drivers who underwent approximately 2-hour trials each, imposes constraints on the depth and breadth of insights gained. While the exploratory nature of the study necessitated a focused approach, the limited duration of trials and the small number of participants may not adequately capture the nuances of driver behavior and fatigue detection. Longer trial durations, coupled with deliberate induction of fatigue, could offer a more nuanced understanding of the DSM system’s performance in real-world driving scenarios. However, ethical considerations and practical constraints may hinder the feasibility of such approaches, highlighting the delicate balance between research objectives and participant well-being.

The study’s data collection process was inherently context-specific, conducted within a specific time of day, location, and with a single safety operator. While this controlled approach may enhance internal validity, it simultaneously compromises the external validity and generalizability of the study’s findings. Future research endeavors should strive to broaden the scope of data collection across diverse driving scenarios, environmental conditions, and more participants to better understand the robustness and adaptability of DSM systems in real-world contexts.

This study had a limited exploration of false alarms, a common issue with DSM systems. While acknowledging the varying sensitivity levels of DSM systems in detecting specific driver behaviors, the study’s scope did not include a detailed examination of false alarm rates and their implications for driver safety and system usability. Future studies might prioritize comprehensive evaluations of false alarms to elucidate their prevalence, underlying causes, and potential mitigation strategies.

The lack of integration between the DSM technology and the vehicle’s ADS presents another significant limitation. Integration of DSM systems with ADS holds promise for enhancing driver safety and overall system effectiveness. However, fully integrating the two DSM systems with one another and the vehicle was outside of the scope of the project. The absence of such integration limits the understanding of the synergistic effects between DSM alerts and existing ADS vehicle safety features. Similarly, the lack of integration between different DSM systems hinders comparative analyses and insights into their relative performance and reliability.

Finally, the study’s reliance on smart watches for physiological measurements introduces inherent limitations in accuracy compared to medical-grade devices. The absence of validation studies to assess the accuracy and reliability of the smartwatch-based measurements underscores the need for caution when interpreting the study’s findings. Future research endeavors should prioritize rigorous validation studies to ensure the integrity and validity of the physiological data collected. Additionally, to assess individual differences, it is important to capture a baseline per participant to interpret the results more accurately.

Overall, while acknowledging these limitations, the study's findings offer valuable insights into the performance and usability of DSM systems in real-world driving scenarios. By addressing these limitations and incorporating them into future research endeavors, we can advance our understanding of DSM technology and its role in enhancing safety and well-being for safety operators and other road users.

5.5 MOTOR-CARRIER GUIDE TO INSURING ADS-EQUIPPED TRUCKS

This section provides insights and recommendations regarding insurance practices involving AVs in general with specific considerations for heavy vehicles. It is based on guidance from the Travelers Institute, an education and public policy division of The Travelers Indemnity Company, a home, vehicle, valuables, and business insurance provider. Most of the information herein was released in a position paper published by Travelers in January 2021 titled, "Insuring Autonomy: How Auto Insurance Will Lead Through Changing Risks."(203) The conclusions and discussion were also based on this paper but were modified to focus on trucking fleets. Other insights are provided based on a technical session entitled "Hands-off Insurance: Insurance Guidelines for Automated Vehicles" that was hosted by the S.18 Automated Vehicles Study Group at the Technology Maintenance Council 2023 Annual Conference and Transportation Technology Exhibition in Orlando, Florida, on Tuesday, February 28, 2023. The review is directed towards answering the three questions stated below. *The information and positions stated in this section are shared to inform the developing conversation about insuring AVs. The information is based on the public paper and conference session and is not necessarily representative of positions held by VTTI or the USDOT.*

What are AVs' current and future states?

- To support the advancement of AVs, it is important to address public policy questions and challenges in a comprehensive manner that increases public safety, provides peace of mind, protects drivers and pedestrians, and spurs innovation.
- The auto insurance industry should—and will—play a critical role, as lawmakers, regulators and society adapt to the newest mode of transportation.
- There continue to be many unknowns associated with AVs. For example, how long will it take to transition to a fully automated fleet? How long will it take for the anticipated benefits of AVs to be realized? What unintended consequences and disruptions will arise during the transition?

How will auto insurance meet society's needs in an AV world?

- Leveraging the existing automobile insurance structure, both commercial and personal, is the best method for compensating crash victims quickly and efficiently—now and in the future.
- The current insurance structure is already designed to adapt to evolving risk environments and would minimize regulatory uncertainty, market disruptions, and consumer confusion.
- Continuing to rely on auto insurance for coverage, regardless of vehicle type, will also help to ensure consistency during the period in which AVs and driver-operated vehicles share the road.
- Whether a vehicle is automated or driver operated, auto insurance offers vehicle owners the most peace of mind when it comes to other concerns such as weather damage or theft.

What are the critical insurance-related components for AV regulation?

- Any proposed legal and regulatory framework governing AVs must include provisions specifically related to auto insurance.
- Vehicle owners should be required to purchase and maintain adequate insurance for their AV, whether it is a personal, ride-hailing, or company-owned vehicle. Coverage limits should be high enough to account for more expensive technology in AVs.
- The insurance industry should play a central role in AV policymaking and stakeholder discussions. Local, State, and Federal lawmakers and regulators must coordinate and seek input from all relevant constituents to ensure a consistent, rational regulatory framework that addresses all potential issues.
- Insurance providers should support the development of a model State law relating to AV insurance that builds on the current State-based regulatory and oversight structure for auto insurance.
- Insurance providers should engage with coalitions that help educate the public and make recommendations on AV-related issues. Insurers have extensive consumer communication programs and can help educate key groups on AV safety.

5.5.1 Overview: The AV World Today and Tomorrow

The growth of the AV industry accelerated significantly in recent years and continues to rapidly expand. As of December 2020, 58 companies had active AV testing permits in the State of California, which was a significant increase since Travelers' Insurance first publication on the insurance of ADS in 2018.(204) Those companies collectively drove over 2.8 million miles while utilizing automated driving technology on California roads in 2019.(205) As recently as 2018, the most advanced AVs on the road were defined as Level 2 by the SAE levels of vehicle automation. SAE L2 is considered "partial automation" where the human is still considered the driver and is responsible for supervising the AV functionality. The first public autonomous ride-hailing service (Waymo One) was launched at the end of 2018 and began fully driverless rides in 2019.(206) While this document focuses on AVs and the insurance system in the United States, it is important to recognize that countries around the world are also making significant progress in autonomous technologies. However, progress does come with its challenges. Consumer sentiment, regulatory considerations, and infrastructure support present challenges to AV adoption and deployment.

In addition, the effects of the COVID-19 pandemic on the transportation industry have been far-reaching. Due to statewide shutdowns, quarantine rules and regulations, pandemic fears, and a large portion of the country working remotely, miles driven were down 14.5% year over year during the first 9 months of 2020, according to preliminary government data.(207) While crash frequency also dropped, dangerous new trends emerged. For example, traffic fatalities rose 13.1% in the third quarter of 2020 when compared to the corresponding quarter in 2019, according to preliminary data.(208) COVID-19 had a profound impact on automotive transportation in 2020. Moreover, AVs have the potential to provide transportation in a manner that mitigates exposures arising out of future pandemics.

As expressed in Figure 63, cities across the United States continue to embrace AVs and many may be seen as hot spots for this technology due to their favorable regulatory environment, heavy tech presence and, in some cases, weather.

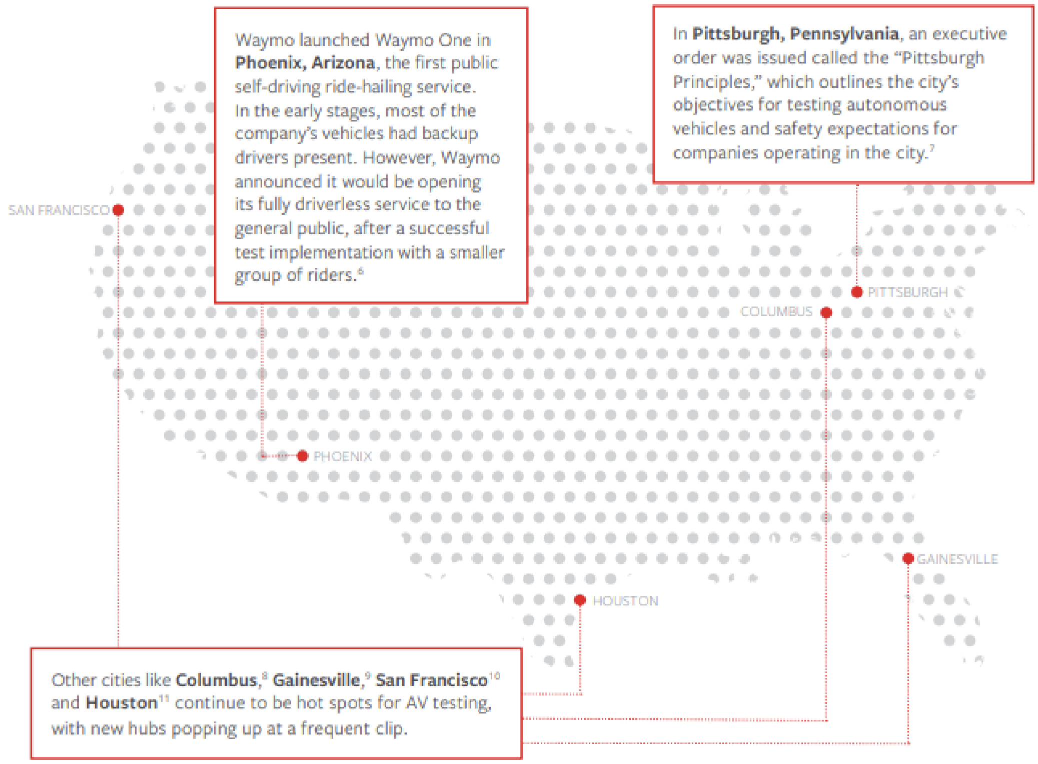

Figure 63. Map. Hotspots for AV technology.

The AV industry continues to attract significant investment from traditional auto manufacturers and technology companies. In the last two years, the AV landscape has changed dramatically, with technology progressing as more companies have entered the industry. Today, every major auto manufacturer takes part in the AV ecosystem in some fashion, but it does not stop there. Countless startups and tech giants are also dedicating resources to this industry.

Beyond auto manufacturers and tech companies, academia and insurance companies are also engaging in the AV industry. For example, Carnegie Mellon University in Pittsburgh, Pennsylvania, has been a long-standing contributor to AV technology. In June 2019, it announced a multiyear partnership with AV startup Argo AI, which committed $15 million to AV sponsored research.(209) The Massachusetts Institute of Technology (MIT) launched its Advanced Vehicle Technology Consortium in 2015 to, among other goals, better understand how drivers engage with vehicle automation and driver assistance technologies. This academic and industry partnership brings together stakeholders including automakers, insurance companies, Tier 1 suppliers, and research organizations.(210)

AV research and development is now well established. However, one of the largest barriers is consumer readiness to embrace AV technology. In a 2020 survey conducted by Partners for Automated Vehicle Education, of which the Travelers Institute is a member, nearly three-quarters of respondents stated they believe "AV technology is not ready for primetime," with 20% of respondents saying they believe AVs will never be safe.(211) While the promise of safer roads and more leisurely drives appeals to some, the difficulty of producing and deploying AV technology still looms in the present.

In 2018, an Uber autonomous test vehicle crash in Tempe, Arizona, resulted in a fatality, and the automated system was found partially at fault. In the case of this crash, which killed a pedestrian crossing the street, it was deemed that the vehicle programming did not include consideration for jaywalking pedestrians, and therefore, did not recognize the pedestrian in its path soon enough to engage emergency braking.(212) How systems handle scenarios like this will be a subject for important discussion as AV adoption becomes more widespread.

With 94% of crashes attributed to driver error as the final, critical reason for the crash, an obvious goal is for AVs to increase roadway safety.(213) However, lower levels of automation that rely partially on automated systems and partially on a human driver can present risks related to misuse, including driver distraction and lack of attention on the road. DMS and driver attention reminder methods may be key factors in maintaining safety during this transition.(214)

NHTSA reports that there were 36,096 motor vehicle fatalities in the United States in 2019 alone, which is visualized in Figure 64.(215,216) In addition, as previously noted, early estimates show a 13.1% year-over-year increase in traffic fatalities in the third quarter of 2020, during the COVID-19 pandemic.(217)

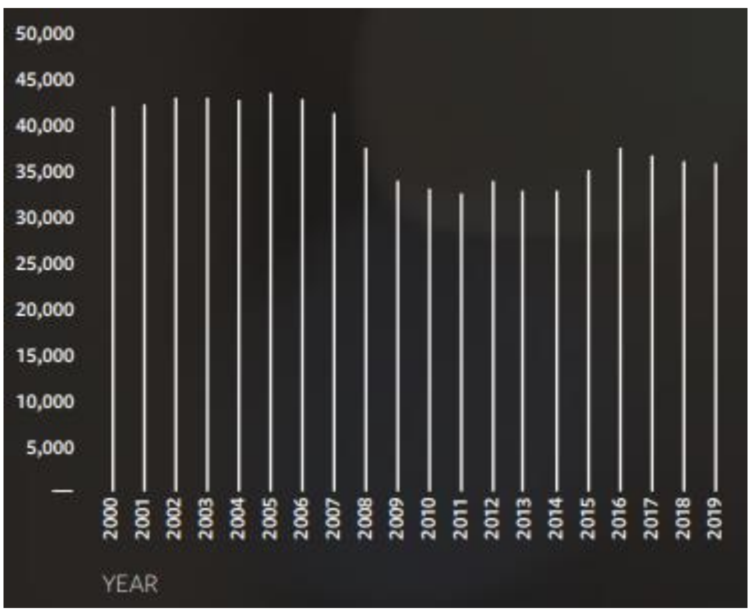

Figure 64. Graph. Total U.S. motor vehicle traffic fatalities.

5.5.1.1 Trends to Watch

Distracted driving related to technology may be one of many factors contributing to collisions and fatalities. This issue may take on more relevance in the near term as new semi-autonomous technologies requiring driver interventions are rolled out to the public.

The insurance industry may see collision rates decline as AV adoption rises. However, while the industry had been experiencing some level of favorable frequency over the last few years, early predictions of dramatic reductions have not materialized as of 2021.

Although some experts predict that market saturation for full AVs may not occur for a few more decades, the market is clearly moving in that direction, and policy and regulatory regimes (along with industries like insurance) must adapt now. According to the IIHS, as of January 2021, 28 States and the District of Columbia have already passed some form of AV legislation.(218) Those States are shown in Figure 65. However, State laws vary in their content and do not currently provide comprehensive AV regulatory frameworks. Some authorize operation of AVs, some promote and/or liberalize requirements for AV testing, and others direct further study on how best to safely deploy AV technology on public roadways.

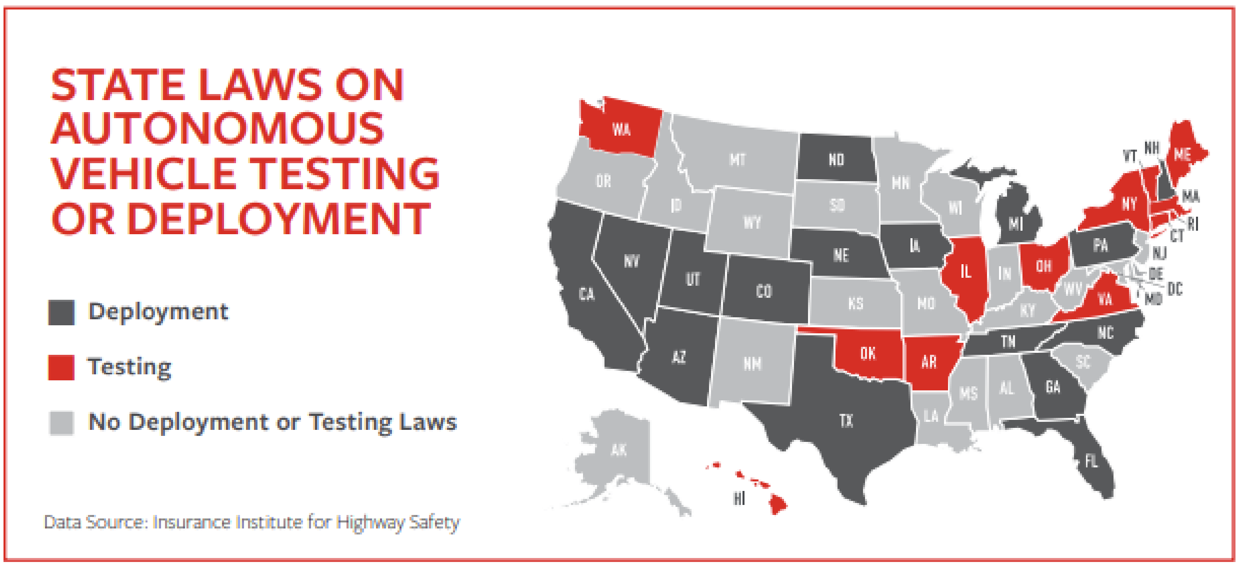

Figure 65. Map. States that have passed AV legislation.

To date, only a few States have begun to address insurance-specific issues with respect to AVs, and most of those are focused on AV testing requirements. Similarly, only a few States have begun to address insurance requirements for AVs for personal use.

At the Federal level, in January 2021, the U.S. Department of Transportation released a set of updated guidelines for AVs, the Automated Vehicles Comprehensive Plan. The framework is organized around three goals: promoting collaboration and transparency to stakeholders and the public, modernizing the regulatory environment to remove unnecessary barriers, and preparing the transportation system to safely evaluate and integrate ADS.(219)

In the policy arena, early State-level movement underscores the need for a comprehensive, rational, and uniform AV regulatory structure (recognizing that State law likely will continue to govern both insurance and any compensation/liability system). For the reasons we will discuss on the following pages, any regulatory structure should explicitly address insurance-specific issues and needs in the new AV landscape, which will be vital to ensuring a fair and efficient compensation scheme.

5.5.2 Auto Insurance Can Meet Society's Needs in an AV World

Auto insurance may be well suited to address the compensation issues (e.g., bodily injury, property damage, cyber incidents) arising from the emerging AV world. The following section discusses some of the major advantages of using the current insurance structure, versus alternative models (e.g., product liability), as the primary compensation method.

5.5.2.1 Auto Insurance Compensates Victims Quickly, Fairly, and Efficiently, Especially When Compared to Other Risk Transfer Mechanisms

Leveraging the current auto insurance structure as the primary risk transfer mechanism in a new AV world allows for greater speed, fairness, and efficiency from a consumer's perspective. The existing insurance structure is designed to quickly get vehicle owners back in vehicles and efficiently compensate crash victims for both bodily injury and property damage. In addition, most vehicle owners are familiar and comfortable with the existing insurance structure (e.g., purchasing coverage, having a basic understanding of coverage and policy documents, filing claims) and know how to take advantage of its benefits.

Moreover, the existing auto insurance structure can adapt more effectively than alternative structures to the evolving regulatory and legal environment by creating or enhancing insurance products. Given auto insurers' deep understanding of compensation systems, they are uniquely positioned to assist policymakers in developing or modifying such systems.

While there has not been widespread attention paid to how liability and compensation will be addressed as AVs multiply, product liability has been raised as the inevitable default option. That presumption should be challenged.

Unlike auto insurance, alternative risk transfer mechanisms, such as product liability, are not structured to be primary, comprehensive solutions. In a recent study, the RAND Corporation found that a critical component of an insurance framework for AVs is how effectively it will compensate the victims of collisions.(220) A product liability-type regime for AVs that is in lieu of, or with primacy over, the current auto insurance structure could force consumers and victims to pursue complex, lengthy lawsuits to seek compensation. Such suits involve intensive and drawn-out investigative and evidentiary hurdles before anyone sees a day in court.

Further, the product liability legal and regulatory environment is ill-suited for handling auto collisions as the sheer number of discrete incidents would bog down court systems and significantly delay compensation. Victim compensation, if it happens at all, could take years. The RAND Corporation report also states that the large number of automobile crashes that occur today requires "a vast infrastructure of specialists who resolve, adjudicate and repair these claims," and that insurance companies have built teams of experts who specialize in doing just that.(221)

The Takata air bag case is an example of the limitations of product liability in compensating victims. It has taken well over a decade for this case to proceed through the report filing, regulatory investigation, recall, and compensation phases of the product defect regime that governs automakers and equipment manufacturers. Some auto companies have settled with consumers, but others are still embroiled in litigation. This is a particularly striking fact given that the initial product problems and driver injuries occurred in 2004.

Notably, and not surprisingly, the primary risk transfer and compensation mechanism for even more sophisticated modes of transportation (e.g., trains, airplanes, boats) goes beyond product liability and is based upon insurance. For consumers, businesses, and regulators, it makes sense that AVs will follow suit, but the final answer as to the best path forward for insuring AVs, considering the current auto insurance structure and product liability, may require more research and analysis.

5.5.2.2 Using Existing Auto Insurance Systems Minimizes Consumer Confusion, Regulatory Uncertainty, and Market Disruptions

Fundamentally, there is a high level of certainty and stability for consumers, businesses, regulators, and legal systems in the current auto insurance structure. For example, we know that generally all vehicles and drivers are covered with some liability protection. Coverage can be through insurance (most common with the vast majority of drivers), bonds or cash deposits in place of traditional insurance, or proof of ability to pay for an at-fault accident (e.g., in New Hampshire). And auto insurance has a robust legal and regulatory infrastructure with proper, comprehensive consumer protections in place to govern insurance providers and policyholders.

Utilizing the existing insurance structure for AVs and non-AVs alike avoids complex jurisdictional and enforcement issues. Additionally, auto insurance industry distribution systems are already in place and will evolve to accommodate new technologies and risks. Pricing and underwriting will likely shift to include both driver- and vehicle-based systems. This will allow insurers to play their traditional role in risk mitigation by sending pricing signals vis-a-vis premium differentiation among covered autos to encourage AV technological improvements. In a December 2020 report published by the RAND Corporation, one auto manufacturer is quoted as saying there is “no reason that the current system cannot keep working.” Other experts weighed in, stating that historically the auto insurance industry has remained resilient in the face of technological improvements and innovation.[(222)] Given the technology and data capture that is occurring in real time, insurance policies addressing data sharing may be implemented to help ensure that premiums are appropriately matched to exposures. Further, AVs may present new risks and liabilities (e.g., cybersecurity threats) that may need to be addressed by a new generation of insurance products and coverages.

During the period in which AVs and non-AVs will likely be sharing the road, auto insurance systems must, and will, be able to accommodate and adequately address both types of vehicles. During this transition, a thoughtful compensation system is needed to prevent consumers from becoming mired in lengthy and expensive legal and technical disputes about whether human error or technological malfunction caused a collision. Significantly, the lack of a timely and efficient compensation system could also hinder the more widespread adoption of AVs. Consistency in delivery, customer experience, and expectations, with clear “rules of the road” (e.g., regulatory oversight, legal requirements, etc.), are vital to a rational risk transfer regime. If AVs and other vehicles are governed by different primary insurance structures or different liability standards, the resulting consumer confusion and regulatory/enforcement uncertainty may increase expenses associated with contentious liability determinations and market disruptions.

Dividing the market in such a way would create a veritable patchwork on the roadways with respect to who is covered, for what, and under which regulatory and legal framework.

Moreover, if separate compensation and liability structures govern and/or have primacy over different types of vehicles and their owners, questions and uncertainty may arise around issues such as appropriate forum, liability and evidentiary standards, and the application of various no-fault-type systems. During the period in which AVs and non-AVs will likely be sharing the road, auto insurance systems must, and will, be able to accommodate and adequately address both types of vehicles.

5.5.2.3 Subrogation Is Already an Important Element of the Auto Insurance System

Today, insurers compensate crash victims for personal injuries and property damage and then, if appropriate, seek to recover those payments from vehicle manufacturers if some defect caused the loss. This process is called subrogation. Several years ago, Toyota faced numerous "sudden acceleration" cases, which were alleged to have been caused by product defects. As there were both property damage and bodily injury claims associated with these Toyota vehicles, auto insurers paid the claims even if there was evidence that the crash might have been caused by a sudden acceleration defect. Subsequent to paying the claims, some of the insurers filed subrogation actions against Toyota.[(223)] This is an important element of the auto insurance system: the claimants are promptly compensated by the insurer, and the insurer then assumes the burden (and has the resources) to pursue the product manufacturer to recover those losses.

These product liability claims can be complex and expensive. Potential product liability claims involving AVs could involve additional complexity and related cost. A system that prioritizes compensation over resolving whether an AV was defective provides the most consistency and certainty to consumers and leverages the existing legal and regulatory frameworks that have routinely adapted to technological advances. Avoidance of these subrogation actions also creates an incentive for AV manufacturers to design and build safer vehicles, which is a key benefit of this system.

5.5.2.4 Insuring AV Risks in the Commercial Insurance Sector Today

Insurers should make a concerted effort to better understand emerging risks and provide marketplace solutions for their insureds. Building partnerships with companies in the AV industry is an excellent example of this. There is a growing market in the commercial insurance sector for AV risks among technology developers, operators, support services, etc. Through extensive research, engagement with experts, industry-related partnerships, and thoughtful underwriting, it is possible that these risks present opportunities for insurers. For progress to continue, it is imperative that insurance markets have solutions for these emerging risks.

5.5.2.5 Auto Insurance Will Have an Important Role to Play in an AV World

AV owners will still need coverage for non-collision-related incidents such as weather and theft. Even with full AVs, human involvement will not disappear, and individuals will still need auto insurance. For the foreseeable future, vehicles with some driver involvement will continue to face issues around liability for crashes. As increasingly distracting technologies are employed in partial AVs, liability insurance may become even more important.

Also, vehicle maintenance by owners (e.g., getting tires and brakes fixed, installing technology/ software updates, sensor maintenance) can result in personal responsibility and liability, which is properly addressed through insurance. Further, AV owners will still need coverage for non-collision-related incidents such as theft and weather damage. Product liability simply does not cover the entirety of essential coverage areas related to vehicle operation and ownership.

Finally, AV owners—like all other vehicle owners—want peace of mind that they are protected against the costs of unforeseen events. Auto insurance provides consumers with 24/7 protection, unlike other risk transfer systems that are dependent upon specific legal criteria and/or circumstances (e.g., a provable mechanical or design product malfunction/defect).

5.5.3 Critical Insurance-related Components for AV Regulation

Any comprehensive AV legal/regulatory structure must include insurance-specific policies. The following are recommended to address pressing insurance-related issues associated with AVs.

5.5.3.1 Specifically Address Insurance Liability Standard as the Primary Risk Transfer Mechanism.

Today, there are several risk transfer and liability schemes governing and impacting the auto market. These include insurance, common law negligence, various no-fault and personal injury protections, statutory systems, product liability, Federal Trade Commission representation and advertising regulations, State claims practice acts, fraud laws, and licensing requirements. This will likely be seen in an AV world as well. Auto insurance should play the same primary risk transfer role in that world as it does now for non-AVs.

Notably, legal systems are already considering how to address novel compensation issues surrounding AV collisions. For example, in its review of a fatal crash involving a Tesla vehicle, the National Transportation Safety Board determined that use of the Tesla autopilot feature contributed to the crash, along with the two drivers involved.(224) The decision demonstrates the ability of our existing legal system to evaluate the complex and varied risks presented by the emerging AV world.

Thus, public policy proposals regarding governance of AV liability may consider addressing compensation systems and insurance liability standards, including who is responsible for obtaining coverage. As with the current auto insurance system, AV owners should be responsible for obtaining and maintaining adequate insurance. This should apply whether the vehicle is for personal, ride-hailing, or company use.

Because there may be many possible approaches to liability and compensation for AVs, including systems that may not exist today, a framework is needed to evaluate various options. An AV liability system should be evaluated on its ability to achieve the best balance of the following three objectives:

- **Provide full and timely compensation for victims** – Injured parties should be made whole without delay.
- **Efficient claim resolution** – Minimize expensive and protracted liability determinations for most crashes.

- **Encourage adoption of AVs and increased safety of AVs** – A liability system should encourage the AV industry to achieve safer outcomes. Insurers have encouraged safer vehicles for decades through risk pricing, safety research conducted by the Insurance Institute for Highway Safety, and other efforts.

5.5.3.2 Provide for Sufficient Coverage Limits at the Vehicle Level

It is anticipated that eventually fewer collisions will occur with more AVs on the road, but the collisions that do occur could be more costly, particularly with respect to vehicle damage. The parts used in vehicles with AV technology are more costly to repair or replace. The industry is seeing this today as more and more vehicles are coming equipped with the latest in ADAS technology. Therefore, any insurance scheme must require sufficiently high coverage limits, including adequate limits for property damage to address more expensive technology in AVs. Higher minimum limits, especially for bodily injury, may also provide peace of mind and remove barriers to societal adoption of AVs.

5.5.3.3 Standardize Data Governance and Cybersecurity Requirements

AVs present new questions and opportunities with respect to data collection and management, which have only been heightened by recent developments related to social media data and privacy. Standardization (via legislation or regulation, for instance) of data collection, sharing, storage, and security requirements could prove valuable in streamlining the coverage process. To facilitate an effective and efficient AV auto insurance system, public agencies may consider providing guidance on timely data sharing (by auto manufacturers and others who obtain data on crashes and AV performance) with insurance providers, while ensuring adequate protections for consumer privacy. Sharing data with insurers has the potential to help facilitate insurance coverage in several ways, including:

- Establishing liability/causation in the event of a crash (a function performed by the insurance carrier, not the customer).
- Assisting with accurate underwriting and pricing of insurance policies.
- Supporting risk mitigation and control activities (e.g., via software updates).

Ultimately, standardization of data governance and assurance of data sharing with insurers benefit all parties involved, including vehicle owners, collision victims, manufacturers, and insurance providers.

NHTSA introduced the Automated Vehicle Transparency and Engagement for Safe Testing (AV TEST) Initiative in June 2020. This initiative includes a platform that allows companies to voluntarily share information about any current on-road testing.(225) This is a positive step toward companies making testing information more widely available to the public and signals that NHTSA understands the importance of a centralized, publicly available data collection system. Further, insurers should support the creation of an expert advisory board or committee to help address data and cybersecurity issues, including how these issues are related and how they can effectively be addressed together. Insurer representation on any such body would be essential.

Strong cybersecurity requirements for AVs should be developed. This is an issue that is intertwined with the creation of data management standards. Cyber-related risks impact the safety of our communities in an AV world, and thus must be addressed. This also highlights the need for appropriate data sharing protocols. If a cyber incident occurs, it will be important to have the data explaining what happened, not only for insurance-related purposes, but also for future risk mitigation and preventive efforts.

5.5.3.4 Ensure Representation of the Insurance Industry in Policymaking and Stakeholder Forums

Insurers should use advisory boards and task forces comprising private and public sector experts to help inform AV policymaking processes and content and should encourage public policies that ensure the insurance industry has a seat at the table. Many stakeholder groups beyond insurers will have an interest in the development and implementation of new AV policies, including consumer groups, manufacturers, technology developers and suppliers, attorneys, regulators, legislators, public policy academics/researchers, and countless others. Insurers will have unique and valuable insights into several key issues that will likely arise from AV technology, such as risk assessment and mitigation, big data analysis, the functioning of comprehensive liability regimes, and navigating State-Federal coordination issues. Insurers should position themselves to contribute to these policymaking discussions.

5.5.3.5 Promote Communication and Coordination Between Policymakers and Other Stakeholders

Many lawmakers and regulators at the local, State, and Federal levels are grappling with the policy challenges and opportunities related to the AV world, as are private industry groups and individual companies. Coordination among these players is essential to develop a coherent and rational regulatory structure that will promote growth and adoption of AV technology, as well as public safety, during the transition to AVs. One important step is public-private cooperation via standing advisory boards or similar structures. Such bodies generally promote consensus building and creation of best practices, while also recognizing the need for flexibility to promote consumer-driven, private-market competition and innovation.

At the policymaker level, insurers should encourage local, State, and Federal officials to work together to the greatest extent possible. The current State-based regulatory and oversight structure for insurance is well established and provides certainty for businesses and consumers. To build upon this existing structure and promote uniformity between AV-related insurance approaches, both during the AV transition/testing phase and after full AVs are publicly available, insurers could support development of a model State law, as well as collaboration between the U.S. Department of Transportation and State regulators (perhaps through the National Association of Insurance Commissioners). Finally, it is recommended that all policymakers communicate openly and regularly with the public as policy discussions are conducted and decisions are made. Transparency in the process will encourage public trust with respect to evolving AV technology and related safety measures.

5.5.3.6 Utilize Existing Insurer Delivery Systems to Communicate with Consumers

As noted, AVs will likely require some level of human involvement for the foreseeable future. Accordingly, there may be opportunities to increase safety by educating drivers about the evolving technology and their roles and responsibilities with respect to driving functions. To the extent that government officials develop consumer notification standards and requirements regarding AV technology, safety guidelines, distracted driving notifications, and other important information, insurers can use their extensive delivery systems to facilitate communication of those standards to consumers.

5.5.3.7 Unsafe Driving Behaviors, Like Distracted Driving, Will Continue to Present Challenges

The evolution toward AVs may eventually help reduce collisions that occur today due to distracted driving. In the meantime, unsafe driving behaviors will continue to present challenges. A Travelers survey in September 2020 found that 37% of American consumers reported using social media while driving, and another 36% reported shopping online behind the wheel.[(226)] In the lead-up to a fully automated transportation system and during the transition period, Travelers is taking on roadway safety issues like distracted driving through its Every Second Matters® education campaign, led by the Travelers Institute, its public policy division. The key principles to this initiative are highlighted in Figure 66. The campaign, which launched in 2017, recognizes that every driver, passenger, cyclist, and pedestrian has a role to play in combating distraction and enhancing roadway safety. Programs held at universities, industry and transportation safety conferences, and other public events provide valuable insights on distracted driving risks.

Figure 66. Slide. Key principles to Travelers' Every Second Matters initiative.

5.5.4 Considerations for ADS-equipped CMVs

A mini-technical session entitled, "Hands-off Insurance: Insurance Guidelines for Automated Vehicles," was hosted by the S.18 Automated Vehicles Study Group at the TMC 2023 Annual Conference and Transportation Technology Exhibition in Orlando, Florida, on Tuesday, February 28. During this session, experts from the trucking industry discussed implications of insuring ADS-equipped trucks in today's freight market, including representatives from TMC, Koffie Financial (https://getkoffie.com/), Paul Hanson Partners (https://www.paulhanson.com/), and KOOP Technologies (https://www.koop.ai/). The session was moderated by a representative from Kenan Advantage Group, a tanker trucking fleet, and opening comments at this session were provided by Earl Adams, Jr., Chief Counsel at the FMCSA. This section focused on the discussion from industry experts regarding insuring ADS-equipped CMVs and most specifically trucks. The panel identified some core topics that should be addressed or require further investigation. The following are high-level summaries of topics discussed in the session. Additionally, other leading trucking insurance experts were asked to provide further insight regarding the article from Travelers and the technical session mentioned above. The insight will be used to supplement the recourse provided in the following section and this insight will be called out specifically to separate it from material that was obtained from the session.

5.5.4.1 Evaluating ADS-equipped CMV Risk

Clearly defining the ODD of AVs provides valuable information to the policy holder in understanding the degree of risk they may be accepting. For example, delineating procedures such as a "safe stop" or how a vehicle should react in a situation that it does not understand allows a policy holder to better utilize their equipment to meet expectations of risk. It is recommended that policy holders clearly understand the ODD of the technology they use so that no assumptions are made as to the technology's functionality.

Additional Expert Insight

Through addressing public policy questions and challenges, it is important to consider cargo in terms of risk mitigation. This is in addition to improving safety for the public, and more specifically drivers and pedestrians. Safety is the core concern, but loss of cargo, due to the nature of trucking, is paramount for consideration.

5.5.4.2 Liability for ADS-equipped CMVs

Due to the integration of AI in ADS-equipped CMVs, fleet maintenance will play a large role in the liability writing process. Typically, significant focus is placed on drivers regarding liability. The single-point focus of driver operation for liability determination will be blurred across AV function and maintenance. For example, if equipment is maintained but not kept to manufacturer specifications, fleets are responsible.

OEMs may need to start to carry product liability of their own. These types of policies would have to account for large crashes or patterns of behaviors across many vehicles that all operate similarly. However, many claims are related to property damage only, and it makes less sense to apply product liability. Panelists commented that they did not see the framework for the product liability now. In early adoption, theoretically, fleets will have 10% automated and 90% manual driven CMVs. The question that appears is, how do you have a product liability that is mixed? It is important to also recognize that product liability is difficult to litigate. Will it be financially viable to pay the claim? It would be useful to create regulations that guide affected organizations on responsibility and payments.

Additional Expert Insight

Insurance coverage regarding AVs will require different approaches when utilizing existing automobile insurance structure. Coverage will need an acute focus on liability. Additionally, the level of automation will likely procure varying approaches from Level 1 to Level 5 autonomy. The question of liability is a large focus for insurance coverage of AVs. There are many variables to consider: is the manufacturer at fault, the software designer, or the individual that was driving? The level of autonomy pairs with this question. As autonomy increases, is the driver less liable? It is suggested that coverage incrementally evolves as levels of automation are engaged.

5.5.4.3 Improving Collaboration and Communication

It may be beneficial to increase the degree of communication or functionality between ADS-equipped CMVs and traffic agencies or law enforcement. If a vehicle is unable to reach a decision on how to react to its environment, features are needed that allow an external party to guide the vehicle to a safe stopping place.

Additionally, if an ADS-equipped CMV is connected to its insurance provider, as well as traffic agencies and law enforcement, in the instance of a collision the vehicle will immediately be able to communicate with dispatchers and agents to potentially reduce the time it could take to get emergency services on the scene to increase safety. Also, claims could be set up immediately utilizing AV data to reduce some of the hassle that arises from filing claims.

5.5.4.4 Collecting, Sharing, and Using ADS Data

AVs produce a tremendous amount of data that has the potential to impact the insurance industry. Further investigation is necessary to determine how this data can best be utilized.

Providing data such as types of actions and frequency of actions could prove beneficial in reducing rates for consumers by rewarding drivers or, in this case, ADS operators, for safe driving habits.

Not all ADS developers allow fleets to collect their own data from the vehicle. There is a trust factor involved in the communication of data between developers and owners. This data could prove critical in delineating the right to repair, as well as further understanding the operating boundaries or ODD. Furthermore, there is a need for consideration regarding how second- or third-party technicians affect liability regarding the right to repair.

5.5.4.5 Costs

The cost of ADS-equipped CMVs will be considerably higher than for current trucks. The availability of equipment and technicians for repair is valuable in reducing the time and cost of returning ADS-equipped CMVs to service. From the fleet perspective, improvements need to be made in this domain to advance the viability of ADS-equipped CMVs.

5.5.4.6 Infrastructure

<u>*Additional Expert Insight*</u>

When questioning the unknowns of AVs, such as how long it will take to transition to autonomous fleets or when will the benefits of AVs be truly realized, infrastructure is a topic that is sometimes forgotten. It should be addressed that roadway infrastructure will likely need to adapt in some way to accept AVs. How long will it take for this change to occur?

5.5.4.7 Cybersecurity and Cargo Theft

There are some inherent risks regarding theft and cybersecurity for ADS-equipped CMVs since no individual is present to prevent tampering with the systems or cargo theft. Since these vehicles can operate at all hours and typically have a 360-degree view, this may be a deterrent to potential transgressors.

5.5.4.8 Software Updates

Updates to software may become mandatory in the future. Individual vehicle performance may be affected by mandatory "over the air" updates. Additionally, this occurrence may become more prevalent as technology transitions from driver assistance systems to full ADS autonomy. The benefits of this are valuable, allowing users to remain current with the most effective software versions for their hardware. The exception is that when or if there is an issue or malfunction with an update, the issue could potentially lead to sub-optimal driving behaviors and affect many vehicles at the same time.

5.5.4.9 Can the Current Insurance Structure Hold with the Introduction of AVs?

<u>*Additional Expert Insight*</u>

Some professionals disagree on whether the current automobile insurance structure can be utilized when covering AVs. Though the current system has been effective at addressing innovation and adapting to current technology so far, AVs propose a different process to addressing the driving task and overall automobile utilization. Additionally, AVs change the landscape of risk exposure (such as the introduction of cybersecurity threats) and the context of risk exposure is adapting with it. To adequately address risk, carriers are going to need to review their entire value stream to identify risk, such as if real-time data or new data sources propose avenues for risk.

5.5.4.10 Additional Topics for Further Review

Some topics in the session were brought up but not discussed in detail. These topics are mentioned here to recognize the need for further examination and should receive continuing discussion and investigation as automation technology evolves and becomes more commonplace on the roadways. They are as follows:

- How should legislation be created and reformed to manage ADS technology?
- How could public awareness and image be improved for ADS-equipped CMVs?
- What should the limitations be for ADS-equipped CMVs?

ADS technology is developing at a rapid pace. These discussions only scratch the surface regarding impacts and solutions for insuring ADS-equipped CMVs. It is important for broad collaboration to elevate and resolve issues as the ADS-equipped CMV industry continues to evolve.

Additional Expert Insight

To expand upon the article written by Travelers, it is valuable to consider the date when it was written. The article was produced in 2021 and may contain outdated information about the AV sector. The industry is evolving rapidly, and the AV stage looks different today than it did three years ago. For example, on December 13, 2022, Waymo acquired the permits necessary to drive fully autonomously in California, and as of October 2023 Cruise pulled all of their robotaxis off of the road to perform a full safety review in the wake of a pedestrian suffering injuries due to a Cruise robotaxi. Additionally, ArgoAI, a company investigating AV technology shut down in October of 2022 after Ford and VW pulled their funding for this company. The lidar technology used on AVs has continued to improve drastically since 2021 with improved range, accuracy, data collection, and more (https://www.electronicsforu.com/technology-trends/latest-).

Lastly, it is important to note that though ADAS technology is being implemented on a continuously larger and more available scale, there is no guarantee that individual drivers will use the full extent of the technology. Some drivers disengage ADAS features with user preferences and some report distrust of these systems.

5.5.5 Summary of Findings

In summary, auto insurance can meet society's needs in an AV world by continuing to compensate affected consumers with speed, fairness, and efficiency. Also, any comprehensive AV legal/regulatory structure must include insurance-specific components, including:

- Addressing insurance liability standards as the primary risk transfer mechanism;
- Providing sufficient coverage limits at the vehicle level;
- Standardizing data governance and cybersecurity requirements; and
- Ensuring representation of the insurance industry in policymaking and stakeholder forums and discussions.

5.6 ADS-EQUIPPED TRUCK SAFETY METRICS/VARIABLES

5.6.1 Background

Surface transportation in the United States has become the primary means of transporting goods, with a heavy reliance on large trucks. Trucks affect every U.S. citizen regardless of personal mode of transportation, as nearly all consumer goods are delivered by trucks at some point in the delivery cycle.(227) There are approximately 3.5 million commercial truck driving licenses in active use,(228) and approximately 1.8 million of these licenses are used by drivers operating heavy and tractor-trailer trucks.(229) Trucks hauled 11.4 billion tons of freight in 2015, valued at more than $13 billion in 2012 dollars.(230) Following the 2008 recession, demand for freight services has steadily increased as the economy has grown, and truck drivers have needed to move more goods. As of 2015, there were 551,150 interstate motor carriers actively operating in the United States.(231) The trucking industry contributes significantly to the nation's economic portfolio, hauling 61% of the total freight transported in the United States by value in 2016(232) and contributing an estimated 3.5% of the nation's gross domestic product.(233)

Contrary to the transportation system's gradual evolution, vehicle technology is undergoing rapid changes that could affect all types of road transportation, and its effects on trucking could have a particularly important effect on society. Increasing demand for consumer goods and just-in-time inventory strategies (i.e., receiving goods only as needed) place a significant demand on truck drivers and the U.S. highway system as more and more goods are delivered by trucks. According to the Bureau of Labor Statistics, while the heavy and tractor-trailer truck driver workforce will only grow by slightly over 100,000 individuals from 2016 to 2026, with the level of expected retirements there will be openings for over 210,000 drivers per year over this period.(234) This may amount to over 100% turnover in some segments of the industry. In addition, the trucking industry has been aware of a truck driver shortage for some time,(235) and industry surveys of member firms show that turnover rates in an important industry segment (long distance truckload) have been persistently high for decades.(236)

Traffic congestion is one of the most critical challenges compromising the efficiency of the transportation system. The annual cost to the U.S. economy of travel delays caused by traffic congestion amounts to $160 billion, or $960 per commuter; each year, delays keep travelers stuck in their vehicles for 7 billion extra hours, corresponding to 42 hours per commuter, and waste 3 billion gallons of fuel.(237) In addition, traffic congestion leads to higher crash rates and negative environmental impacts resulting from increased CO_2 emissions and noise. These effects degrade the public's quality of life.

Beyond the costs associated with reduced efficiency and pollution, trucks represent a safety concern. Large truck and bus crashes place an estimated $112 billion burden on the U.S. economy, including costs related to lost productivity, property damage, medical treatment and rehabilitation, travel delays, legal services, emergency services, insurance, and costs to employers.(238) Although large trucks have lower rates of involvement in property-damage-only crashes and injury crashes compared to passenger cars, due to their size and weight, large truck crashes are more likely to result in severe consequences and costs. In fact, over two thirds of fatal truck crashes, which usually involve a passenger vehicle, result in the death of the other vehicle's driver. In 2014, there were 326,000 property-damage-only crashes, 3,424 fatal crashes, and 82,000 injury crashes involving large trucks.(239) Compared to the general U.S. working population, heavy truck drivers are 12 times more likely to die on the job[240] and 3 times more likely to suffer an injury involving time off work.[241]

It is for all these reasons (demand for goods, better safety, reduced congestion, environmental concerns, and lower driver costs) that OEMs and technology firms are pouring funds into the development of ADS. The introduction of ADS is expected to bring about a major change in the transportation system. By 2050, 80% of vehicles sold and contributing to miles traveled will likely be ADS-equipped.[242] This is expected to result in an estimated 21,700 lives saved and 4.2 million fewer crashes each year, as well as reduced traffic congestion, increased fuel efficiency, and increased productivity.[243] As a disruptive yet beneficial technology, ADS will also profoundly affect the U.S. economy.

Fleet personnel will need data on the safety of an ADS before implementing ADS-equipped vehicles into their operations. They will also need data to monitor how the ADS performs while deployed in their operations. The public will require data on the safety efficacy of ADS-equipped trucks to ensure they feel comfortable sharing the road with these vehicles. However, traditional safety metrics, such as crashes and moving violations, may be inadequate for monitoring the efficacy of ADS-equipped trucks once they are deployed or for convincing the public of the safety of these technologies. New safety metrics must be explored and must provide objective measures of ADS safety, but these metrics should also be informative to the end users (i.e., fleet decision-makers and the driving public). In a similar vein, an operational definition of truck ADS safety must also be developed (i.e., what is the minimum level of ADS-equipped truck safety required to deploy these vehicles and to maintain deployment?).

5.6.2 Objective

What are appropriate safety metrics and variables for ADS-equipped trucks? The goal of this section is to outline potential variables that might be used by fleet decision-makers and the public to evaluate the safety of the ADS. Existing metrics (e.g., miles driven, disengagements, crashes) used by ADS technology vendors may fall short of the industry's stated safety aspirations. For example, it is common to report the total miles driven to tout technological progress and imply greater safety. However, progress in ADS development does not equate to overall safety; thus, these two criteria should be viewed separately. If total miles driven are allowed to stand as a proxy for safety, ADS technology developers might be incentivized to put the public at additional risk by driving more than necessary (e.g., it appears Uber ATG was driving an unjustifiable number of miles to accumulate more "total miles driven," which likely contributed to the fatal crash in Arizona in 2018).[244]

Similarly, ADS technology developers have historically been good at avoiding at-fault crashes but do a poor job of avoiding preventable crashes. The ADS-equipped shuttle crash in Las Vegas in 2017 is a perfect example. A large truck backed into the ADS-equipped shuttle, which resulted in a crash where the truck driver was legally at fault. This crash was in fact preventable, but the ADS did not make any effort to avoid the crash in the manner that a human driver would have (i.e., by backing out of the way).[245] To date, there has not been a systematic evaluation of the safety practices and metrics used by the industry.

5.6.3 Criteria for Safety Metrics

The VTTI team systematically identified and quantified the shortcomings and misaligned incentives of traditional ADS safety metrics. Then, we investigated alternative metrics that may be better indicators of ADS safety and that better align with incentives to develop and deploy ADSs in a prudent manner. (See references 246, 247, 248, 249, 250, and 251.) As a final step, the VTTI team consulted FMCSA, other policymakers, safety advocates, and ADS developers on which variables will be used to evaluate the safety of the ADS to get their feedback on the suggested safety metrics. There will likely not be any single metric and resulting "magic number" that indicates an ADS is safe to deploy. Also, the safety evaluation of an ADS should not be considered a one-time event (e.g., certification the ADS is safe), but should rather be a continual process given there will be new software upgrades, vehicle platforms, ODDs, etc.

5.6.4 Characteristics of Safety Metrics

An ideal metric to track ADS vehicle safety must be valid, reliable, feasible, non-manipulatable, and informative to the end user.(252) For a metric to be valid, it must directly measure the characteristic being tested (as opposed to a proxy variable). Reliability here means the safety metric is well-defined and consistent. Feasible means the metric can be easily tracked, considering time and resources. Non-manipulatable means it is not possible to "game" the data. End-user comprehension means the safety metric provides useful or interesting information to end users (i.e., fleet decision-makers and the public); thus, the safety metrics must be something end users can easily interpret and understand (otherwise, additional education and training are necessary).

Measurement Stage: The goal of the CONOPS project is to develop a living, comprehensive document that describes the ADS characteristics from the viewpoint of the truck fleets that will use ADS technology. This CONOPS will provide the trucking industry with clear guidelines on how to safely implement, and benefit from, ADS-equipped trucks. Thus, the safety metrics will focus on ADS truck deployment in fleets rather than development (establish and improve the ADS) or demonstration (exhibit ADS functionality).(253,254) Given the focus is on deployment, the safety metrics will focus on the ADS rather than any ADS subsystems or specific components or subcomponents.

ODD: Safety metrics, where possible, should be stratified by ODD.(255,256,257) The ODD specifies where the ADS can operate. Stratifying safety metrics by ODD will inform where the ADS performs better or worse, which is useful for driver training and education (if a driver is present) and route planning. These metrics will also be useful for refining the ADS through continued development and demonstration. The ODD can be defined by many different factors, including road geometry (straight vs. curved, incline vs. level, etc.), weather, time of day, road lighting, road surface (wet vs. dry, dry vs. snow, etc.), level of service (i.e., traffic density), road classification (see MAF/TIGER Feature Class Code definitions),(258) etc.

Tactical Maneuvers: Further stratification of safety metrics may occur through identification of performed tactical maneuvers. These tactical maneuvers are presented as control-related tasks of the ADS-equipped vehicle,(259) and the safety metrics would demonstrate outcomes across instances of tactical maneuvers. Metrics calculated within tactical maneuvers reflect a more precise means to define behavioral outcomes that serve as a comparison to other ADS-equipped vehicles, human performance, simulated models, or predetermined safety performance thresholds. For example, lane changes performed by the ADS-equipped vehicles can be parsed from the data, and safety metrics can be calculated across lane changes to determine the safety performance of the vehicle. Though the metrics calculated within tactical maneuvers are expected to be very informative as a comparison and a benchmark against safety thresholds, the ability of a fleet to define, parse, and stratify data pertaining to maneuvers remains burdensome. Future efforts investigating means for extracting tactical maneuvers may alleviate the burden on fleets by constraining or limiting needed parameters for calculations.

5.6.4.1 Summary of Exposure

This section provides an overview of the potential segmentation of safety metrics of a single or multiple ADS-equipped vehicle. Table 37 provides a list of the exposure characteristics (feasible and specificity) and the rating levels (high, medium, low) for each characteristic.

Table 37. Exposure characteristics and rating levels.

Characteristic	High	Medium	Low
Feasible	Collected with limited effort (e.g., time, cost, resources).	Collected with moderate difficulty.	Exposure is difficult to capture.
Specificity	Exposure provides insight into metrics at a granular level.	Exposure provides some insight into metrics.	Exposure produces high-level or overview metrics.

Table 38 provides a list of the potential exposures available used to segment safety metrics and the rating level for each characteristic, along with examples. As indicated in Table 40, fleet decision-makers are familiar with lagging safety metrics, as these metrics are currently used to evaluate their fleets' safety performance.

Table 38. Potential ADS exposure calculations and rating characteristics.

Exposure Type	Feasibility	Specificity	Examples
Organization	High	Low	Entire organization, miles driven, hours driven
Site	High	Low	Site location, yard
Vehicle Type	High	Low	OEM-specific
ADS Version	High	Low	AV release version
Operation Type	High	Low	Hub-to-hub, port drayage
Trips	High	Medium	Specific trips
ODD: routes	High	Medium	Interstate, exit-to-exit
ODD: conditions	Medium	Medium	Weather, work zones, time of day
ADS Mode	Medium	Medium	ADS engaged or disengaged
Events	Medium	High	Crashes, near-crashes
Tactical Maneuvers	Low	High	Lane change, backing, vehicle cut-in

5.6.4.2 Operational Definition of Safety

What is an acceptable level of safety in an ADS (how safe is safe)? The CONOPS project does not answer this question. However, the authors would like to acknowledge its importance with respect to safety metrics, which can be measured against this level and/or the relative difference.

Fraade-Blanar et al.[260] provides a good summary on this topic—surprisingly, there is no agreed upon operational definition of safety. Some have argued that ADS should be compared against the behavior of human drivers.[261,262,263] However, this method also poses challenges in terms of what the appropriate human comparison would be (truck driver, teen driver, drunk driver, crash-free driver, attentive driver). Even if an ADS were as safe as the average driver, 50% of the driving population would be riding in a vehicle that was less safe compared to their own driving.

Although achieving zero crashes is the vision in ADS implementation, it is likely that crashes will still occur. An appropriate human reference is an important benchmark for evaluating ADS. Krum et al.[264] provided baseline driving performance from 3.12 million miles of naturalistic truck driving data. These data were stratified by ODD and six maneuvers—speed behavior, longitudinal deceleration, following distance, lateral acceleration, lane deviation, and lane stability—which provide a human reference of driving performance in a particular ODD. Also included in that study is a public-use data tool for querying event rates based on a range of selectable parameters. These data provide baseline safety performance measures from human-operated trucks.

5.6.5 Safety Metrics

The safety metrics noted below are grouped as lagging or leading metrics with respect to ADS safety. Lagging safety metrics measure ADS "incidents" in the form of prior safety statistics. As they are lagging indicators, they are a poor measure for preventing safety incidents. These are the most commonly used safety metrics, including incidents per vehicle count, incidents per million miles, incidents per division or business unit, year-over-year number of vehicle crashes, and on-road injuries per 200,000 hours worked (aligned to Occupational Safety and Health Administration reporting). A leading safety metric precedes or indicates a future event and measures activities carried out to prevent and control safety incidents. These metrics are proactive and provide information on how the ADS is performing on a regular basis.[265] As indicated above, the safety metrics (regardless of lagging or leading) should be calculated for each specific ODD, as should accounting for exposure (using a denominator to obtain a rate, such as vehicle miles traveled, driving hours, per ADS-equipped truck, trips, events, etc.). Of these measures of exposure, the gold standard has been to calculate using vehicle miles traveled or driving hours. However, recent efforts have discussed evaluating safety metrics within incidents of events or scenarios, describing vehicle behaviors at a refined level. Applying that concept of leading indicators, an example safety metric would be the distance to all other vehicles when the ADS-equipped vehicle is performing a turn, or the speed and headway adjustment after the ADS-equipped vehicle experiences a cut-in by another vehicle.

5.6.5.1 Lagging Metrics

In this section, we provide a high-level overview of the suggested lagging indicators. Table 39 provides a list of the safety metric characteristics (valid, reliable, feasible, non-manipulatable, and informative) and the rating levels (high, medium, low) for each characteristic. As indicated in Table 40, fleet decision-makers are familiar with these metrics, as they are currently used to evaluate their fleets' safety performance with their current (human-driven) power units. These data is available for fleet decision-makers with little input from the ADS developer.

Table 39. Safety metric characteristics and rating level (adapted from Fraade-Blanar et al.[266]).

Characteristic	High	Medium	Low
Valid	Directly measures ADS safety.	Somewhat measures ADS safety.	Indirectly measures ADS safety.
Reliable	Safety metric is well defined and quantitative.	Safety metric is somewhat defined and quantitative.	Safety metric is qualitative, subjective, anecdotal.
Feasible	Collected with limited effort (e.g., time, cost, resources).	Collected with moderate difficulty.	Safety metric is difficult to capture.
Non-manipulatable	Limited opportunity to manipulate this safety metric.	Moderate opportunity to manipulate this safety metric.	Easy to manipulate.
End User Comprehension	Well understood by the end user, use is common practice.	Used by some end users.	Not currently used by end users.

Table 40 provides a list of the potential lagging safety metrics (described below) and the rating level (high, medium, low) for each characteristic (valid, reliable, feasible, non-manipulatable, and informative). Fleet decision-makers are familiar with lagging safety metrics, as they are currently used to evaluate their fleets' safety performance.

Table 40. Potential ADS lagging safety metrics and rating characteristics.

Safety Metric	Temporal	Valid	Reliable	Feasible	Non-Manipulatable	End-User Comprehension
Crash	Lagging	Medium	Medium	High	High	High
FMCSA-reportable	Lagging	Medium	High	Medium	High	High
Preventable Crash	Lagging	High	High	Medium	High	High
Non-preventable Crash	Lagging	Low	High	Medium	High	High
Injury Crash	Lagging	Medium	Medium	Low	High	High
Fatal Crash	Lagging	High	High	Medium	High	High
Tow-away Crash	Lagging	Medium	Medium	High	High	High

Miles Driven: Miles driven refers to the total miles driven under control of the ADS. These can be subdivided by specific ODD. Although miles driven is an important measure of exposure, which should be included as a denominator in the safety metrics, it does little to reflect the ADS's safety.[267]

Crashes: Crashes are the most widely used safety metric. They are defined as the ego vehicle contacting another vehicle, pedestrian, animal, road debris, other stationary object, or a road departure. Crashes can be further divided based on their severity (see KABCO Injury Classification)[268] and/or cost. Below are the most commonly used crash metrics.

FMCSA-reportable Crashes: FMCSA-reportable crashes must be reported to FMCSA. These crashes involve a fatality, injury that requires immediate medical treatment away from the crash scene, or a vehicle that is disabled as a result of the crash and must be transported away by a tow truck or other vehicle.[269]

Preventable Crashes: Each fleet has their own operational definition of a preventable crash. The National Safety Council defines a preventable crash as one in which the driver failed to exercise every reasonable precaution to prevent the accident. This is irrespective of whether there was property damage or personal injury, the extent of the loss or injury, to whom it occurred, and the location of the crash.[270] An example of this type of crash would be a vehicle hitting another vehicle that was stopped at an intersection facing the direction of travel.

Non-Preventable Crashes: By definition, a non-preventable crash is any crash that was not determined to be a preventable crash. Non-preventable means any crash in which everything that could have been reasonably done to prevent it was done and the crash still occurred. For example, a vehicle stopped at an intersection facing the direction of travel is struck from behind by another vehicle.

Fatality: A crash that results in one or more fatalities. Death is recorded within a period after the crash (e.g., 30 days).

Injury: A crash that results in one or more injuries. These can be nested based on the severity of the injuries (e.g., incapacitating injury, non-incapacitating injury, possible injury). Injury is recorded within a period after the crash (e.g., 30 days).

Tow-away Crash: A crash that results in a vehicle that is disabled and must be transported away by a tow truck or other vehicle.

5.6.5.2 Leading Metrics

This section provides a high-level overview of the suggested leading indicators. As indicated in Table 41, most fleet decision-makers are unfamiliar with these metrics; thus, training and education are needed to increase awareness. Most of the leading safety metrics described below are not readily available to fleet decision-makers and require input from ADS developers.

Table 41 provides a list of the potential leading safety metrics (described below) and the rating level (high, medium, low) for each characteristic (valid, reliable, feasible, non-manipulatable, and informative).

Table 41. Potential ADS leading safety metrics and rating characteristics.

Safety Metric	Temporal	Valid	Reliable	Feasible	Non-Manipulatable	End-User Comprehension
Near-crash	Leading	Medium	Medium	High	High	Medium
Traffic Violation	Leading	Low	Low	Medium	Low	Medium
Disengagement	Leading	Low	Medium	High	Low	Low
Simulated Manual Disengagement	Leading	Medium	High	Medium	Low	Low
Conventional Indicators	Leading	High	High	Low	Medium	Medium

Safety Metric	Temporal	Valid	Reliable	Feasible	Non-Manipulatable	End-User Comprehension
Perception-based Indicators	Leading	High	High	Low	Medium	High
Safety Envelop Violation	Leading	High	Medium	High	Medium	Low
Fleet Integration	Leading	Medium	Medium	Medium	Low	Medium
Confidence and Accuracy	Leading	Medium	Medium	Medium	Medium	Low

Near-crashes: Until recently, lagging metrics were the only widely available metric for fleet decision-makers. Although the use of near-crashes is a relatively new safety metric in trucking, near miss reporting has been used successfully in the aviation industry for many decades. Near-crashes are non-crash events (a subjective judgement on the potential for a crash); however, there is no standardized operational definition for these events. Hankey et al.[271] defined a near-crash as “any circumstance that requires a rapid evasive maneuver by the subject vehicle, or any other vehicle, pedestrian, cyclist, or animal, to avoid a crash is considered a near-crash. A rapid evasive maneuver is defined as steering, braking, accelerating, or any combination of control inputs.”

Traffic Violations: A traffic violation is a State or Federal (in the case of FMCSA) law that regulates the operation of trucks on streets and highways. These laws vary by State. Traffic violations can be moving (i.e., vehicle is in motion) or non-moving (i.e., vehicle is not in motion). Moving violations include speeding, failure to yield, turning into the wrong lane, etc., whereas non-moving violations are usually reflective of parking violations (e.g., parking in front of a fire hydrant, parking in a no-parking zone). Most of the latter are unrelated to safety per se.[272]

Disengagements: A disengagement is when the ADS-equipped vehicle is in automated mode and control of the vehicle is returned to the human driver. There are two types of disengagements: (1) automatic and (2) manual. An automatic disengagement is when an ADS-equipped vehicle exits the automation mode through an error or kickout, or, if able, when the system requests a human driver to take over the dynamic driving task (as depicted in SAE Level 3 automation). A manual disengagement is when the human driver is not confident with the ADS (e.g., discomfort, adverse weather conditions, heavy traffic, poor infrastructure, potential adverse situation) and takes control of the vehicle from the ADS.[273,274] The relationship between disengagements and safety is unclear, as fewer disengagements may not necessarily reflect better safety.[275] One potential option to increase the validity of manual disengagements is to simulate the ADS’s behavior (and the behavior of other actors) had it not been disengaged by the driver. This could be a useful solution to determine if the disengagement was warranted.[276] Thus, manual disengagements could be subdivided into those where the ADS would have functioned safely and those where the ADS was unsafe. A subset of manual disengagements includes both disengaging the system for test-related or normal operations, such as exiting automation to take an exit to refuel or leaving the parameters of the ODD testing area, and accidental disengagements from the safety operator. These disengagements would be irrelevant to the functional safety of the vehicle and would not be counted as part of a safety metric.

Conventional Indicators: Traditional metrics used to demonstrate the capabilities of a manned vehicle have been represented across numerous studies, both experimental and naturalistic. These metrics typically relate to specific outcomes of the vehicle and are reflective of immediately comprehensible vehicle parameters. The calculation of these indicators will typically rely on sensors (non-visual) equipped on the vehicle as well as kinematic data and other information coming from the CAN bus's J1939 protocol. Metrics can be summarized through typical statistical methods, including creating averages, ranges, minimums and maximums, or standard deviations of data across some exposure level. Examples include yaw rates, acceleration, and speed, each of which can be calculated across trips, ODDs, tactical maneuvers, or another meaningful stratification method.

Perception-based Indicators: Similar safety metrics can be calculated using processed visual sensors in conjunction with conventional indicators to determine safe operation of the ADS-equipped vehicle in relation to roadway elements and other traffic actors. The inclusion of perception sensors allows for a more real-world understanding of the vehicle's position in relation to all elements, static or dynamic, on the roadway. Further, perception-based safety metrics include the placement of the ADS-equipped vehicle in lane and the relative proximity and velocity of other road users. Examples of metrics include lane tracking and lane centering, car following, and distance to other vehicles or objects. These metrics can also be stratified within vehicle or system, or across trips, ODDs, or tactical maneuvers. One further example is to parse out tactical maneuvers in which the ADS-equipped vehicle merges or changes lanes in front of another vehicle and calculate the average minimum distance to that following vehicle across every instance of the maneuver. This average minimum would serve as an easily understood metric of safety that can be compared to other ADS technologies or against a human baseline of performance. These metrics are typically presented as lower-order metrics that combine to create higher-order metrics representing the safety envelope of the vehicle.

Safety-Envelope (Risk-based) Violations: Fraade-Blanar et al.(277) termed safety-envelope violations "roadmanship" (i.e., the ability of the ADS to drive safely without creating hazards and/or responding to other hazards). These violations can be counted and defined by an initiator and a responder so the violation can be attributed to the ego vehicle or the other road user. These violations are likely to vary by ODD and ADS developer unless there are standards or regulations. These safety envelopes could be defined based on the safe lateral and longitudinal distance to another vehicle, defensive driving, quickness to give right-of-way, and infrastructure limitations. Fraade-Blanar et al.(278) envision a series of boundaries, each with a more extreme evasive response from the ADS. See the Underwriters Laboratories(279) standard, UL 4600, for specific safety-envelope violations. Practical applications of risk-based metrics include Responsible Sensitive Safety and NHTSA's Model Predictive Instantaneous Safety Metric. These metrics attempt to define the safety status of the ADS-equipped vehicle.

Fleet Integration: The introduction of ADS-equipped vehicles requires continuous evaluation of metrics related to the efficient implementation of the technology into the existing organizational structures. As ADS technologies are first introduced, a close relationship between the ADS developer and the incorporating fleet is required for mixed-fleet operations. This relationship should produce an implementation plan that will safely incorporate ADS technologies into the existing system. While integration metrics may include operational (e.g., number of trucks involved, tasks assigned) or monetary (e.g., efficiency) components, the metrics related to safe implementation are critical. These metrics may include lagging (e.g., crashes) or leading (e.g., conventional metrics) indicators as described above, but could also include non-traditional metrics relating to the training of personnel (e.g., safety operators, support team, maintenance), implementation of operational policies (e.g., coaching, culture) and protocols (e.g., communications, interactions), and tracking of individual behaviors surrounding ADS operations.

Confidence and Accuracy: Across each decision made during the motion or path planning of the ADS-equipped vehicle, the system is expected to produce an internal go/no-go for each choice the ADS makes. These decisions are dependent on many parameters, and the integration of each relevant factor will ultimately dictate the behavior of the vehicle. A potential option to evaluate vehicle behaviors during edge case events is to insert the ADS into a simulated situation and record which behaviors the vehicle is most likely to execute, along with confidence or similar outputs that dictate the choice of behavior selected by the ADS. Other opportunities for evaluation using naturalistic data may provide similar insight into the likely behavioral competencies of the ADS during scenarios that are not often encountered on the roadway.

5.7 ADS ROAD ASSESSMENT SYSTEM

The objective of this section was to develop a road readiness assessment system for large trucks equipped with ADS. A road readiness assessment system distinguishes roads that are suitable for the operation of ADS-equipped trucks from roads that are not, in which case intervention by a human operator (either within the truck or overseeing truck operations remotely) may be needed. The road readiness assessment system was developed for U.S. Interstate highways, although recommendations are provided on how the assessment system can be applied to other roadway types. The assessment system was developed using data from cross-country trips based on Pronto's ADS technology. However, it can be applied to other ADS technologies or to road readiness assessment using data that were not gathered by an ADS. As developed, the assessment is based on a combination of road characteristics data gathered by a truck ADS and existing data gathered from other sources. The developers believe that the road readiness assessment system will be the most realistic and accurate when based on road characteristics data gathered by a truck ADS. However, the system has been developed so that, where appropriate, it can be applied solely with road characteristics data from other sources.

The road readiness assessment system has been developed for operation at two levels of detail. The first is a basic road readiness assessment system that is applicable to truck ADS in general, without reference to any specific ADS technology. This basic system has been fully formulated and is presented in this section. In addition, plans have been developed for future development of an advanced system that can be adapted for application to specific ADS technologies. Plans for the advanced road readiness assessment system have been formulated in recognition that truck ADS differ in their capabilities and, therefore, in how they are related to road readiness. The primary products of the research are a basic road readiness assessment system for ADS-equipped trucks, demonstration of the application of that basic assessment system to U.S. Interstate highways using data collected by the Pronto ADS, recommendations for how the assessment system might be adapted to other roadway types, and recommendations for how an advanced road readiness assessment system might be adapted to other ADS technologies.

5.7.1 Approach to Road Readiness Assessment System Development

The basic road readiness assessment system was developed using data collected by the Pronto truck ADS during the cross-country drives with ADS-equipped trucks (described in Chapter 3). The cross-country drive database includes information generated by Pronto's ADS that is not available from any other existing source, such as road lane score, which represents lane marking quality (see explanation below). In the testing of Pronto's Level 4 ADS in the cross-country drives, the ADS was operated as a Level 2 system under an ODD which specified that the ADS would be engaged only on the mainline lanes of Interstate highways but not on ramps or other roads. The ADS was engaged by the driver and disengaged by the driver, as appropriate, and the driver always remained responsible for the safe operation of the vehicle. Because of the live-traffic environment during the testing and data collection, the ADS operation was restricted to SAE Level 2, where longitudinal and lateral control by the ADS was active but the driver maintained full responsibility for monitoring the roadway. Therefore, the driver was always in place to assume control of the truck and take appropriate action.

The basic road readiness assessment system development also used data from existing sources other than the ADS. The most useful existing source of road characteristics data found in the research is the publicly available portion of the FHWA HPMS database. HPMS has data available for all Interstate highways nationwide and for a sample of other roads. However, HPMS does not include all variables relevant to road readiness assessment for ADS-equipped trucks, though it does include some key variables discussed later. Other existing databases were reviewed, including the Second Strategic Highway Research Program (SHRP 2) Roadway Information Database (RID) and State DOT roadway inventory files. However, no database was identified that includes all the data that would be needed to implement a road readiness assessment system. Sourcing data from individual States would mean that the availability, format, and content of specific data elements would vary from State to State, which would make nationwide application impractical. Furthermore, many of these State DOT databases are considered proprietary and may not be available to all users who might wish to apply the road readiness assessment system.

It, therefore, appears impractical to base a road readiness assessment system entirely on data from non-ADS sources, unless the system were to be applied within a single State or users were to acquire the needed data themselves. For example, lane marking quality could be assessed by visual review of roadway photos or video logs. This is potentially feasible but is likely to be impractical for most users because of the level of effort required for data acquisition. An exception might occur if an assessment were needed for one relatively short section of roadway. Based on this review, it appears that a road readiness assessment system that combines data collected from ADS and non-ADS sources is the most practical for nationwide application.

5.7.2 Candidate Variables for Inclusion in a Road Readiness Assessment System

The ADS used by Pronto in the cross-country drives gathered four variables appropriate for inclusion in a road readiness assessment system. These variables, each of which were gathered once per second during most of each cross-country drive, include:

- *Lane marking quality*—A score between 0 and 1 indicating the ability of the ADS to detect lane lines during each second of travel time; 1 is the best score, and 0 is the worst score.
- *Road condition*—The condition of the road surface, classified into categories of “bumpy” or “smooth” calculated over each second of travel time.
- *Cellular connectivity*—The percentage of received signal strength for the ADS’s LTE modem during each second of travel time. LTE is commonly referred to as a 4G cellular network. The signal strength is quantified as a percentage from 0% to 100% of the maximum signal strength.
- *GPS connectivity*—The number of GPS satellites visible to the ADS during each second of travel time. The number of satellites visible varies from 0 to 15.

There is one other variable that appears important to road readiness assessment that is not available in the data collected in the cross-country drives: the availability at any given point in time of a stopping area outside the traveled way suitable as a location for an ADS-equipped vehicle to reach a minimal-risk condition. Therefore, the inclusion of a shoulder presence and width variable in the road readiness assessment system is recommended. The five variables proposed for inclusion in the road readiness assessment system will be referred to as road readiness assessment measures and are discussed in greater detail in this section.

5.7.3 Cross-Country Drives for Which Data Acquired from an ADS Are Available

Data is available for five cross-country drives made by Pronto. These include:

- Trip 1: Cross-country circular loop: San Francisco to New Jersey to Florida and return to San Francisco
- Trip 2: San Francisco to Texas and return to San Francisco
- Trip 3: Calgary, Alberta, to San Francisco
- Trip 4: San Francisco to Florida and return to San Francisco
- Trip 5: San Francisco to Montana to Las Vegas and return to San Francisco

The road readiness assessment system development effort focused on Interstate highways within the United States. These five drives covered approximately 15,400 miles of travel on Interstate highways. This includes travel on approximately 10,790 centerline-miles of Interstate highways, 81% of which were driven in one direction of travel only and 19% of which were driven in both directions of travel. Some Interstate highways were driven more than once in a given direction of travel. Because these drives were made at different times (typically on different trips), they provide separate observations, and both trips over a given direction of travel were used as separate observations in the analysis. The 10,790 centerline-miles of Interstate highways traveled constitute approximately 23% of Interstate freeways in the United States. Appendix B lists the specific Interstate highway sections that were driven during the five cross-country drives; data were collected by the truck ADS for most of these roads and have been analyzed in the research. The length of road for which data is available is summarized in Section 5.7.4.

The cross-country drives by Pronto's ADS-equipped truck collectively include travel in 29 of the 50 States, primarily (but not exclusively) on Interstate highways. The States whose highways are included in the cross-country drive data include:

- Alabama
- Arizona
- California
- Delaware
- Florida
- Georgia
- Idaho
- Illinois
- Indiana
- Iowa
- Louisiana
- Maryland
- Mississippi
- Montana

- Nebraska
- Nevada
- New Jersey
- New Mexico
- North Carolina
- Ohio
- Oklahoma
- Oregon
- Pennsylvania
- South Carolina
- Texas
- Utah
- Virginia
- Washington
- Wyoming

The cross-country drives include a portion of the Interstate highway system in each of these 29 states, selected based on the logical routing to the final or intermediate destination of each trip. The truck also briefly entered a 30th state, New York, but did not travel on any freeways in New York that are part of the Interstate highway system. The data recorded by the ADS at 1-second intervals during these cross-country drives included the following variables of potential interest to road readiness assessment system development:

- Time stamp identifying the day, month, year, hour, minute and second at which the data were recorded;
- Latitude and longitude at which the truck was located;
- Speed (mph) and other kinematic and orientation (pitch, roll, yaw) variables;
- Lane marking quality;
- Road condition;
- Cellular connectivity; and
- GPS connectivity.

These data is available in the form of CSV files in which each record represents a 1-second interval. The CSV files are a publicly available product of the CONOPS grant. The cross-country drive data also includes photographic images made at 25 fps from the front-facing camera by the ADS as the truck travels along the road.

5.7.4 Initial Review of Cross-Country Drive Data

An initial review of the cross-country drive data was conducted for the five available cross-country drives. Files for the travel in each State by the ADS-equipped truck were imported into Google Earth® for review. Based on this review, each record in the CSV files was supplemented with a *location type* code identifying the type of road facility the truck was traveling on during that 1-second interval. The categories used for these location codes include:

- Mainline lanes of an Interstate highway (identified by route number);
- Sections of non-Interstate U.S. or State highways (identified by route number);
- Weigh station/rest area/etc. (i.e., a facility on the highway right-of-way accessed by the truck);
- Work zone (median crossover to opposing direction of travel and return);
- Gap in data (beginning and ending records for sections of roadway in which no ADS data were gathered);
- Ramp;
- Local access road (incidental travel on public roads used for access to and from particular off-road locations); and
- Off-road location (food/fuel/hotel, etc.).

The codes for weigh stations/rest areas/etc., work zones, and gaps can be used to identify the locations of portions of the mainline Interstate highways for which no data recorded by the ADS are available. The ramps define locations at which the ADS-equipped vehicles leave the mainline Interstate highway to move from one road to another, or to access food, fuel, or hotel facilities, or for other reasons, and to subsequently return to the mainline lanes. Where the ADS-equipped truck leaves the Interstate highway via a ramp for any reason and then returns to the highway, there is typically a short section of the mainline Interstate highway lanes for which no data from the ADS are available. Where the ADS-equipped truck passes through work zones that could be identified from the ADS data, those work zones were excluded from the data analysis because such locations temporarily have characteristics that differ from their normal configuration. Generally, the only work zones that could be readily identified occurred where the ADS-equipped truck followed a temporary roadway that crossed through the highway median, operated in a lane normally reserved for opposing traffic, and then at some distance downstream crossed back through the median to the normal lanes. The vehicle path crossing through the median at such locations can be readily identified with the truck path (based on latitude and longitude) superimposed on aerial photographs.

Only the portions of the five cross-country drives that were coded as mainline Interstate highways (i.e., not coded as non-Interstate routes, ramps, weigh stations, work zones, or gaps) were analyzed for development of the basic road readiness assessment system. Table 42 shows the highway mileage for which ADS data were available by State and trip number, as well as the Interstate routes that were traveled in each State. The table shows that ADS data were available for a total of 12,826 miles of directional roadways on Interstate highways out of the 15,400 miles shown in Table 42.

5.7.5 Supplementary Variables Added to Cross-Country Drive Data

As noted earlier, the publicly available HPMS database appears to be a promising source for roadway characteristics data to supplement the cross-country drive data collected by the ADS.

This supplementary data from HPMS includes additional information about the highways that were traveled by the ADS-equipped truck and was obtained for the mainline Interstate highway lanes in the cross-country drive data. Variables from HPMS were added to the cross-country drive records by location matching with latitude and longitude coordinates within a GIS software package (specifically, ArcGIS). The selected HPMS variables being added to the cross-country drive files include:

- Annual average daily traffic volume (AADT);
- Combination truck AADT;
- Single-unit truck AADT (includes buses);
- County code;
- Urban area code;
- Posted speed limit;
- Number of through lanes;
- International Roughness Index (IRI);
- Structure (bridge/tunnel/causeway);
- Surface type (bituminous/Portland cement concrete);
- Toll facility indicator; and
- National truck network indicator.

Table 42. Total length of directional roadways for which ADS data were collected in the five cross-country drives.

State	Trip 1 Roadway Length (mi)	Trip 2 Roadway Length (mi)	Trip 3 Roadway Length (mi)	Trip 4 Roadway Length (mi)	Trip 5 Roadway Length (mi)	Total Roadway Length (mi)	Routes Included
Alabama	25			147		171	I-10 EB & WB, I-65 SB
Arizona	346			663	29	1,039	I-10 WB, I-15 SB, I-40 EB
California	653	98	265	657	398	2,072	I-5 NB & SB, I-10 WB, I-15 NB & SB, I-40 EB, I-80 EB & WB, I-210 WB, I-238 WB, I-505 NB & SB, NB & SB, I-590 EB & WB, I-880 EB & WB
Delaware	16					16	I-85 SB, I-295 SB

State	Trip 1 Roadway Length (mi)	Trip 2 Roadway Length (mi)	Trip 3 Roadway Length (mi)	Trip 4 Roadway Length (mi)	Trip 5 Roadway Length (mi)	Total Roadway Length (mi)	Routes Included
Florida	65			494		556	I-4 EB & WB, I-10 EB & WB, I-95 NB & SB, I-295 NB, SB & WB
Georgia	110					110	I-95 SB
Idaho			12			12	I-90 WB
Illinois	162					162	I-80 EB
Indiana	160					160	I-69 SB, I-80 EB, I-465 WB
Iowa	302					302	I-80 EB
Louisiana	247			333		580	I-10 WB, I-20 EB
Maryland	103					103	I-95 SB
Mississippi	69			131		199	I-10 WB, I-20 EB & WB, I-59 NB & SB
Montana					326	326	I-15 NB, I-90 EB
Nebraska	452					452	I-80 EB
Nevada	392				117	509	I-15 SB, I-80 EB
New Jersey	137					137	I-78 WB, I-80 EB, I-95 SB, I-295 SB
New Mexico	152	214		529		895	I-10 WB, I-40 EB
North Carolina	180					180	I-95 SB
Ohio	217					217	I-80 EB
Oklahoma		274				274	I-35 NB, I-40 WB
Oregon				85	185	279	I-5 NB, I-82 EB, I-84 WB, I-405 NB
Pennsylvania	299					299	I-80 EB
South Carolina	198					198	I-95 SB
Texas	763	595		448		1,806	I-10 WB, I-20 EB & WB, I-35E NB, I-35W SB, I-40 EB & WB, I-44 WB, I-635

State	Trip 1 Roadway Length (mi)	Trip 2 Roadway Length (mi)	Trip 3 Roadway Length (mi)	Trip 4 Roadway Length (mi)	Trip 5 Roadway Length (mi)	Total Roadway Length (mi)	Routes Included
							NB & WB, I-820 SB
Utah	193				375	568	I-15 SB, I-80 EB & WB
Virginia	174					174	I-95 SB
Washington			98		161	259	I-5 NB, I-82 EB, I-90 WB, I-182 WB
Wyoming	391				386	777	I-25 NB & SB, I-80 EB & WB, I-90 EB
TOTAL	5,806	1,180	460	3,403	1,977	12,826	

NB = northbound; SB = southbound; EB = eastbound; WB = westbound

The urban area code was used to create an area type (rural vs. urban) indicator variable. The FHWA HPMS data for Interstate highways is generally based on both directions of travel combined. For this research, the two-way AADT and number of lanes were divided by two to obtain values applicable to directional roadways. Many of the added HPMS variables listed above are not necessarily intended for direct use in the road readiness assessment system but provide useful context on the characteristics of the road network. Overall, the road network can be summarized as follows:

- 79% rural; 21% urban;
- 80% with two through lanes in the direction of travel of interest; 13% with three through lanes; 5% with four through lanes; and 3% with five or more through lanes;
- 36% with directional AADT under 10,000 vehicles/day; 46% with directional AADT between 10,000 and 30,000 vehicles/day; and 18% with directional AADT exceeding 30,000 vehicles/day; and
- Maximum directional AADT on any portion of the roadway network of interest: 179,000 vehicles/day.

5.7.6 Analysis Approach for Cross-Country Drive Data

Eight steps were followed in the analysis of the cross-country drive data:

1. Access and review each cross-country drive data file available in CSV form on the CONOPS project website. Each record in these files represents 1 second of elapsed time.
2. Add a location code to the file, as described above.
3. Based on the location code, select the records representing travel in the mainline lanes of Interstate highways for analysis.
4. Add supplementary variables from the FHWA HPMS database, as described above.

5. Compute the distance traveled during each 1-second interval (i.e., speed in miles per hour multiplied by the elapsed time of 1 second or 1/3600 hours represented by each record). This computation allows data from the cross-country drives to be summarized based on miles of road traveled rather than elapsed time. For example, for a truck traveling at 70 mph, the distance traveled by the truck in 1 second of travel time is 70/3600 = 0.019 miles, equivalent to 103 feet.
6. Tabulate distributions of key assessment measures by distance traveled for individual routes, individual States, and all States combined.
7. Create graphs of selected distributions of key assessment variables.
8. Review distributions and assess potential use of specific measures in a road readiness assessment system.

5.7.7 Summary of Key Variables from Cross-Country Drive Data

This section presents a summary of the key variables from the cross-country drive data that represent road readiness measures for ADS-equipped trucks, including lane marking quality, road condition, cellular connectivity, and GPS connectivity.

5.7.7.1 Lane Marking Quality

Table 43 summarizes the lane marking quality data for the Interstate highways assessed by the ADS in the five cross-country drives at the time the roads were driven. The road lane score, which represents lane marking quality, is a measure of the ADS's ability to detect the lane lines on the roadway. The road lane score is presented on a scale from 0 to 1, with higher scores representing increased ability to detect lane lines. The road lane score varies with the quality or condition of the lane markings on the roadway pavement surface. The road lane score, as measured by the Pronto ADS, is not a linear scale, but is derived from inferences in automated matching of the view of the roadway markings to standard images.

Table 43. Distribution of lane marking quality by road length based on cross-country drive data for Interstate highways.

Range of Road Lane Score	Total Length of Roadway (mi)	Percentage of Roadway Length	Cumulative Percentage of Roadway Length
0.0	1,265.74	9.9	9.9
> 0.0 to 0.1	12.26	0.1	10.0
0.1 to 0.2	18.40	0.1	10.1
0.2 to 0.3	25.92	0.2	10.3
0.3 to 0.4	40.37	0.3	10.6
0.4 to 0.5	47.10	0.4	11.0
0.5 to 0.6	66.48	0.5	11.5
0.6 to 0.7	110.80	0.9	12.4
0.7 to 0.8	296.44	2.3	14.7
0.8 to 0.9	2,812.92	21.9	36.6
0.9 to 1.0	8,129.29	63.4	100.0
Total	12,825.79	100.0	--

Figure 67 illustrates the cumulative distribution of road lane scores graphically. The table and figure show that the lane marking quality is excellent (between 0.9 and 1.0) for approximately 63% of the road length and very good (between 0.8 and 0.9) for nearly 22% of the total road length on the highways assessed. However, some sections of the road were classified with low road lane scores, suggesting that road lane score is a relevant measure for a road readiness assessment system because it varies over a substantial range between roadway locations. For nearly 10% of the total road length assessed, the road lane score was zero.

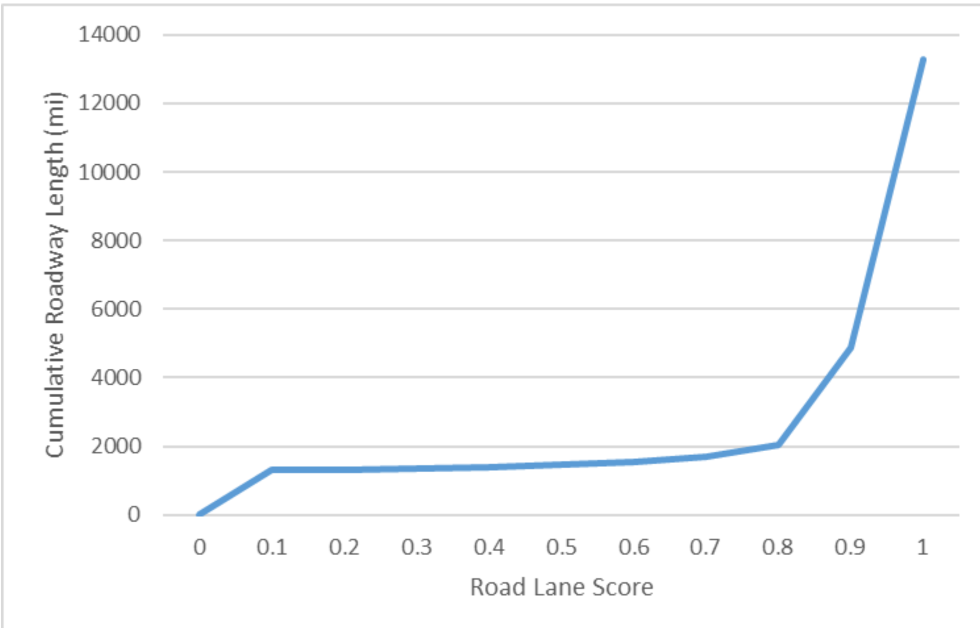

Figure 67. Graph. Cumulative distribution of road lane scores by road length based on cross-country drive data for interstate highways.

5.7.7.2 Road Condition

The condition of the roadway surface has a potential impact on the operation of an ADS-equipped truck. First, a bumpy or rough roadway surface potentially affects the dynamic control of the truck. When the truck's tires do not have full contact with the road surface, the ability of the truck to stop, steer, and maintain traction may be affected; the ADS's commands might not be carried out as expected and the ADS would need to correct for this. A bumpy road would also create more noise in the control signals to the ADS (e.g., yaw rate, direction of travel, and speed). Although these signals are filtered to make them more stable, the bumpiness does create more noise for the filters, which may need more computing resources and can be a source of control errors. For visual cameras, a bumpy road can cause variations in pitch; even slight variations in pitch can make detection of lane lines more difficult. Irregularities in the roadway surface may cause water to accumulate during and after rainstorms and reflect signals for lidar or camera data acquisition at varying angles. Finally, rougher roads cause more wear and tear on the truck itself and on the ADS hardware, increasing maintenance needs.

Table 44 summarizes the road condition results for the Interstate highways assessed in the five cross-country drives as determined from data gathered by the ADS at the time the roads were driven. Road condition for each 1-second interval of elapsed time was classified into two categories, bumpy or smooth, based on kinematic and vehicle orientation data gathered by the ADS. The parameters used to determine the road condition include average acceleration, standard deviation of acceleration, average vehicle pitch, and standard deviation of vehicle pitch. The incorporation of the two measures of vehicle pitch in the definition of road condition reflects that the road condition categories are sensitive to variations in the profile of the road that induce variations in the vehicle pitch. However, the algorithm used to process these data and classify the road condition as bumpy or smooth is not fully documented.

Table 44. Distribution of road condition categories by road length based on cross-country drive data for Interstate highways.

Road Condition	Total Length of Roadway (mi)	Percentage of Roadway Length	Cumulative Percentage of Roadway Length
Bumpy	3,593.73	28.2	28.2
Smooth	9,151.40	71.8	100.0
Total	12,745.13	100.0	--

NOTE: Missing road condition data for 80.60 miles (0.6% of total road length)

Figure 68 illustrates the road condition data from Table 44 in a bar chart. The table and figure show that the road is classified as bumpy for approximately 28% of the roadway length and is classified as smooth for the other 72% of the roadway length. The road condition was missing/unknown for less than 1% of the roadway length.

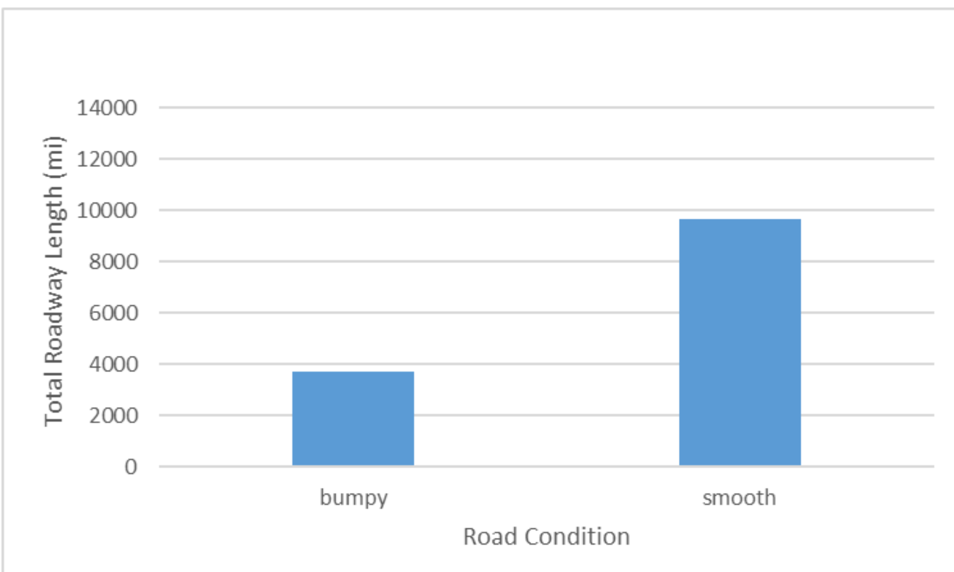

Figure 68. Chart. Distribution of road condition categories by road length based on cross-country drive data for Interstate highways.

5.7.7.3 Cellular Connectivity

Truck ADS use cellular communications in various ways. Some ADS are able to operate a truck effectively in most situations without cellular connectivity, but rely on cellular connections to transmit human commands, coordinate operations with other ADS-equipped trucks, and receive software updates. By contrast, other ADS depend on cellular connectivity to perform basic driving maneuvers. Table 45 summarizes the cellular connectivity data, represented by the cellular LTE signal strength data for the Interstate highways assessed in the five cross-country drives as gathered by the ADS at the time the roads were driven. Cellular LTE signal strength is expressed as a normalized percentage of maximum signal strength on a scale from 0% to 100%, with 0% representing no connectivity and 100% representing the practical maximum signal strength. This cellular LTE signal percentage is derived from a received signal strength indicator measured in dBm (decibels relative to a milliwatt). Figure 69 illustrates the distribution of cellular LTE signal strength percentages graphically. The table and figure show that the cellular LTE signal strength is zero or near zero (10% or less) for 14% of the road length. Very little road mileage has cellular LTE signal strengths between 10% and 40%. However, the remainder of the data shows some road mileage in each of the cellular LTE signal strength categories from 40% to 100%. About 2% of the roadway length had unknown or missing cellular LTE signal strength. This distribution shows sufficient variation in cellular LTE signal strength to suggest that cellular LTE signal strength should be a potentially useful factor in characterizing road readiness for ADS.

Table 45. Distribution of cellular LTE signal strength by road length based on cross-country drive data for Interstate highways.

Cellular LTE Signal Strength	Total Length of Roadway (mi)	Percentage of Roadway Length	Cumulative Percentage of Roadway Length
0	1,096.36	8.5	8.5
>0 – 10	719.63	5.7	14.2
10-20	724.58	5.8	20.0
20-30	716.30	5.7	25.7
30-40	670.56	5.3	31.0
40-50	646.82	5.1	36.1
50-60	710.12	5.6	41.7
60-70	833.71	6.6	48.3
70-80	1,058.75	8.4	56.7
80-90	1,549.97	12.4	69.1
90-100	3,875.21	30.9	100.0
Total	12,574.89	100.0	--

NOTE: Missing cellular LTE signal strength data for 250.84 miles (2.0% of total road length)

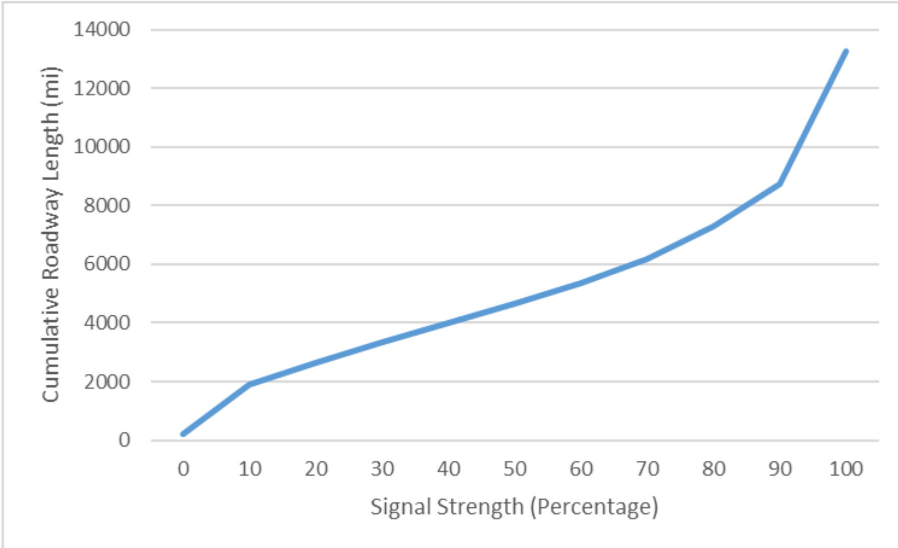

Figure 69. Graph. Cumulative distribution of cellular LTE signal strength by road length in cross-country drive data for Interstate highways.

5.7.7.4 GPS Connectivity

Table 46 summarizes the data for GPS connectivity, represented by the number of GPS satellites visible to the ADS at specific locations on the Interstate highways assessed in the five cross-country drives, as gathered by the ADS at the time the roads were driven. Figure 70 illustrates the data from Table 46 in a bar chart. The table and figure show that two of the most common values for number of GPS satellites visible are 0 and 15. With the exception of six or seven satellites visible, very little road mileage was found for any other values of the number of GPS satellites visible. Thus, the number of satellites visible is a very useful measure for distinguishing between sites with sufficient GPS connectivity and sites with potentially insufficient GPS connectivity.

Table 46. Distribution of number of GPS satellites visible by road length based on cross-country drive data for Interstate highways.

Number of GPS Satellites Visible	Total Length of Roadway (mi)	Percentage of Roadway Length	Cumulative Percentage of Roadway Length
0	211.43	1.6	1.6
1	0.00	0.0	1.6
2	0.00	0.0	1.6
3	0.00	0.0	1.6
4	0.64	0.0	1.6
5	6.78	0.1	1.7
6	122.24	1.0	2.7
7	244.02	1.7	4.4
8	75.03	0.6	5.0
9	63.51	0.5	5.5
10	37.04	0.3	5.8

Number of GPS Satellites Visible	Total Length of Roadway (mi)	Percentage of Roadway Length	Cumulative Percentage of Roadway Length
11	59.41	0.5	6.3
12	46.45	0.4	6.7
13	41.42	0.3	7.0
14	80.15	0.6	7.6
15	11,857.12	92.3	100.0
Total	12,825.73	100.0	--

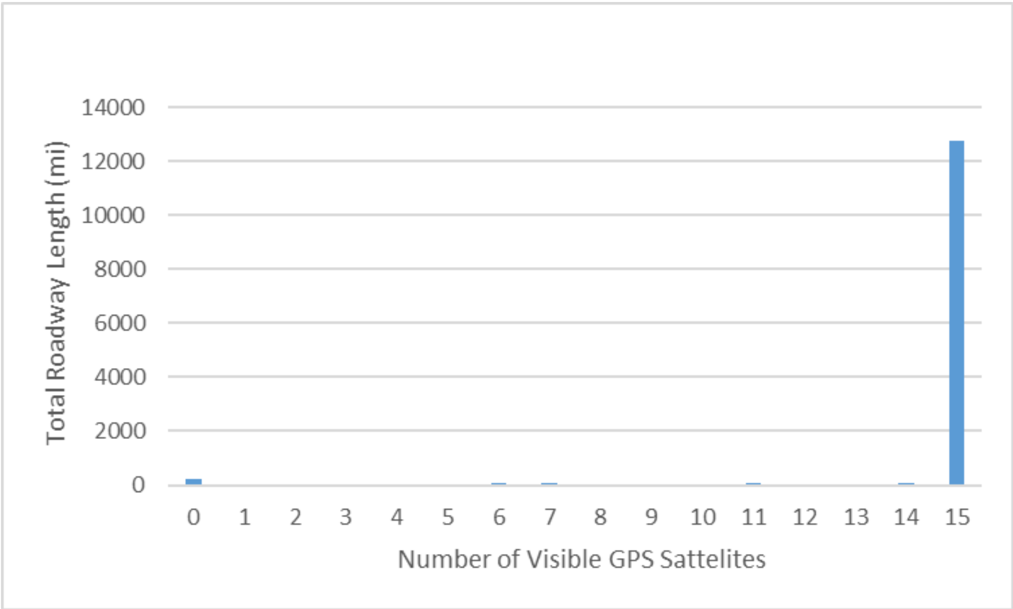

Figure 70. Chart. Distribution of number of GPS satellites visible by road length based on cross-country drive data for Interstate highways.

5.7.8 Formulation of a Basic Road Readiness Assessment System

This section addresses the formulation of a basic road readiness assessment system that can potentially be used without alteration to assess road readiness for a broad range of truck ADS. Section 5.7.9 discusses the potential formulation of more advanced road readiness assessment systems, with the caveat that such systems would potentially need to be adjusted based on the nature and capabilities of individual truck ADS.

5.7.8.1 Overview of Basic Road Readiness Assessment Approach

The discussion in this section identifies five key variables that have been identified for inclusion in road readiness assessment for ADS-equipped trucks. These five key variables are:

- Lane marking quality;
- Road roughness;
- Cellular connectivity;

- GPS connectivity; and
- Shoulder presence and width.

The first four of these variables were measured in the five cross-country drives discussed in Section 5.7.7. A fifth variable, shoulder presence and width, has been added for reasons explained below in Section 5.7.8.6. Three of these variables, lane marking quality, road roughness, and shoulder presence and width, are explicit roadway attributes. The remaining two attributes, cellular connectivity and GPS connectivity, are attributes of a roadway location rather than attributes of the roadway itself. In the basic road readiness assessment system, each of the five key variables would be scored using a binary approach: suitable or potentially unsuitable. The term "potentially unsuitable" is used because of the inherent uncertainty in assessing the threshold values at which truck ADS operation might become unsuitable. A conservative approach has been taken to selecting threshold values for suitability to assure that the variable ranges classified as suitable would definitely be considered suitable. For each scoring variable, the suitable range would be assigned a score of 1, and the possibly unsuitable range would be assigned a score of 0. Sections 5.7.8.2 through 5.7.8.6 review each of the five key variables, show what threshold values are recommended for each variable to define the suitable and potentially unsuitable categories, and describe how data for scoring those categories can be obtained. Section 5.7.8.7 describes how the scoring of the individual variables is combined in the basic road readiness assessment system.

5.7.8.2 Lane Marking Quality Scoring

Table 43 shows the distribution of the road lane scores on the Interstate highways that were measured in the cross-country drives. The road lane score, expressed on a 0 to 1 scale, represents the quality of the lane markings, as detected by the truck ADS. Detection of lane markings is considered a key element of suitable ADS operation, so a conservative approach to assessing lane marking quality is recommended. An appropriate conservative assumption is that any lane marking with a road lane score in the 0.8 to 1.0 range will be detected effectively by an ADS, while a marking with a road lane score less than 0.8 raises a concern that the marking is not of sufficient quality to be detected by the ADS. Based on this criterion, the data in Table 43 show that approximately 85% of roadway length on Interstate highways has sufficient lane marking quality to be detected by an ADS. For 15% of the roadway length, there is concern that that lane marking quality is not sufficient to be detected.

The data from the cross-country drives used in assessing the lane marking quality was gathered at 1-second intervals. On a tangent roadway, the road lane score might fall below 0.8 for several seconds in a row without affecting the operation of an ADS-equipped truck because the truck should not encounter any difficulty if it continues to travel forward in a straight line. Thus, our initial presumption was that limited pavement marking quality might not be a concern unless present over several seconds of travel time. However, there is a potential for lane departure with even 1 second of travel time with poor lane marking quality on a horizontal curve, and especially not at the beginning of a horizontal curve. Consider the case of a truck with a width of 8.5 feet traveling within a 12-foot lane on a freeway at the beginning of a horizontal curve with a 1,810-foot radius, the sharpest curve that should be designed on a typical rural freeway with a 70-mph design speed (AASHTO, 2018). A truck traveling at 70 mph in a straight line on such a curve would depart from its lane within less than 0.8 seconds. Thus, it appears that loss of lane marking detection for even 1 second could lead to an unfavorable outcome. Such a loss of lane marking detection could be compensated for by a tie to a high-resolution digital map and location-specific information learned by the truck's ADS in previous trips accessed through the truck's GPS coordinates or by appropriate commands transmitted through cell phone communications. This suggests that loss of one of the key road readiness measures for 1 second might not be critical, but loss of two or more such attributes could be.

Based on this review, a road lane score of 0.8 is recommended as a threshold for assessing lane marking quality. Table 43 indicates that approximately 85% of Interstate highways have road lane scores above this threshold value. Figure 67 shows that there is a clear break in the shape of the cumulative distribution curve at the value of 0.8. Table 47 shows road lane quality scoring that implements the threshold lane marking quality value for use in the basic road readiness assessment system.

Table 47. Recommended scoring for lane marking quality in the basic road assessment system.

Scoring Category	Range of Road Lane Score	Assigned Lane Marking Quality Score
Suitable	>0.8 to 1.0	1
Potentially Unsuitable	0 to 0.8	0

The scoring in this report has been based on lane marking quality assessments made with the Pronto truck ADS during the five cross-country drives. For future applications, newer assessments could be made with the Pronto truck ADS. It is also likely that ADS technologies from other vendors will have available a measure comparable to the road lane score from the Pronto system. The basic road readiness assessment system is intended to be sufficiently flexible so that it can be adapted to the outputs from other ADS technologies. For example, it is likely that the lane marking quality output from other ADS technologies can be normalized on a 0 to 1 scale like the values shown in Table 43.

While lane marking quality assessments made with an ADS are preferred, it should also be possible for the basic road readiness assessment system to be applied using results from a visual review of lane marking photographs or videos to assess the quality of the lane markings. A lane marking quality score of 1 should be assigned to lane markings that appear complete and easily distinguished from the background pavement color. A lane marking score of 0 should be assigned to lane markings that are worn, deformed, faded, chipped, or otherwise incomplete or missing. This visual assessment should be based on the daytime visibility of the lane markings rather than nighttime visibility or retro-reflectivity. Wider markings (e.g., markings with a 6-inch width) are generally more visible than conventional 4-inch markings (FHWA, 2009). In fact, a revision to the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) currently under consideration would require normal width markings to be 6 inches wide on freeways, expressways, and ramps, with a normal width in the range from 4 to 6 inches used elsewhere. One specifically stated rationale for use of 6-inch pavement marking widths is to enhance ADS operation (NCUTCD, 2019).

Lane marking quality may also be scored with data from existing highway agency pavement marking management systems, which document the pavement marking materials used and the date most recently applied (and may also include inspection data).

5.7.8.3 Road Roughness Scoring

Scoring road condition based on the categories “bumpy” and “smooth,” as summarized in Table 44, appears undesirable because these categories do not have commonly accepted definitions. Additionally, there is unlikely to be a reliable visual method of assessing road condition for application where data from an ADS is unavailable. However, the FHWA HPMS includes IRI as a related data element.

IRI is the measure most commonly used worldwide for evaluating and managing the roughness of road surfaces. IRI is determined from longitudinal road profiles and can be measured with accelerometer-based systems, so it appears to be closely related to the ADS road condition measure. IRI is expressed as a road surface slope measure, typically in units of inches/mile (Janoff et al., 1985; Paterson, 1986). The model most commonly used to determine IRI is a “quarter-car” model, so IRI characterizes the effect of road roughness on a passenger car, rather than a truck. Nevertheless, IRI appears to characterize a road roughness characteristic that is very similar to the ADS-derived road condition measure. The larger the IRI values, the rougher the road surface. IRI appears to be a potentially useful measure for a road readiness assessment system because it is available in the publicly available FHWA HPMS for nearly the entire Interstate highway system and for other roads as well. An advantage of the IRI data is that they provide a measure on a continuous quantitative scale. IRI data for the Interstate highway locations measured in the five cross-country drives were obtained from the publicly available FHWA HPMS and added to the project database.

Table 48 shows the distribution of IRI values from FHWA HPMS data for the same roads covered by the road condition data in Table 44. Figure 71 illustrates the distribution of IRI values graphically.

Table 48. Distribution of IRI by road length based on FHWA HPMS data for Interstate highways being considered in the research.

IRI (inches/mi)	Road length (mi)	Percentage of road length	Cumulative percentage of road length
1 - 25	151.48	1.3	1.3
26 - 50	3,983.46	34.0	35.3
51 - 75	3,766.22	32.1	67.4
76 - 100	1,847.95	15.8	83.2
101 - 150	1,406.13	12.0	95.2
151 - 200	394.77	3.4	98.6
201 - 250	113.13	1.0	99.6
251 - 300	36.16	0.3	99.9
301 - 350	11.02	0.1	100.0
>350	4.82	0.0	100.0
Total	11,715.11	100.0	--

NOTE: IRI data were obtained from the FHWA HPMS) NOTE: Missing IRI data for 1,110.62 miles (8.7% of total road length)

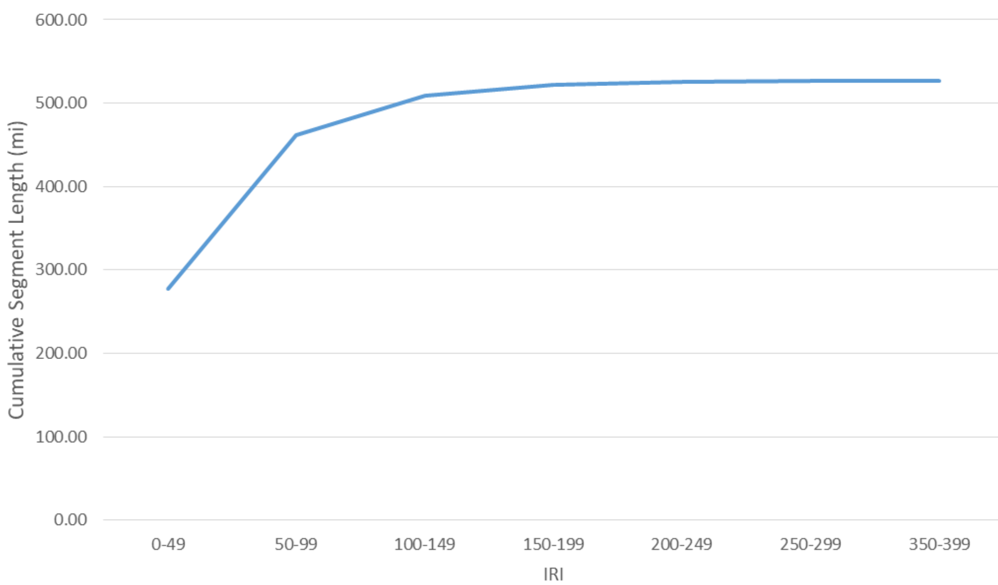

Figure 71. Graph. Cumulative distribution of IRI by road length for the Interstate highway sites included in the five cross-country drives.

Table 48 shows that 33% of the road length on Interstate highways has an IRI greater than 75 inches/mile, while 67% of the road length on the Interstate highway network of interest has an IRI less than or equal to 75 inches/mile. Table 49 shows IRI data for the "bumpy" and "smooth" categories determined with the Pronto system for the cross-country drives. The table shows that the road condition categories have minimum and maximum values that broadly overlap, but that the "bumpy" category has a higher mean IRI than the "smooth" category (85 inches/mile vs. 67 inches/mile). The midpoint between these mean values (i.e., an IRI of 75 inches/mile) is a logical threshold value between the "bumpy" and "smooth" categories.

Table 49. Comparison of IRI values from the FHWA HPMS data to the road condition categories from the cross-country drive data.

Road Condition Category	Road Length (mi)	Percent of Road Length	Mean IRI (inches/mi)	Minimum IRI (inches/mi)	Maximum IRI (inches/mi)
Bumpy	3,369.12	28.9	85	16	755
Smooth	8,277.48	71.1	67	2	700

NOTE: Road condition category unknown for 0.6% of road length; IRI value missing for 8.7% of road length.

Given the use of IRI values, it seems appropriate to rename the road condition category using the more technical term road roughness. Table 50 shows road roughness scoring that implements the threshold IRI value for use in the basic road readiness assessment system. The road roughness data used in this report was obtained from the FHWA HPMS database as it existed in 2022. For future application of the road readiness assessment system, updated road readiness data should be obtained from the latest version of HPMS. IRI data may also be available from the pavement management systems of individual transportation agencies.

Table 50. Recommended scoring for road roughness in the basic road assessment system.

Scoring Category	Range of IRI (inches/mi)	Assigned Road Roughness Score
Suitable	1 to 75	1
Potentially Unsuitable	>75	0

5.7.8.4 Cellular Connectivity

The appropriate threshold value for cellular LTE signal strength likely varies with the type of ADS being used. Cellular LTE signal strength of 60% appears to be an appropriate and conservative break point between excellent signal strength and signal strength that is merely good, OK, or marginal. Therefore, cellular LTE signal strength of 60% has been used as the threshold value to separate suitable operation from potentially unsuitable operation. Approximately 58% of road length on Interstate highways has cellular LTE signal strength that exceeds 60%, while 42% of road length on Interstate highways has cellular LTE signal strength less than or equal to 60%. Based on this criterion, Table 51 shows cellular connectivity scoring that implements the threshold cellular LTE signal strength value for use in the basic road readiness assessment system.

Table 51. Recommended scoring for cellular connectivity in the basic road assessment system.

Scoring Category	Range of Cellular LTE Signal Strength (%)	Assigned Cellular Connectivity Score
Suitable	>60 to 100	1
Potentially Unsuitable	0 to 60	0

Cellular connectivity is best determined based on the availability of cellular connections for an actual truck ADS. However, where ADS data on cellular connectivity is not available, cellular connectivity can be scored based on cellular coverage maps published by many cellular service providers; in addition, cellular coverage may be limited in tunnels or in mountainous terrain. The selection of a cellular LTE signal strength of 60% as the threshold value is a conservative choice, appropriate for truck ADS that fully depend on cellular connectivity for all truck operations. A lower threshold value of cellular LTE signal strength (e.g., 45%, treating both excellent and good signal strength as suitable) may be appropriate for truck ADS that depend less completely on cellular connectivity.

5.7.8.5 GPS Connectivity

Table 52 shows that the number of GPS satellites visible to a truck ADS at any given time and place can range from 0 to 15. The number of satellites visible may be influenced by the position of the truck relative to the satellite positions, whether specific satellites are in service or out of service, and objects that may interfere with the GPS satellite signals such as tall buildings, tunnels, bridge structures, terrain (e.g., hills, canyon walls), and metal walls or roofs.

A minimum of four satellites must be visible for onboard systems to determine a GPS position for a truck. However, visibility of substantially more than four satellites is desirable. For example, if the four visible satellites happen to be in the same general portion of the sky, the calculated GPS position may be less accurate than if the satellites are in distinctly different directions from the truck. The availability of additional visible satellites makes it likely the computed GPS position will have increased accuracy. An appropriate threshold value for the number of GPS satellites visible at any location on the road is 10. This is a conservative threshold value, as the availability of 10 visible satellites should be sufficient to assure that these visible satellites include at least four satellites with well-separated locations. Table 52 shows GPS connectivity scoring that implements the threshold value for use in the basic road readiness assessment system.

Table 52. Recommended scoring for GPS connectivity in the basic road assessment system.

Scoring Category	Range of Number of GPS Satellites Visible	Assigned GPS Connectivity Score
Suitable	10 to 15	1
Potentially Unsuitable	0 to 9	0

GPS connectivity is nearly universal throughout the United States, with the possible exception of locations in tunnels, on enclosed bridges or roofed roadways, alongside tall buildings, and in mountainous or canyon areas. In future applications of the basic road readiness assessment system, measurements made with an ADS are preferred; where this is not practical, studies should focus on verifying GPS connectivity in the potentially limited locations listed above.

5.7.8.6 Shoulder Presence and Width

An important performance criterion for truck ADS is the capability to reach an MRC when the truck ADS cannot identify the appropriate path forward and no human-based guidance is available. MRC generally means bringing the truck to a safe stop. Some truck ADS developers consider a stop in the traveled way of the road to be an appropriate MRC, but a truly MRC would involve reaching a safe stop outside the traveled way, such as in a paved shoulder area.

Most Interstate highways have paved shoulders. Interstate highways are generally intended to be designed with paved shoulders at least 10 feet in width on the right (outside) of each roadway (or 8 feet in some mountainous areas), so an MRC for stopping should generally be available on the right side of the roadway at nearly all locations on Interstate highways (AASHTO, 2005; AASHTO, 2018). Heavy trucks generally have a maximum width of 8.5 feet, so a 10-foot right (outside) shoulder should provide a suitable stopping area for an MRC. Stopping locations for reaching an MRC should generally be available continuously on Interstate highways. So, road readiness assessment should focus on identifying the limited set of locations where, for some reason, a full paved shoulder is not available on the right (outside) of the roadway. Such locations may include:

- Long bridges;
- Tunnels;
- Locations at which the shoulder has been narrowed to provide an additional travel lane;
- Locations at which traffic is permitted to use the right (outside) shoulder as a travel lane during part of the day;

- Locations where the shoulder has been narrowed to provide space for a traffic barrier, such as at some overpass structures; and
- Roadways in mountainous areas where shoulders with widths of 8 feet may be used.

Shoulders are not necessarily always narrowed or omitted at the types of locations listed above, but such locations can be reviewed to assess road readiness for operation by ADS-equipped trucks. Data on shoulder presence and width are not included in the publicly available HPMS data used in the research. However, locations without wide right (outside) shoulders are sufficiently rare on Interstate highways that it should be practical for users of a road-readiness assessment system to assess them visually on a reasonably wide scale. Future road readiness assessments could use shoulder data from individual transportation agency databases. It may also be possible to assess the availability of a wide right (outside) shoulder suitable for stopping from an automated visual review of photographic images like those obtained from a truck ADS. Shoulders may also be narrowed in some work zones on Interstate highways; however, since work zones are temporary features, they would not generally be considered in road readiness assessment unless it is known that they will be in place for an extended time period.

On an Interstate highway with two travel lanes in a given direction of travel, left (median) side paved shoulders may be as narrow as 4 feet in width (AASHTO, 2005; AASHTO, 2018). Therefore, the mileage of Interstate roadways without a suitable stopping area on the left (median) side of the roadway is likely to be more substantial than for the right (outside) side of the roadway. Nevertheless, even where left (median) shoulders are 4 feet in width, a 10-foot right (outside) paved shoulder should generally be available as a location for a truck to reach a minimal-risk condition. With three or more lanes in a given direction of travel, 10-foot paved shoulders are intended to be provided on both the right and left sides of each roadway (AASHTO, 2005; AASHTO, 2018). Table 53 shows scoring for right (outside) paved shoulder width that implements the threshold paved shoulder width value of 10 feet discussed above as used in the basic road readiness assessment system.

Table 53. Recommended scoring for right (outside) paved shoulder width in the basic road assessment system.

Scoring Category	Right (Outside) Paved Shoulder Width (ft)	Assigned Shoulder Presence and Width Score
Suitable	10 or more	1
Potentially Unsuitable	0 to <10	0

5.7.8.7 Application of Key Variables in Scoring Basic Road Readiness Assessment

The basic road readiness assessment is based on the five scores presented above:

- Lane marking quality score;
- Road roughness score;
- Cellular connectivity score;

- GPS connectivity score; and
- Shoulder presence and width score.

Basic road readiness may be scored as sum of the five scores as shown above:

$$S_{BRR} = S_{lmq} + S_{rr} + S_{cc} + S_{gpsc} + S_{spw} \quad (1)$$

where

S_{BRR} = basic road readiness assessment score,

S_{lmq} = lane marking quality score (see Table 47),

S_{rr} = road roughness score (see Table 50),

S_{cc} = cellular connectivity score (see Table 51),

S_{gpsc} = GPS connectivity score (see Table 52), and

S_{spw} = shoulder presence and width score (see Table 53).

Each of the five individual scores are either 0 or 1. So the basic road readiness score ranges from 0 to 5. For the basic road readiness scoring, it is assumed that a truck ADS can operate successfully with any one score in the potentially unsuitable range, but if two or more scores are in the potentially unsuitable range then successful operation of a truck ADS cannot be assured. For example, if lane marking quality is found to be insufficient for ADS operation, the truck should be able to operate safely if the other four attributes are satisfactory. Specifically, cellular and GPS connectivity should assure that the ADS knows where the truck is and that the ADS can tie to map data or receive commands over the cellular connection. A smooth roadway surface should assure the dynamic stability of the truck. And, ultimately, the availability of a paved shoulder of sufficient width provides the opportunity to reach an MRC where needed. Based on this approach, roads with values of 4 and 5 for the basic road readiness assessment score (S_{BRR}) are considered suitable for truck ADS operations. Roads with values of S_{BRR} of 3 or less are considered potentially unsuitable for truck ADS operations.

5.7.8.8 Demonstration of the Basic Road Readiness Assessment System for Interstate Highways

A demonstration of the basic road readiness assessment system for Interstate highways was conducted as part of the research. Data from the five cross-country drives was used to assess lane marking quality, cellular connectivity, and GPS connectivity. IRI data from the FHWA HPMS was used to represent road roughness. Since sites without wide right (outside) paved shoulders are rare on Interstate highways, it was assumed for purposes of this demonstration that they are available for the entire study network.

Table 54 shows the distribution of basic road readiness assessment scores [S_{BRR} computed with Equation (1)] for the Interstate highways that make up the study network. The table shows that approximately 76% of the Interstate highways for which complete data is available appear to be suitable for truck ADS operations, while 24% are potentially unsuitable. Approximately 10% of the roadways in the study network had missing data for at least one of the scoring components, so the basic road readiness assessment score could not be determined. In any full-scale application of the basic road readiness assessment, efforts to minimize missing data would be needed. These results should be interpreted keeping in mind that the approach to assigning scores in the basic road readiness assessment system is very conservative.

Table 54. Distribution of basic road readiness assessment scores for the study network on Interstate highways.

Basic Road Readiness Assessment Score		Total Length of Roadway (mi)	Percent of Roadway Length	Cumulative Percent of Roadway Length
1	potentially unsuitable	10.94	0.10	0.10
2	potentially unsuitable	609.38	5.30	5.40
3	potentially unsuitable	2,131.84	18.53	23.93
4	suitable	4,708.03	40.93	64.86
5	suitable	4,042.27	35.14	100.00

NOTE: Basic road readiness assessment scores could not be computed for 1,323.7 miles of Interstate highways (10% of total road network length) because of missing data for one or more of the scoring components.

An advanced road readiness assessment, such as that discussed in Section 5.7.9, would tailor the assessment to individual truck ADS capabilities. Greater specificity in the characteristics of individual truck ADS, such as would be possible if the assessment were performed by an ADS developer or truck operator, could potentially increase the road readiness assessment suitability percentage to a percentage of road network length higher than 76%. In other words, higher suitability percentages could potentially be obtained with more specific knowledge of the capabilities of a particular ADS. Figure 72–Figure 75 shows a map of the study network on Interstate highways showing roads that are color-coded to represent the basic road readiness assessment scores (S_{BRR}) 5 to 2 used in Table 54. There were no roads with a score of 1, so that map is excluded. Figure 76 combines all roadway sections. Since colored points for road segments as short as 0.01 miles cannot be distinguished at the scale of the map shown in the figure, the color codes are based on the mean value of S_{BRR} within a 10-mile segment.

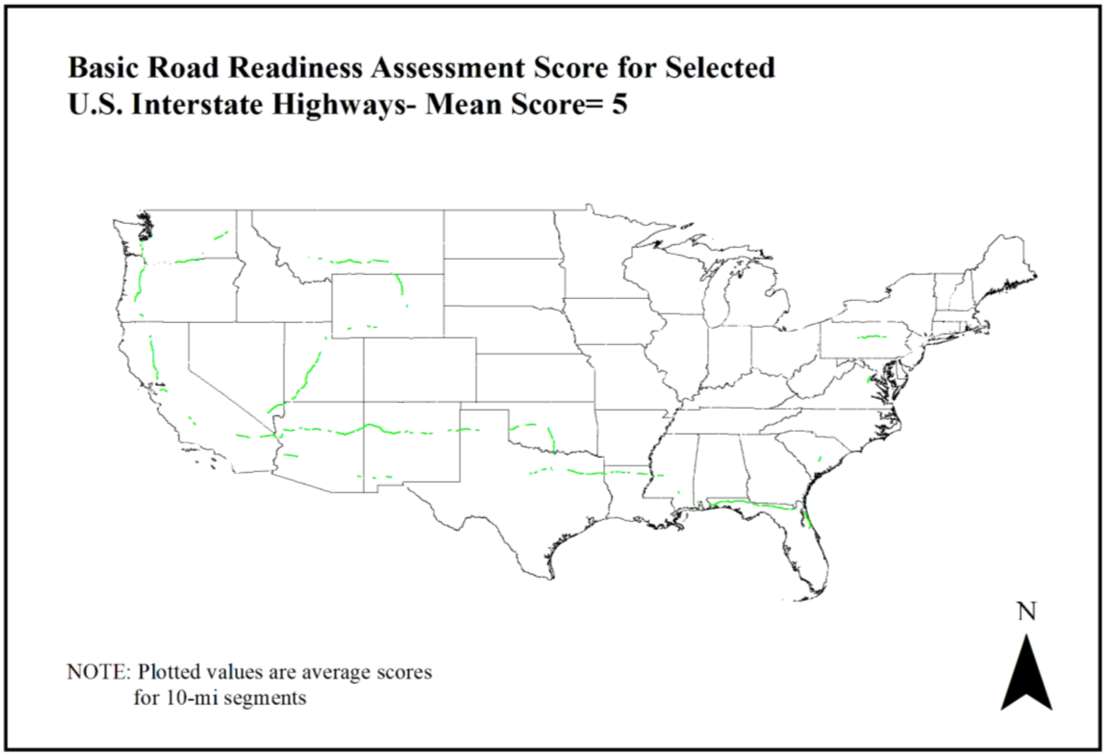

Figure 72. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean score = 5.

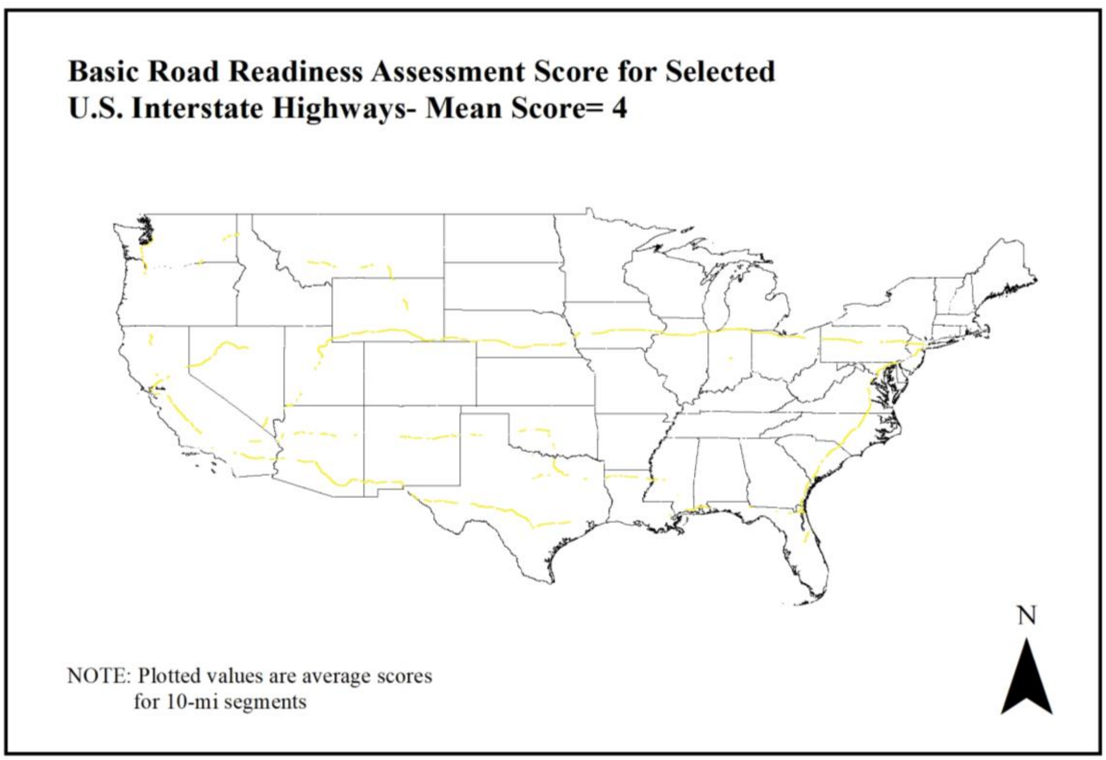

Figure 73. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean score = 4.

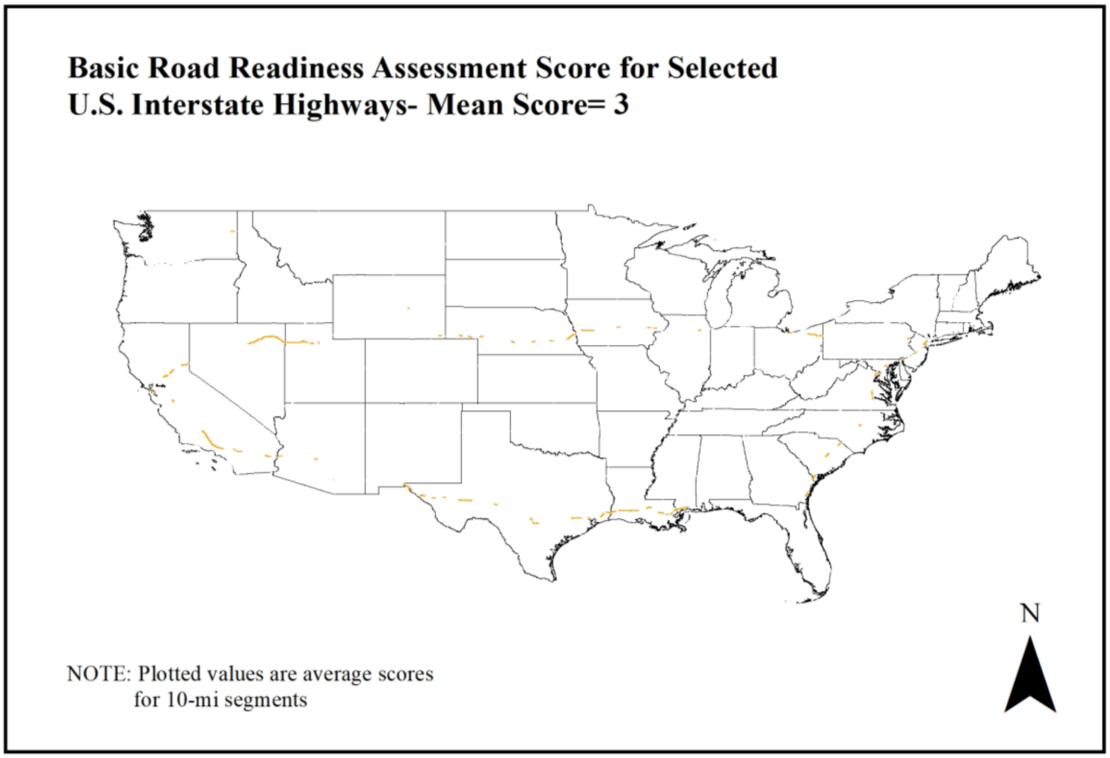

Figure 74. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean score = 3.

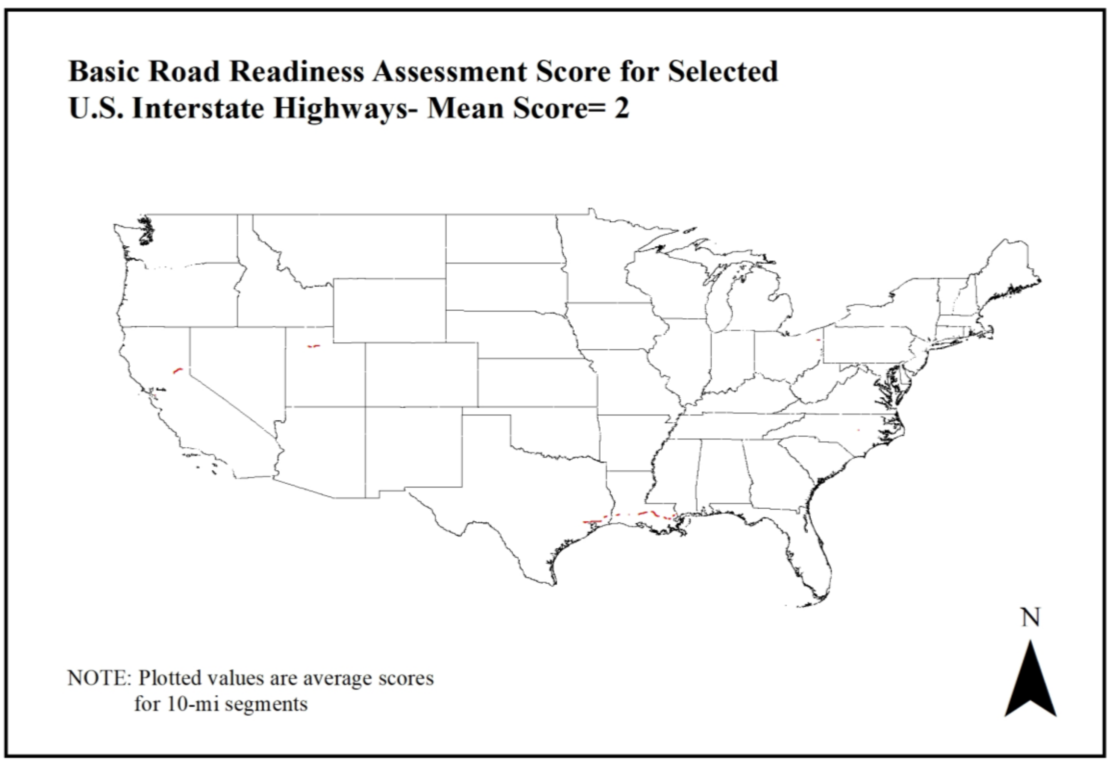

Figure 75. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean score = 2.

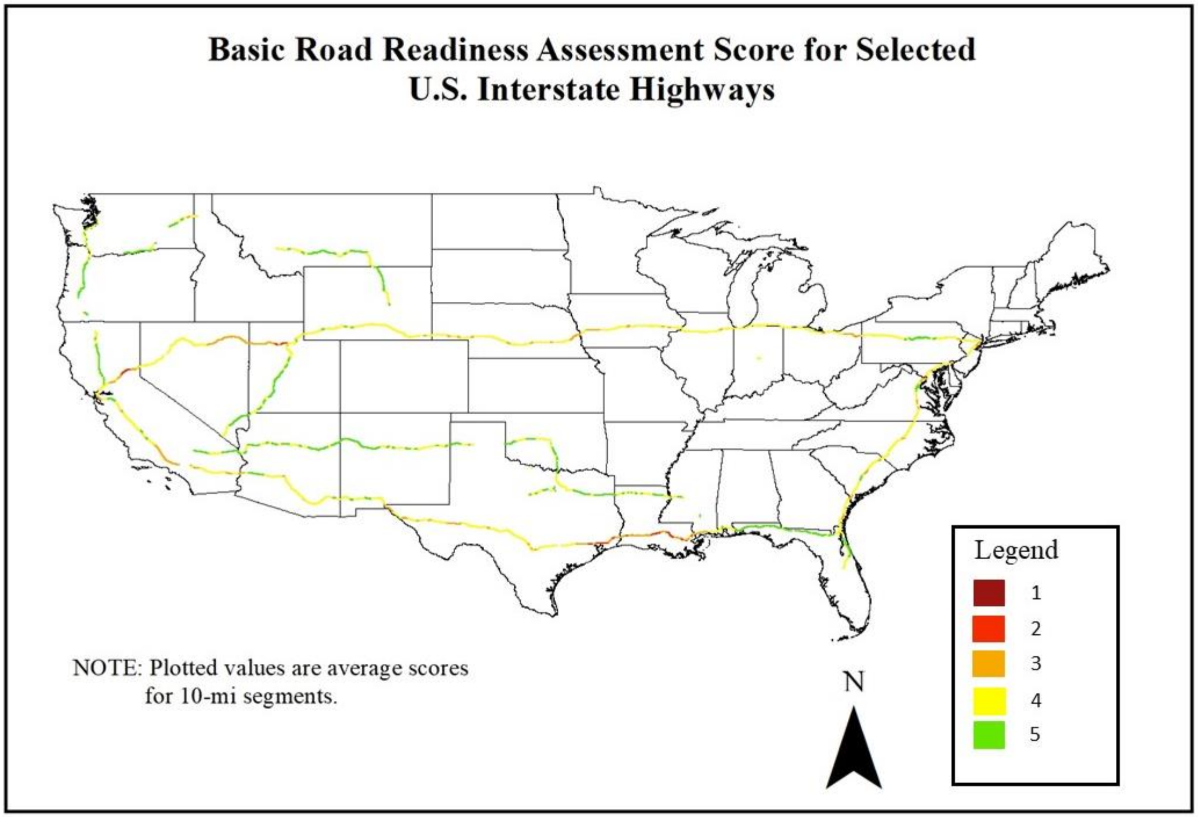

Figure 76. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean scores combined.

5.7.9 Potential Advanced Road Readiness Assessment System

This section describes a potential approach to developing an advanced road readiness assessment system using separate values for each of the road readiness assessment measures and weights assigned to the individual measures. The scoring rules and weight values for individual assessment measures are intended to be determined by ADS developers or truck operators as being appropriate for their specific ADS technology. The weights may vary between ADS technologies based on the importance of each measure to that technology. While a combined score would be formulated, interpretation as to acceptable or unacceptable ranges of that score would be left to the user.

As an illustration, Table 55 presents a structure for a potential scoring scheme for the road readiness attributes in an advanced road readiness assessment system. In this potential scoring scheme, each of the five road readiness measures is assigned a score in the range from 0 to 100. The scores to be assigned for the five road readiness attributes (S_1 through S_5) are shown in the fourth column of the table and generally represent unsuitable, marginal, good, and excellent conditions for truck ADS operations. The ranges of the road readiness attributes to which these scores apply (A_1 to A_4, B_1 to B_4, C_1 to C_4, and D_1 to D_4) cannot be specified at this time because they are presumed to vary with the capabilities of individual truck ADS. Suitable values of A_1 to A_4, B_1 to B_4, C_1 to C_4, and D_1 to D_4 would need to be chosen by ADS developers or truck operators for the capabilities of their ADS.

Table 56 shows how the individual scores would be used to compute an advanced road readiness assessment score. Users will assign weight factors (W1 to W5) to each road readiness measure based on its perceived importance to the ADS technology for which the ratings are being developed. The only fixed rule is that the five weights must sum to 1.00. The scoring will proceed by multiplying the score for each measure by the applicable weight factor and summing the products of the scores and weights. Formulating the road readiness assessment in this way assures that the total score (the sum of the products of the individual scores and weights) will be in the range of 0 to 100. A road with a relatively high total score would be well suited to the operation of ADS-equipped trucks. A road with a relatively low score might not be well suited to the operation of ADS-equipped trucks.

Table 57 shows hypothetical numerical examples for a road with a relatively high score (90) and for a road with a relatively low score (38), to illustrate how the scores are calculated. In the examples in Table 57, the weight factors were set with equal values (i.e., each of the five weight values is 1/5 = 0.20). However, the weight factors do not necessarily need to be equal. Rather, the weights should depend on the relative importance of each measure to the ADS technology being assessed. Therefore, the values of the weight factors need not necessarily be the same for each ADS technology to which the road readiness assessments are applied.

Table 55. Template for scoring road readiness measures in advanced road readiness assessment system.

Road Readiness Category	Road Readiness Measure (Remark)	Range of Road Readiness Measure	Road Readiness Score
Lane Marking Quality	Road lane score or equivalent (Unsuitable)	0 to A_1	$S_1 = 0$
Lane Marking Quality	Road lane score or equivalent (Marginal)	A_1 to A_2	$S_1 = 30$
Lane Marking Quality	Road lane score or equivalent (Good)	A_2 to A_3	$S_1 = 70$
Lane Marking Quality	Road lane score or equivalent (Excellent)	A_3 to 100	$S_1 = 100$
Road Roughness	IRI (inches/mi) or equivalent (Unsuitable)	0 to B_1	$S_2 = 0$
Road Roughness	IRI (inches/mi) or equivalent (Marginal)	B_1 to B_2	$S_2 = 30$
Road Roughness	IRI (inches/mi) or equivalent (Good)	B_2 to B_3	$S_2 = 70$
Road Roughness	IRI (inches/mi) or equivalent (Excellent)	B_3 to 100	$S_2 = 100$
Cellular Connectivity	Cellular signal strength or equivalent (Unsuitable)	0 to C_1	$S_3 = 0$
Cellular Connectivity	Cellular signal strength or equivalent (Marginal)	C_1 to C_2	$S_3 = 30$
Cellular Connectivity	Cellular signal strength or equivalent (Good)	C_2 to C_3	$S_3 = 70$
Cellular Connectivity	Cellular signal strength or equivalent (Excellent)	C_3 to 100	$S_3 = 100$
GPS Connectivity	Number of GPS satellites visible (Unsuitable)	0 to D1	S4 = 0
GPS Connectivity	Number of GPS satellites visible (Marginal)	D1 to D2	S4 = 30

Road Readiness Category	Road Readiness Measure (Remark)	Range of Road Readiness Measure	Road Readiness Score
GPS Connectivity	Number of GPS satellites visible (Good)	D2 to D3	S3 = 70
GPS Connectivity	Number of GPS satellites visible (Excellent)	D3 to 15	S4 = 100
Shoulder Presence and Width	Presence and width of right (outside) paved shoulder (Unsuitable)	<10 ft paved shoulder	$S_5 = 0$
Shoulder Presence and Width	Presence and width of right (outside) paved shoulder (Excellent)	≥ 10 ft paved shoulder	$S_5 = 100$

Table 56. One potential candidate scoring scheme for road readiness assessment.

Road Readiness Measure	Score	Weight	Score * Weight
Lane Marking Quality	S_1 out of 100	W_1	$S_1 * W_1$
Road Condition	S_2 out of 100	W_2	$S_2 * W_2$
Cellular Connectivity	S_3 out of 100	W_3	$S_3 * W_3$
GPS Connectivity	S_4 out of 100	W_4	$S_4 * W_4$
Right Shoulder Width	S_5 out of 100	W_5	$S_5 * W_5$
TOTAL		1.00	$\sum S_n * W_n$

Table 57. Two hypothetical numerical examples of potential candidate scoring scheme for road readiness assessment.

Road Readiness Measure	Score	Weight	Score * Weight
Lane Marking Quality	70 out of 100	0.20	14
Road Condition	70 out of 100	0.20	14
Cellular Connectivity	100 out of 100	0.20	20
GPS Connectivity	100 out of 100	0.20	20
Shoulder Presence and Width	100 out of 100	0.20	20
TOTAL		1.00	88
Lane Marking Quality	30 out of 100	0.20	6
Road Condition	30 out of 100	0.20	6
Cellular Connectivity	30 out of 100	0.20	6
GPS Connectivity	0 out of 100	0.20	0
Shoulder Presence and Width	100 out of 100	0.20	20
TOTAL		1.00	38

5.7.10 Potential Extension of Road Readiness Assessment to Other Roadway Types

This study applied a road readiness assessment for truck ADS to roads on the Interstate highway system. Interstate highways present the most suitable scenario for truck ADS operation since there is no direct access to the road except by way of entrance and exit ramps at designated interchange locations. Interstate highways are also best suited to a road readiness assessment system because more existing data for potential use in road readiness assessments is available for Interstate highways than any other road type. Non-Interstate freeways are very similar to Interstate highways from an operational standpoint and are also generally well suited to truck ADS operation. The same road characteristics would serve as road readiness measures for non-

Interstate freeways as for Interstate highways. Road characteristics data from existing sources may be slightly less available for non-Interstate freeways than for Interstate highways.

Conventional roads without full access control present a substantially greater challenge than Interstate highways or non-Interstate freeways, both for truck ADS operations and for road readiness assessment. A key characteristic that distinguishes conventional roads from Interstate highways and non-Interstate freeways is the presence of at-grade intersections and driveways. Vehicles may be making left or right turns to enter or leave the road, or maneuvers crossing the road. These intersections and driveways may include locations with traffic signal control, all-way stop control, minor-road stop control, yield control, or no control. Another key characteristic that that distinguishes conventional roads from Interstate highways and non-Interstate freeways is the presence of pedestrians and bicyclists, which travel more slowly than motor vehicles but are smaller in size and more maneuverable. Motor-vehicle turning maneuvers and motor-vehicle, pedestrian, and bicycle volumes vary on conventional roads, with higher volumes (and therefore greater challenges to the operation of ADS-equipped trucks) in urban areas than in rural areas.

At this time, there are no truck ADS developed for a full range of operations on conventional roads. As such systems are developed, assessing the readiness of specific conventional roads for operations by ADS-equipped trucks will not only need to consider all of the road readiness measures for Interstate highways but also measures related to at-grade intersection and driveway frequency, types of traffic control at such locations, motor-vehicle turning and crossing maneuvers permitted at such locations, likely volumes of motor-vehicle turning and crossing maneuvers, and pedestrian and bicycle volumes. Assembling such data from existing sources will be a substantial challenge.

5.7.11 Potential Application of Cross-Country Drive Image Data

As noted in the description of the data collected during the cross-country trips, photographic images were collected at 25 fps from the front-facing camera by the ADS as the truck traveled along the road. The research team did not apply these images to the Road Readiness Assessment System, but the team did explore their application for future implementation. Particularly, the images could be used for the following applications: to detect shoulder existence and estimate the shoulder width of roadways for ADS operation under emergency conditions; to evaluate and understand roadway signs for better ADS operation; and to test modern algorithms for lane line detection via images from ADS in real-world scenarios or evaluate lane line readiness for ADS operation on the roadway network throughout the country. The CONOPS Dataverse data was used to pilot these applications.

5.7.11.1 Shoulder Detection and Width Estimation

Knowing the availability of a shoulder allows the ADS to select the best course of action. Knowledge of the presence and condition of a shoulder is vital for an ADS to make informed decisions related to emergency situations, roadside assistance, route planning, lane changes, and traffic incident management. If an ADS-equipped CMV encounters a breakdown or mechanical issue, having information about the presence of a shoulder allows the system to guide the vehicle to a safe location, minimizing disruption to traffic flow. In the case of an emergency, such as an obstacle or a disabled vehicle on the road, a shoulder provides an area for emergency maneuvers or for safely stopping to arrive at an MRC. As illustrated above, information on shoulder presence and width would benefit a road readiness assessment system to evaluate the roadway suitability for ADS-equipped CMV operation.

The images in CONOPS offer rich data for training and testing computer vision algorithms to address two key questions: does the roadway have a shoulder, and what is the width of the shoulder?

Two methods were explored. The first method used a lane detection algorithm to identify the lanes on the road and determine the width between them. This method allows the information to be extracted about the road shoulder width based on the detected lanes. The second method used a semantic segmentation to classify each pixel in the image as belonging to the road, shoulder, or other classes of roadway and furniture. The next step was to analyze the segmented image to measure the width of the shoulder region using projective geometry. These two methods could be compared in terms of efficiency and accuracy for future potential integration into an ADS-equipped CMV. Figure 77 shows the result of applying the CONOPS image data in the first method. The figure shows that the lane detection algorithm (e.g., CLRerNet[280]) was able to detect the end of the shoulder, especially when the ego vehicle was driving near the shoulder. Another method that could be explored is the customization of deep learning algorithms.

Figure 77. Image overlay. The images show the application of the CLRerNET algorithm to ADS CONOPS Cross-Country data to measure shoulder width.

5.7.11.2 Evaluate Roadway Signs

Roadway signs are an integral part of the roadway system. They communicate important information to drivers and the ADS. This includes information about road rules, information about exits, work-zone-related information, wildlife-related information, and other uses. While high-definition maps and GPS are valuable for ADS navigation, they may not provide real-time or detailed information about temporary changes in traffic conditions, construction zones, or other dynamic situations. Traffic sign recognition allows ADS to interpret and respond to current regulatory information, warnings, or guidance on the road (e.g., exit identifiers, speed limit, high-occupancy vehicle lanes, work-zone information, temporary roadway changes), contributing to safer and more adaptive driving in diverse environments. Integrating traffic sign understanding into ADS enhances their ability to navigate effectively and make informed decisions in real time—especially in areas where map or GPS data may be insufficient or outdated. Therefore, the quality of roadway signs could be an important factor when evaluating road readiness for ADS-equipped CMVs.

The collected image data in CONOPS can be used to run object detectors and optical character recognition algorithms to understand how well the road signs are perceived by the ADS. Further, the images collected at night can be used to evaluate the visibility of roadway signs to ADS via classification algorithms. The visibility of roadway signs can be categorized into “good,” “fair,” and “poor” conditions. This automatic process helps efficiently and accurately identify signs with “poor” visibility for ADS during day or night operations and could be fed to roadway managers for proactive replacement or repair.

5.7.11.3 Assess Algorithms for Lane Line Detection

Lane detection serves as the foundation for numerous applications such as ADS and ADAS. The primary objective of lane detection is to identify and track lanes on roadways, providing essential information for vehicle navigation, lane-keeping assistance, and overall road safety. In addition to the lane score between 0 and 1 from the ADS discussed in the assessment, state-of-the-art algorithms for lane detection can be used to investigate if an advanced algorithm can improve lane line detection via images from ADS in real-world scenarios.

For instance, Honda et al. (2023) proposed CLRerNet[(281)] to address the challenges faced by traditional vision systems in self-driving cars, particularly in scenarios with blurry lanes or heavy shadows. To overcome these difficulties, another method such as LaneIoU, a novel approach that improves the confidence of lane detection, could be applied. The images in Figure 78 showcase the efficacy of a deep learning-based lane detection algorithm with LaneIoU.

Figure 78. Image overlay. The images show the application of the CLRerNET algorithm to ADS CONOPS Cross-Country data to measure lane lines.

In addition to evaluating real-time lane-detection algorithms, lane line quality for ADS operation could be evaluated. First, drawing from the collected images in CONOPS, clear images are selected from different locations (e.g., interstate highways, ramps, city streets, bridges, tunnels, ports). The lane line uniformity and variations could be evaluated across locations nationwide to identify potential challenges that may affect ADS performance. For example, some exit ramps may have dashed lines, while others do not. Then, the selected algorithms can be applied to the selected images to investigate how the ADS could detect lane lines across different locations. The algorithm’s performance could be manually grouped into good, fair, and poor for each location. These results could be used to support a road assessment and guideline to analyze the potential reasons for poor performance of ADS on these locations, summarize lane line readiness across the country, and recommend engineering practices to improve the standardization of lane line quality to support the needs of ADS-equipped CMVs.

5.7.12 Application to Fleet Operations

The road readiness assessment system developed here provides a mechanism to measure the ability of existing roadway infrastructure to support ADS and provides insights into how fleets can safely and gradually integrate ADS technologies into their operations based on the roadway rating systems. The rating system can be used to support fleet resource optimization, such as servicing roadways with high readiness ratings with ADS-equipped trucks and assigning human drivers to roadways with low readiness ratings. With such an approach, driver HOS can be maximized on low-readiness-rating roadways, and ADS technology can be maximized on high-readiness-rating roadways. Additionally, a hybrid approach of pairing drivers with ADS technology can be made possible through route planning optimization. Within the same service schedule, human drivers can work along with ADS on routes involving both low-readiness and high-readiness ratings. This way, drivers can take over when the roadway rating is low, and ADS can take over otherwise. Longer routes can be better served, operations can be optimized, and productivity can be improved.

Further, by gradually taking humans out of the driving loop, ADS technology can provide safer driving, leading to fewer driving crashes. This is especially beneficial to truck drivers, as long HOS often result in driver fatigue and tiredness. Drivers can transfer control to the ADS on roadways with high-readiness ratings whenever they are fatigued or tired and need to take a break. This cooperation can lead to better working conditions for human drivers and more driver resources available for fleets.

5.7.13 Recommendations for Stakeholders

This section has provided a mechanism for measuring the infrastructure readiness of certain roadway segments to support the deployment of ADS technology. The mechanism provides stakeholders and decision-makers tools to measure their existing roadways on a local level, as well as insights into what infrastructure is needed to support the safe integration of ADS into fleet operations and, potentially, vehicle operations generally. Considering the benefits that are expected to accompany ADS technology deployment, stakeholders are faced with the responsibility of conducting larger-scale assessment of the roadway system and how to improve low-rating roadways to adequately support new and emerging technologies such as ADS. State DOTs can start with improving roadway maintenance operations, such as repainting lane markings, clearly identifying shoulders, and improving pavement condition. Further, the efficiency and coverage of communication technologies such as GPS and cellular can be assessed for various roadways, especially those serving fleets.

5.7.14 Next Steps

There are two logical next steps in testing and further development of road readiness assessment systems for ADS-equipped trucks that might be implemented in follow-on work. First, the basic road readiness system presented in this report should be tested by ADS developers and/or truck operators to determine how effectively it can be used in conjunction with their truck ADS. Second, ADS developers and/or truck operators should be asked to suggest how advanced road readiness assessment systems can be formulated to better address specific individual ADS technologies. In both of these steps, comments from the ADS developers and truck operators should be considered in revising the approaches to road readiness assessment for ADS-equipped trucks. Once both of these steps have been completed, the road readiness assessment systems should be ready for wider distribution. Ultimately, the USDOT should make the decisions as to whether and how these road readiness assessment systems are distributed for implementation.

5.8 DATA TRANSFER AND CYBERSECURITY BEST PRACTICES

This section provides an overview of cybersecurity protocols for the developer's (Pronto) ADS. Although this section includes some aspects of the cybersecurity measures that the developer uses in its internal ADS development processes and service operations, the focus is on topics that are directly relevant to *end users* who adopt ADS technologies. More specifically, the focus is on cybersecurity from the point of view of an ADS-equipped CMV fleet as opposed to an ADS developer.

The section includes general guidelines for understanding what cybersecurity is, how mixed fleets (both conventional and automated trucks) and cybersecurity relate to each other, and how fleets should tailor these guidelines to meet their specific systems; the intended audience includes people operating mixed fleets for commercial purposes. The information in this section addresses cybersecurity topics from a unique angle that has not previously been studied in detail and is continuously evolving. We believe that this will be of practical use to CMV fleets, policymakers, and other stakeholders. Like many new technologies, ADS development continues to evolve at a rapid pace, especially regarding cybersecurity. As such, this section does not focus on technical details for implementation. Rather, it is best viewed as a starting point for CMV fleets and other audiences with a general interest in the practical, real-world implementation of cybersecurity measures in ADS deployment.

The section includes discussions around general best practices for managing mixed fleets based on different aspects of cybersecurity, and specific cybersecurity best practices for mixed fleets, including cybersecurity measures for use cases involving wireless and wired network connections. Also, we discuss general cybersecurity best practices in terms of background information, cybersecurity considerations, and data transfer and security.(282) It should be noted that the terms "cybersecurity" and "security" are both used here. In general, "cybersecurity" is defined as the art of protecting networks, devices, and data from unauthorized access or criminal use and the practice of ensuring confidentiality, integrity, and availability of both information(283) and the systems themselves. "Security" is a much broader term that describes the state of being free of danger or threat in general. However, the term "security" will be used interchangeably with the term "cybersecurity" in this section.

5.8.1 Cybersecurity Background on Managing Mixed Fleets

In ADS cybersecurity literature, the focus has been on the internal practices of ADS developers and vehicle manufacturers. This document is a first step toward filling an important knowledge gap in that literature. To date, relatively little attention has been given to the roles, responsibilities, and vulnerabilities of CMV fleets. For ADS technologies to be safely introduced and scaled to CMV fleets, a deeper understanding of cybersecurity topics from the perspective of CMV fleets is critical. Although all ADS developers aim to provide a product that is as safe as possible for CMV fleets, customers have a key role to play in maintaining safe data and network practices.

As technology continues to advance, the transportation industry is witnessing a shift towards mixed fleets, which comprise a combination of conventional trucks and automated trucks, such as those equipped with ADS. This integration of automated trucks into traditional fleets brings numerous benefits, including improved efficiency, reduced fuel consumption, and enhanced safety. However, it also introduces new challenges, particularly in the realm of cybersecurity.

In general, cybersecurity is about protecting information, including when it is stored in memory media, being processed, or in transit across a network. Cybersecurity plays a vital role in managing mixed fleets to ensure the secure and reliable operation of both conventional and ADS-equipped trucks. Conventional and ADS-equipped CMVs both exchange data with other similar vehicles, with the roadway infrastructure, and with a logistics network. However, ADS-equipped CMVs are equipped with high levels of automation that provide more control to the parties handling operational information. Therefore, safety-critical functions on CMVs with ADS features can be manipulated based on the data or through remote actuation.

The integration of automated trucks, which heavily rely on interconnected systems, introduces new vulnerabilities that may not be present in conventional trucks. These vulnerabilities can be exploited by malicious actors to compromise the safety, privacy, and integrity of the fleet's operations. Therefore, it is imperative to develop robust cybersecurity strategies specifically tailored to the unique characteristics and requirements of mixed fleets. We list these new vulnerabilities associated with ADS-equipped CMVs in section 5.8.2.1.

One key aspect of cybersecurity in managing mixed fleets is the integration and compatibility of different vehicle types and technologies. Conventional trucks and automated trucks often have distinct communication protocols, software systems, and security measures. Ensuring seamless interoperability and secure data exchange between these diverse vehicles is crucial for efficient fleet management and mitigating potential vulnerabilities.

Additionally, the cybersecurity focus in mixed fleets extends beyond the vehicles themselves. It encompasses the network infrastructure that facilitates communication between vehicles, fleet management systems, and external entities. The security of these networks is paramount to prevent unauthorized access, data breaches, or disruptions that could impact the entire fleet's operations and compromise the safety of drivers and cargo.

Moreover, the protection of sensitive data generated and exchanged within mixed fleets is of utmost importance. This data includes driver information, vehicle telemetry, maintenance logs, and cargo details. Cybersecurity measures are necessary to safeguard this information from unauthorized access, tampering, or theft, ensuring compliance with data privacy regulations and maintaining the trust of customers and stakeholders.

5.8.1.1 Vulnerabilities in ADS Environments

Software and Communication Vulnerabilities: In the ADS environment (i.e., in an operating environment with ADS vehicles), the complex software systems that power ADS can have bugs, coding errors, or security weaknesses that attackers could exploit. These vulnerabilities can allow unauthorized access, manipulation of data, or control of the vehicle. In 2015, two security researchers exposed the security vulnerabilities in automobiles by hacking into cars remotely, overtaking the cars' various controls from the radio volume to the brakes,[(284)] and leading to 1.4 million vehicles being recalled from the car manufacturer. In 2020, a Tennessee-based trucking and logistic company was targeted by a new and relatively unknown group of ransomware operators called “Hades” in December, which caused damage to the fleet’s reputation and disrupted operation.[285]

Meanwhile, the information shared among ADS and between the ADS and infrastructure can trigger safety-critical functions on the vehicles. Recent studies have revealed concerns of major risks associated with connected vehicles and AVs as the technology advances; these risks include not only the risk of traditional cyberattacks on the information and running of the vehicle, but also a new breed of attacks around such things as ransomware, Internet of Things (IoT) attacks, and vehicle theft.[286] ADS technology relies heavily on software, communication systems, and other advanced technologies to operate. These systems can be vulnerable to cyberattacks, which can compromise the vehicle’s control systems and compromise the safety and security of the driver, passengers, and cargo. Protecting this information must be included in any cybersecurity strategy for ADS-equipped vehicles, along with vehicle development itself. The vehicle development process is focused on continuous verification and validation. To discover issues early, such as requirements failing or failing to meet objectives, cybersecurity should be a fundamental objective in this process and should be subjected to continuous testing and confirmation.[287]

Sensor Spoofing or Tampering: Sensor spoofing refers to the act of sending falsified or manipulated data to the sensors of an AV. These sensors, including cameras, lidar, radar, and other perception systems, provide crucial information about the vehicle’s surroundings. If an attacker can feed incorrect data to these sensors, the automated system may misinterpret its environment, potentially causing the vehicle to make incorrect decisions. For example, an attacker could send false signals to a vehicle’s lidar sensors, making the system perceive obstacles that do not exist or fail to detect real obstacles like pedestrians or other vehicles. This could lead the vehicle to take unnecessary evasive actions or fail to respond appropriately to an actual threat. Sensor tampering involves physically modifying or interfering with the sensors on a vehicle. This can be done to either disrupt the vehicle’s perception of the environment or to manipulate the automated system’s behavior. Attackers might aim to disable certain sensors or alter their settings to create confusion for the autonomous system. For instance, an attacker could cover or obstruct the cameras or lidar sensors, making it difficult for the vehicle to see its surroundings accurately. Alternatively, attackers might modify the radar sensors’ settings to either exaggerate or diminish the perceived distances to objects, leading to unsafe driving decisions.

Both sensor spoofing and tampering pose serious risks to AVs and the people around them. These attacks can undermine the trust and reliability of automated systems, potentially causing accidents and fatalities. Manufacturers and developers of AV technology must implement robust security measures to detect and prevent such attacks, including encryption, authentication protocols, and redundant sensor systems. As with software vulnerabilities and communication weaknesses, protecting against sensor spoofing and tampering should be an integral part of the overall cybersecurity strategy for AVs. Continuous testing, validation, and monitoring are essential to ensure the integrity and safety of these advanced technologies as they become more prevalent on our roads.

Physical Access Vulnerabilities: Physical access vulnerabilities arise when attackers can physically interact with the vehicle’s hardware, software, or communication systems. This can occur through direct access to the vehicle, its components, or the infrastructure that supports it. Once an attacker gains physical access, they might exploit weaknesses in the vehicle's design or security measures to compromise its functionality or data. For instance, an attacker could gain access to the internal systems of an AV by exploiting a weak point in its physical security, such as a compromised diagnostic port or an insecure software update mechanism. Once inside, the attacker could manipulate the vehicle's software, alter its configurations, or even insert malicious hardware devices that grant control over the vehicle. Physical access vulnerabilities can have far-reaching consequences. Attackers with physical access can potentially take any of the following actions:

- Take Control of the Vehicle: By gaining access to critical systems, attackers might take control of the vehicle's functions, such as acceleration, braking, and steering, which could lead to accidents or intentional harm.

- Steal Sensitive Data: Access to the vehicle's internal systems can expose sensitive data, including personal information about the driver and passengers, travel history, and more.

- Install Malware: Attackers might install malicious software that can compromise the vehicle's security, monitor its activities, or even spread to other connected vehicles.

- Tamper with Safety Systems: Attackers could manipulate safety-critical systems, such as airbags or collision avoidance systems, leading to compromised occupant safety.

To address physical access vulnerabilities, users must take several precautions:

- Physical Security: Utilize robust physical security measures, including secure access points, tamper-resistant hardware, and intrusion detection systems.

- Secure Updates: Implement secure mechanisms for software updates, ensuring that only authorized and authenticated updates are accepted.

- Encryption: Encrypt sensitive data and communications to protect against data theft during physical access attacks.

- Multi-Layered Security: Apply a multi-layered security approach that combines physical, digital, and network security to create a comprehensive defense strategy.

- Continuous Monitoring: Employ real-time monitoring systems to detect and respond to any unauthorized physical access attempts.

As the automotive industry advances toward more automated and connected vehicles, acknowledging and addressing physical access vulnerabilities is crucial to maintaining the safety and security of both the vehicles and their occupants. Like other cybersecurity aspects, the prevention and mitigation of physical access vulnerabilities should be a fundamental component of the overall security strategy for these vehicles. This topic is revisited under the specific cybersecurity best practices section to further elaborate in the context of fleet operations at different locations, in different circumstances, and during different operations.

Supply Chain Vulnerabilities: In the field of ADS technology, the intricate network of supply chains that contribute to the development and manufacturing of these systems can introduce their own set of vulnerabilities. These vulnerabilities stem from the various components, software modules, and technologies sourced from different suppliers and integrated into the final product. Like software and communication vulnerabilities, supply chain vulnerabilities also pose significant risks to the security and functionality of ADS-equipped vehicles. Within this complex ecosystem, compromised components or software modules introduced at any point in the supply chain can have far-reaching consequences. Malicious actors could potentially insert backdoors, malware, or other forms of malicious code into the components or software, allowing unauthorized access, manipulation of data, or even complete takeover of the vehicle. The interconnected nature of supply chains amplifies these risks, as a vulnerability introduced by a single supplier can propagate across the entire network.

A prominent example of supply chain vulnerabilities came to light in various industries when the SolarWinds incident occurred.[(288)] This cybersecurity breach exploited vulnerabilities in the supply chain of a widely used network management software, ultimately affecting numerous organizations and government agencies. In the context of ADS, similar attacks on the supply chain could result in catastrophic outcomes, compromising not only the safety of the vehicle's occupants but also the broader transportation ecosystem.

To mitigate these risks, a robust cybersecurity strategy for ADS technology must encompass supply chain security. This involves rigorous vetting of suppliers, ensuring their adherence to security best practices, and conducting thorough assessments of the components and software they provide. Additionally, establishing mechanisms for ongoing monitoring and verification of the components throughout their life cycle is crucial to detect and address vulnerabilities as they arise.

Incorporating cybersecurity into the vehicle development process should extend to encompass the entire supply chain. Just as software vulnerabilities are subject to continuous testing and validation, the components and technologies sourced from suppliers should undergo similar scrutiny. By proactively addressing supply chain vulnerabilities and promoting a culture of security across all stakeholders, the ADS industry can work towards building safer and more resilient ADS.

Lack of Cybersecurity Awareness and Training: When advanced technology meets transportation or safety, a significant challenge always arises from insufficient awareness and training, and this applies to cybersecurity on ADS-equipped CMVs as well. The sophisticated nature of ADS technology demands a heightened level of vigilance and understanding about the potential risks associated with cyber threats; a gap in cybersecurity awareness and training can leave both developers and end users vulnerable to manipulation.

Developers and engineers working on ADS technology may not always have comprehensive knowledge of cybersecurity principles. This can lead to oversights in design and implementation, inadvertently leaving vulnerabilities in the system. Inadequate training can result in coding practices that inadvertently expose entry points for attackers, such as weak authentication mechanisms or improper data handling. This lack of awareness might also lead to underestimating the importance of security features, potentially prioritizing functionality over safeguarding against potential breaches.

Beyond the development stage, users and operators of ADS-equipped vehicles might lack the necessary cybersecurity awareness to make informed decisions. This can range from not recognizing phishing attempts aimed at gaining unauthorized access to the vehicle's systems to failing to install critical software updates that address security vulnerabilities. In some cases, users might unknowingly engage in actions that compromise the security of their vehicles, such as connecting to unsecured networks or using unauthorized third-party software.

To address these challenges, a comprehensive approach to cybersecurity awareness and training is imperative. Developers and engineers must be equipped with a strong foundation in cybersecurity principles and practices. This includes understanding secure coding practices, threat modeling, and risk assessment. Continuous training programs can help ensure that these professionals stay up-to-date with the evolving threat landscape and best practices. Similarly, users and operators of ADS-equipped vehicles need accessible and clear guidance on how to interact with the technology securely. This can involve educating users about the importance of strong and unique passwords, the risks of sharing personal data, and the significance of promptly applying software updates. Moreover, fostering a culture of cybersecurity awareness among the general public can contribute to a safer and more resilient ADS ecosystem.

5.8.1.2 Challenges of ADS-equipped CMV

An ADS-equipped CMV is a commercial vehicle equipped with an ADS feature (see SAE J3016 and J3164).[289] An ADS feature operating a vehicle within its ODD faces challenges in mitigating vulnerabilities, as noted in section 5.8.2.1, and in obtaining the information required for ADS feature functions. These functions include trip and path planning, path management, assessing path plans in the current operating environment, assessing current vehicle and environmental status, and execution of a path plan.

Beyond these challenges are potential functional and safety benefits to a system with the ability to *learn from the vehicle's past decisions* (i.e., recognize similar operating conditions and assess which decisions had a better outcome). However, this capability would require the vehicle to possess and evolve metrics for both safety and function.

Technologies, software, and networking that address each of these ADS-equipped CMV challenges will bring additional dimensions to cybersecurity measures.

As the industry is learning, "as modern vehicles are capable to connect to an external infrastructure and vehicle-to-everything (V2X) communication technologies mature, the necessity to secure communications becomes apparent. There is a very real risk that today's vehicles are subjected to cyberattacks that target vehicular communications."[290] The sensing, communication, and control elements of vehicular communications are important to understand and critical in terms of identifying cyberattacks and presenting the appropriate countermeasures.

5.8.1.3 Challenges of Mixed Fleets

Mixed fleets, which consist of a combination of conventional vehicles and vehicles with advanced technologies (such as autonomous or automated features), can present several challenges due to the coexistence of different vehicle types and technological capabilities. Some of the key challenges of mixed fleets include the following:

- Integration Complexity: Integrating diverse vehicle types with varying technological capabilities into a single fleet can be complex. Ensuring seamless communication, interoperability, and compatibility between different vehicle systems and technologies requires careful planning and technical expertise.

- Operational Variability: Conventional vehicles and advanced technology-equipped vehicles might have different operational requirements, maintenance schedules, and fuel consumption patterns. Fleet managers need to balance these differences to optimize overall fleet efficiency and performance.

- Training and Skill Diversification: Drivers and maintenance personnel need to acquire different skill sets to operate and maintain various types of vehicles. Training programs must be tailored to address the specific needs of both conventional and advanced technology-equipped vehicles, ensuring that all personnel are adequately skilled.

- Maintenance and Repairs: Maintaining and repairing mixed fleets can be challenging due to the differences in vehicle technologies. Advanced technology-equipped vehicles may require specialized diagnostics and repair procedures that conventional vehicles do not need. This could lead to increased maintenance costs and potential delays.

- Data Management: Mixed fleets generate diverse types of data, including vehicle performance data, sensor information, and advanced technology diagnostics. Managing and analyzing this data to derive meaningful insights requires robust data management systems and analytics capabilities.

- Technology Upgrades and Obsolescence: Advanced technologies in mixed fleets can become outdated quickly due to the rapid pace of innovation. Fleet managers need to consider the life cycle of these technologies and plan for upgrades or replacements to remain competitive and compliant with industry standards.

- Regulatory and Compliance Challenges: Different vehicle types may be subject to varying regulatory requirements and standards. Fleet operators must ensure that all vehicles, whether conventional or equipped with advanced technology, meet the necessary compliance criteria.

- Cost Considerations: Integrating advanced technology-equipped vehicles into a mixed fleet can be expensive, from initial procurement costs to ongoing maintenance and training expenses. Fleet managers must carefully assess the return on investment and consider the long-term financial implications.

- Driver Adoption: Drivers accustomed to conventional vehicles might need time to adapt to new technologies. Ensuring a smooth transition and addressing any resistance to change is important for maximizing driver acceptance and efficiency.

- Risk Management: Introducing advanced technology-equipped vehicles brings new cybersecurity and safety risks. Fleet operators must implement robust cybersecurity measures to protect these vehicles from cyber threats, ensuring the safety of drivers, cargo, and other road users.

- Supply Chain and Spare Parts: Managing a mixed fleet requires efficient supply chain management for spare parts and components. Availability of spare parts for advanced technology-equipped vehicles can be challenging, affecting downtime and maintenance schedules.

Navigating these challenges requires strategic planning, effective communication, ongoing training, and a thorough understanding of the specific operational dynamics of the mixed fleet. By addressing these challenges proactively, fleet operators can harness the benefits of mixed fleets while mitigating potential drawbacks.

5.8.2 Cybersecurity Considerations

Designing cybersecurity features requires consideration of access from authorized and unauthorized users and intentional and unintentional attacks on ADS operations. Implementing safe and easily maintained security measures—such as logging, auditing, and recovery—ensures that the ADS can be safely integrated into the CMV fleets, especially when end users lack technical expertise. Stakeholders for CMV fleets must always remain aware that any ADS can be misused or abused. This awareness must be at the forefront when considering how to deploy and manage an ADS-equipped CMV fleet. Potential damage is minimized by implementing a variety of operational safeguards and frequent system audits.

Training on and education about ADS safety measures is critical. System checks are sometimes missed in conventional-only fleets today, as well as best practices not followed, causing incidents to happen. This may become an issue in future ADS-equipped CMVs when deployed in large numbers in mixed fleets. Designing and implementing a robust ADS that can monitor itself, self-audit, and prompt an external audit when needed mitigates the adverse results of human error. An end user who is not completely trained, or who is unsure of the ADS's capabilities, should not endanger others by continuing to interact with the ADS. As such, one key goal for any ADS cybersecurity program should be to have as many built-in automatic safety checks and audits as possible. A CMV fleet that adopts ADS technology needs to understand how these safety checks and reports work. CMV fleets must also develop operational procedures, safeguards, and Emergency Action Plans (EAPs) to respond appropriately to any issues, including contacting the ADS developer when needed through their regular contact and support channels, or escalating when necessary.

Maintaining appropriate user access is another key goal of cybersecurity. Physical or virtual access to the ADS by an internal or external party without approval from the developer or another authorized party is considered "unapproved access." This type of access can result in a loss of control over the ADS. Unapproved monitoring, viewing, editing, or other communications to or from the ADS are all examples of "misuse," which could result in repurposing part or all of the ADS. Inappropriately using the system can cause the ADS to operate outside of its normal safety parameters, which can disrupt workflows and, in extreme cases, harm workers or other road users. Proper access and misuse procedures must therefore be one of the highest priorities for any CMV fleet that adopts ADS technologies.

Cybersecurity should not be considered only a "virtual" matter that involves potentially valuable information and data. There is also a critical physical component. Keeping the hardware as secure and robust as possible helps to maintain the safest possible *physical* operations. Although each ADS deployment is unique, the goal of any cybersecurity program should be that any significant failure avoids physical harm or damage. The ADS-equipped truck should be capable of stopping the operation in a manner that minimizes potential harm to surrounding traffic and people. ADS developers and other stakeholders are already familiar with the concept of MRC. The MRC is a low-risk, reasonably safe operating mode that an ADS-equipped truck attempts to achieve when the truck's ADS fails in a way that renders the vehicle unable to perform the entire DDT. Fleets should adopt the same mindset when it comes to serious cybersecurity breaches—bringing the ADS-equipped truck to a reasonably safe state to prevent the cybersecurity issue from becoming a physical danger to others.

In addition, there are malicious programs on the internet designed to damage or repurpose computers. Trucking fleets should be vigilant and aware of potential threats targeting connected devices. In this respect, ADS should be treated like other highly sensitive computer systems. General best practices for computer security and monitoring from organizations like the Automotive Information Sharing and Analysis Center[(291)] and the National Institute of Standards and Technology[(292)] should be followed. Although it is recognized that ADS developers follow procedures similar to those of other highly data-sensitive industries like aerospace, defense, electric utilities, and other critical infrastructure, trucking fleets should approach the cybersecurity of their ADS-equipped fleet with the same level of rigor and protection that they would apply to their most sensitive digital assets (e.g., financial systems, customer and pricing information, logistics and dispatch platforms).

5.8.2.1 Exposure

Exposure describes where and how the ADS communicates beyond internal communication with its components. As the ADS operates in a constantly changing environment, it relies on a suite of sensors to monitor its surroundings to inform its decisions. The ADS needs to be able to do this accurately and without interference from external actors. Knowing where and with whom the ADS communicates is important for identifying potential risks. Monitoring and using software-based checks to verify the authenticity of communications is an important step in preventing potential attacks and/or data leaks.

The cellular modem, wireless network, or other means of connecting the ADS to the broader internet is one of the greatest exposure risks. In this respect, it is important for trucking fleets to remain vigilant about overall internet cybersecurity risks. Leaving any internet-connected device unsecure and unattended can be a significant threat. Bad actors, hackers, and security researchers dig through the relatively small number of internet protocol addresses probing for connectivity and looking for interesting or exploitable ports. Pronto's system is designed to talk to other vehicles that are equipped with the Pronto ADS, other pre-approved devices, and Pronto engineers' laptops (only through a virtual private network, or VPN). However, the ADS is still open to the rest of the internet during debugging stages, allowing developers access to online resources for development.

Access to the internet is largely unnecessary, as updates and control commands should continue to go through the ADS developer's VPN. Nevertheless, it is critical for the trucking fleet to be vigilant about who has access to manage the VPN and who can communicate across it. This is a critical step in keeping the ADS secure, as unapproved devices could leak data from the VPN and thus be an ingress point for attackers. VPNs are suitable for securing communication channels in mixed fleets, as they ensure data transmitted between vehicles and the central system is encrypted and secure. Zero Trust architecture—also often referred to as Zero Trust Security or the Zero Trust model—on the other hand, provides a comprehensive security approach that encompasses access control, continuous monitoring, and strict user/device verification.[(293)] This approach can be applied in mixed fleet cybersecurity systems, making it well suited for securing resources and access within mixed fleets while adhering to the principle of least privilege (PoLP). Under Zero Trust architecture, vehicles and devices are never trusted by default; they must authenticate and prove their security posture before accessing fleet resources. According to a 2022 VPN risk report published by *Cybersecurity Insiders*, 80% of companies are in the process of adopting Zero Trust in 2022, and many organizations may use a combination of both VPNs and Zero Trust principles to create a layered security approach.[(294)]

Internet exposure represents the single biggest ingestion point for downloading or installing malicious code or external parties gaining unauthorized access to the ADS. Careful restrictions, such as authentication verification and access control lists (ACLs) should be used to prevent unauthorized or unintended access to the system.

> Risk Example: During development, an engineer working for an ADS developer needs to host a simple web page from the ADS to monitor whether the system is visualizing correctly. The software package the engineer chooses to install is not listed in a closely monitored repository and contains a malicious ransomware package. The engineer adds the repository and installs a webserver to host the page, but also inadvertently installs the ransomware package. After restarting, the system is encrypted and will not boot or decrypt unless a ransom is paid to the bad actor who inserted the ransomware package.

This scenario can be avoided by carefully vetting allowed devices. Configuring the system to drop or deny unapproved inbound and outbound connections by default—and only allowing pre-approved connections—allows the necessary control over communications to maintain a safe and secure network. This can be achieved by using a simple firewall, implemented as close to the interface to the internet as possible.

Across the local internal network and through the secure VPN tunnel, developers use several standardized protocols, including Transmission Control Protocol (TCP), User Datagram Protocol (UDP), and ZeroMQ Message Transport Protocol (ZMTP), to send commands and receive updates from the ADS. Implementing local firewalls (1) at the router that provides network access and (2) on the main computer of the ADS on the truck itself helps to "harden" system security. A firewall allows or denies traffic based on a policy (e.g., regular web traffic may be allowed on TCP port 80, but remote shell access through port 22 is blocked). More advanced solutions go beyond identifying the port that traffic comes through to also inspecting and verifying the data as it passes through.

Limiting traffic on the internet, or even the local network, ensures that an ADS runs as intended and is not affected by unapproved directions or actions from bad actors. The VPN solution already implements similar features in the network ACLs, where the ADS developer can control which ports are allowed for communication. The VPN should not respond when an unauthorized actor attempts to use a port where they are not allowed. Dropping traffic and not responding is a preferred security posture, as it does not confirm the presence of a system on the other end (which a rejected response would). The less exposure there is overall, the less possibility there is for attacks and fewer items to monitor for potential incidents.

The information coming from GPS and video cameras could also be vulnerable, but the related risks would involve more targeted attacks on the ADS. Unlike the broader internet risks discussed earlier, disrupting the accuracy of the GPS or video system requires a well-organized and skilled attacker who is specifically targeting a particular ADS. While these types of attacks are worrying, they are not as likely as the more common cybersecurity issues. However, when someone tampers with both GPS and video data in a mixed fleet of vehicles, the potential risks can be significant. Manipulating GPS and video data simultaneously can lead to severe navigation errors, disrupt route planning and monitoring, aid thieves in tracking and intercepting cargo, cause complex liability and legal challenges, expose sensitive information about vehicle occupants, drivers, and cargo, and ultimately damage the fleet's reputation for reliability, safety, and security.

All the above scenarios are means of protecting ADS-critical information in transit. This information, of course, needs to be protected when being processed and when being stored, either on the ADS or at the fleet control center.

5.8.2.2 Access

Wireless Access to ADS: Wireless access to ADS plays a fundamental role in enabling communication, data sharing, and control within mixed fleets of vehicles. However, it also presents unique cybersecurity challenges and considerations. Wireless access facilitates real-time communication between vehicles, infrastructure, and centralized fleet management systems. It enables the exchange of critical information, such as vehicle status, sensor data, GPS coordinates, and operational instructions. This communication is vital for managing and coordinating mixed fleets efficiently. There are several widely used types of wireless access:

- Cellular Networks: Many ADS rely on cellular networks to transmit data. This includes 4G and 5G networks, which provide high-speed connectivity and low latency, making them suitable for time-sensitive applications.
- Wi-Fi: Wi-Fi connectivity is often used for short-range communications within fleets or at depots. It can be employed for data transfer, software updates, and diagnostics.

- Satellite Communication: In remote or challenging environments, satellite communication provides a reliable means of connectivity for ADS, ensuring that vehicles remain connected even in areas with limited terrestrial network coverage.
- V2X Communication: This technology allows vehicles to communicate with other vehicles (V2V), infrastructure (V2I), pedestrians (V2P), and more (V2X).

In section 5.8.2.1, cybersecurity software and communication vulnerabilities were discussed that rely heavily on wireless access to ADS. Although wireless access serves as an essential component in modern fleet management and AV operations, it also brings many unique cybersecurity challenges. Without proper security measures in place, malicious actors can potentially compromise the integrity and safety of the fleet. To address these challenges, several cybersecurity solutions are commonly employed. Strong encryption protocols protect data in transit over wireless networks, ensuring its confidentiality even if the data is intercepted. Robust access control mechanisms guarantee that only authorized devices and users can access the ADS wirelessly, including multifactor authentication mechanisms. Intrusion detection and prevention systems (IDS/IPS) continuously monitor for and respond to suspicious activity on wireless networks. Regular software updates, security audits, and penetration testing help identify and mitigate vulnerabilities proactively.

Physical Access to ADS: Physical access to ADS should also be considered when evaluating cybersecurity risks. The installed components should be easy to service but difficult to break into (i.e., preventing unauthorized physical access). Unauthorized physical access could bypass many of the network software restrictions, providing access to the local network the ADS is attached to or direct access to the onboard computer. At a lower level, physical access to the main ADS computer or other additional hardware leaves the system open to the threat of tampering.

To combat this, the bulk of an ADS product should reside in a closed metal (or other ruggedized) enclosure, secured with non-standard security screws to prevent unapproved access. Any physical connections not needed after development and installation should be removed. Exposed physical ports (serial, USB, SATA, Ethernet) pose potential risks for unapproved access to the ADS. Although physical access may not be something that a CMV fleet can constantly monitor in real time, tamper-resistant physical designs, along with tamper tape or seals across physical service or access points, will identify unauthorized access.

Besides physical access to the installed ADS components on the vehicles, physical access to infrastructure including roadside sensors, control units, and charging stations can also be a potential penetration point for cyberattack. Such physical components can provide opportunities to attackers for malicious activities such as data extraction, ADS device tampering/sabotage, and malware injections. Physical security, device tamper detection, secure boot and firmware validation, and the mechanisms to immobilize the vehicle under critical circumstances should all be taken into consideration.

User Account Access: All accounts that are set up for end-user access to an ADS should require strict authentication measures and should be regularly audited. After authentication, a level of access needs to be defined for each account, emphasizing PoLP[(295)], which refers to a user only receiving the level of access required to perform their job functions. To help manage what tasks each user can perform, the ADS developer should limit the kind of input the user can provide and retrieve from the ADS. This definition of access would span from absolute control over all aspects of the system (limited to senior internal development use only), all the way to read-only access for narrowly defined reporting and monitoring purposes. Starting from the least amount of access and working towards complete access, the developer should gradually add the appropriate amount of access for each user, making sure to add only the properties that are needed to the relevant user's account.

One simplified way to organize the increasing levels of a CMV fleet's access to the ADS could be to define user roles such as Administrator (Admin), Site Supervisor, Senior Foreman, Foreman, Operator, and Monitor. This type of access control is often referred as role-based access control (RBAC).[(296)] In general, Admins will have the greatest access, including the ability to create and remove accounts, set permissions for different accounts, and monitor the system, but they may not necessarily need access to set a destination and command the vehicles to drive. The Admin account level should only be given to trusted users who have shown proficiency in using the ADS and fully understand its capabilities and limitations, as this access level carries the most responsibility. Site Supervisors oversee and have access to most of the controls at the deployment locations and will need proficiency in the deeper workings of the system. A Foreman could handle journey planning and programming specific routes for the trucks to drive, as well as oversee a group of Operators who are running and supervising a particular ADS operation. A Monitor would only be able to access accounts and view what is happening within the ADS-equipped trucks.

> Risk Example: A disgruntled employee maliciously uses their system access to try to cause the ADS truck to cause harm. They program an unsafe path, but the vehicle correctly perceives a collision threat and refuses to proceed. The disgruntled employee uses their user account to repeatedly override the ADS's built-in protections (which keep activating) in the hopes of forcing the vehicle to crash.

There are several ways to avoid or mitigate this type of (extreme) incident. The ADS could be programmed with a limited number of overrides in a set period. After exceeding the criterion overrides, a higher-level account approval is needed to approve the override. Any override should be logged, audited, and monitored to ensure that someone with a high-level classification is notified of the incident.

Along with limiting who can operate the ADS (via user accounts) and setting levels of access (permission properties), CMV fleets should also implement a schedule of when systems can operate and when and where individual accounts are allowed to run them. A GPS coordinates check should be implemented to limit any access by devices that are not near sites authorized to send commands to the ADS-equipped truck. In addition to requiring individual user accounts, shared device use should be discouraged, as shared devices reduce the visibility and accountability for who was operating or connected to the ADS at a specific time. Multiple accounts might be used on the same device, but only one account should be logged in at a time. Lastly, standard password rules (eight or more characters long, three of the four [alpha, num, symbol, special] categories used) and password rotation should be employed (see the Cybersecurity and Infrastructure Security Agency password guidelines[(297)].

Risk Example: An operator lets another member of their family use their phone (that includes the ADS control app). That family member opens the control app and starts a program, causing the truck to engage in a work mode without supervision or interrupting in-progress work.

These types of "accidental" or negligent risks are likely to be more common than malicious "hacks," especially when ADS trucks are deployed at scale. Fortunately, these risks are also mitigated in a straightforward manner that is within the capability of sophisticated CMV fleets that would adopt ADS trucks. A time lock can prevent use of any ADS-related program if the operator is off duty. In addition, geofencing (using GPS) can limit where the control app is run in relation to the ADS truck. It should not be possible to operate any sort of device that controls the ADS without some form of authentication.

Beyond the accidental or negligent access of a user account, one must also consider the possibility of a high-level account being compromised, whereby commands are maliciously sent to the ADS from a third party. To protect against this type of situation, each account should have the ability to safely command vehicles to go to an MRC and/or flag an action for review. A master intent and audit log of all running vehicles should be published as a tab in all controls of the ADS. This tab should have a clear description of the planned truck's path, what accounts activated the path, when all actions were taken, and the number of overrides performed.

For end users who control the ADS by means of a mobile device (iOS, Android, etc.), device security is of utmost importance. Securely logging into the app should require a username and password, in combination with multifactor authentication. Just as lower access accounts should be time locked out of running programs, access to the app must be reauthorized whenever a user turns their focus away or the device sleeps. At a regular interval, a password reentry should be required, regardless of the sleep or focus status of the app. Multiple accounts might be used on the same device, but only one account should be logged in at a time.

Passwords should also be kept secure. Having a pre-authorized account and password would be the easiest way for a bad actor to compromise the system. Standard password rules and rotating any passwords in use during development at regular intervals promotes regular auditing of all development devices in use. Leaving "stale" computer configurations in any part of the product life cycle makes the ADS an easier target. ADS developers can prevent this by setting a lifespan for a configuration. If a system has not been updated in a certain number of days, it should retire itself automatically or sunset itself until updated.

It should also be noted that while predefined passwords and access are easy to deploy in a small development environment, they may pose a significant vulnerability at larger scales. If the same password and account is used across multiple systems, then only one system needs to be attacked for all systems to be vulnerable. Moving towards a certificate-based authentication system would make the system easier for development engineers to access and make the system more secure overall. Certificates can be set to expire at specific dates and/or times, limiting the possibility of credentials being captured and used by bad actors.

5.8.2.3 Security Assurance Opportunities

This section discusses the opportunities to assure cybersecurity via the fleet's policy so that potential cyberattack can be minimized or eliminated in advance.

Training and Education: As mentioned under section 5.8.2.1, addressing the vulnerability caused by lack of cybersecurity awareness and training can involve educating users about the importance of strong and unique passwords, the risks of sharing personal data, and the significance of promptly applying software updates. Moreover, fostering a culture of cybersecurity awareness among the public can contribute to a safer and more resilient ADS ecosystem. When assuring cybersecurity, it is critical for the employees to have a clear understanding of how certain procedures should be performed and how to handle data safely. This requires thorough and easy-to-follow training supported by a thorough and concise cybersecurity policy from the fleet's management. This section discusses the importance of cybersecurity training and education of employees, such as building knowledge of cybersecurity and ADS and providing clear instructions on how certain procedures should be performed.

Training and education play a pivotal role in enhancing the cybersecurity resilience of ADS. Comprehensive training and education programs not only empower developers, engineers, and users with the knowledge needed to identify and address potential vulnerabilities but also foster a culture of cybersecurity awareness that extends throughout the ADS ecosystem. This security assurance opportunity provides benefits in multiple ways:

- Skill Enhancement: Cybersecurity training equips professionals with the skills to identify, assess, and mitigate vulnerabilities and threats specific to ADS technology. Developers and engineers learn to integrate security measures into the design and development stages, reducing the chances of vulnerabilities being introduced into the system. By staying current with the latest cybersecurity techniques and tools, professionals can proactively defend against emerging threats.

- Risk Mitigation: Educated professionals are better equipped to perform threat modeling, risk assessment, and vulnerability analysis. This proactive approach enables the identification of potential attack vectors and the implementation of appropriate safeguards, reducing the likelihood of successful cyberattacks.

- User Empowerment: Users and operators of ADS-equipped vehicles need to understand how to interact with the technology securely. Education empowers users to make informed decisions, such as recognizing suspicious behavior, managing software updates, and practicing safe driving habits while using autonomous features.

- Cultural Shift: Establishing a culture of cybersecurity awareness is essential. Comprehensive education programs help create a mindset where cybersecurity is prioritized at all stages of ADS development and use. This cultural shift fosters a collective responsibility for security among all stakeholders.

There are multiple feasible methods to implement training and education effectively, such as collaborating with cybersecurity experts, academic institutions, and industry leaders to develop comprehensive curricula that cover a range of topics, from secure coding practices to incident response strategies. Providing certification programs or awareness campaigns can stimulate and encourage people to voluntarily gain understanding of cybersecurity, and certifications can serve as a milestone for knowledge building and skill levels. Hands-on training can also help employees translate theoretical knowledge into real-world scenarios through simulations and labs, and it can provide invaluable experience in dealing with security incidents and rehearsal for EAPs. Meanwhile, cybersecurity is a rapidly evolving field. It will benefit stakeholders to implement continuous learning programs that encourage professionals to stay updated with the latest trends, vulnerabilities, and countermeasures. In addition, advocating for regulatory frameworks that require a minimum level of cybersecurity training and awareness for professionals working with automated systems is also recommended.

By investing in robust training and education initiatives, and with knowledgeable professionals and informed users, the risk of cyber threats affecting the safety and functionality of ADS can be substantially reduced.

Integrate Rulemaking for Facility Access and Device Security: Physical facility access and individual login devices are crucial elements that demand dedicated rulemaking to fortify security measures. Implementing regulations in these areas can establish a comprehensive defense strategy that not only prevents unauthorized physical access but also safeguards against unauthorized device usage.

Comprehensive security stands as a cornerstone of ADS cybersecurity. The introduction of rulemaking covering facility access and individual login devices bolsters defense mechanisms, reducing potential vulnerabilities and avenues for cyberattacks. This holistic approach acknowledges that safeguarding ADS technology encompasses both the digital and physical realms. Furthermore, rulemaking is essential to mitigating insider threats, as unauthorized facility access by malicious insiders could lead to severe breaches. Establishing regulations ensures that only authorized personnel gain entry to critical systems, significantly minimizing the risk posed by insider attacks.

The significance of end-to-end security in ADS cannot be overstated. Rulemaking in physical facility access and individual login devices contributes to an integrated cybersecurity framework. By enforcing stringent access control policies and advocating for multifactor authentication, organizations can prevent unauthorized access and enhance user verification. Biometric verification methods, like fingerprints and facial recognition, further strengthen security measures. Regular audits and inspections of physical access points and devices are vital to identifying vulnerabilities and maintaining compliance with security protocols. This proactive approach complements digital cybersecurity efforts, creating a more resilient defense against potential threats.

Collaboration and continuous improvement are key aspects of successful rulemaking. Partnering with regulatory bodies and industry experts helps establish standardized guidelines that align with evolving technological advancements. By fostering a culture of vigilance through training and awareness programs, personnel become more proactive in identifying and addressing potential facility security risks. Additionally, incident response protocols ensure a coordinated approach in case of security breaches or compromised devices.

Monitoring of Facility, Property, Driver States, and Vehicle Information: When systems are under cyberattack through physical or wireless sources, abnormal behavior inside the system might be the key to detecting such an attack. This section discusses the importance of developing a visually observable mechanism that monitors the system at all times to report any detected cyberattack to the system or the human users. Such a monitoring function should have access in all aspects of the fleet's operations.

Developing and embedding a visually observable monitoring system within mixed CMV fleets provides an additional layer of cybersecurity that enhances the overall safety and integrity of the fleet. This system acts as a vigilant watchdog, constantly monitoring all systems for signs of cyberattacks. Its rapid detection capabilities enable early intervention and response, crucial for mitigating potential threats before they escalate. By offering real-time visibility into the fleet's status, the system empowers human operators to make informed decisions and respond effectively, preventing false positives from causing unnecessary actions.

In the context of mixed CMV fleets, where various levels of automation coexist, a visual monitoring system builds trust among drivers, fleet managers, and passengers. It reassures stakeholders that cybersecurity is actively maintained, promoting confidence in the safety of the fleet's operations. Additionally, the system aids in regulatory compliance by providing visible evidence that cybersecurity standards are being upheld, simplifying reporting and audits.

Mixed fleets should have a unified fleet management platform developed that is capable of integrating the monitoring system and overseeing both automated and non-automated vehicles. Standardized communication protocols must be established to ensure compatibility with the system. Visual alerts should be user-friendly, displayed on dashboards or conveyed through notifications to drivers and fleet managers. Data fusion and analysis should provide a comprehensive cybersecurity overview by integrating data from various vehicle systems and sensors.

Human intervention remains crucial, thus facilitating bidirectional communication between the monitoring system and human operators. Operators must be equipped to validate alerts and make informed decisions based on real-time information. Training sessions should be conducted to familiarize drivers and fleet managers with the system's features and proper response procedures. Secure data transmission is paramount to prevent unauthorized access or tampering.

As the fleet evolves, scalability should be a design consideration, and fleet operators should ensure that the system is updated regularly to address emerging threats and incorporate new security measures. Striking a balance between cybersecurity and privacy is essential, ensuring that driver and passenger privacy is maintained while enabling necessary monitoring capabilities. Incorporating a visually observable monitoring system into mixed CMV fleets establishes a robust cybersecurity framework. With rapid detection capabilities, real-time awareness, and human intervention, this system bolsters security measures and promotes a safer environment for both automated and non-automated vehicles.

Internal Cybersecurity Team Risk Assessment: NHTSA released its *Cybersecurity Best Practices for the Safety of Modern Vehicles* in 2022, an update to its 2016 edition.[(298)] This NHTSA document states that the cybersecurity risk assessment process "should include a cybersecurity risk assessment that is appropriate and reflects mitigation of risk for the full life cycle of the vehicle" and "Safety of vehicle occupants and other road users should be of primary consideration when assessing [cybersecurity] risks." This document places significant emphasis on the necessity of a comprehensive cybersecurity risk assessment process that aligns with the entire life cycle of the vehicle while keeping the safety of vehicle occupants and other road users at the forefront. This directive reflects the evolving nature of vehicle technology, highlighting the imperative to ensure the security of increasingly connected and AVs. In this complex landscape, robust risk assessments conducted by internal cybersecurity teams serve as a cornerstone for identifying vulnerabilities, evaluating potential threats, and implementing effective mitigation strategies.

The importance of internal cybersecurity team risk assessment for mixed CMV fleets is multifaceted. Firstly, it enables the comprehensive identification of potential vulnerabilities that may affect different vehicle models within the fleet. This tailored approach ensures that mitigation strategies are focused and relevant, addressing specific risks faced by each type of vehicle. Moreover, risk assessments prevent systemic vulnerabilities from propagating by considering the fleet as a cohesive ecosystem. This prevents a single vulnerability from compromising the security of the entire fleet.

In alignment with the guidance from NHTSA(299), risk assessments should span the entire life cycle of the fleet. Collaboration with vehicle manufacturers, technology providers, and regulatory bodies is crucial to ensure that assessments encompass the full spectrum of technological components. Through scenario-based analysis, internal teams can anticipate potential cyber threats and vulnerabilities, enhancing their ability to proactively address risks before they materialize.

To implement effective internal cybersecurity team risk assessment in mixed CMV fleets, a combination of factors comes into play. Regular audits and testing of implemented security measures validate their effectiveness and relevance. Integrating threat intelligence feeds into the system allows stakeholders to stay updated on evolving threats. Training and awareness programs for fleet personnel, drivers, and operators foster a culture of security consciousness, enhancing the overall effectiveness of risk assessment measures. Ensuring alignment with industry standards and regulations guarantees that risk assessment methodologies remain robust and relevant.

Internal cybersecurity team risk assessment is a critical aspect of the cybersecurity strategy of mixed CMV fleets. Its role in identifying vulnerabilities, prioritizing mitigation, and fostering a proactive approach contributes significantly to the overarching goal of establishing a safer and more secure transportation ecosystem.

Penetration Testing and Review: Penetration testing and reviews are vital in proactively identifying vulnerabilities, assessing the resilience of security measures, and fine-tuning defenses to effectively protect both autonomous and non-autonomous vehicles. By simulating real-world cyberattacks and conducting assessments, penetration testing and reviews contribute significantly to the overarching goal of maintaining a robust and secure fleet.

Penetration testing and reviews allow for the proactive identification of potential vulnerabilities that adversaries could exploit. By simulating diverse cyberattack scenarios, internal cybersecurity teams gain valuable insights into the fleet's weak points, enabling targeted mitigation strategies. Moreover, penetration testing and reviews help validate the effectiveness of existing security measures. Identifying gaps in the defense architecture allows prompt corrective actions, bolstering the overall cybersecurity posture.

To effectively implement the penetration testing and reviews, fleet managers must first define a comprehensive scope that includes all types of vehicles, communication protocols, and potential attack vectors. They should collaborate closely with third-party security experts who bring an external perspective to the assessment and conduct both black-box and white-box testing(300) to replicate different attack scenarios, testing not only the system's robustness but also the organization's response to breaches. After testing, they should perform an in-depth review of the findings, prioritizing vulnerabilities based on potential impact and likelihood. Fleets should implement timely and targeted mitigation measures, addressing identified weaknesses. To ensure continuous improvement, they should also conduct regular follow-up assessments to validate the effectiveness of implemented changes and identify new vulnerabilities that may arise due to evolving threat landscapes. Lastly, stakeholders should foster a culture of learning and awareness within the fleet, sharing insights and lessons learned from penetration testing and reviews with personnel, drivers, and operators. This helps develop a collective understanding of potential threats and cultivates a sense of ownership in maintaining cybersecurity.

5.8.2.4 Failure and Recovery

An ADS failure is an unexpected cessation of operations for unexplained reasons. A failure may be the result of a bad configuration, software or hardware bug, or intentional disruption of service. Just as hardware must be operated with a "fail-safe" mentality, the software must also "fail safely." If the ADS detects an interruption of regular operations, it should be able to restart itself and safely continue its job. However, if the ADS cannot safely continue its job, it needs to enter an MRC failure state. This includes failures related to cybersecurity.

Robust monitoring systems, with the ability to evaluate the severity of the failure, should be implemented to observe the ADS and determine if any action is necessary. There are different types of cybersecurity failures, from "small concern" to "immediate halt." The severity of the incident and the frequency of the incident should be considered when classifying these failures. Depending on deployment site and ODD, the scale may shift and need to be determined by a supervisor at the truck fleet and the ADS developer.

Recovery should be as fast as possible, as the risk of a stopped vehicle in an MRC may also be a hazard to other vehicles or people. Keeping at least one baseline software image on the system in a protected partition or disk could serve as an absolute fallback boot option. This baseline image should always be able to start the ADS and command the vehicle to safely come to a stop. A second "boot" image should exist that would store the latest good configuration changes and run the ADS during regular operation. A third "staging" image should be used to house any settings that need to change. Maintaining these separate images should allow the ADS to restart in a known good and safe configuration every time, even if it is not the desired configuration for a particular job.

It is critically important to ensure that restarting services while the vehicle is in operation does not lead to a cascade of issues. Each service that runs on the main computer should be able to do so as independently and modularly as possible. Although the ADS will need the coordination of many subsystems and services, smooth transition between failure and recovery can be the difference between operations that run for a long time and those that require frequent, in-person maintenance.

5.8.2.5 Emergency Action Plan

An EAP holds immense importance for a CMV fleet due to its role in managing cybersecurity incidents. In today's environment where cyber threats can disrupt operations, compromise data, and undermine safety, having a well-structured EAP is essential for the fleet's resilience. This strategy outlines a comprehensive plan for responding to cybersecurity incidents and breaches involving CMVs. Its significance lies in its ability to help fleet personnel navigate the challenges posed by cyber threats and minimize their impact on operations, safety, and reputation.

Developing an effective EAP requires a systematic approach that integrates various elements. First and foremost, the fleet needs to conduct a thorough risk assessment specific to its CMVs and operational context. This assessment identifies potential vulnerabilities, threat vectors, and areas of concern that might be targeted by cyber attackers. Stakeholder involvement is critical during this phase, encompassing fleet managers, drivers, IT professionals, and cybersecurity experts. Their collective insights and expertise provide a well-rounded understanding of the potential risks and appropriate response strategies.

The heart of the EAP lies in its documentation. The fleet should create a comprehensive plan that outlines procedures for different types of cybersecurity incidents. These procedures cover incident detection, escalation, containment, recovery, and communication protocols. By clearly defining these steps and the responsibilities of various personnel, the fleet can ensure a coordinated response, minimizing confusion and improving overall effectiveness.

A crucial aspect of EAP is its communication strategy. Timely and accurate communication is vital during cybersecurity incidents to prevent further damage and coordinate efforts. The plan should establish communication channels within the fleet and define how and when to communicate with external parties, such as technology vendors, law enforcement, regulatory authorities, and customers.

Training and awareness play a pivotal role in the successful implementation of the EAPs. Fleet personnel must be educated on the plan's details, their roles, and the actions they need to take during different incident scenarios. Conducting regular drills and exercises helps familiarize everyone with the EAP and enhances their ability to respond effectively during real incidents.

There is no panacea that solves all security problems, and the EAP is not a static document but a dynamic framework that requires regular review and updates. As technology evolves and new cyber threats emerge, the fleet should refine and adapt the plan to stay effective. Collaborating with cybersecurity experts, technology vendors, and industry associations can provide valuable insights into best practices and emerging trends. By systematically developing, implementing, and refining the EAP, the fleet demonstrates its commitment to cybersecurity preparedness, safeguarding its operations, reputation, and the trust of stakeholders in the ever-evolving landscape of digital threats.

5.8.2.6 Life Cycle

To maintain and continually improve cybersecurity, ADS will need to evolve through several clearly defined stages of its life cycle. These stages define different levels of severity in maintaining cybersecurity, from fairly low in early development to very high in customer deployment. During the development stage of an ADS, the focus is on building and refining its capabilities. In this stage, it is essential to lay the groundwork for cybersecurity. While free and open network and system communication may be necessary to facilitate development, implementing security policies in a well-controlled environment is also crucial. This early attention to security sets the stage for a secure future. As part of this stage, ADS developers should establish a framework for secure software updates. Even at this early stage, considering how updates will be securely delivered and verified is important.

As the ADS progresses to the testing stage, more stringent cybersecurity measures should be enforced. Access control should include certificate authentication for access, ensuring that only authorized personnel can make changes. Communication should occur through secure channels, such as a VPN, to protect data during transit. Additionally, an audit schedule should be established to monitor for any anomalies. This is also the stage where the communications critical to running the ADS are defined, and extraneous methods are blocked or removed. It is vital to implement testing and verification of software updates to ensure they do not compromise the system's security.

In the deployment stage, the ADS should be ready to operate autonomously with robust cybersecurity measures in place. Access should be tightly controlled, debugging ports should be closed (and possibly sealed), and unnecessary communication methods and wireless networks should remain disabled unless required for specific functions. Software updates are critical at this stage to address vulnerabilities and improve performance. The ADS should be capable of securely communicating updates to authorized parties, ensuring that its software remains up to date and resilient against emerging threats.

The service stage represents a period when the ADS might require maintenance or updates while in operation. Some previously disabled communications may need to be re-enabled for servicing purposes. This is where the importance of secure software updates becomes evident. If the ADS enters the service stage due to internal system issues, it should automatically return to the deployment stage after a successful audit and safety engineer approval. Regular service stages should also include software audits and testing to ensure the ADS's ongoing security.

The end-of-life stage is a critical consideration. Here, the ADS may be nearing obsolescence, making it vulnerable to cyberattacks due to discontinued support and security updates. Meanwhile, the regulatory and legal risks of using outdated operating systems can result in breach of contract, failure to meet industry standards, and a series of other liability issues.(301) It is essential to plan for the secure retirement of older ADS by building in safeguards, such as a maximum run-time limit, to ensure the systems do not operate without mandatory updates. This stage highlights the importance of secure software updates, even as ADS approach the end of their operational life.

5.8.2.7 CMV Fleet Expectations

As described above, good management practices with respect to authorized user accounts at a CMV fleet are critical. In addition, control and tracking of the physical access to the ADS-equipped truck are also important components in a CMV fleet's cybersecurity approach. It is critical that CMV fleets have the highest standards of security for all their networks. Regularly reviewing and updating the security systems is a simple and effective way to mitigate most threats.

Before deploying ADS technologies at a site, ADS developers should talk with the personnel at the CMV fleet partner to ensure that they understand the capabilities and the safety requirements for deploying an ADS. The devices the CMV fleet uses to control and supervise ADS-equipped trucks should only be used for this purpose. Other unapproved applications or functions should not be installed on the device without the approval of the ADS developer. As the device will need an internet connection to communicate with the ADS-equipped truck, the ADS developer might need to monitor this connection and block most other traffic. CMV fleets should not attempt to circumvent these restrictions, as they are in place to keep the ADS safe. Any device, whether personal or deployed, that connects with the ADS should not share access with unauthorized personnel. Using devices that are unprotected, unlocked, or unattended is akin to leaving the keys to the truck accessible to anyone.

5.8.3 Data Transfer/Security

Data resides in multiple states, including data in storage, data being processed, and data in transit. Data and information are vulnerable in all three states, and there are protective cybersecurity measures appropriate to each. In this section, we discuss protecting information in each of these states. We also discuss several information assurance measures, including data sharing rules, data logging, and data auditing.(302)

5.8.3.1 Data Storage

Data storage is a critical component of data security and cybersecurity for mixed CMV fleets. One fundamental practice is encryption at rest, which involves encrypting data before storing it in databases, servers, or storage devices.(303) This ensures that even if an attacker gains physical access to the storage, the data remains unreadable without the encryption key. Fleets should implement industry-standard encryption algorithms, like Advanced Encryption Standard 256 encryption, which is a symmetric encryption algorithm that uses a 256-bit key to convert plain text or data into a ciphertext.(304) While encryption is essential for data security, it is equally important to store encryption keys securely and restrict access only to authorized personnel.

Access control is another crucial aspect of data storage security. Preventing unauthorized individuals from accessing sensitive data is essential. Access control limits data access to those with a legitimate need for it, reducing the risk of data breaches. Implementing RBAC, as mentioned in section 5.8.3.2, is a common practice, where permissions are assigned based on job roles. Regularly reviewing and updating access privileges as job roles change is vital, as is monitoring and auditing access logs to detect and respond to unauthorized access attempts.

Secure backups are essential not only for data recovery in case of hardware failures or cyberattacks but also for data security. Securely storing backups in off-site locations or encrypted cloud storage protects against data breaches. Data retention policies, which define how long data should be stored and when it should be securely deleted, are critical for compliance with regulatory requirements. Developing clear data retention policies, automating data deletion processes, and regularly reviewing and updating these policies as regulations evolve ensures data is managed securely and compliantly.

Data masking or data anonymization techniques are essential for protecting sensitive data while maintaining its utility, especially in non-production environments or for testing purposes.(305) These techniques transform sensitive data so that it is of little or no interest to unauthorized users but still remains usable to those who need it. Secure disposal of data is equally important. When data is no longer needed, it must be securely disposed of to prevent data breaches. Data wiping or disk shredding methods are used to securely delete data from storage devices before disposal, and any decommissioned hardware must be thoroughly cleaned of sensitive data.

5.8.3.2 Data Processing

Data being processed by components of an ADS is also subject to multiple threats, including unauthorized access and modification, processing errors, and presence of unexpected software components. It involves several key practices aimed at maintaining data integrity, identifying anomalies, and safeguarding against cybersecurity threats.

One crucial practice is data validation. This involves implementing routines to validate and cleanse incoming data to ensure its accuracy and integrity. Doing so reduces the risk of malicious or erroneous data affecting fleet operations. Data validation routines check for inconsistencies, missing values, and outliers, ensuring that only reliable information is processed. This practice is particularly important when dealing with real-time data from various sources, such as vehicle sensor data.

Another essential practice is anomaly detection.(306) Anomaly detection algorithms are used to identify unusual patterns or behaviors in data. This is vital for promptly detecting potential cybersecurity threats or system malfunctions. By continuously monitoring data for deviations from expected norms, fleet operators can identify and respond to suspicious activities in real time. This proactive approach is essential for maintaining the data security and reliability of CMV fleets.

Furthermore, secure data processing includes a focus on secure APIs.(307) If data is shared through APIs, it needs to be protected with robust authentication mechanisms, rate limiting, and security tokens. API security ensures that data is exchanged securely between different systems and applications and prevents unauthorized access or tampering with data during transit. Fleet operators should also continuously monitor data processing pipelines for signs of unusual activity or unauthorized access. This includes setting up alerts and notifications to respond promptly to potential breaches or issues. Real-time monitoring not only helps detect cybersecurity threats but also ensures that the fleet operates smoothly and efficiently. Once again, logging, tagging with validating information, and performing audits pre and post processing can help identify whether modification or processing errors have occurred.

5.8.3.3 Data In Transit

Secure data transit practices are designed to safeguard information as it moves between vehicles, central systems, and external entities. One of the fundamental principles in this context is encrypted communication (e.g., Google[(308)]). Data in transit should always be encrypted using strong cryptographic protocols. Encryption ensures that data remains confidential and cannot be intercepted or tampered with by unauthorized parties. Secure Socket Layer and Transport Layer Security are commonly used encryption protocols for establishing secure connections.[(309)]

VPNs are important tools for ensuring secure data transit in CMV fleets. VPNs protect data as users interact with apps and web properties over the internet, and they can keep certain resources hidden.[(310)] This is particularly vital when CMV fleets need to transmit data over untrusted or public networks, such as the internet. VPNs establish a secure path for data to travel, ensuring its confidentiality and integrity throughout the process.

Meanwhile, secure APIs are also essential tools when facilitating secure communications within CMV fleet infrastructure. APIs (as mentioned in 5.8.4.2) enable the exchange of data between systems and applications. Secure API practices involve implementing strong authentication mechanisms, such as API tokens or Open Authorization (OAuth) tokens. Rate limiting and access controls are also essential to prevent misuse or unauthorized access. API security guarantees that data is exchanged securely, maintaining data integrity.

Certificate-based authentication serves as a robust means of verifying the identities of devices and users involved in data transit. Each device or user is issued a digital certificate, which is used to authenticate them during data exchange. This practice ensures that only trusted entities can access and transmit data. By employing certificate-based authentication, CMV fleets mitigate the risk of unauthorized access and data breaches.

To proactively monitor data transit for potential security incidents, CMV fleets should also deploy IDS/IPS. These systems continuously monitor network traffic for signs of unauthorized access or malicious activities.[(311)] When unusual patterns or threats are detected, IDS/IPS can trigger alerts or take preventive actions. This real-time monitoring helps safeguard data integrity and respond swiftly to potential cybersecurity threats.

5.8.3.4 Data Sharing Rules

Data sharing rules are established protocols and regulations that dictate how data is collected, stored, transmitted, and shared within a system or organization. These rules ensure that data is handled securely and responsibly, reducing the risk of unauthorized access, data breaches, and cyberattacks. By outlining clear guidelines for data sharing, mixed CMV fleets can enhance their overall cybersecurity posture, fostering a safer and more reliable transportation ecosystem.

Data collected from both automated and non-automated vehicles can include sensitive information about vehicle operations, passengers, and locations. To implement effective data sharing rules within mixed CMV fleets, a systematic approach is essential. Fleet operators should begin by defining clear guidelines for the types of data collected, who has access to it, and the purposes for which it will be used. They should collaborate with legal experts and relevant regulatory bodies to ensure compliance with privacy and cybersecurity regulations. Fleets should also develop a data classification system that categorizes data based on its sensitivity, allowing appropriate levels of access and protection.

Encryption plays an essential role in data security. Fleets will need to implement robust encryption protocols for data both at rest and in transit. This safeguards data from unauthorized access and tampering, even if a breach were to occur. Regularly updating encryption algorithms and methods will allow the fleet to stay ahead of emerging threats. They should also incorporate strict access controls to limit data access to authorized personnel only. Fleets should implement multifactor authentication for users accessing sensitive data to enhance verification processes and monitor data access and usage patterns to identify any suspicious activities promptly. Regular audits and assessments are crucial to ensuring ongoing compliance with data sharing rules, so stakeholders should conduct routine evaluations of data handling practices, security measures, and compliance with regulatory requirements. They should periodically review and update the data sharing rules to align with emerging threats and evolving technology. Lastly, fleet managers and operators should educate all stakeholders within the mixed CMV fleet ecosystem about the importance of data sharing rules and cybersecurity practices. Drivers, operators, fleet managers, and personnel should understand their roles in adhering to these rules and promoting a culture of responsible data handling.

5.8.3.5 Data Logging

All ADS-equipped vehicles engage in significant data logging, recording, and making notations to files of different types of events that happen in and around the vehicle. To promote security, the ADS should also keep track of system events, access to the system from any source (CAN, communication/data transfer network, local, etc.), and any potential hardware or software errors. Access to this type of logged data is important, as it can be used to pinpoint where, when, and by whom any setting was changed (in case an incident requires investigation). Besides knowing what happened after the fact, having a dedicated service for monitoring logs and looking for non-standard events can mitigate incidents proactively. Non-standard events could be anything from the system recognizing an object that does not belong in its operating environment to an intermittent loss of GPS signal or network connectivity. Thresholds set in a monitoring system can notify engineers and end users of developing issues and can prevent escalation of issues and potential unexpected downtime.

Log storage should be redundant to prevent any data loss or manipulation. Data backup standards, such as a centralized logging system,[(312)] will need to be implemented to maintain records of all actions at any particular site. To maintain the integrity of the log, any commands and operations performed by the ADS should be logged internally but should also notify at least two other devices installed at a site.

Copying the logs as often as possible into a mass storage solution, either in the cloud or at a data center, mitigates onboard storage problems and enables auditing of the ADS-equipped vehicles while deployed. Secured internet access is the fastest means of data transfer. When a secure internet connection is unavailable, the CMV fleet would need to support a local transfer of logs during regular service intervals (and before local storage capacity onboard the truck runs out).

5.8.3.6 Auditing

Auditing in data security is all about ensuring the confidentiality, integrity, and availability of data while identifying vulnerabilities, compliance issues, and potential security threats. Before the start of the auditing process, organizations must determine what data and systems will be audited, the goals of the audit (e.g., security assessment, compliance verification), and the specific criteria against which performance will be evaluated. Once the objectives and scope have been determined, one of the first areas assessed during an audit is data access and permissions. Auditors review who has access to data, the level of access they possess, and whether access rights are appropriately granted and revoked. Unauthorized or inappropriate access can lead to data breaches. Data encryption is another critical component of data security audits. Auditors evaluate whether encryption is used to protect sensitive data during transmission and while at rest. Proper implementation of encryption protocols and key management is vital for safeguarding data against unauthorized access.

During these audits, comprehensive logging and monitoring practices are thoroughly examined. Organizations should maintain detailed logs of data-related activities, system events, and user actions. Auditors ensure that logs are consistently generated, securely stored, and regularly reviewed for anomalies or security incidents. In parallel, auditing includes verifying that organizations have established and adhered to data retention policies. These policies define how long data should be stored and when it should be securely deleted, contributing to efficient data management and compliance.

Should a data security incident occur, an audit will assess incident response and recovery capabilities. Auditors evaluate an organization's preparedness to detect, respond to, and recover from incidents like breaches or data loss. Auditing also ensures compliance with regulatory requirements and relevant data security regulations. Furthermore, vulnerability assessment is one of the core components of auditing. Auditors identify potential weaknesses in data security, including software vulnerabilities, misconfigurations, and gaps in security controls. Remediation plans are often developed based on these findings. Employee training and awareness programs are evaluated to ensure that employees are educated about data security best practices. Awareness is key to ensuring that employees understand their roles and responsibilities in maintaining data security.

Lastly, auditing is not a one-time event but rather an ongoing process. Auditors recommend improvements and track the organization's progress in implementing security measures. Continuous improvement is vital to stay ahead of evolving security threats.

5.8.4 Specific Best Practices for Fleet Cybersecurity (Scenarios & Mitigation Strategies)

This section goes beyond generic cybersecurity advice to provide actionable insights for fleets. It focuses on fleet management-specific challenges to ensure the recommendations are directly applicable to stakeholder needs and operational scenarios. By highlighting specific attack scenarios, this section raises awareness of potential threats that fleet operators might not have considered.

5.8.4.1 Cyberattack Through Wireless Connections

Wireless Network Intrusion: Wireless network intrusion is a concerning scenario, as it can happen in seemingly innocuous locations. This type of intrusion refers to cyberattacks that target the wireless networks utilized within connected vehicle fleets. Attackers often target public Wi-Fi networks at rest stops, exploiting unsuspecting drivers and weak network security. Fleet operators need to prioritize the security of wireless connections, implement robust encryption, and educate drivers about the risks associated with connecting to unfamiliar networks, especially when the internet connection is free.

> Scenario: Attackers can infiltrate the fleet's wireless networks, including Wi-Fi and cellular connections, at various points such as rest stops or fuel stations. They may exploit weak security, steal credentials, and gain unauthorized access to fleet systems.
>
> Impact: Unauthorized access can lead to data theft, privacy leaks, manipulation of vehicle functions, or disruption of communication between vehicles and the control center.

Mitigation measures:

- Implement strong encryption protocols to protect data transmitted over wireless networks.
- Enforce strict access control policies to limit who can access the wireless network.
- Deploy IDS to continuously monitor network traffic for any suspicious activities or intrusion attempts.
- Keep network equipment, including routers, access points, and connected devices, up to date with the latest security patches and firmware updates.
- Isolate critical vehicle systems and data from less critical parts of the network.
- Provide cybersecurity training for fleet personnel to raise awareness of the risks associated with wireless network intrusion.
- Develop a comprehensive EAP to address network breaches promptly. This plan should include steps for identifying, containing, and mitigating security incidents.
- Ensure that third-party vendors responsible for providing network hardware and services adhere to strict security standards.

GPS Spoofing and Manipulation: GPS spoofing and manipulation can be more sophisticated than one might think. Attackers can disrupt entire supply chain routes by deceiving vehicles about their location. Ensuring the integrity of GPS data is crucial, and fleet operators should consider implementing GPS signal authentication mechanisms to detect and prevent spoofing.

> Scenario: Cybercriminals can manipulate GPS signals or spoof satellite signals to deceive fleet vehicles about their actual location.
>
> Impact: GPS manipulation can result in incorrect routing, lost cargo, unsafe driving conditions, operational inefficiencies, and financial losses.

Mitigation measures:

- Implement GPS signal authentication mechanisms to verify the authenticity of received GPS signals.
- Regularly perform integrity checks on GPS data to identify anomalies or inconsistencies that may indicate manipulation.
- Educate drivers about the possibility of GPS manipulation and instruct them on verifying routes manually when GPS information appears inaccurate.
- Utilize multiple data sources, such as onboard sensors and external mapping data, to cross-reference and validate GPS information.
- Consider integrating blockchain or tamper-evident technologies into GPS data storage and transmission to ensure the integrity of location data.
- Implement monitoring systems that can detect sudden and unexpected changes in vehicle positions and trigger alerts when inconsistencies are detected.
- Keep GPS navigation software and maps up-to-date with the latest versions to minimize vulnerabilities to known exploits.
- Secure GPS receivers and antennas to prevent physical tampering or unauthorized access.
- Ensure compliance with regulations related to location data accuracy, especially in industries with strict safety and compliance requirements.
- Collaborate with cybersecurity experts and organizations specializing in GPS security to stay informed about emerging threats and best practices.

Cargo Theft at Transfer Points: Cargo theft at transfer points is a cybersecurity scenario that involves cyberattacks targeting cargo tracking and monitoring systems at locations where goods are transferred, such as ports, warehouses, loading docks, and transfer hubs, which should be a serious concern for fleet management. Attackers exploit vulnerabilities in these systems to facilitate cargo theft. Fleet operators must enhance cybersecurity measures at cargo transfer points, employ robust access controls, and consider implementing blockchain or tamper-evident technologies to ensure cargo data integrity.

> Scenario: Cyberattacks can target cargo tracking and monitoring systems at ports, warehouses, or loading docks. Attackers may manipulate cargo data or disrupt tracking systems to facilitate cargo theft.
>
> Impact: Cargo theft can result in significant financial losses, disrupt supply chain operations, and erode trust between fleet operators, customers, and partners, potentially impacting future business relationships.

Mitigation measures:

- Implement strict access controls such as biometrics, access cards, or personal identification numbers at transfer points, limiting entry to authorized personnel only.

- Employ video surveillance and monitoring systems to oversee cargo transfer operations.
- Utilize advanced cargo tracking technologies, such as IoT devices and radio-frequency identification tags, to monitor cargo location and condition in real time.
- Employ tamper-evident packaging and security seals on cargo containers to detect unauthorized access or tampering during transit.
- Consider implementing blockchain technology in the supply chain to provide an immutable and transparent record of cargo movements.
- Conduct regular security audits and vulnerability assessments of transfer points to identify and address weaknesses in physical and digital security.
- Train personnel at transfer points on security protocols, recognizing suspicious behavior, and reporting incidents promptly.
- Collaborate with law enforcement agencies and local authorities to share information on cargo theft trends and facilitate investigations.
- Implement geofencing technology to create virtual perimeters around transfer points. Any movement of cargo outside of these boundaries can trigger alarms and alerts.
- Develop a comprehensive EAP specifically tailored to cargo theft incidents.

Remote Diagnostics Exploitation: Remote diagnostics exploitation refers to cyberattacks that target the wireless connections used for remote diagnostics and maintenance in connected vehicles. These connections enable vehicle manufacturers or fleet operators to access the vehicle's onboard systems and collect diagnostic data, allowing remote troubleshooting, maintenance, and performance monitoring. However, cybercriminals can exploit these connections for malicious purposes.

> Scenario: Attackers may exploit wireless connections used for remote diagnostics and maintenance. They can gain unauthorized access to vehicle systems, tamper with diagnostics, or disrupt critical maintenance procedures.
>
> Impact: Unauthorized access can compromise vehicle safety, lead to operational disruptions, and result in costly repairs.

Mitigation measures:

- Implement robust encryption and secure communication protocols to protect remote diagnostic connections from unauthorized access.
- Implement multifactor authentication for remote diagnostics access to enhance security. This ensures that only authorized personnel can access and control vehicle systems.
- Employ IDS to monitor network traffic and system behavior for any unusual or malicious activities.
- Require fleet personnel to receive training on recognizing and responding to potential cybersecurity threats related to remote diagnostics. They should be cautious about sharing access credentials and report any suspicious activities.

- Regularly update vehicle software and firmware to patch known vulnerabilities. This reduces the risk of exploitation through outdated software.
- Isolate remote diagnostics systems from critical vehicle control systems. This segmentation prevents attackers from moving laterally through the network if they gain access.

Telematics System Vulnerabilities: Telematics systems are the lifeblood of fleet management, providing critical insights into vehicle performance, location, and driver behavior. Safeguarding these systems is essential to maintain accurate data and operational efficiency. Employing data integrity checks and secure communication channels can mitigate this risk.

> Scenario: Fleet telematics systems, which provide real-time vehicle data, are susceptible to cyberattacks. Attackers can manipulate telematics data to provide false information about vehicle performance or location.
>
> Impact: False telematics data can lead to data manipulation, privacy leaks, misinformed decision-making, route deviations, and compromised safety.

Mitigation measures:

- Regularly update telematics system firmware and software to patch known vulnerabilities and improve security.
- Implement strong authentication mechanisms and access controls to ensure that only authorized users can access and manipulate telematics data.
- Encrypt telematics data during transmission and storage to protect it from interception and tampering.
- Incorporate the ability to revert to the prior firmware version if an over-the-air update fails or introduces vulnerabilities and use false injection mitigation methods such as redundant verification safeguards.[313]
- Deploy IDS to continuously monitor telematics system traffic for any suspicious activities or intrusion attempts.
- Use secure communication protocols to protect data transmitted between vehicles and the central control center.
- Provide cybersecurity training for personnel who interact with or manage telematics systems to raise awareness of potential risks and threats.
- Evaluate the security practices of telematics system vendors and choose vendors that prioritize cybersecurity.
- Isolate telematics systems from critical vehicle control systems to limit the potential impact of a breach.
- Develop an EAP specifically tailored to telematics system breaches. This plan should outline steps for identifying, containing, and mitigating security incidents.

- Ensure compliance with relevant data privacy and security regulations, especially in industries with strict safety and compliance requirements.

IoT Device Exploitation: IoT device exploitation involves cyberattacks that target the interconnected devices and sensors that are an integral part of connected vehicle fleets. These devices collect data on vehicle performance, environmental conditions, cargo condition, and driver behavior, providing valuable insights for fleet management, but they can be entry points for cyberattacks. Attackers exploit vulnerabilities in IoT devices to compromise data integrity or gain unauthorized access. Fleet operators should prioritize securing IoT devices through firmware updates, network segmentation, and regular vulnerability assessments.

> Scenario: Fleets often employ IoT devices for cargo tracking and monitoring. These devices can be targeted by attackers seeking to tamper with cargo data or disrupt the IoT network.
>
> Impact: Unauthorized access can lead to data manipulation, cargo mismanagement, operation delays, privacy concerns, and potential theft.

Mitigation measures:

- Regularly update IoT device firmware and software to patch known vulnerabilities and enhance security.
- Implement strong authentication mechanisms and access controls to ensure that only authorized users can access and manipulate IoT device data.
- Encrypt data transmitted by IoT devices to protect it from interception and tampering.
- Deploy IDS to continuously monitor network traffic involving IoT devices for any suspicious activities or intrusion attempts.
- Evaluate the security practices of IoT device vendors and select vendors that prioritize cybersecurity.
- Isolate IoT device networks from critical vehicle control systems to limit the potential impact of a breach.
- Provide cybersecurity training for personnel who interact with or manage IoT devices to raise awareness of potential risks and threats.
- Develop an EAP specifically tailored to IoT device breaches. This plan should outline steps for identifying, containing, and mitigating security incidents.
- Ensure compliance with relevant data privacy and security regulations, especially in industries with strict safety and compliance requirements.

5.8.4.2 Cyberattack Through Physical Connections

Physical cyberattacks involve malicious actions targeting connected vehicles and their systems when they are stationary, undergoing maintenance and repair, or making stops at various locations. Such attacks involve malicious actions targeting connected vehicles through physical connections. Attackers may exploit vulnerabilities in vehicle systems or access points to compromise data integrity, gain unauthorized control, or plant malware. The attack vectors encompass all the physical connections that could be established between the vehicle and an external attacker (direct access attacks[(314)]) using access points such as the on-board diagnostic (OBD) port, the USB and jack connections, and the vehicles' chargers.

Physical cyberattacks typically happen when the vehicle is stationary during events such as maintenance and repair, rest and fuel stops, cargo transfer at different locations, charging at electric charging station, and inspection at truck stops. Physical cyberattacks when the vehicle is not stationary are more challenging but not impossible, but the attack vector usually still revolves around gaining physical access to the vehicle's OBD port.

Maintenance and repair activities could be performed either by ADS vehicle operator personnel or a third party, but in any case, these activities may require establishing physical connection with the vehicle network, which brings the possibility of cyberattacks. Attackers exploit vulnerabilities in vehicle systems, diagnostic tools, or network connections to compromise data integrity, gain unauthorized control, or implant malware. In a collision, there may be damages to components responsible for protection against cyberattack, potentially leaving vulnerabilities that hackers could exploit.[(315)] In fact, NHTSA suggests considering the resilience of cybersecurity measures to crashes as a key component of CMV fleet security.[(316)] Routine maintenance is planned maintenance to the vehicle and system usually performed by a third party. These activities encompass a range of tasks such as inspections, diagnostics, tune-ups, and component replacements. Physical connections through the OBD-II port are often required during the operations.

With incidents during rest and fuel stops, if the attackers have identified the fleet's predefined rest stop locations and have access to the vehicle GPS data, they can arrive at a stop ahead of the fleet vehicles. They can potentially pose as a maintenance crew or a fellow driver to gain physical access to the vehicles; once they gain physical access to a vehicle, they can install a small malicious device within the vehicle's OBD port. Such devices usually contain a wireless transmitter and allow the attackers to capture sensitive data relating to the vehicle, the driver, and the cargo; it may even grant them remote access into the vehicle's systems to manipulate vehicle functions. Attacks can happen during cargo transfer at different locations and truck inspections at truck stops in similar structures. Attackers using this strategy usually start with knowledge preparation to get familiar with the fleet's schedule and predefined locations, using forged identification and impersonation to bypass security with different methods and different levels of social engineering tactics (as fellow driver, uniformed inspection officer, crew members, contracted workers, etc.), then physical installations through the vehicle's OBD port.

Electric vehicle (EV) battery management systems (BMS) within a mixed fleet require regular charging at charging stations to maintain their operational range. Charging stations are essential infrastructure for EVs, and fleet operators rely on them to keep their EVs powered. An attacker with knowledge of the fleet's EV charging schedules can potentially gain access to the infrastructure of commonly used charging stations during low-visibility hours along fleet routes, then install malicious hardware within the charging infrastructure with the intent to activate during fleet charging sessions. During charging, the attackers may manipulate charging parameters, such as voltage levels, to damage the BMS or gain access to sensitive data or vehicle functions.

Impact: These attacks can result in data tampering, vehicle damage, malware injection, operation disruption, cargo theft through cargo diversion, financial loss, and reputation damage.

Mitigation measures:

- Promote secure vehicle lockdown and physical security awareness; implement mechanisms to lock down vehicles during stops and train drivers and operational personnel to recognize suspicious activities and report potential security threats. Encourage personnel to lock the doors, secure the keys, and park the vehicle in secure locations.[(317)]
- Limit access to parked vehicles during rest stops and employ security personnel or surveillance systems to monitor the area; establish rigorous inspection procedures for vehicles during rest stops to detect and remove unauthorized devices.
- Isolate the diagnostic port (OBD) used to identify vehicle broken parts from the vehicle network via firewalls and/or gateway modules. It may be useful to isolate the vehicle bus(es).
- Disconnect the component(s) under repair from the vehicle network during service and reconnect only after services are completed.
- Identify and select reputable charging station providers and inspect stations for signs of tampering or unauthorized access.
- Train personnel to inspect hardware, vehicles, and infrastructure for signs of tampering or damage.
- Explore the option of blocking message transmissions between the OBD-II port and the vehicle network when third parties are present. One way to address this is by equipping fleet vehicles with mechanisms to detect attacks and implementing cryptographic solutions to monitor frame injection, allowing for remote security updates upon attack detection.[(318)] However, it is generally important that cybersecurity measures designed to safeguard data must ensure the integrity of vehicle maintenance procedures while concurrently monitoring non-maintenance-related information.
- Ensure that cybersecurity measures recover and are back to their nominal state, check for any compromised software, evaluate the integrity of cryptographic systems, and verify that communication channels remain secure.
- Implement robust physical security controls at maintenance and repair facilities, including surveillance, access control, and secure storage for diagnostic tools and software.
- Conduct regular security audits of maintenance facilities to identify vulnerabilities and weaknesses in physical security.
- Establish procedures to verify the integrity of diagnostic devices and software used during maintenance to detect unauthorized modifications.
- Ensure secure communication protocols are in place for transferring data between vehicles and maintenance facilities to safeguard data integrity during service operations.

- Develop a comprehensive EAP tailored to address physical cyberattacks during maintenance and repair. The plan should include procedures for identifying, containing, and mitigating security incidents.
- Evaluate the security practices of maintenance service providers and select vendors that prioritize cybersecurity and data protection.
- Ensure compliance with industry-specific regulations and standards related to cybersecurity and data privacy in the maintenance and repair process.

5.8.4.3 Customized Vehicle Parts from Third-party Providers

Customized vehicle parts from third-party providers can introduce both opportunities and risks for fleet management. Customized vehicle parts have had their design modified to meet the needs of the fleet owner or operator. These customized components are typically designed to enhance vehicle performance, functionality, or aesthetics. Security measures that applied to the original parts may no longer be effective protections for the custom design. Many customized vehicle parts include embedded software for functionality enhancements that may involve vulnerabilities in the software, which attackers could exploit to gain unauthorized access to the vehicle's systems or to introduce malware. In extreme cases, the provider may have knowingly introduced other threats. The supply chain for customized parts may introduce risks, as attackers can target the production or distribution process to inject malicious code or compromise the integrity of the components. Customized parts with communication modules, such as GPS trackers or telematics systems, may be susceptible to cyberattacks. Attackers could compromise these modules to intercept sensitive data or manipulate vehicle behavior. Cyber risk in the supply chain was one of the topics of a recent Presidential Executive Order on U.S. supply chains.[(319)]

Additionally, hardware interoperability is a necessity in the heavy-vehicle sector. Third-party parts may not seamlessly integrate with the existing vehicle software and systems, potentially leading to compatibility issues that cybercriminals could exploit to disrupt vehicle operations or compromise security. Heavy vehicle components often originate from various suppliers, which therefore necessitates cohesive system integration. SAE J1939, which specifies the communication network protocol, facilitates interoperability and flexibility among different components,[(320)] but further cybersecurity measures are necessary to accommodate this need for flexibility.

To mitigate cybersecurity risks from customized third-party parts, fleets should consider these measures:

- Prior to integrating third-party components, conduct thorough security assessments of the embedded software and communication modules. Look for vulnerabilities and work with providers to address any identified issues.
- Choose third-party providers with a strong commitment to cybersecurity. Verify that they follow best practices in software development, employ secure coding standards, and regularly update their software to patch known vulnerabilities.
- Test customized parts for compatibility with existing vehicle systems and software. Ensure that any integration does not introduce weaknesses that could be exploited.

- Stay vigilant about security updates and patches for customized components. Ensure that providers offer timely updates to address newly discovered vulnerabilities.
- Employ strong encryption protocols for data transmitted to and from customized parts with communication capabilities. Protect sensitive information from interception during transit.
- Implement strict access controls to limit who can interact with customized parts. Unauthorized access should be prevented through robust authentication and authorization mechanisms.
- Collaborate with providers to establish supply chain security measures. Verify the integrity of components at each stage of production and distribution to prevent tampering.
- Develop a comprehensive EAP specific to cybersecurity incidents involving customized parts. Clearly define procedures for detecting, containing, and mitigating cyber threats.
- Provide cybersecurity training to fleet personnel to raise awareness about the risks associated with customized components and how to recognize and report potential cyber threats.

These measures to mitigate risks from customized parts, or parts that have been modified, are part of the cybersecurity efforts to protect the supply chain, and it is essential that fleet owners and operators consider them as an integral part of their overall cybersecurity strategy.[(321)]

5.8.4.4 Specialized ADS Use Cases

There are many specialized use cases associated with ADS features. This subsection considers the cybersecurity needs of a few representative cases, including cooperative perception, teleoperation, platooning, and their testing and validation.

Cooperative Perception: Cooperative perception plays an important role in enhancing the safety and efficiency of mixed fleets, especially in the context of cybersecurity scenarios. It involves the exchange of sensing and perception data between ADS and infrastructure elements, such as control centers and roadway infrastructure, to improve situational awareness and reduce uncertainty. However, while cooperative perception offers substantial benefits, it also introduces potential cybersecurity risks that need careful consideration. As noted above, cybersecurity measures will need to address the cyber vulnerabilities that result from cooperative perception.[(322)]

One critical concern is the integrity of the shared data, as malicious actors may attempt to compromise it by injecting false information or manipulating sensor inputs, potentially leading to hazardous situations. Additionally, communication links enabling cooperative perception can be vulnerable to interception or tampering, exposing the data to unauthorized access and posing risks such as data leakage or eavesdropping. A 2022 study on cooperative perception and control supported infrastructure-vehicle systems pointed out the importance of requiring high-bandwidth communication without any delay when transmitting sensing data and ensuring the real-time performance and robustness of the perception and control methods.[(323)] This means the attackers could potentially introduce a noticeable delay or service lag in the network and cause damage to the hardware or software system, interrupt operations and the supply chain, cause personnel harm, or result in property, financial, and reputational loss.

Furthermore, the potential for denial-of-service attacks threatens the functionality of ADS by disrupting cooperative perception, while identity spoofing can allow attackers to impersonate infrastructure elements, giving them access to sensitive cooperative perception data or letting them manipulate traffic information, further exacerbating safety and security hazards.

To mitigate the cybersecurity risks associated with cooperative perception in mixed fleets, general cybersecurity best practices should be followed. Fleet operators and infrastructure providers should prioritize secure communication protocols, employing encryption and strong authentication mechanisms to safeguard data during transmission. Data authentication techniques, including digital signatures, can help verify data integrity and authenticity, preventing tampering or injection attacks. Additionally, deploying IDS to monitor communication channels for anomalies, enforcing access control measures, ensuring redundancy and diversity in data sources, and maintaining secure update procedures are vital steps to fortify cooperative perception security. Comprehensive EAP, cybersecurity training, regular security auditing, and regulatory compliance efforts round out a robust cybersecurity strategy, ensuring that cooperative perception continues to advance fleet safety while mitigating the associated cybersecurity risks.

Teleoperation: Teleoperation, in the context of mixed fleet management and the operation of connected and autonomous vehicles, refers to the remote control and supervision of vehicles by human operators. It is an ADS feature that includes several variants such as remote, collaborative, and fallback driving. All three examples of teleoperation require extensive information sharing and, as such, present significant cybersecurity challenges. In the case of remote driving, vehicle perception is shared with the remote driver, and the remote driver determines the vehicle responses (i.e., two-way communication). Collaborative driving involves sharing of the driving task, or performance of the DDT, between multiple agents and thus potentially requires multiple two-communication channels. Fallback driving occurs when the AV can no longer perform the DDT or when the ADS feature has exited its ODD. As with the previous two examples of teleoperation, fallback driving requires a minimum two-way communication between the vehicle and the fallback driver. All these examples depend critically on channels of communication; as such, teleoperation requires a cybersecurity analysis of the features of the broader system that includes the ADS-equipped CMVs and the teleoperator. Again, general cybersecurity best practices discussed in this report should be followed.

Platooning: "A platoon of connected automated vehicles is defined as a group of connected automated vehicles that exchange information, so that they can drive in a coordinated way, allowing very small spacings, and, still, traveling safely at relatively high speeds."(324) Platooning, or flocking, is an ADS feature involving two or more vehicles that coordinates the performance of the driving task of a platoon. The feature is meant to increase fuel efficiency and equipment utilization via an automated highway system. A connected AV is any ADS-equipped vehicle that communicates with other vehicles or infrastructure. The safe operation of platooning features depends critically on channels of communication and should be addressed by a cybersecurity analysis of the feature in the broader system that includes the group of ADS-equipped CMVs.

There are several cybersecurity concerns related to platooning. One is communication tampering, due to the fact that platooning relies heavily on V2V communication. Cyber attackers may attempt to tamper with these communications, altering the information exchanged between platoon vehicles. This can lead to misalignment or collisions within the platoon, compromising safety. Another concern is sensor manipulation; attackers may target the sensors of platoon vehicles, such as lidar, radar, or cameras, to provide false data. This could result in the platoon reacting inappropriately to its surroundings, potentially causing collisions or disrupting traffic flow. Access control breaching is yet another concern, where unauthorized access to the platooning system could lead to a cyber attacker taking control of one or more vehicles within the platoon. This scenario presents significant safety risks, as the attacker may manipulate the vehicles' behavior. The last concern is related to data and privacy leaks, which may include vehicle telemetry and position information or driver and fleet information. Protection of this data is essential to maintain the privacy of the fleet and the drivers. With the progression of automated driving and cooperative driving technology, the cybersecurity level of a platoon will advance simultaneously. However, since attackers can cause greater damage and disruption by gaining control access into a platoon than in a single CMV, higher cybersecurity levels and requirements should be emphasized for platoons.

General cybersecurity best practices should be followed for platooning as well, such as deploying an IDS, developing EAPs, secure communication protocols, secure over-the-air updates, employee cybersecurity training, security auditing, and enforcing access control. To conclude, platooning offers substantial advantages in mixed fleet management, but it also introduces cybersecurity scenarios that must be addressed. By implementing robust security measures, including secure communication, sensor redundancy, and access control, fleet operators can reap the benefits of platooning while minimizing the associated cybersecurity risks and ensuring the safety of their operations.

6. CONCLUSIONS AND DISCUSSION

This *Trucking Fleet Concept of Operations for Automated Driving System-equipped Commercial Motor Vehicles* project documents and describes the characteristics of the issues and challenges that trucking fleets encounter today when seeking to deploy high levels of automation on heavy truck tractors within their current freight operations. The CONOPS provides guidelines on how to safely implement and benefit from ADS-equipped trucks through (1) collecting and providing CMV fleets with practical information and data on how to integrate ADS-equipped trucks into their operations, (2) demonstrating the safe integration of ADS-equipped trucks into the U.S. freight transportation system, and (3) investigating public and stakeholder attitudes towards ADS-equipped trucks.

This project approached the fast-paced and constantly changing space of heavy vehicle automation by collecting, demonstrating, and sharing information and data in an iterative manner. This approach allowed the team to learn about innovations or challenges in one area of ADS-equipped CMVs that fed other areas. These findings were shared with the public. Feedback from the public in demos was fed back into the needs of the industry, which influenced the guidance being developed. Some examples of this collect-demo-share cycle from the project are discussed.

Early in the project, the team recognized that operations at ports could be an important use case to demonstrate. The entire supply chain is limited by human operations, typically due to hours-of-service. These limitations were magnified by the COVID-19 pandemic. During the port queueing demonstration, intermodal containers were delivered to a port in for-revenue operations. The collection of information and observations from that demonstration were shared at the TMC Roadshow. While this activity was happening, the research team collected information from the passengers that rode in the ADS-equipped CMV. They were asked what and where they would like to see automation deployed next. The two highest ranked use cases were trailer parking and intermodal yards. This suggested that lessons on controlled environment zones such as on ports and in yards would benefit the industry. The team acted on this by developing a demonstration and collecting data for ADS fleet integration at the Port of Whittier. The outcome of that demonstration and collection inside a port resulted in guidance to be shared for an automation domain where the industry requested more assistance.

The team also recognized that information and data on roadways captured in ADS-equipped CMV context was lacking and this information would be useful to public and private stakeholders. One operational use case for heavy trucks that has been broadly recognized is exit-to-exit highway operations, and this ODD was targeted for demonstration. Pronto, the ADS development partner, suggested roadway metrics they were capable of collecting, including lane line quality, road bumpiness, cellular signal strength, and GPS coverage. The data was then uploaded onto the CONOPS Dataverse, where it will remain available to be shared with the public. The data was then applied by partners at Texas Transportation Institute in the development of a concept road readiness assessment system. The guideline can be shared and applied by fleets to get a quick look at ADS deployment factors along their existing routes, by ADS developers to consider operation challenges and development planning, and by roadway managers looking for feedback from fleets and automation developers.

As illustrated by these examples, the research team pooled information from various sources to understand the state-of-practice on the integration of ADS technology into trucks. The team also conducted various outreach activities with the public and deployed ADS-equipped trucks on public roadways to measure the readiness of existing roadway infrastructure. This critical data was collected to inform stakeholders on preparing the roadway system for ADS technology. Hence, this CONOPS is not only for fleets but also for agencies looking to benefit from ADS.

Outreach allowed the research team to obtain insights into the public opinion on ADS technology, including their perception of its usefulness to the driving task, its effectiveness, safety, and its cost-effectiveness, all based on their knowledge of the technology. While the results were positive, as demonstrated during the roadshows activities conducted in this research, the team also observed that real-life demonstrations of the potential use cases of the technology further improved its perception and acceptance by the public. This indicates that there is need to improve existing public knowledge of ADS through showcasing its practical applications and enlightening both truck drivers and decision-makers on how this technology can improve their operations. Attendees of the outreach events, which included fleets, suppliers, government personnel, maintenance/analytics personnel, manufacturers, and inspection/law enforcement officers, were asked what ADS capability demonstration they would like to see in the future. Most of the responses include automated trailer parking, intermodal yard, truck platooning, lane keeping assist, exit-to-exit, teleoperation, and queuing operation. Agencies should work on providing these demonstrations to improve the perception and acceptance of ADS technology.

While studies have shown the potential benefits of ADS technology, the infrastructure needed to support the large-scale implementation of this technology is yet to be assessed. As a first step towards filling this gap, the research team deployed ADS-equipped trucks on select U.S. fleet routes to collect the infrastructure data (lane marking quality, communication signals, and geolocation signals) required to assess the readiness of the roadways on these routes to support ADS technology. Findings show that some roadway segments need to be equipped with the systems required to support ADS. Government agencies and decision-makers need to make investment decisions towards enhancing roadway infrastructure for ADS technology. The team also deployed ADS-equipped trucks for port operations. The idea behind the deployment was to test and refine the technology for a port ODD and observe its effectiveness under this condition. Insights were obtained and documented in this CONOPS to inform stakeholders. Further, guidelines on the integration of ADS technology into fleet operations were also researched and documented as part of this CONOPS. This includes best practices on the installation of ADS and components on existing trucks, the inspection of these components, insurance practices, data transfer and cybersecurity best practices, driver state monitoring, and the safety evaluation of ADS-equipped trucks.

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APPENDIX A: 49 CFR PART 396

§396.1 Scope.

(a) Every motor carrier, its officers, drivers, agents, representatives, and employees directly concerned with the inspection or maintenance of commercial motor vehicles must be knowledgeable of and comply with the rules of this part.

(b) Every intermodal equipment provider, its officers, agents, representatives, and employees directly concerned with the inspection or maintenance of intermodal equipment interchanged or offered for interchange to motor carriers must be knowledgeable of and comply with the rules of this part.

(c) This part does not apply to “covered farm vehicles,” as defined in 49 CFR 390.5, or to the drivers of such vehicles.

(d) The rules in this part do not apply to “pipeline welding trucks” as defined in 49 CFR 390.38(b).

§396.3 Inspection, repair, and maintenance.

(a) *General.* Every motor carrier and intermodal equipment provider must systematically inspect, repair, and maintain, or cause to be systematically inspected, repaired, and maintained, all motor vehicles and intermodal equipment subject to its control.

(1) Parts and accessories shall be in safe and proper operating condition at all times. These include those specified in part 393 of this subchapter and any additional parts and accessories which may affect safety of operation, including but not limited to, frame and frame assemblies, suspension systems, axles and attaching parts, wheels and rims, and steering systems.

(2) Pushout windows, emergency doors, and emergency door marking lights in buses shall be inspected at least every 90 days.

(b) *Required records.* Motor carriers, except for a private motor carrier of passengers (nonbusiness), must maintain, or cause to be maintained, records for each motor vehicle they control for 30 consecutive days. Intermodal equipment providers must maintain or cause to be maintained, records for each unit of intermodal equipment they tender or intend to tender to a motor carrier. These records must include:

(1) An identification of the vehicle including company number, if so marked, make, serial number, year, and tire size. In addition, if the motor vehicle is not owned by the motor carrier, the record shall identify the name of the person furnishing the vehicle;

(2) A means to indicate the nature and due date of the various inspection and maintenance operations to be performed;

(3) A record of inspection, repairs, and maintenance indicating their date and nature; and

(4) A record of tests conducted on pushout windows, emergency doors, and emergency door marking lights on buses.

(c) *Record retention.* The records required by this section shall be retained where the vehicle is either housed or maintained for a period of 1 year and for 6 months after the motor vehicle leaves the motor carrier's control.

§396.5 Lubrication.

Every motor carrier shall ensure that each motor vehicle subject to its control is—

(a) Properly lubricated; and

(b) Free of oil and grease leaks.

§396.7 Unsafe operations forbidden.

(a) *General.* A motor vehicle shall not be operated in such a condition as to likely cause an accident or a breakdown of the vehicle.

(b) *Exemption.* Any motor vehicle discovered to be in an unsafe condition while being operated on the highway may be continued in operation only to the nearest place where repairs can safely be effected. Such operation shall be conducted only if it is less hazardous to the public than to permit the vehicle to remain on the highway.

§396.9 Inspection of motor vehicles and intermodal equipment in operation.

(a) *Personnel authorized to perform inspections.* Every special agent of the FMCSA (as defined in appendix B to this subchapter) is authorized to enter upon and perform inspections of a motor carrier's vehicles in operation and intermodal equipment in operation.

(b) *Prescribed inspection report.* The Driver Vehicle Examination Report shall be used to record results of motor vehicle inspections and results of intermodal equipment inspections conducted by authorized FMCSA personnel.

(c) *Motor vehicles and intermodal equipment declared "out-of-service."* (1) Authorized personnel shall declare and mark "out-of-service" any motor vehicle or intermodal equipment which by reason of its mechanical condition or loading would likely cause an accident or a breakdown. An "Out-of-Service Vehicle" sticker shall be used to mark vehicles and intermodal equipment "out-of-service."

(2) No motor carrier or intermodal equipment provider shall require or permit any person to operate nor shall any person operate any motor vehicle or intermodal equipment declared and marked "out-of-service" until all repairs required by the "out-of-service notice" have been

satisfactorily completed. The term *operate* as used in this section shall include towing the vehicle or intermodal equipment, except that vehicles or intermodal equipment marked “out-of-service” may be towed away by means of a vehicle using a crane or hoist. A vehicle combination consisting of an emergency towing vehicle and an “out-of-service” vehicle shall not be operated unless such combination meets the performance requirements of this subchapter except for those conditions noted on the Driver Vehicle Examination Report.

(3) No person shall remove the “Out-of-Service Vehicle” sticker from any motor vehicle or intermodal equipment prior to completion of all repairs required by the “out-of-service notice.”

(d) *Motor carrier or intermodal equipment provider disposition.* (1) The driver of any motor vehicle, including a motor vehicle transporting intermodal equipment, who receives an inspection report shall deliver a copy to both the motor carrier operating the vehicle and the intermodal equipment provider upon his/her arrival at the next terminal or facility. If the driver is not scheduled to arrive at a terminal or facility of the motor carrier operating the vehicle or at a facility of the intermodal equipment provider within 24 hours, the driver shall immediately mail, fax, or otherwise transmit the report to the motor carrier and intermodal equipment provider.

(2) Motor carriers and intermodal equipment providers shall examine the report. Violations or defects noted thereon shall be corrected in accordance with §396.11(a)(3). Repairs of items of intermodal equipment placed out-of-service are also to be documented in the maintenance records for such equipment.

(3) Within 15 days following the date of the inspection, the motor carrier or intermodal equipment provider shall—

(i) Certify that all violations noted have been corrected by completing the “Signature of Carrier/Intermodal Equipment Provider Official, Title, and Date Signed” portions of the form; and

(ii) Return the completed roadside inspection form to the issuing agency at the address indicated on the form and retain a copy at the motor carrier's principal place of business, at the intermodal equipment provider's principal place of business, or where the vehicle is housed for 12 months from the date of the inspection.

§396.11 Driver vehicle inspection report(s).

(a) *Equipment provided by motor carrier.* (1) *Report required.* Every motor carrier shall require its drivers to report, and every driver shall prepare a report in writing at the completion of each day's work on each vehicle operated, except for intermodal equipment tendered by an intermodal equipment provider. The report shall cover at least the following parts and accessories:

(i) Service brakes including trailer brake connections;

(ii) Parking brake;

(iii) Steering mechanism;

(iv) Lighting devices and reflectors;

(v) Tires;

(vi) Horn;

(vii) Windshield wipers;

(viii) Rear vision mirrors;

(ix) Coupling devices;

(x) Wheels and rims;

(xi) Emergency equipment.

(2) *Report content.* (i) The report must identify the vehicle and list any defect or deficiency discovered by or reported to the driver which would affect the safety of operation of the vehicle or result in its mechanical breakdown. If a driver operates more than one vehicle during the day, a report must be prepared for each vehicle operated. Drivers are not required to prepare a report if no defect or deficiency is discovered by or reported to the driver.

(ii) The driver must sign the report. On two-driver operations, only one driver needs to sign the driver vehicle inspection report, provided both drivers agree as to the defects or deficiencies identified.

(3) *Corrective action.* (i) Prior to requiring or permitting a driver to operate a vehicle, every motor carrier or its agent shall repair any defect or deficiency listed on the driver vehicle inspection report which would be likely to affect the safety of operation of the vehicle.

(ii) Every motor carrier or its agent shall certify on the driver vehicle inspection report which lists any defect or deficiency that the defect or deficiency has been repaired or that repair is unnecessary before the vehicle is operated again.

(4) *Retention period for reports.* Every motor carrier shall maintain the driver vehicle inspection report, the certification of repairs, and the certification of the driver's review for three months from the date the written report was prepared.

(5) *Exceptions.* The rules in this section shall not apply to a private motor carrier of passengers (nonbusiness), a driveaway-towaway operation, or any motor carrier operating only one commercial motor vehicle.

(b) *Equipment provided by intermodal equipment provider.* (1) *Report required.* Every intermodal equipment provider must have a process to receive driver reports of, and each driver or motor carrier transporting intermodal equipment must report to the intermodal equipment provider or its designated agent, any known damage, defects, or deficiencies in the intermodal equipment at the time the equipment is returned to the provider or the provider's designated agent. The report must include, at a minimum, the following parts and accessories:

(i) Brakes;

(ii) Lighting devices, lamps, markers, and conspicuity marking material;

(iii) Wheels, rims, lugs, tires;

(iv) Air line connections, hoses, and couplers;

(v) King pin upper coupling device;

(vi) Rails or support frames;

(vii) Tie down bolsters;

(viii) Locking pins, clevises, clamps, or hooks;

(ix) Sliders or sliding frame lock.

(2) *Report content.* (i) Name of the motor carrier responsible for the operation of the intermodal equipment at the time the damage, defects, or deficiencies were discovered by, or reported to, the driver.

(ii) Motor carrier's USDOT number; intermodal equipment provider's USDOT number, and a unique identifying number for the item of intermodal equipment.

(iii) Date and time the report was submitted.

(iv) All damage, defects, or deficiencies of the intermodal equipment reported to the equipment provider and discovered by, or reported to, the motor carrier or its driver which would

(A) Affect the safety of operation of the intermodal equipment, or

(B) Result in its mechanical breakdown while transported on public roads.

(v) The signature of the driver who prepared the report.

(3) *Corrective action.* (i) Prior to allowing or permitting a motor carrier to transport a piece of intermodal equipment for which a motor carrier or driver has submitted a report about damage, defects or deficiencies, each intermodal equipment provider or its agent must repair the reported damage, defects, or deficiencies that are likely to affect the safety of operation of the vehicle.

(ii) Each intermodal equipment provider or its agent must certify on the original driver's report which lists any damage, defects, or deficiencies of the intermodal equipment that the reported damage, defects, or deficiencies have been repaired, or that repair is unnecessary, before the vehicle is operated again.

(4) *Retention period for reports.* Each intermodal equipment provider must maintain all documentation required by this section, including the driver report and the certification of repairs on all intermodal equipment, for a period of three months from the date that a motor carrier or its driver submits the report to the intermodal equipment provider or its agent.

§396.12 Procedures for intermodal equipment providers to accept reports required by §390.42(b) of this chapter.

(a) *System for reports.* Each intermodal equipment provider must establish a system for motor carriers and drivers to report to it any damage, defects, or deficiencies of intermodal equipment discovered by, or reported to, the motor carrier or driver which would—

(1) Affect the safety of operation of the intermodal equipment, or

(2) Result in its mechanical breakdown while transported on public roads.

(b) *Report content.* The system required by paragraph (a) of this section must include documentation of all of the following:

(1) Name of the motor carrier responsible for the operation of the intermodal equipment at the time the damage, defects, or deficiencies were discovered by, or reported to, the driver.

(2) Motor carrier's USDOT number; intermodal equipment provider's USDOT number, and a unique identifying number for the item of intermodal equipment.

(3) Date and time the report was submitted.

(4) All damage, defects, or deficiencies of the intermodal equipment must be reported to the equipment provider by the motor carrier or its driver. If no defect or deficiency in the intermodal equipment is discovered by or reported to the driver, no written report is required.

(5) The signature of the driver who prepared the report.

(c) *Corrective action.* (1) Prior to allowing or permitting a motor carrier to transport a piece of intermodal equipment for which a motor carrier or driver has submitted a report about damage, defects or deficiencies, each intermodal equipment provider or its agent must repair the reported damage, defects, or deficiencies that are likely to affect the safety of operation of the vehicle.

(2) Each intermodal equipment provider or its agent must certify on the original driver's report which lists any damage, defects, or deficiencies of the intermodal equipment that the

reported damage, defects, or deficiencies have been repaired, or that repair is unnecessary, before the vehicle is operated again.

(d) *Retention period for reports.* Each intermodal equipment provider must maintain all documentation required by this section, including the driver report and the certification of repairs on all intermodal equipment, for a period of three months from the date that a motor carrier or its driver submits the report to the intermodal equipment provider or its agent.

§396.13 Driver inspection.

Before driving a motor vehicle, the driver shall:

(a) Be satisfied that the motor vehicle is in safe operating condition;

(b) Review the last driver vehicle inspection report if required by §396.11(a)(2)(i); and

(c) Sign the report to acknowledge that the driver has reviewed it and that there is a certification that the required repairs have been performed. The signature requirement does not apply to listed defects on a towed unit which is no longer part of the vehicle combination.

§396.15 Driveaway-towaway operations and inspections.

(a) *General.* Every motor carrier, with respect to motor vehicles engaged in driveaway-towaway operations, shall comply with the requirements of this part. Exception: Maintenance records required by §396.3, the vehicle inspection report required by §396.11, and the periodic inspection required by §396.17 of this part shall not be required for any vehicle which is part of the shipment being delivered.

(b) *Pre-trip inspection.* Before the beginning of any driveaway-towaway operation of motor vehicles in combination, the motor carrier shall make a careful inspection and test to ascertain that:

(1) The tow-bar or saddle-mount connections are properly secured to the towed and towing vehicle;

(2) They function adequately without cramping or binding of any of the parts; and

(3) The towed motor vehicle follows substantially in the path of the towing vehicle without whipping or swerving.

(c) *Post-trip inspection.* Motor carriers shall maintain practices to ensure that following completion of any trip in driveaway-towaway operation of motor vehicles in combination, and before they are used again, the tow-bars and saddle-mounts are disassembled and inspected for worn, bent, cracked, broken, or missing parts. Before reuse, suitable repair or replacement shall be made of any defective parts and the devices shall be properly reassembled.

§396.17 Periodic inspection.

(a) Every commercial motor vehicle must be inspected as required by this section. The inspection must include, at a minimum, the parts and accessories set forth in appendix G of this subchapter. The term *commercial motor vehicle* includes each vehicle in a combination vehicle. For example, for a tractor semitrailer, full trailer combination, the tractor, semitrailer, and the full trailer (including the converter dolly if so equipped) must each be inspected.

(b) Except as provided in §396.23 and this paragraph, motor carriers must inspect or cause to be inspected all motor vehicles subject to their control. Intermodal equipment providers must inspect or cause to be inspected intermodal equipment that is interchanged or intended for interchange to motor carriers in intermodal transportation.

(c) A motor carrier must not use a commercial motor vehicle, and an intermodal equipment provider must not tender equipment to a motor carrier for interchange, unless each component identified in appendix G of this subchapter has passed an inspection in accordance with the terms of this section at least once during the preceding 12 months and documentation of such inspection is on the vehicle. The documentation may be:

(1) The inspection report prepared in accordance with §396.21(a), or

(2) Other forms of documentation, based on the inspection report (e.g., sticker or decal), which contains the following information:

(i) The date of inspection;

(ii) Name and address of the motor carrier, intermodal equipment provider, or other entity where the inspection report is maintained;

(iii) Information uniquely identifying the vehicle inspected if not clearly marked on the motor vehicle; and

(iv) A certification that the vehicle has passed an inspection in accordance with §396.17.

(d) A motor carrier may perform the required annual inspection for vehicles under the carrier's control which are not subject to an inspection under §396.23(a)(1). An intermodal equipment provider may perform the required annual inspection for intermodal equipment interchanged or intended for interchange to motor carriers that are not subject to an inspection under §396.23(a)(1).

(e) In lieu of the self-inspection provided for in paragraph (d) of this section, a motor carrier or intermodal equipment provider responsible for the inspection may choose to have a commercial garage, fleet leasing company, truck stop, or other similar commercial business perform the inspection as its agent, provided that business operates and maintains facilities appropriate for commercial vehicle inspections and it employs qualified inspectors, as required by §396.19.

(f) Vehicles passing periodic inspections performed under the auspices of any State government or equivalent jurisdiction in the Canadian Provinces, the Yukon Territory, and Mexico, meeting the minimum standards contained in appendix G of this subchapter, will be considered to have met the requirements of an annual inspection for a period of 12 months commencing from the last day of the month in which the inspection was performed.

(g) It is the responsibility of the motor carrier or intermodal equipment provider to ensure that all parts and accessories on commercial motor vehicles intended for use in interstate commerce for which they are responsible are maintained at, or promptly repaired to, the minimum standards set forth in appendix G to this subchapter.

(h) Failure to perform properly the annual inspection required by this section shall cause the motor carrier or intermodal equipment provider to be subject to the penalty provisions of 49 U.S.C. 521(b).

§396.19 Inspector qualifications.

(a) Motor carriers and intermodal equipment providers must ensure that individuals performing annual inspections under §396.17(d) or (e) are qualified as follows:

(1) Understand the inspection criteria set forth in part 393 and appendix G of this subchapter and can identify defective components;

(2) Are knowledgeable of and have mastered the methods, procedures, tools and equipment used when performing an inspection; and

(3) Are capable of performing an inspection by reason of experience, training, or both as follows:

(i) Successfully completed a Federal-or State-sponsored training program or have a certificate from a State or Canadian Province that qualifies the individuals to perform commercial motor vehicle safety inspections, or

(ii) Have a combination of training or experience totaling at least 1 year. Such training or experience may consist of:

(A) Participation in a commercial motor vehicle manufacturer-sponsored training program or similar commercial training program designed to train students in commercial motor vehicle operation and maintenance;

(B) Experience as a mechanic or inspector in a motor carrier or intermodal equipment maintenance program;

(C) Experience as a mechanic or inspector in commercial motor vehicle maintenance at a commercial garage, fleet leasing company, or similar facility; or

(D) Experience as a commercial motor vehicle inspector for a State, Provincial or Federal government.

(b) Motor carriers and intermodal equipment providers must retain evidence of that individual's qualifications under this section. They must retain this evidence for the period during which that individual is performing annual motor vehicle inspections for the motor carrier or intermodal equipment provider, and for one year thereafter. However, motor carriers and intermodal equipment providers do not have to maintain documentation of inspector qualifications for those inspections performed as part of a State periodic inspection program.

§396.21 Periodic inspection recordkeeping requirements.

(a) The qualified inspector performing the inspection shall prepare a report that:

(1) Identifies the individual performing the inspection;

(2) Identifies the motor carrier operating the vehicle or intermodal equipment provider intending to interchange the vehicle to a motor carrier;

(3) Identifies the date of the inspection;

(4) Identifies the vehicle inspected;

(5) Identifies the vehicle components inspected and describes the results of the inspection, including the identification of those components not meeting the minimum standards set forth in appendix G to this subchapter; and

(6) Certifies the accuracy and completeness of the inspection as complying with all the requirements of this section.

(b)(1) The original or a copy of the inspection report shall be retained by the motor carrier, intermodal equipment provider, or other entity that is responsible for the inspection for a period of fourteen months from the date of the inspection report. The original or a copy of the inspection report must be retained where the vehicle is either housed or maintained.

(2) The original or a copy of the inspection report must be available for inspection upon demand of an authorized Federal, State or local official.

(3) *Exception.* If the motor carrier operating the commercial motor vehicles did not perform the commercial motor vehicle's last annual inspection, or if an intermodal equipment provider did not itself perform the annual inspection on equipment intended for interchange to a motor carrier, the motor carrier or intermodal equipment provider is responsible for obtaining the original or a copy of the last annual inspection report upon demand of an authorized Federal, State, or local official.

§396.23 Equivalent to periodic inspection.

(a)(1) If a commercial motor vehicle is subject to a mandatory inspection program that is determined by the Administrator to be as effective as §396.17, the motor carrier or intermodal equipment provider must meet the requirement of §396.17 through that inspection program. Commercial motor vehicle inspections may be conducted by government personnel, at commercial facilities authorized by a State government or equivalent jurisdiction in the Canadian Provinces, the Yukon Territory, or Mexico, or by the motor carrier or intermodal equipment provider itself under the auspices of a self-inspection program authorized by a State government or equivalent jurisdiction in the Canadian Provinces, the Yukon Territory, or Mexico.

(2) Should FMCSA determine that an inspection program, in whole or in part, is not as effective as §396.17, the motor carrier or intermodal equipment provider must ensure that the periodic inspection required by §396.17 is performed on all commercial motor vehicles under its control in a manner specified in §396.17.

(b) [Reserved]

§396.25 Qualifications of brake inspectors.

(a) Motor carriers and intermodal equipment providers must ensure that all inspections, maintenance, repairs or service to the brakes of its commercial motor vehicles, are performed in compliance with the requirements of this section.

(b) For purposes of this section, *brake inspector* means any employee of a motor carrier or intermodal equipment provider who is responsible for ensuring that all brake inspections, maintenance, service, or repairs to any commercial motor vehicle, subject to the motor carrier's or intermodal equipment provider's control, meet the applicable Federal standards.

(c) No motor carrier or intermodal equipment provider may require or permit any employee who does not meet the minimum brake inspector qualifications of paragraph (d) of this section to be responsible for the inspection, maintenance, service or repairs of any brakes on its commercial motor vehicles.

(d) The motor carrier or intermodal equipment provider must ensure that each brake inspector is qualified as follows:

(1) Understands the brake service or inspection task to be accomplished and can perform that task; and

(2) Is knowledgeable of and has mastered the methods, procedures, tools and equipment used when performing an assigned brake service or inspection task; and

(3) Is capable of performing the assigned brake service or inspection by reason of experience, training, or both as follows:

(i) Has successfully completed an apprenticeship program sponsored by a State, a Canadian Province, a Federal agency or a labor union, or a training program approved by a State, Provincial or Federal agency, or has a certificate from a State or Canadian Province that qualifies the person to perform the assigned brake service or inspection task (including passage of Commercial Driver's License air brake tests in the case of a brake inspection); or

(ii) Has brake-related training or experience or a combination thereof totaling at least one year. Such training or experience may consist of:

(A) Participation in a training program sponsored by a brake or vehicle manufacturer or similar commercial training program designed to train students in brake maintenance or inspection similar to the assigned brake service or inspection tasks; or

(B) Experience performing brake maintenance or inspection similar to the assigned brake service or inspection task in a motor carrier or intermodal equipment provider maintenance program; or

(C) Experience performing brake maintenance or inspection similar to the assigned brake service or inspection task at a commercial garage, fleet leasing company, or similar facility.

(e) No motor carrier or intermodal equipment provider may employ any person as a brake inspector unless the evidence of the inspector's qualifications, required under this section, is maintained by the motor carrier or intermodal equipment provider at its principal place of business, or at the location at which the brake inspector is employed. The evidence must be maintained for the period during which the brake inspector is employed in that capacity and for one year thereafter. However, motor carriers and intermodal equipment providers do not have to maintain evidence of qualifications to inspect air brake systems for such inspections performed by persons who have passed the air brake knowledge and skills test for a Commercial Driver's License.

APPENDIX B: INTERSTATE HIGHWAYS ON WHICH DATA WERE COLLECTED IN CROSS-COUNTRY DRIVES

State	Route	Direction	From	To	Approximate Road Length (mi)
Trip 1: Cross-Country Circular Loop					
California	I-80	EB	University Ave (Berkeley)	Nevada State Line	194
Nevada	I-80	EB	California State Line	Utah State Line	411
Utah	I-80	EB	Nevada State Line	Wyoming State Line	198
Wyoming	I-80	EB	Utah State Line	Nebraska State Line	403
Nebraska	I-80	EB	Wyoming State Line	Iowa State Line	455
Iowa	I-80	EB	Nebraska State Line	Illinois State Line	307
Illinois	I-80	EB	Iowa State Line	Indiana State Line	164
Indiana	I-80	EB	Illinois State Line	Ohio State Line	151
Indiana	I-69	SB	IN 37 (Fishers)	I-465 (Indianapolis NE)	5
Indiana	I-465	WB	I-69 (Indianapolis NE)	US 31 (Carmel)	6
Ohio	I-80	EB	Indiana State Line	Pennsylvania State Line	237
Pennsylvania	I-80	EB	Ohio State Line	New Jersey State Line	311
New Jersey	I-80	EB	Pennsylvania State Line	I-95 (Teaneck)	68
New Jersey	I-95	SB	I-80 (Teaneck)	NJ Turnpike Exit 15 (Newark)	12
New Jersey	I-78	WB	NJ 139 (Hoboken)	I-95/NJ Turnpike Exit 14 (Newark)	8
New Jersey	I-95	SB	I-78/New Jersey Turnpike Exit 14 (Newark)	NJ Turnpike Exit 6 (Mansfield)	54
New Jersey	I-295	SB	NJ Turnpike Exit 2 (Carneys Point)	Delaware State Line	2
Delaware	I-295	SB	New Jersey State Line	I-95 (Newport)	6
Delaware	I-95	SB	I-295 (Newport)	Maryland State Line	12
Maryland	I-95	SB	Delaware State Line	Virginia State Line	109
Virginia	I-95	SB	Maryland State Line	North Carolina State Line	178
North Carolina	I-95	SB	Virginia State Line	South Carolina State Line	181
South Carolina	I-95	SB	North Carolina State Line	Georgia State Line	199
Georgia	I-95	SB	South Carolina State Line	Florida State Line	112
Florida	I-95	SB	Georgia State Line	I-295 (Jacksonville N)	20
Florida	I-295	SB	I-95 (Jacksonville N)	I-10 (Jacksonville W)	14
Florida	I-10	WB	I-295 (Jacksonville W)	Alabama State Line	357
Alabama	I-10	WB	Florida State Line	Mississippi State Line	66
Mississippi	I-10	WB	Alabama State Line	Louisiana State Line	77
Louisiana	I-10	WB	Mississippi State Line	Texas State Line	274
Texas	I-10	WB	Louisiana State Line	New Mexico State Line	877

New Mexico	I-10	WB	Texas State Line	Arizona State Line	164
Arizona	I-10	WB	New Mexico State Line	California State Line	392
California	I-10	WB	Arizona State Line	CA 210 (Redlands)	166
California	I-210	WB	CA 210 (Glendora)	I-5 (Los Angeles N)	45
California	I-5	NB	I-210 (Los Angeles N)	I-580 (Tracy S)	286
California	I-580	WB	I-5 (Tracy S)	I-238 (Castro Valley)	47
California	I-238	WB	I-580 (Castro Valley)	I-880 (San Leandro)	2
California	I-880	EB	I-238 (San Leandro)	I-80 (Oakland N)	15
Trip 2: San Francisco-Texas-San Francisco					
California	I-40	EB	I-40BL/Needles Hwy (Needles)	Arizona State Line	14
Arizona	I-40	EB	California State Line	1 mi E of Road 7380/Pinta Rd	320
New Mexico	I-40	EB	NM 45 (Albuquerque)	Texas State Line	218
Texas	I-40	EB	New Mexico State Line	US 287 (Amarillo E)	78
Texas	I-35W	SB	US 287 (Fort Worth N)	US 287 (Fort Worth S)	10
Texas	I-820	SB	US 287 (Fort Worth SE)	I-20 (Forth Worth SE)	2
Texas	I-20	EB	I-820 (Fort Worth SE)	US 175 (Balch Springs)	38
Texas	I-635	NB/WB	I-20 (Balch Springs)	I-35E (Dallas N)	28
Texas	I-35E	NB	I-635 (Dallas N)	I-35 (Denton)	28
Texas	I-35	NB	I-35E (Denton)	Oklahoma State Line	36
Oklahoma	I-35	NB	Texas State Line	I-40 (Oklahoma City)	127
Oklahoma	I-40	WB	I-35 (Oklahoma City)	Texas State Line	151
Texas	I-40	WB	Oklahoma State Line	TX 335 (Amarillo E)	101
California	I-15	SB	I-40 (Barstow E)	CA 58 (Barstow W)	4
California	I-5	NB	CA 58 (Buttonwillow)	5.32 mi N of CA 33 north junction	97
Trip 3: Calgary to San Francisco					
Idaho	I-90	WB	US 95 (Coeur d'Alene)	Washington State Line	12
Washington	I-90	WB	Idaho State Line	US 395 (Ritzville)	261
Washington	I-182	WB	US 395 (Pasco N)	US 395 (Pasco W)	2
Washington	I-82	EB	US 395 (Kennewick S)	Oregon State Line	20
Oregon	I-82	EB	Washington State Line	I-84 (Hermiston SW)	11
Oregon	I-84	WB	I-82 (Hermiston SW)	US 97 (Riggs Junction)	74
California	I-5	SB	US 97 (Weed)	I-505 (Dunnigan SE)	195
California	I-505	SB	I-5 (Dunnigan SE)	I-80 (Vacaville)	33
California	I-80	WB	I-505 (Vacaville)	I-580 (Oakland N)	48
Trip 4: San Francisco-Orlando-San Francisco					
California	I-580	EB	I-80 (Oakland N)	I-5 (Tracy S)	63
California	I-5	SB	I-580 (Tracy S)	CA 58 (Buttonwillow)	189
California	I-15	NB	CA 58 (Barstow W)	I-40 (Barstow E)	4
California	I-40	EB	I-15 (Barstow E)	Arizona State Line	155
Arizona	I-40	EB	California State Line	New Mexico State Line	359
New Mexico	I-40	EB	Arizona State Line	Texas State Line	373
Texas	I-40	EB	New Mexico State Line	US 287 (Amarillo E)	78

Texas	I-44	WB	US 287 (Wichita Falls N)	US 277/281/287 (Wichita Falls)	3
Texas	I-35W	SB	US 287 (Fort Worth N)	US 287 (Fort Worth S)	10
Texas	I-820	SB	US 287 (Fort Worth SE)	I-20 (Forth Worth SE)	2
Texas	I-20	EB	I-820 (Fort Worth SE)	Louisiana State Line	194
Louisiana	I-20	EB	Texas State Line	Mississippi State Line	190
Mississippi	I-20	EB	Louisiana State Line	US 49 (Jackson S)	47
Mississippi	I-59	SB	US 49 (Hattiesburg NW)	US 98 (Hattiesburg SW)	9
Alabama	I-65	SB	US 98 (Mobile NW)	I-10 (Mobile)	6
Alabama	I-10	EB	I-65 (Mobile)	Florida State Line	46
Florida	I-10	EB	Alabama State Line	I-295 (Jacksonville W)	357
Florida	I-295	NB	I-10 (Jacksonville W)	US 1/23 (Jacksonville NW)	7
Florida	I-95	NB	FL 111 (Jacksonville N)	FL 105 (Jacksonville N)	1
Florida	I-295	SB	FL 105 (Jacksonville N)	FL 9B (Jacksonville S)	16
Florida	I-95	SB	FL 9B (Jacksonville S)	I-4 (Daytona Beach)	73
Florida	I-4	WB	I-95 (Daytona Beach)	FL 528 (Orlando)	61
Florida	I-4	EB	FL 435 (Orlando)	I-95 (Daytona Beach)	57
Florida	I-95	NB	I-4 (Daytona Beach)	FL 9B (Jacksonville S)	73
Florida	I-295	NB	FL 9B (Jacksonville S)	FL 105 (Jacksonville N)	16
Florida	I-295	NB/WB/SB	FL 105 (Jacksonville N)	I-10 (Jacksonville W)	21
Florida	I-10	WB	I-295 (Jacksonville W)	Alabama State Line	357
Alabama	I-10	WB	Florida State Line	Mississippi State Line	66
Mississippi	I-10	WB	Alabama State Line	MS 15 (Biloxi N)	30
Mississippi	I-59	NB	US 98 (Hattiesburg SW)	US 49 (Hattiesburg NW)	9
Mississippi	I-20	WB	US 49 (Jackson S)	Louisiana State Line	47
Louisiana	I-20	WB	Mississippi State Line	Texas State Line	190
Texas	I-20	WB	Louisiana State Line	I-10 (Kent E)	636
Texas	I-10	WB	I-20 (Kent E)	New Mexico State Line	187
New Mexico	I-10	WB	Texas State Line	Arizona State Line	164
Arizona	I-10	WB	New Mexico State Line	California State Line	392
California	I-10	WB	Arizona State Line	CA 210 (Redlands)	166
California	I-210	WB	CA 210 (Glendora)	I-5 (Los Angeles N)	45
California	I-5	NB	I-210 (Los Angeles N)	CA 99 (Wheeler Ridge)	60
Trip 5: San Francisco-Montana-San Francisco					
California	I-580	WB	Cutting Blvd/Harbor Way (Richmond)	Canal Blvd (Richmond)	1
California	I-80	EB	Hilltop Dr (Richmond)	I-505 (Vacaville)	37
California	I-505	NB	I-80 (Vacaville)	I-5 (Dunnigan SE)	33
California	I-5	NB	I-505 (Dunnigan SE)	Liberal Ave (Corning S)	75
Oregon	I-5	NB	Garfield St/Highland Dr (Medford S)	Old Stage Rd (Gold Hill)	17
Oregon	I-5	NB	Edenbower Blvd (Roseburg)	OR 217 (Tigard/Lake Oswego)	166
Oregon	I-405	NB	US 26 (Portland)	I-5 north junction (Portland)	3
Oregon	I-5	NB	I-405 north junction (Portland)	Washington State Line	5

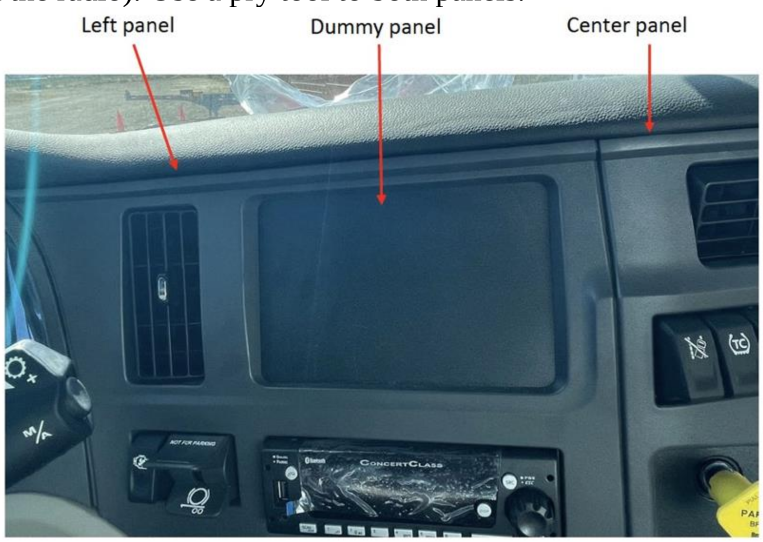
Washington	I-5	NB	Oregon State Line	WA 520 (Seattle)	168
Montana	I-15	NB	Harrison Ave (Butte)	I-90 east junction (Butte E)	2
Montana	I-90	EB	I-15 east junction (Butte E)	Wyoming State Line	329
Wyoming	I-90	EB	Montana State Line	I-90 BL (Buffalo N)	56
Wyoming	I-25	SB	I-25 BL (Buffalo SE)	0.59 mi E of Beverly St (Casper)	112
Wyoming	I-25	NB	0.59 mi E of Beverly St (Casper)	US 20/26 (Casper)	1
Wyoming	I-80	WB	I-89BL (Rawlins E)	Utah State Line	216
Utah	I-80	WB	Wyoming State Line	I-15 south junction (Salt Lake City)	74
Utah	I-15	SB	I-80 south junction (Salt Lake City)	Arizona State Line	305
Arizona	I-15	SB	Utah State Line	Nevada State Line	29
Nevada	I-15	SB	Arizona State Line	California State Line	124
California	I-15	SB	Nevada State Line	CA 58 (Barstow)	116
California	I-5	NB	CA 119 (Buttonwillow S)	I-580 (Tracy S)	202
California	I-580	WB	I-5 (Tracy S)	I-238 (Castro Valley)	47
California	I-238	WB	I-580 (Castro Valley)	I-880 (San Leandro)	2
California	I-880	WB	I-238 (San Leandro)	I-80 (Oakland N)	15
California	I-80	EB	I-880 (Oakland N)	I-580 north junction (Albany)	5
California	I-580	WB	I-80 north junction (Albany)	Cutting Blvd/Harbor Way (Richmond)	4

NOTE: Gaps in coverage by ADS-acquired data may be present along these roads where the truck collecting the data left the road to reach food, fuel, and hotel facilities; traveled through work zones involving a median crossover; utilized rest areas or weigh stations; or for other reasons.

APPENDIX C: PORT ADS INSTALLATION GUIDES

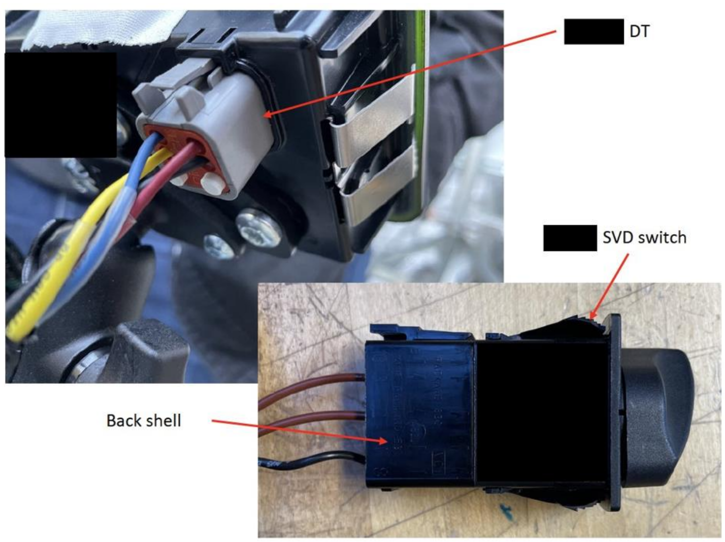
UI & Internal SVD Installation

1. Prep all parts and tools.
    - Consult the part and tool lists to ensure that everything is accounted for before starting work.
2. Run the cables.
    - This step should already have been completed. If it is not, please return to the Internal routing guide and complete it.
3. Remove the OE dash panels.
    - In order to remove the dummy panel, the trim panel to the right and to the left need to be removed. First remove the center panel (with the parking brake). Then remove the left panel (with the radio). Use a pry tool to both panels.



4. Remove the OE dummy panel.
    - Remove the 4 screws and set aside. They will be reused. Remove the dummy panel.

5. Connect the harness.
   - Connect the DT6 plug into the back of the XXX. Connect the XXX back shell to the SVD switch.

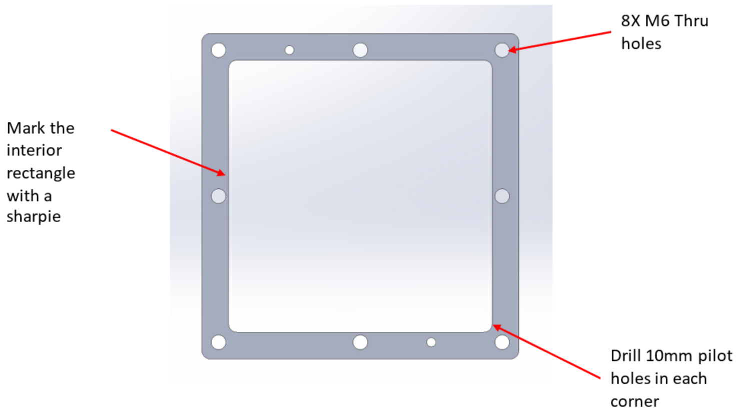


6. Install the assembled UI panel.
   - Reinstall the four screws into the UI panel. Replace the trim panels in the reverse order that they were removed.

Snorkel Installation

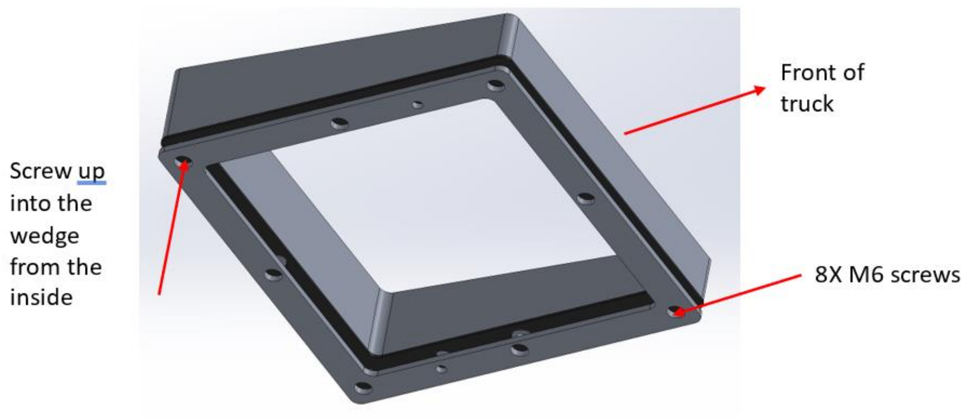
1. Prep all parts and tools.
   - Consult the part and tool lists to ensure that everything is accounted for before starting work.
2. Measure and mark the location.
   - Measure from the back of the center light.
   - The edge of the snorkel wedge plate should be 37cm.
   - Mark the six M6 hole locations with a sharpie and then center punch

3. Drill M6 through holes and pilot holes.
   - Drill the eight M6 through holes with a 7mm drill bit.
   - Line the holes on the backing plate up with the freshly drilled holes and trace the rectangular roof cutout.
   - Drill 10mm holes in each corner so that the jig saw blade fits into the hole.

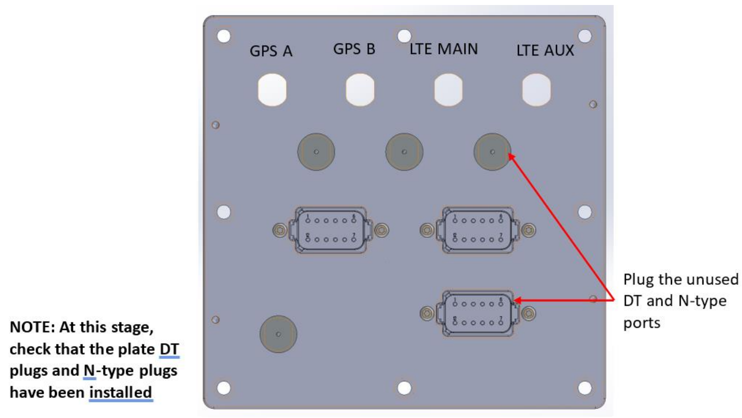


4. Rough cut the hole
   - Using a Sawzall or jig saw with a thin composite cutting blade, cut out the roof section marked in the previous step. Clean the edges with a router and/or file.
5. Install the snorkel backing plate and wedge.
   - Make sure the adhesive backed gasket has been installed on the wedge.
   - Position the backing back inside the cab between the headliner and the roof. This can be done from the outside.
   - Position the wedge so that the taller side is facing the back of the truck.

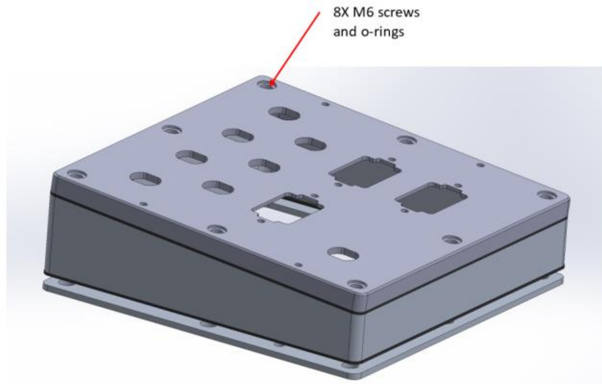
- Secure the wedge to the roof with eight M6 screws. Torque to 10Nm.



6. Attach the N-type cable to the snorkel plate.
   - Drop the GPS and LTE RF cables into the roof.
   - Attach the N-type bulkheads on the cables to the appropriate port on the snorkel plate. Use Loctite 242 and torque to 10Nm.



7. Run The Interior GPS & LTE Rf Cables
   - At this point, run the GPS cables using the RF harness routing guide. Return here when complete.
8. Install the snorkel plate assembly.
   - Connect the snorkel plate to the wedge with the remaining eight M6 screws and o-rings. Torque to 10 Nm

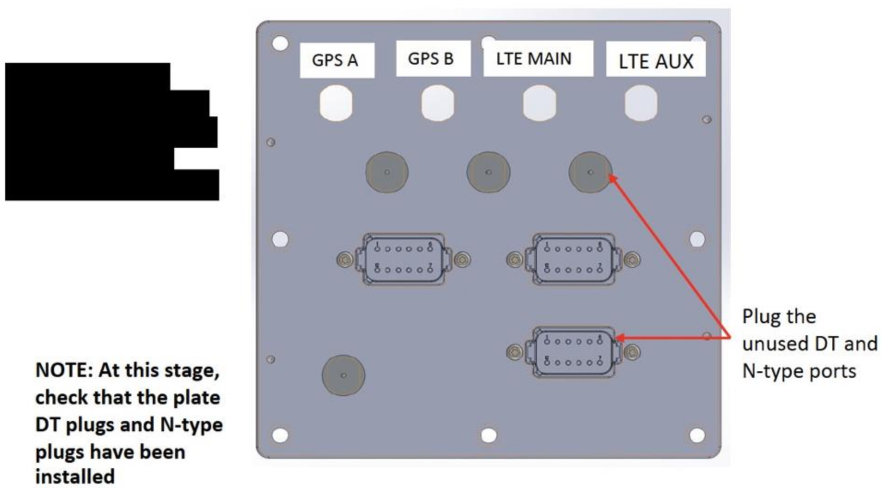


9. Run The Exterior GPS & LTE RF Cables
    - At this point, run the GPS cables using the RF harness routing guide. Return here when complete.
10. Install the snorkel kick guard.
    - Install the snorkel kick guard with the 4 M4 screws. Torque to 2 Nm.
    - Zip tie the RF cables and install the zip tie spacers as shown.

RF Harness Installation

1. Prep all parts and tools.
    - Consult the part and tool lists to ensure that everything is accounted for before starting work.
2. Remove the trim panel.
    - Take down the back wall upholstery and hard plastic panel and the front left above-dash cabinet.

3. Check that the snorkel installation has been reached step 7.
   - Before beginning this installation, step 6 of the snorkel installation must be complete.
   - The RF cables should be connected to their respective ports.
   - Before beginning, label each cable at both ends with a colored zip tie for identification later.

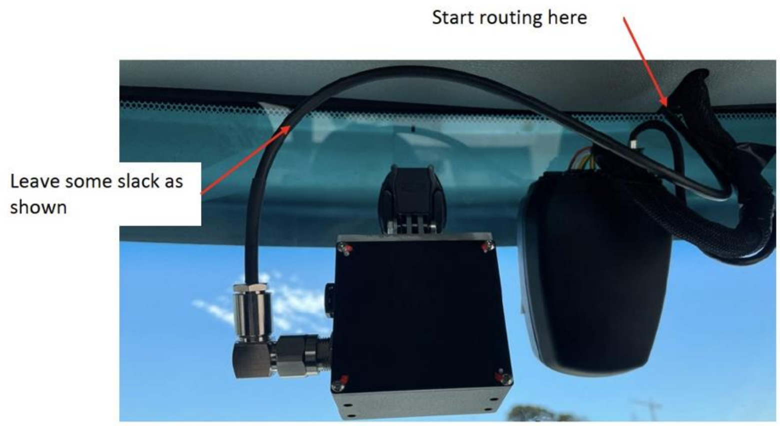


4. Thread the cables from the snorkel along the headliner towards the back of the cab.
   - Outside the cab, after the snorkel hole has been cut in the roof, start routing the internal RF cables into the cab.
   - Guide them toward the right back pillar, above the headliner.
   - Take care to properly unspool the cables. Do not attempt to pull them straight.
   - Once the cables have reached the back corner or can no longer be guided back, proceed to the next step.
5. On the inside of the cab, retrieve the SMA ends.

- Have the second installer on the inside of the cab, ready to receive the cables as they come toward the back right from the snorkel.
- The headliner does not need to be fully removed but it does need to be loosened to be able to reach in between the roof and the headliner.
- Once the SMA ends are in hand, gently guide the cables toward the back right pillar.

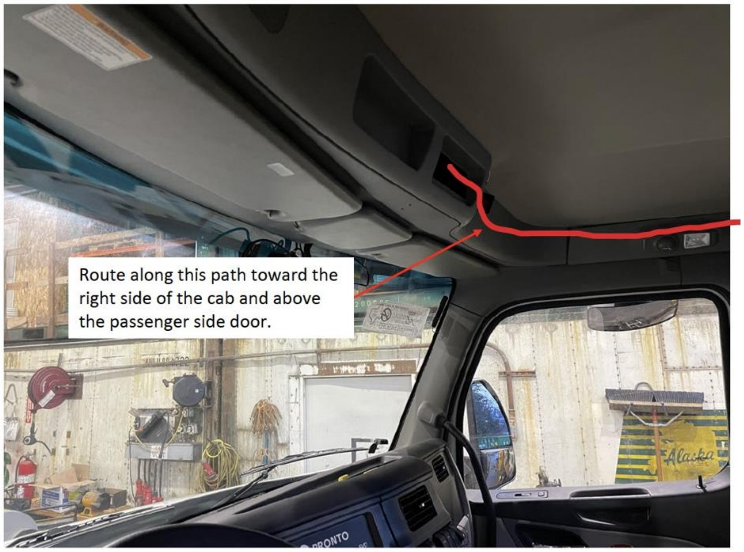
6. Route toward the back right pillar
    - Once the SMA ends are in hand, gently guide the cables toward the back right pillar.
    - Zip tie to features.
    - Do not fully tighten the zip ties until completing all the routing to allow for any repositioning.
7. Join the rear camera cable with the rest of the bundle.
    - The rear camera should already be installed on the windshield at this point. If it has not been, please complete that guide and return here.
    - Feed the SMA end of the rear camera cable into the rest of the bundle near the back right pillar.
    - Take note of the N-type and check that it is lined up with the rear camera.

8. Thread the front camera cable through the gap between the cabinet and the windshield.
    - The front camera should already be installed on the windshield at this point. If it has not been, please complete that guide and return here.
    - Thread the SMA end into the opening in the headliner.



9. Retrieve the SMA end from inside the cabinet space.
    - Retrieve the SMA end from behind the removed trim panel.
    - After getting hold of the end, work the cable from both ends, gently threading it through.

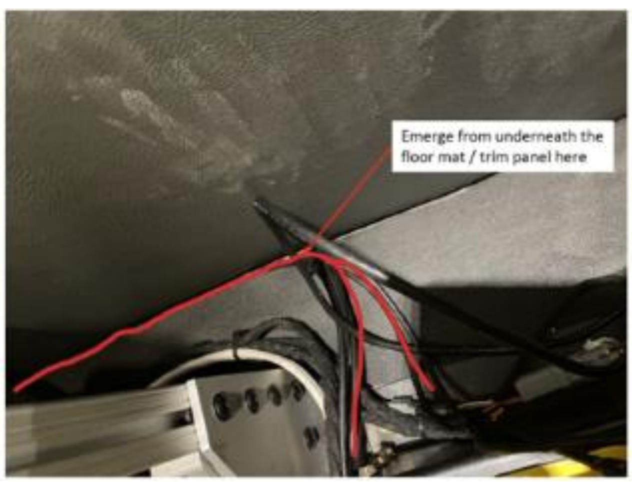
10. Route the cable inside the plastic molding to the right
    - Continue routing the front camera cable inside the plastic trim panels following the path shown.



11. Route the front camera cable above the door to the rear pillar
    - Continue routing in sections, pushing and pulling so as not stress the cable.
    - Remove more trim panels as needed.

12. Route down the pillar toward the floor
    - Route down the pillar toward the floor
    - Zip tie to clip.

13. Route along the floor to the center
    - Route underneath the floor mat/behind the upholstery panel. Pop out near the center, in between the brake and compute the mount rivet nuts.



14. Return to the snorkel installation.
    - Return to the snorkel installation guide here.
15. Install zip tie mounts to the roof of the cab
    - Clean the surface of the roof thoroughly with a degreaser.
    - Prep the surface with XXX
    - Install each mount and press for 60 seconds.

16. Connect the GPS cables to the antennas.
    - Apply a small amount of Loctite 242 to the threads on the GPS antennas.
    - Thread the TNC end through the access hole and tighten until snug. Turn 1/8th turn with XXX

17. Route the GPS and LTE cables to the snorkel
    - Separate the LTE main and aux from each other and join with GPS A and one with GPS B.
    - Zip tie to the mounting bases.

18. Connect the GPS and LTE cables to the RF bulkhead.
    - Creta a service loop with the LTE cables.
    - Apply Loctite to each of the N-type bulkheads and connect the corresponding cables. Torque to 2.2 Nm.
    - Return to the Snorkel installation guide.

Rear Camera Installation

1. Prep parts and tools.
    - Consult the part and tools list to ensure that everything is accounted for before starting work.
2. Clean back windshield and treat with XXX
    - Locate the install location.

– Center of the back windshield, 70mm from the top edge

- First clean glass with normal glass cleaner
- Then treat the install area with XXX. Follow the instructions on the bottle.
- After drying, XXXXXXXX

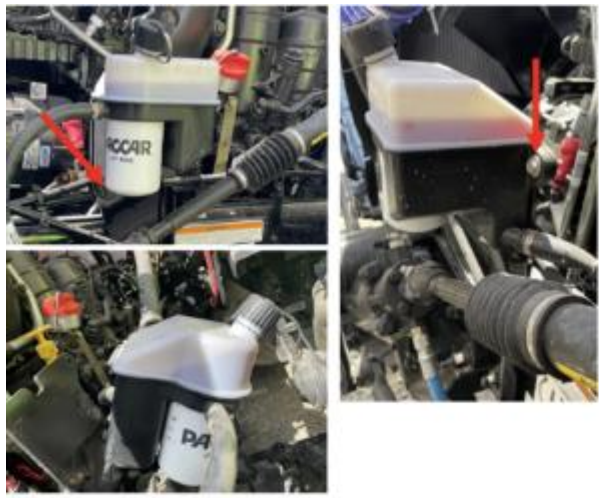
3. Install the Pronto Camera
   - Remove the VHB liner and carefully line up the mounting pad so that it is straight.
   - Press the pad firmly into the glass for 60 seconds.

4. Connect the RF cable
   - Apply a small amount of Loctite 242 to the external threads. Tighten to 2.2 Nm

Pronto Steering Installation

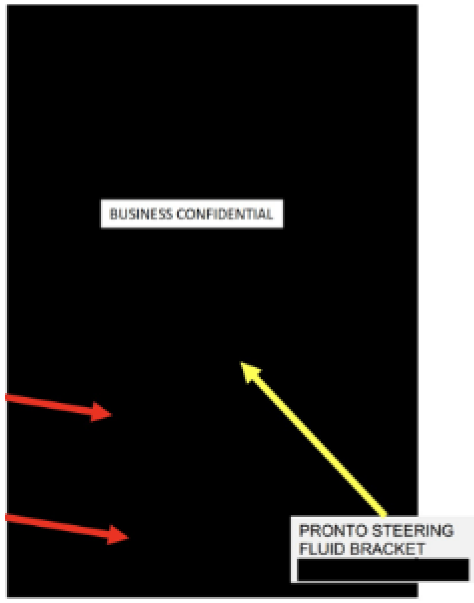
1. Remove steering shaft by removing the bolts and nuts at the steering gear and firewall. 11/16” for the nut and 5/8” for the bolt. XXXXXXXXXXX


2. Remove the two steering fluid reservoir screws with a 13mm socket. Set them aside, they will be needed for reinstallation. Then unhook the reservoir from the back and let it hang by the hoses.



3. Remove the steering fluid bracket with a 24mm socket and wrench. The bolts will be tight, so it is recommended to use a breaker bar and a second installer for extra leverage. Set the bracket with the steering shaft. It will no longer be needed.

4. Install the Pronto steering fluid bracket where the original bracket was using the original nuts and bolts. Torque to 200Nm and a torque stripe. Reattach fluid reservoir and torque screws 15-20 Nm.



5. Now it is time to install XXXX steering motor. First, it needs to be prepared. Here is an overview of the XXXX. It will come with the fasteners pre-installed loosely. To prepare it for installation on the truck, completely remove the nuts and bolts on each end and keep the middle nut and bolt installed loosely. The end fasteners need to be completely removed sot that the shafts can be fully inserted into each end. Note: there are no washers used on this part.

redacted image

6. Attach XXX. Pronto steering motor. Start by attaching the steering gear end of the XXX on the steering gear input shaft. Then, slide the Pronto steering motor XXX not the XXX. To hold the steering motor in place, it is recommended to put the first screw in the location shown below but do not fully tighten. Do not put screws in the 2 other holes yet. Once the bottom screw is secured, make sure the shaft is fully inserted into each end of the XXX. By lining up all the pinch bolt holes. Once the end nuts and bolts that were initially removed get reinstalled, the XX should all be locked in place (even if the bolts are not yet tight).

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7. Attach the support brace. Now the remaining two screws going into the steering motor can be attached. Once all the screws are started, they can then be tightened down. Add Loctite 242 and tighten all M10 hardware into the steering motor with a 15mm socket 29-31 Nm and the M8 screws for the support brace to 20 – 25 Nm. Add torque strip to all screws once tightened.

Here is a picture if the XXX and the steering motor attached to the truck.

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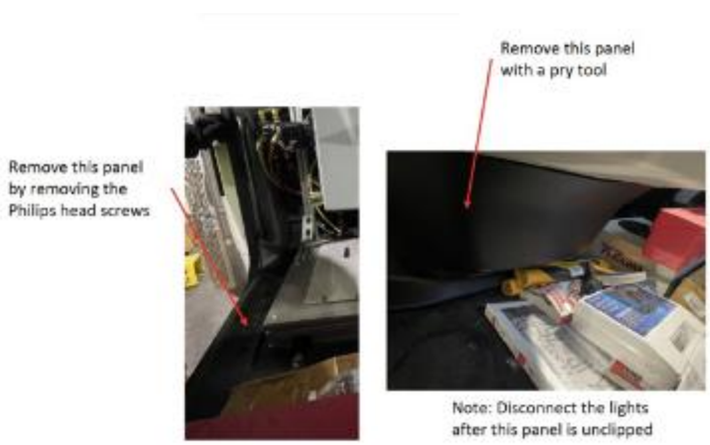
8. Now it is time to install the XXX. First, here is an overview of the XXX. It will come with the fasteners pre-installed loosely, but they are labelled below for reference. Note: there are no washers used on this part.
9. Install XXX. It can XXX which helps with assembly. The splined end that installs at the firewall must be clocked in the correct orientation so that the flat spot of the XXX aligns with the flat spot int eh shaft. Add Loctite 242 and tighten M10 hardware into the steering motor with a 15mm socket and 17mm wrench to 29 – 31 NM and the M8 hardware at the firewall to 20 – 25 Nm.

Internal Harness Installation

1. Prep all parts and tools.
    - Consult the part and tool lists to ensure that everything is accounted for before starting work.
2. Remove the trim panels.
    - Remove the trim panel that covers the cable routing channel on the floor near the passenger side entry way.
    - Remove the trim panels underneath the dash and XXXX



- Remove the trim panels that cover the steering column.

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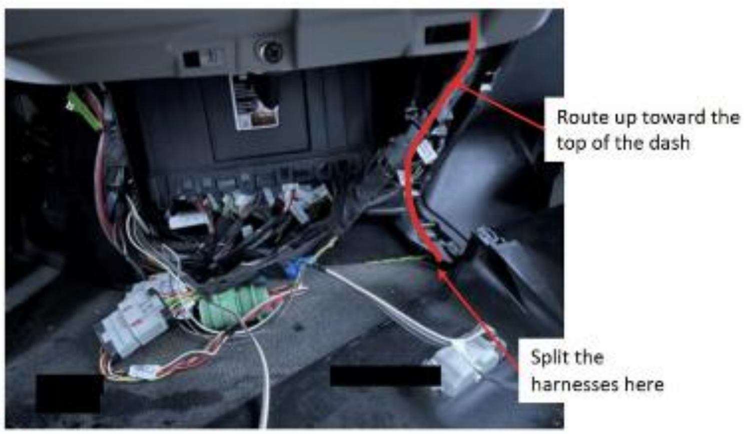
- First remove the center panel (with the parking brake). Then, remove the left panel (with the radio). Use a pry tool to both panels. The dummy panel will be removed in the UI installation, but it can also be removed now.

3. Place the Squid and brake box harness ends.
    - Locate the approximate brake box mounting location. This can be done relative to the OE rivet nuts in the floor and the floor pass through.
    - Route the Squid branch XXX around the back right corner of the truck so that the connectors are in the approximate location of the squid mounting plate.
    - Akso place the end of the XXXXXXXXXXXX
4. Bundle and set aside harness branches that will be finished with the brake box install.
    - The XXX branch of XXX, steering branch of XXX, XXX branch of XXX, and all the pigtails of XXX will be routed later. Bundle them and set aside.
5. Route selected harness to the front of the cab.
    - The XXX, XXX, XXX, and XXX branches from the XXX harness XXX and the SVD and XXX branches from the DT12 pigtail XXX all route to the front of the cab.
    - Gather all these branches together so that they can be routed together
    - The XXX input and the XXX will also be run with the XXX and the internal SVD harness.
        - 5.1 Tuck under the back right of the floor mat
            - Tuck the harness XXX underneath the floor mats at the back right of the cab, zip tying to existing cables.

- 5.2 Route in the passenger side door channel
  - Route the harnesses XXX in the channel next to the passenger side entry way. Zip tie loosely to the existing cables. This will allow for repositioning later if needed. Be careful not to block the rivet nuts that are used to install the trim panel.

- 5.3 Route along the back of the passenger foot well
  - After reaching the end of the passenger channel, route the harnesses XXX underneath the floor mat in the corner between the floor and the firewall.
  - Pull the floor mat back to do this.

- 5.4 Route up to the UI panel.
  - Split the XXX branch, SVD branch, and the XXX right before the center.
  - Route up along the existing harness to UI

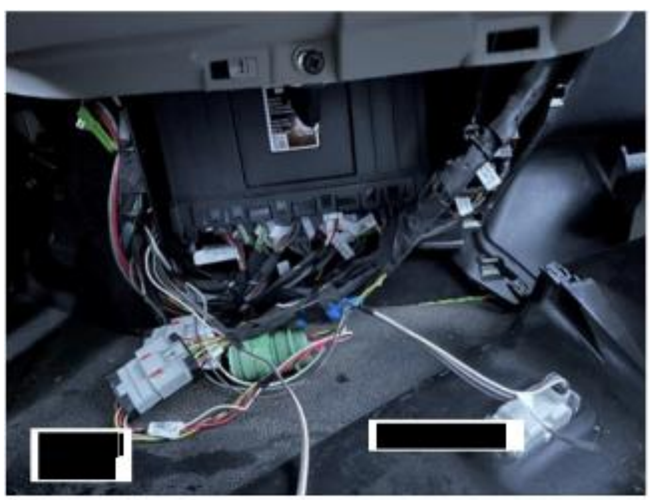


  - Route the harnesses up and to the back of the dummy UI panel
  - Route XXX

- 5.5 Route under the center of the dash

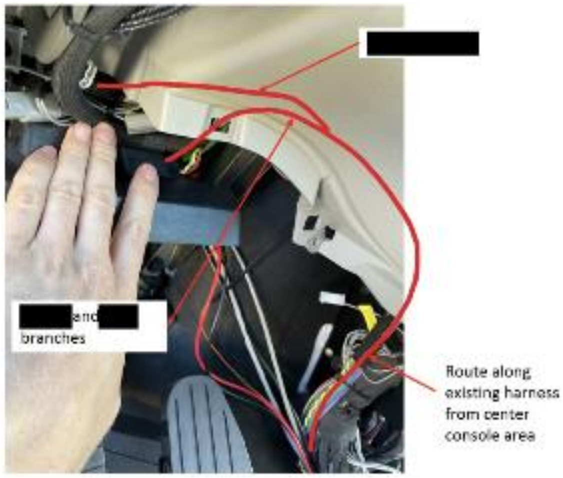
- Route the harness under the center of the dash, zip tying loosely to the existing harnesses.
- Be careful not to zip tie the lights into the bundle.
- Follow the existing harness as they move up and to the left.

– 5.6 Connect the XXX
  - Connect the XXX to the XXX receptable.
  - Coil any excess harness.
  - Zip tie to existing harness for strain relief.

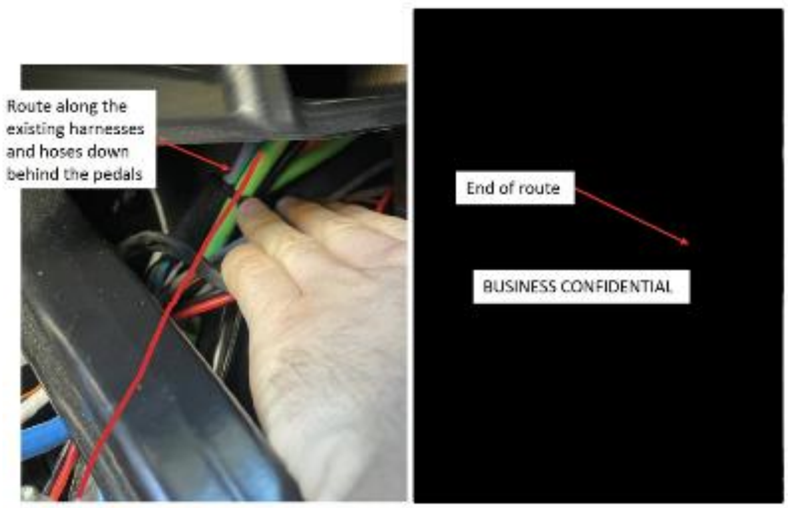


– 5.7 Route the XXX and branches to the steering column
  - After passing the supporting U-beam that is to the right of the steering column, split the XXX branch from the XXX and XXX branch.
  - Once the XXX and the XXX branches are at this point. Set it aside. There should be 30-45 cm left of the harness.
    - If there is more remaining, check that no short cuts have been taken that could damage the harness (running tightly of edges, long unsecured runs). Fix any short cuts and create a service loop with any remaining.

- If there is less remaining, return to the beginning of the harness and remove any excess slack, cutting zip ties and rerouting if necessary.



– 5.8 Route the XXX branch to the XXX
  › Following the existing harness and zip tying loosely, route the XXX down toward the XXX passing underneath the linkage.



  › The end path is to the left of the XXX
  › At this point, there should be 15-20cm of the XXX branch remaining.
    - If there is more remaining, check that no short cuts have been taken that could damage the harness (running tightly of edges, long unsecured runs). Fix any short cuts and create a service loop with any remaining.
    - If there is less remaining, return to the beginning of the harness and remove any excess slack, cutting zip ties and rerouting if necessary.
  › Leave XXX branch aside.

– 5.9 Finish securing the harness
  › At this stage, the preliminary routing is complete. Secure the harness by tightening the zip ties that were placed along the way. Add more zip ties as needed.

6. Lay out the routing for the compute harness.
    - Returning to the outer end of the harness, loosely route the XXX, XXX, DTM-A XXX and DTM-B XXX branches.

NOTE: Neither the brake box mount nor the compute box mount will have been installed at this point. This is just an approximate route. It will be adjusted when those steps are completed.

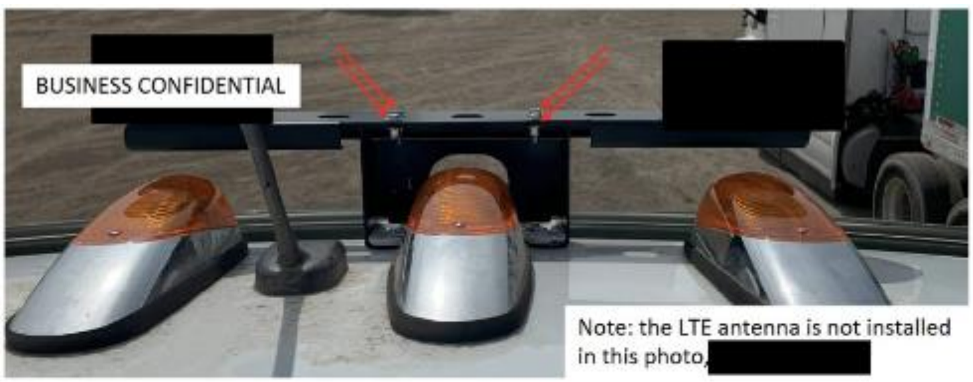
7. Floor pass through harness
    - This step will be completed in the Brake Box Installation. See that guide for details.
8. Note on brake box harness.
    - The internal harness for the brake box will be installed during the brake box installation step. See that guide for details.
9. Connect the harness to the squid.
    - This step will be completed in the Brake Box Installation. See that guide for details.

GPS AND LTE Mount Installation

1. Prep all parts and tools.
    - Consult the part and tool lists to ensure that everything is accounted for before starting work.
2. Remove the OE visor.
    - The OE visor is attached to the top of the cab with a combination of screws into rivet nuts and nuts that screw onto threaded studs in the roof. Remove the visor completely as shown.

3. Position the Pronto GPS & LTE mount standoff.

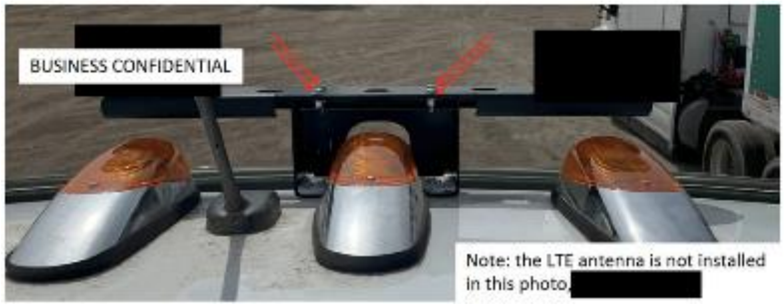
   - Apply Sikaflex sealant to each of the 4 rivet nut holes. Align the standoff bracket over the holes. Align XXXXXXXXXXXXXXXX



4. Reinstall the OE visor.

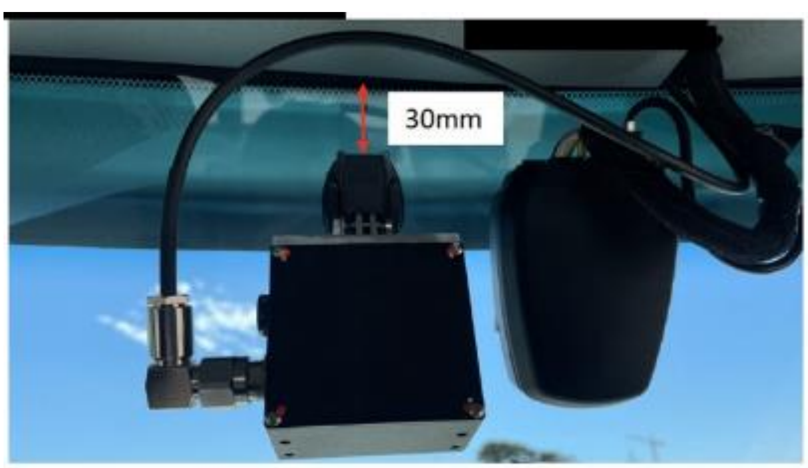
   - Insert and tighten the 4 screws that go through the standoff bracket XXX to 25 – 30 Nm and then the 6 nuts onto the threaded studs to 25 – 30 Nm.

5. Fasten down the Pronto GPS & LTE mount.
   - Secure the assembled LTE and GPS mount to the standoff with the 5 M6 screws. Use Loctite 243 and torque to 10Nm.



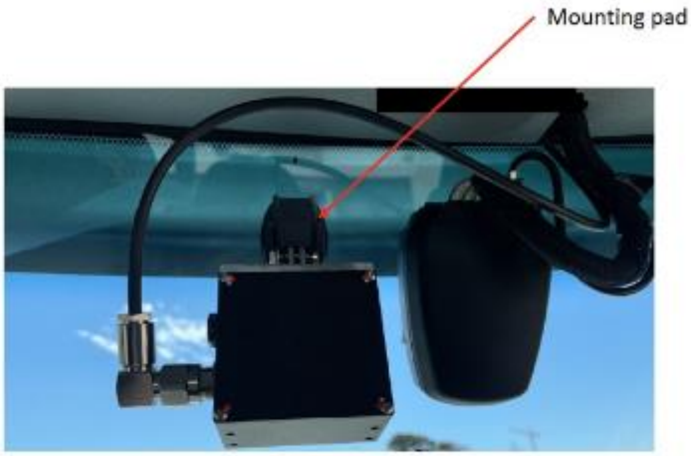
Front Camera Installation

1. Consult the part and tool lists to ensure that everything is accounted for before starting work
2. Remove the XXX
   - The optimal position for the Pronto camera XXX. Remove the XXX using a plastic pry tool.
3. Clean windshield and treat XXX spray.
   - Locate the install location.
     – Center of the windshield, 30m from the top edge
   - First clean the windshield with the normal glass cleaner
   - Then, treat the install area with XXX spray. Follow the instructions on the bottle
   - After drying, XXXXXXXXXXXXXXXXXXXXXX



4. Install the Pronto camera.
   - Remove the VHB liner and carefully line up the mounting pad so that it is straight.

- Press the pad firmly into the glass for 60 seconds.



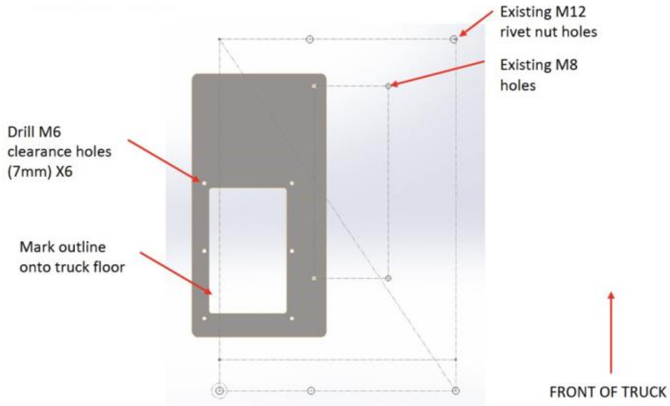
5. XXXXXXXXXXXXXXXXXXXX

6. Connect the front camera RF cables
   - Apply a small amount of Loctite 242 to the external threads. Tighten to 2.2Nm

Floor Pass Through Installation

1. Prep parts and tools.
   - Consult the part and tool lists to ensure that everything is accounted for before starting work.
2. Peel back the floor mat.
   - Peel back the floor mat and foam insulation to expose the OE rivet nuts in the sheet metal floor. Tuck the mat back so it is not in the way.

3. Use the jig to mark the pass through the holes.
   - Orient the jig so that it is aligned over the two 8mm holes in between the larger set of five 12mm holes.
   - Mark with a center punch and drill 6x 7m clearance holes through the sheet metal floor

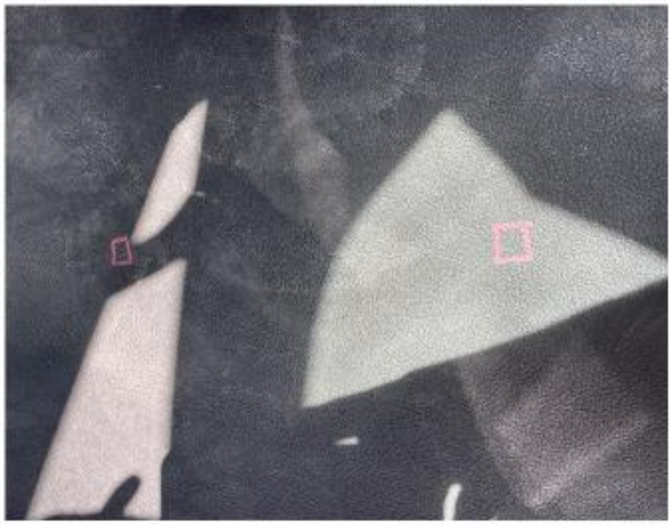


4. Cut out the pass-through cutout.
   - Using a sharpie, mark the rectangular cut out and set the jig aside
   - Drill large pilot holes (10mm) into each corner of the traced hole so that the jig saw blade will fit through.
   - Cut with a jig saw along the line. Clean the edges with a file and debur tool.

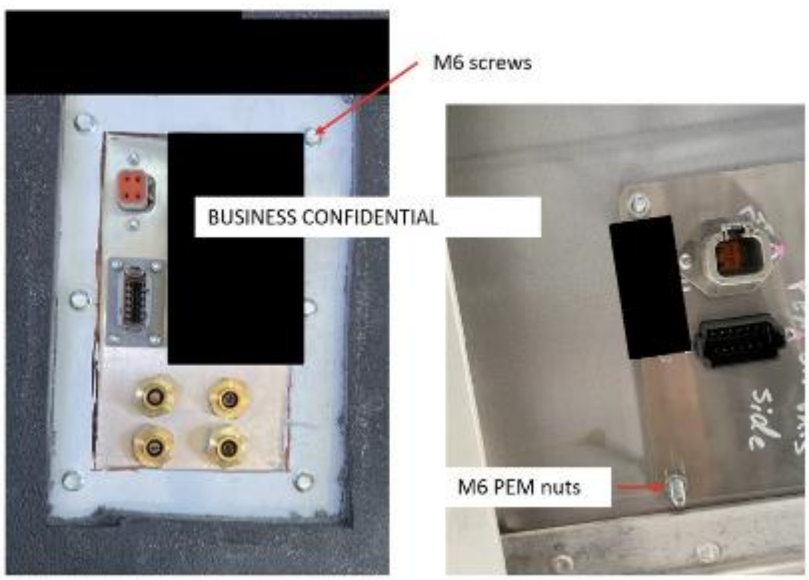
5. Mark the hole locations for the compute box mounting bracket.
   - Center the compute mounting bracket along the forward axis of the truck.
   - Position the bracket so that the back edge is 150mm from the back wall of the cab.
   - Mark each of the six-hole locations with a sharpie and center punch

6. Drill the compute box mounting holes and install the rivet nuts.
   - Drill the six clearance holes (13.5mm) for the M8 rivet nut. Install the rivet nuts with the rivet nut installation tool. Use the 11/16" and 7/8" imperial combo wrenches.
7. Replace the floor mat and cut the clearance around the pass through.
   - Use a paint marker to mark a rectangle around that floor pass through that gives planet of clearance for the M6 screws.
   - Using a utility knife, cut through the rubber floor mat and the foam installation.

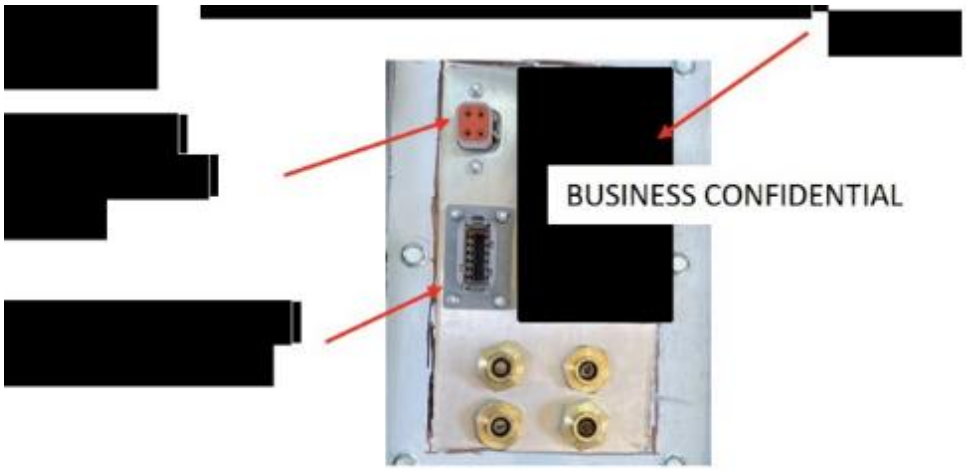
8. Locate the mounting rivet nuts in the floor of the cab.
   - Mark ~20mm square around each rivet nut. The five OE rivet nuts and the six pronto installed rivet nuts. With the utility knife, cut out each square.



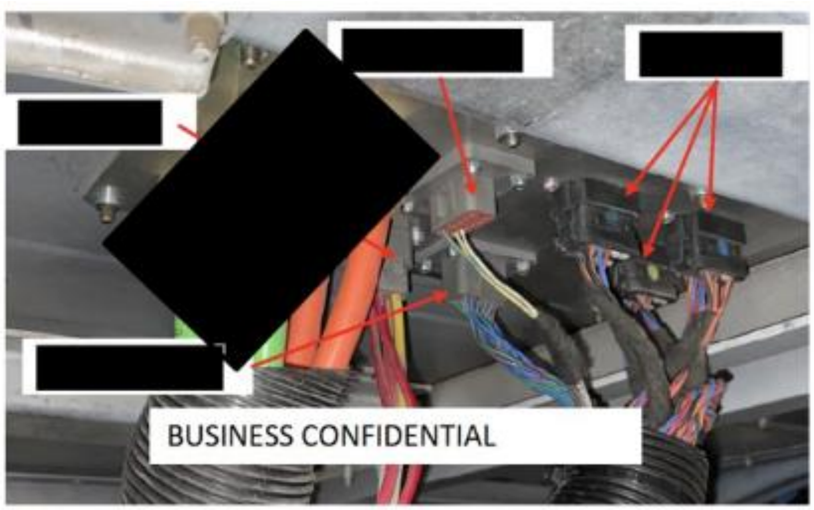
9. Install the pass through assembly.
    - From the outside of the cab, line up pass through in the cutout. A second installer then installs the screws inside the cab going through the floor and into the PEMs on the pass-through plate. Torque to 10Nm.



10. Connect the interior harnesses.
    - Note: this step needs to be completed during the brake assembly installation
    - Connect the XXX into the XXX PCB
    - Install the XXX into the pass-through plate. It should be part of the harness.
    - After completing step 11, connect XXX and XXX in the DTM bulkheads XXX



11. Connect the exterior harness.
    - Note: this step will be completed during the exterior harness installation
    - Connect the three external XXX DTs and the XXX DTP
    - Using the M4 screws, install the Deutsch bulkheads that are a part of the XXX and XXX into the pass-through plate.
    - Finish step 10



Exterior SVD Switch Installation

1. Prep all parts and tools.
    - Consult the part and tool lists to ensure that everything is accounted for before starting work.
2. Remove the upholstery at the back of the cab.
    - The upholstery is attached with plastic furtrees. Remove with pry tools.

3. Mark the correct installation location
   - Center the holes between these two rivets. The bottom edge of the jig should be 3.5cm above the rivets.

4. Drill the mounting holes into the sheet metal.

- Use a center punch to mark the hole locations and then start the hole with a center drill. Drill the thru hole with a 6mm bit.

5. Install the backing plate with VHB

- Secure the pem'ed backing plate to the inside of the wall with VHB. Ensure the holes line up.

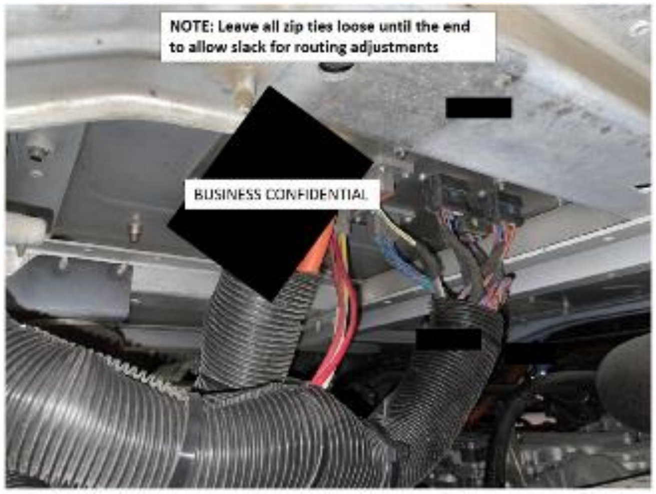
6. Install the switch box

- Use the M5 screws and install the box through the mounting flanges and into the backing plate. Torque to 5 Nm

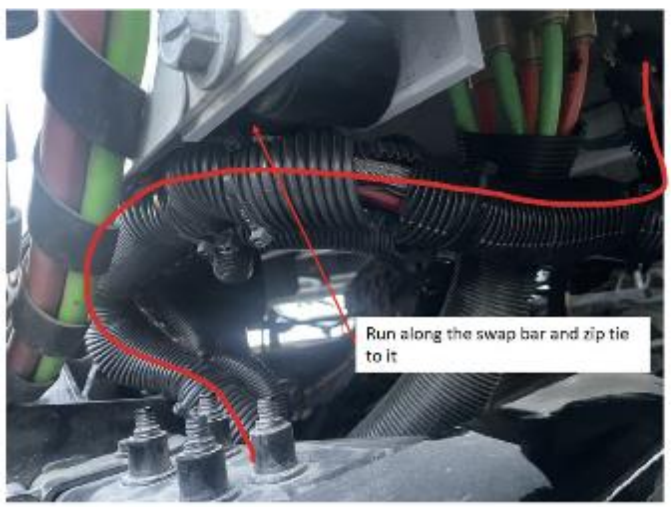

7. Connect the harness to the switch box
   - Connect the DT plug on the harness into the DT receptacle on the bottom of the box. Secure the cable with a P-clip to the bottom right screw. Torque to 5 Nm

Exterior Harness Installation

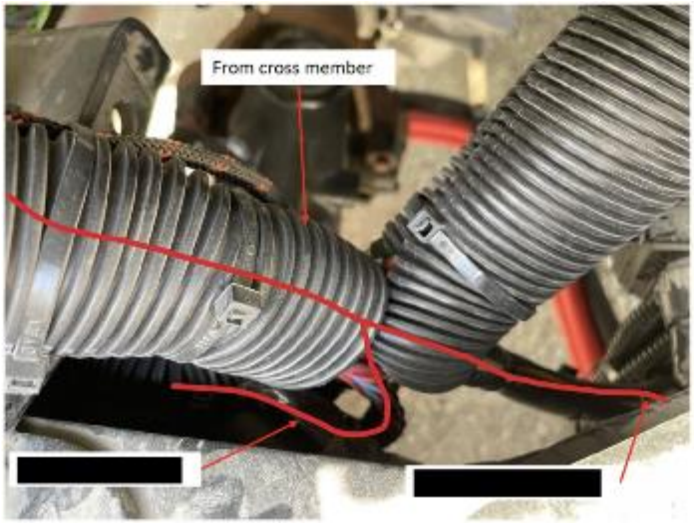
1. Prep all parts and tools.
   - Consult the part and tool lists to ensure that everything is accounted for before starting work.
   - Before starting work ensure the battery disconnect is off
2. Place the XXX DTP at the bulkhead.
   - The internal DTP bulkhead will not be connected at this time so estimate the distance needed.



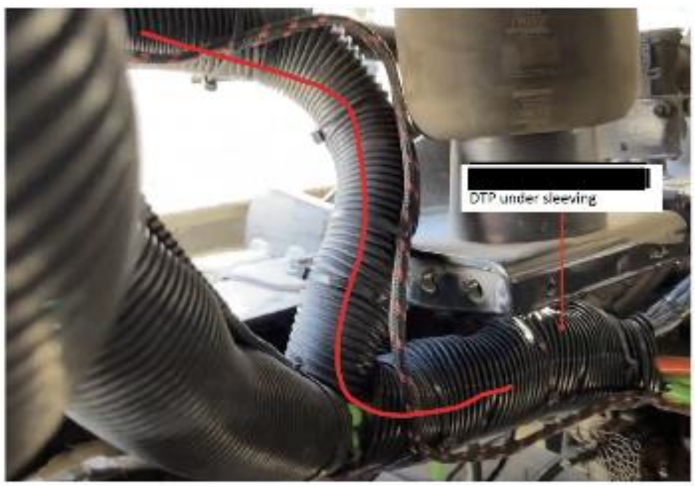
3. Route the harness back toward the cross member
   - Route the harness back towards the cross member
   - Got toward the pivot and then snake back.



   - Snake back in front of the cross member and toward the OE power harness.
   - Route the XXX DTP to the left and XXX to the right



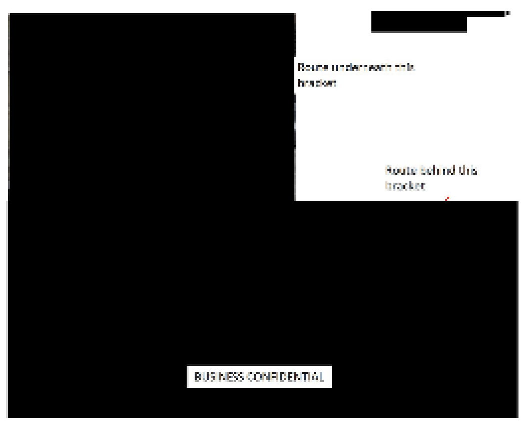
4. Route the XXX disconnect.
   - The XXX DTP should end up neat the center of the cab near here.



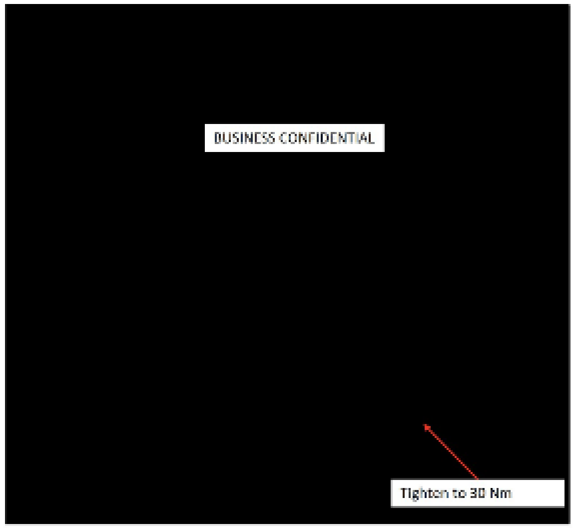
5. Route under the cross member and join with the OE power cables.

6. Route both XXXXXXX cables toward the XXXXXXXX

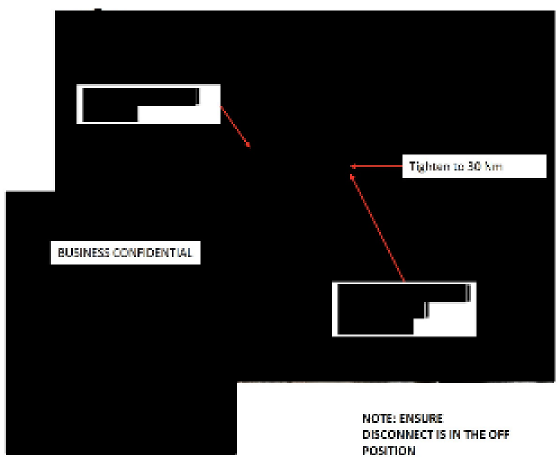
7. Continue routing XXXXXX along the OE power.
   - Pass into XXXXX



8. Connect to the XXXXX
   - After routing into the XXX, any excess can be wrapped in a service loop.



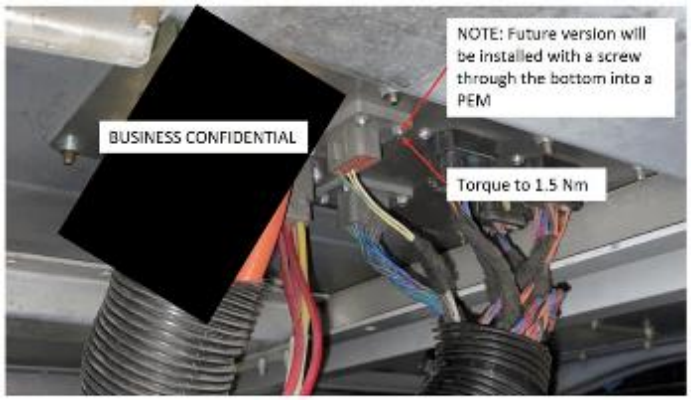
9. Return to the XXXXX and connect XXXXXX
    - Create a service loop with any excess length.



10. Add corrugated cable sleeving to all XXXXX cables.
    - Add corrugated sleeving to cover the Pronto harness. Add this in all locations.

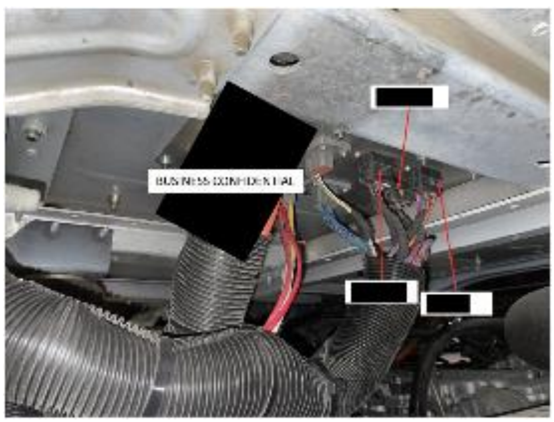
11. Install the XXX DTM and the XXXXX DT bulkheads.

- Connect the three external XXX DTs and the XXX DTP
- Using the M4 screws, install the Deutsch bulkheads that are a part of the XXXXXX and XXXXXXX harness into the pass-through plate.



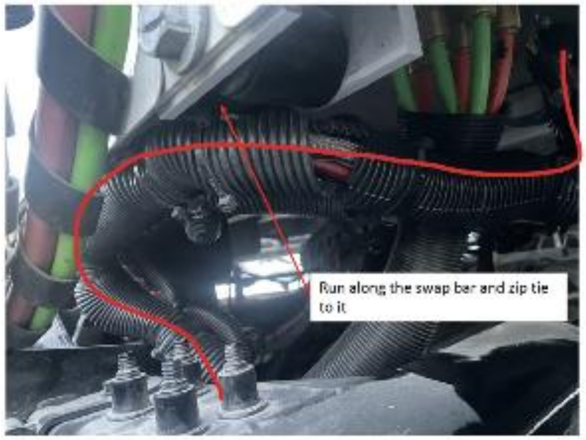
12. Connect the XXX DTS at bulkhead.

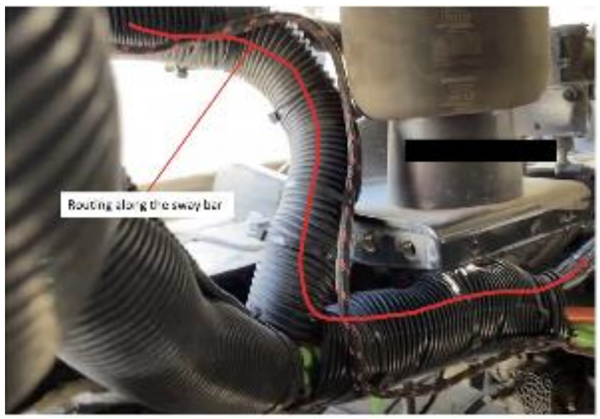
- Make sure to match the plug to the correct receptable (harness XXX and XXX)



13. Route along the same path as the XXXXXXX disconnect.

- Follow the same path as the XXXXX routing back toward the cross member at the back of the cab.



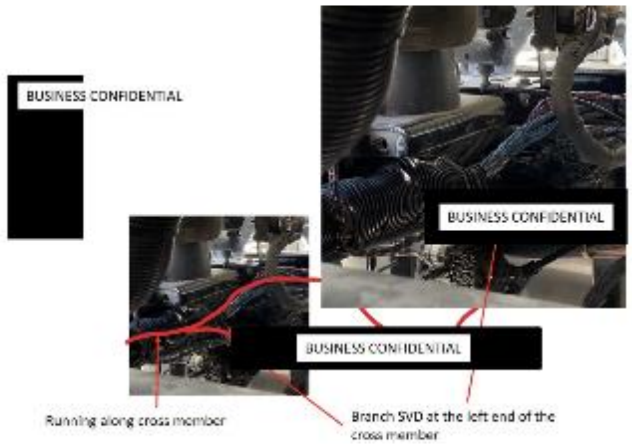


14. Connect the XXXXXXXXX pigtail

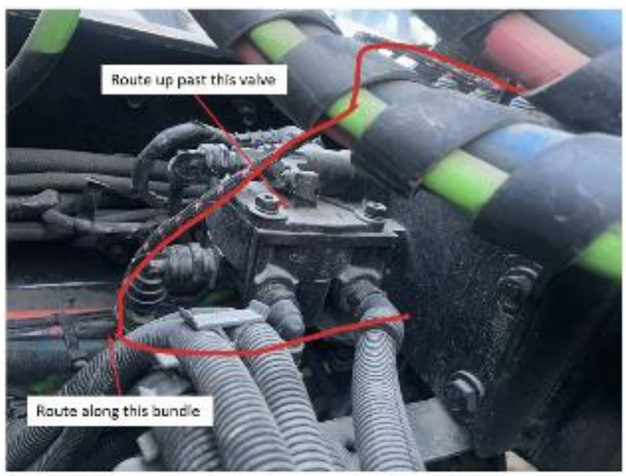
- Along the cross member, connect the XXX harness (XXX) to the XXX DTP ()

15. Branch the SVD harness.

- After routing along the cross member, route the SVD harness under the cross member toward the back of the cab.



16. Route the SVD harness under the cross member and up to the cab
    - After branching, route underneath the cross member along the OE hoses
    - Then route the harness up after passing this valve



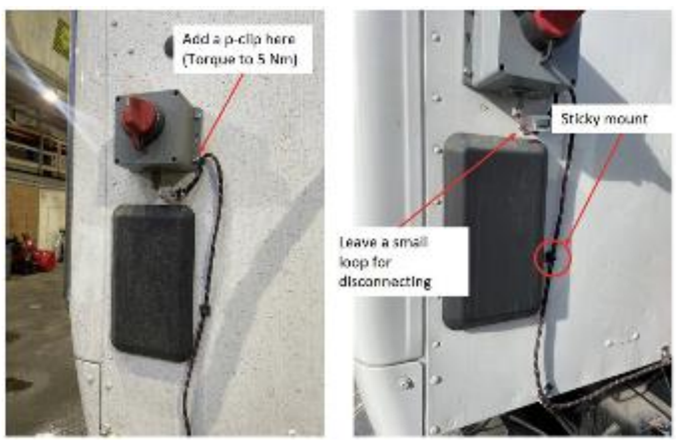
    - Make sure to leave a small amount of slack to account for the motion of the cab relative to the chassis.

17. Add zip tie brackets to the bottom of the cab.

- Install zip tie brackets at the bottom of the cab by drilling through the hem and thru bolting the bracket. Use the M6 screws and nylock nuts. Torque to 10Nm.
- Install two in between rivets at the locations shown.

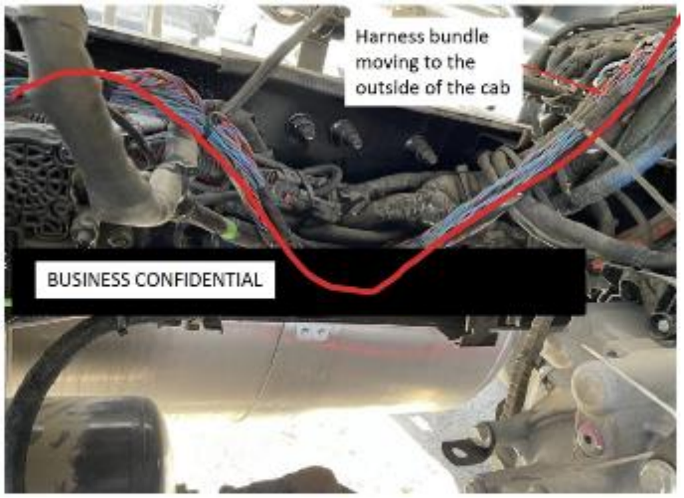
18. Install a zip tie mount and P-clip and connect the SVD.

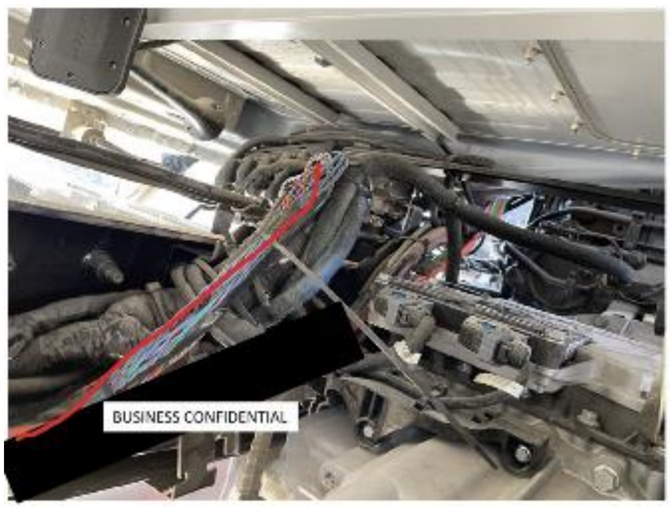
- Install a stick mount halfway between the SVD box and the bottom of the cab.
- Clean the surfaces with cleaner and then use a 3m 94 primer. Press the stick mount on for 60 seconds.



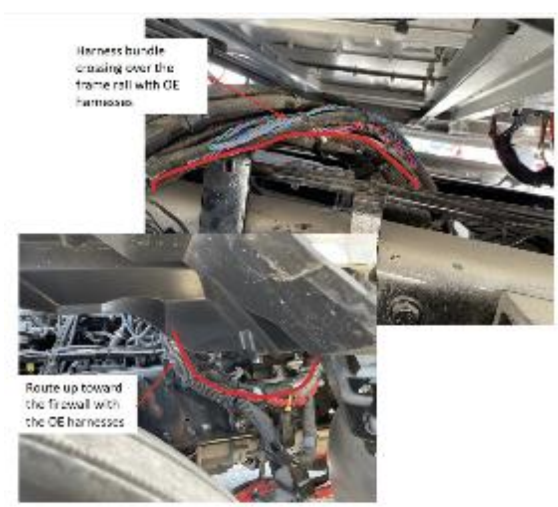
19. Route bundle along left side frame rail

- Return to the main harness bundle and continue routing along the existing harness.
- Follow the OE harness as they move to the outside of the frame near the front of the cab.



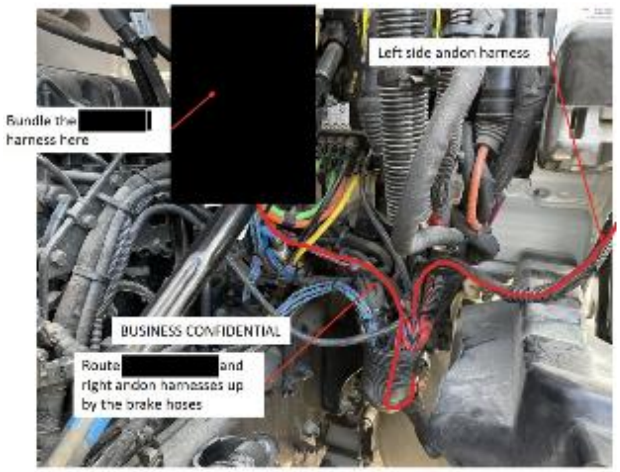


20. Route to the outside of the frame rail

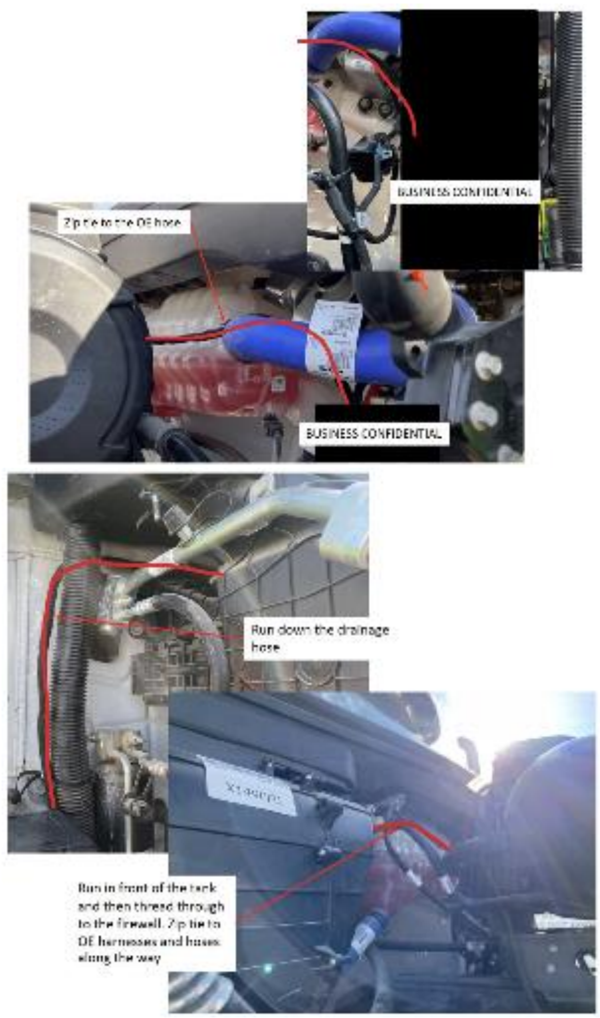


21. Route and on right and XXX up to the treadle valve

- At this time, bundle the XXX harness. The final installation will occur during the Squid installation.

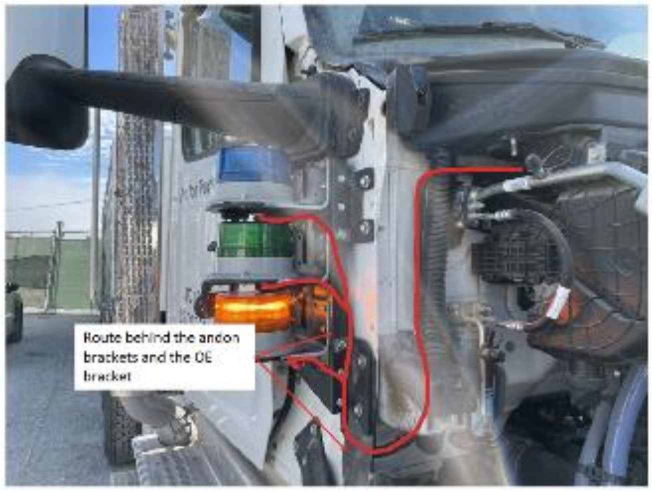


22. Split of Andon right and route across the top



23. Finish the right-side Andon routing

- Complete the routing to the Andon lights and connect the DTS

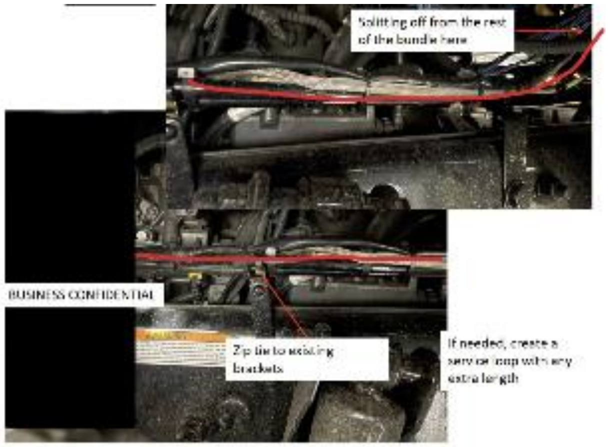


24. Route the left Andon harness to the left side lights

- Complete the routing to the Andon lights and connect the DTs

25. Continue routing XXX along the frame

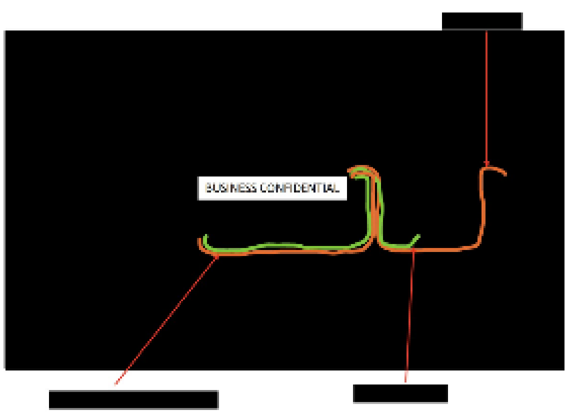
- Route both the XXX harness along the frame. Connect to the XXX



26. Tighten zip ties and add harness protection
    - Go back over the harness and add more zip ties as needed.
    - Add split corrugated sleeving where it is shown in the images. Add more if there are any potential heat or rubbing hazards.

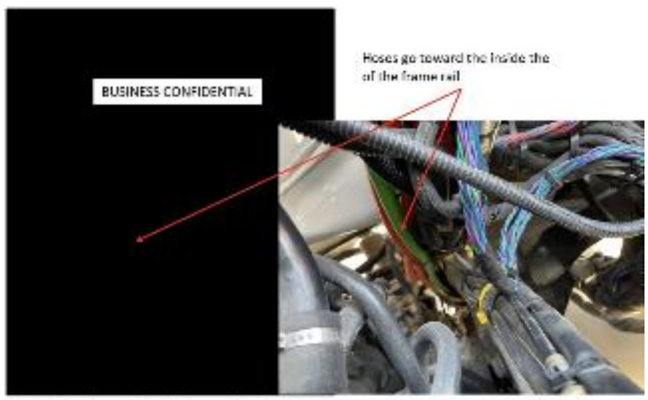
Exterior Brake Hose Installation

1. Prep all parts and tools.
    - Consult the part and tool lists to ensure that everything is accounted for before starting work.
    - Note for all XXXXXXXX will be used. Foal XXXXXXXX will be used
    - Primary – orange
    - Secondary – green
    - Air hose routing top view



2. Drain the supply tanks.
    - Before doing any work on the brake system, you need to discharge the air tanks. Locate the pull cord at the back of both tanks and pull until the tanks are empty.

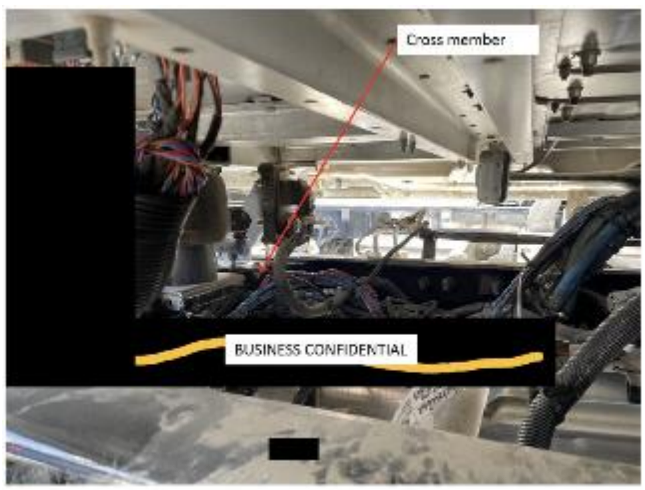
3. Route the XXX hoses from the XXXXXXX to the frame rail
   - As this step is completed before the XXXXXXX, leave the hoses with the excess length to ensure they do not end up too short.



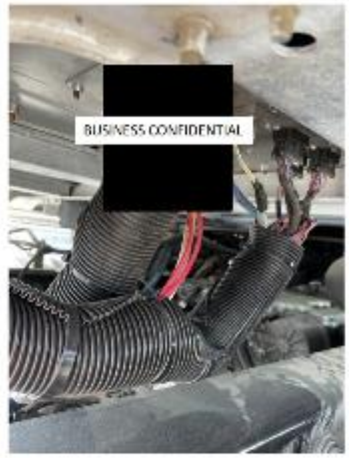
Note: This photo shows the hoses after they have been fully installed

4. Route along the existing bundle to the back of the cab
   - Thread the hoses through existing routing features. Ensure the hoses never kink during this process. Make sure hoses are clear of any hot or moving parts.

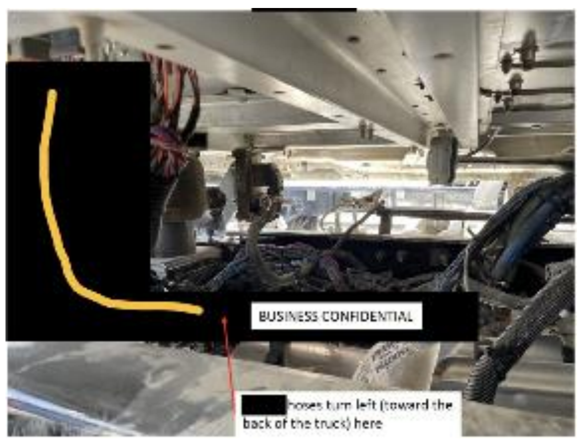
- Continue routing to the back of the cab, turning the hoses without kinking at the cross member.



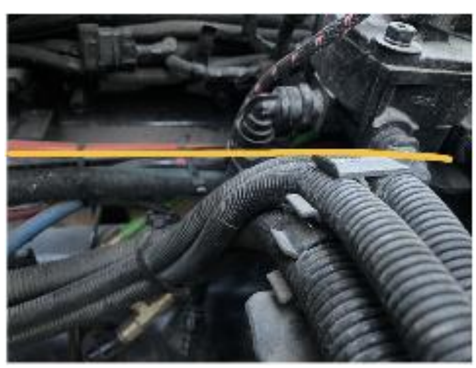
5. Route along the back of the cab to underneath the pass through
    - Make sure to keep clear of the drive shaft. Do not zip tie fully yet as the XXX hoses will route along this path as well.



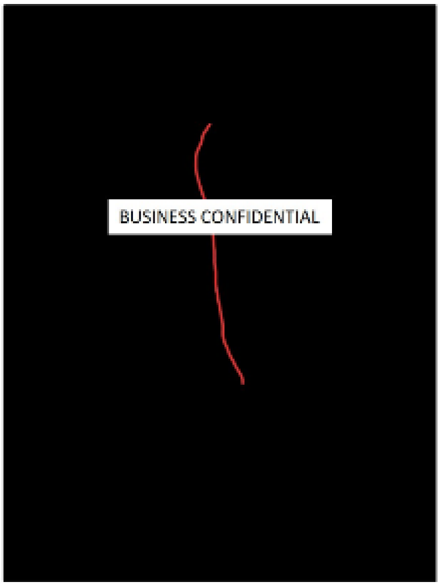
6. Route the XXX hose from the bulkhead along the cross member
    - Route the XXX hoses along the same path as the XXX hoses



7. Route the XXX hoses along the left frame rail toward the back of the cab
    - There are OE hoses here that should be followed, and zip tied to

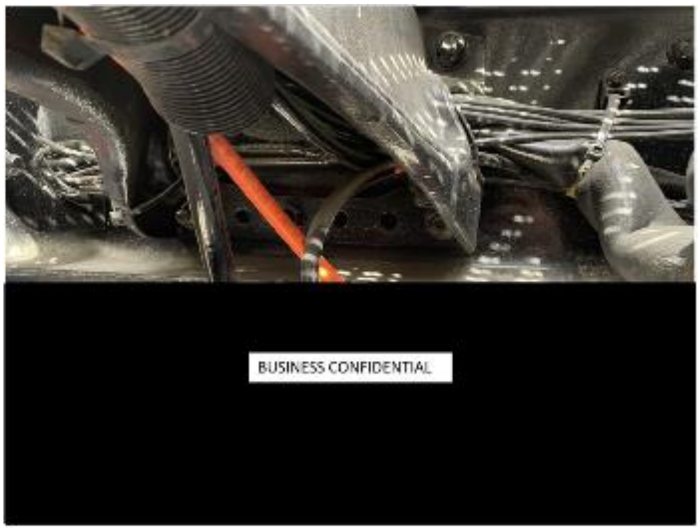


8. Route the XXX hose to the XXXXXXX
    - Drop down from the main bundle to the XXXXXXXXX on the left side of the truck.

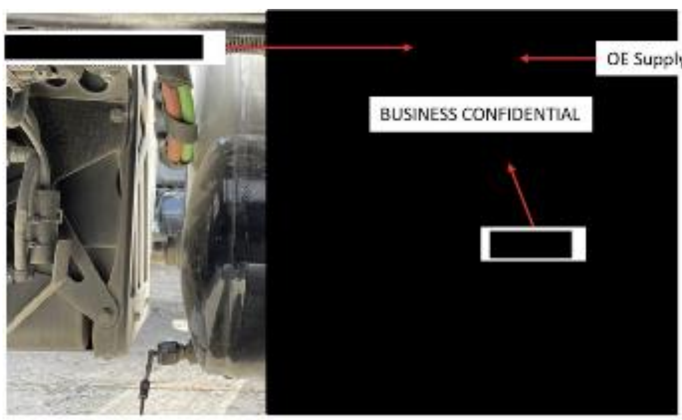


9. Route the XXXXXX hose along the back cross member to the XXXXX
    - Secure the hose to the OE hose bundle.

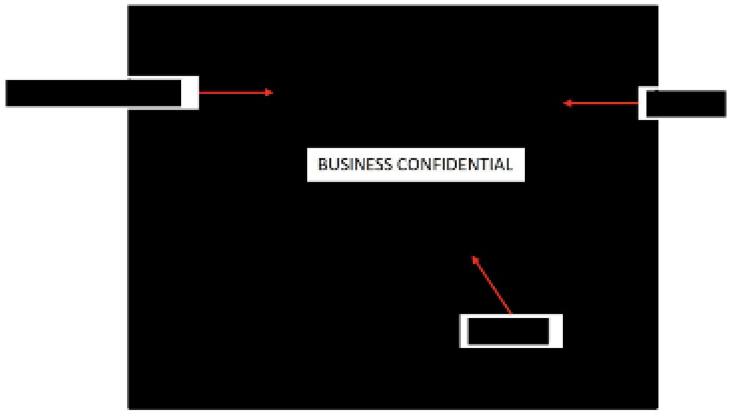

- Minimize the unsupported hose length as it XXXXXXXXXXX



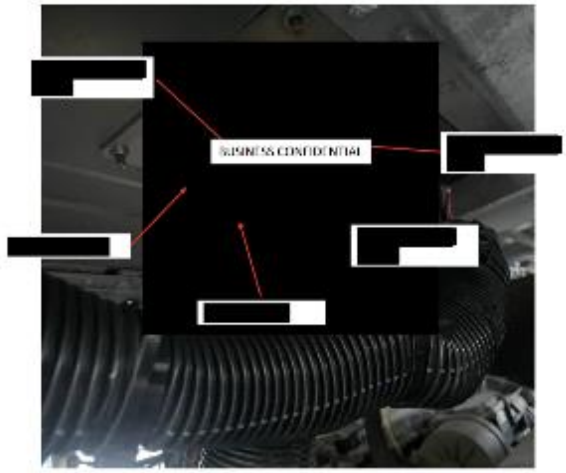
10. Spice in a XXX connection in the XXXXXXXXXXXXXXXXXX
    - Disconnect the OE hose with 5/8” air fitting wrench
    - Add a small section of XXXXXXXXXXX to XXXXXXXXXXXXXXXXXXXXXXXXX
    - Connect as shown with the Pronto XXX on the XXXXXXXXXX



11. Same as above

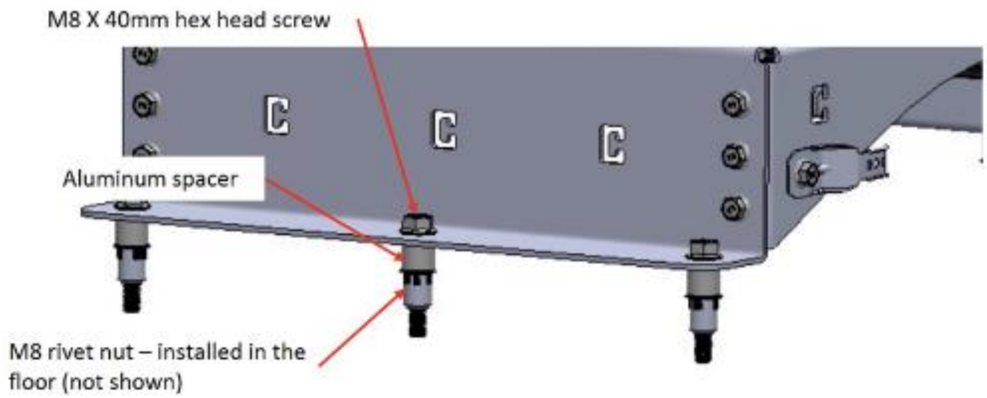


12. Install the hoses in the bulkheads.
    - Connect the hoses to the corresponding bulkheads.



Compute Box and Mount Installation

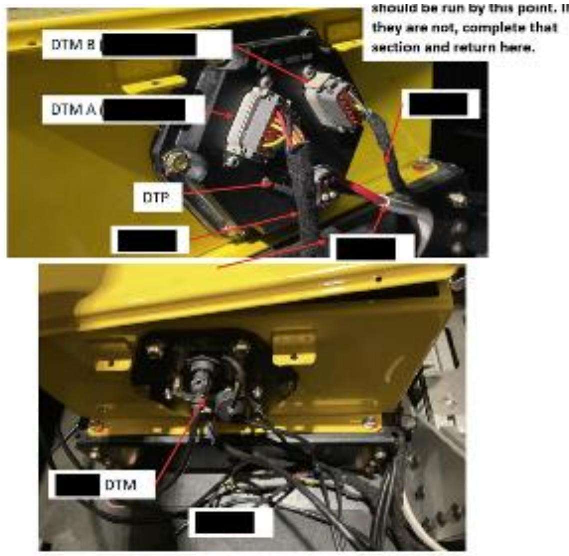
1. Prep parts and tools.
    - Consult the part and tool lists to ensure that everything is account for before starting work
2. Locate the mounting rivet nuts in the floor of the cab.
    - These are the 6 rivet nuts that were installed in the pass-through installation. They must be installed to continue. The floor mat and foam installation should be cut around the rivet nuts at this stage.
3. Place the spacers.
    - Place the aluminum spacers so they are lined up over the rivet nuts



4. Fasten down the compute mounting bracket assembly.
   - NOTE: the compute box should already be installed on the bracket
   - Line up the bracket over the mounting holes. Install the six M8 screws. Tighten to 15 Nm

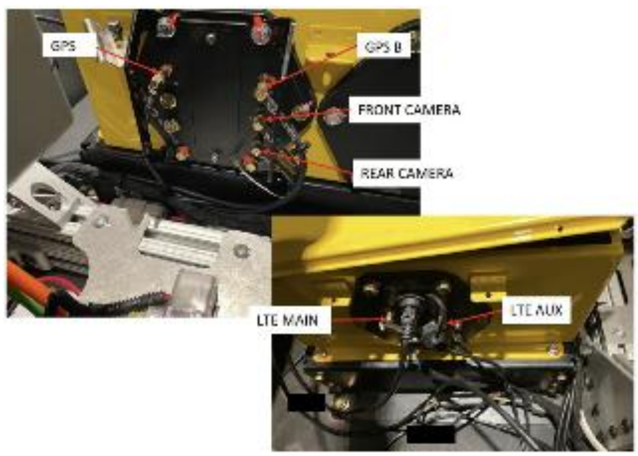
5. Connect the power disconnect to the side of the compute box.
   - The clip should already be installed on the compute mount.
   - Slide the DTP receptable into the clip until it latches in the orientation shown.

- Ensure that you are connecting to the correct bulkhead.



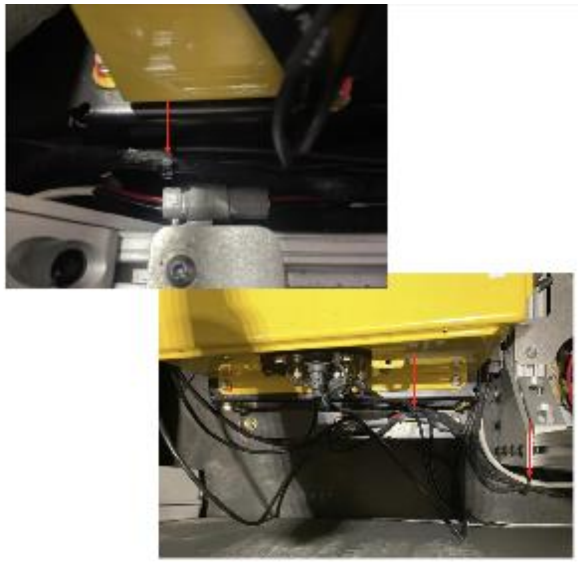
6. Connect the RF cables.

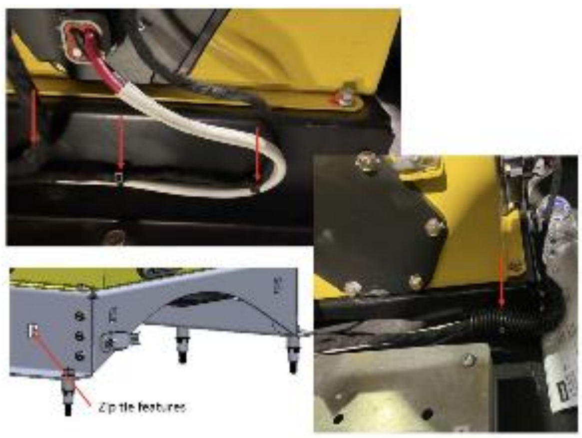
   - Connect each RF cable to its appropriate port (each port is labeled). Use a very small amount of Loctite 242 and tighten to 0.6 Nm.



7. Zip tie the harness and cables

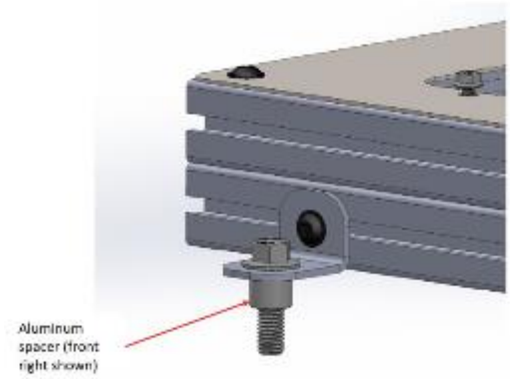
   - Secure the harness such that there is little slack with zip ties. There are zip tie features built into the mount.



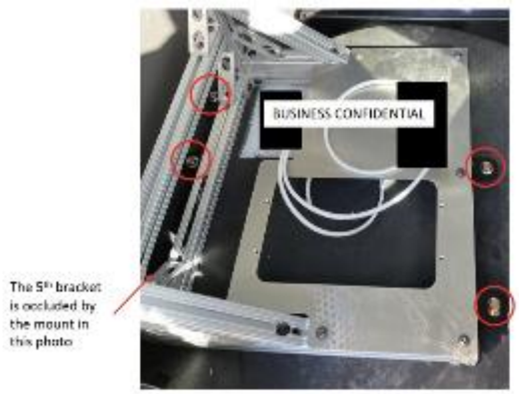


Brake System Installation

1. Prep parts and tools.
   - Consult the part and tool lists to ensure that everything is accounted for before starting work. Ensure the truck battery disconnect is off before starting any wiring work.
2. Locate the mounting rivet nuts in the floor of the cab.
   - This step is completed in the floor pass through the installation guide. Please reference that guide for the installation steps.
3. Cut the carpet/floor liner around the rivet nuts.
   - This step is completed in the floor pass through installation guide. Please reference that guide for the installation steps.
4. Place the spacers.
   - Place the aluminum spacers so they are lined up over the rivet nuts

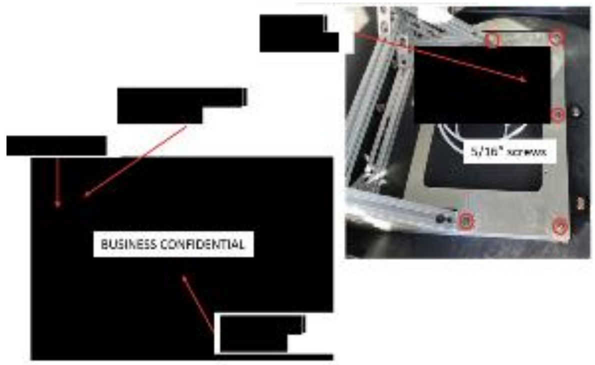


5. Fasten down the brake box mounting bracket.
    - Place the brake box mounting bracket so the L-brackets on the frame line up with the rivet nuts. For each of the 5 holes, thread the M12 screw through the spacer and into the rivet nut. Tighten to 20 Nm.
    -

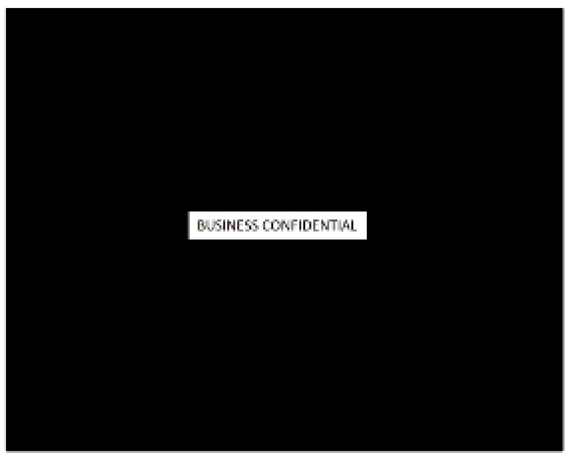


    - NOTE: the location of the L-bracket is present but if they need to be adjusted, the 5/16” screw can be loosened, and the bracket can be slid down

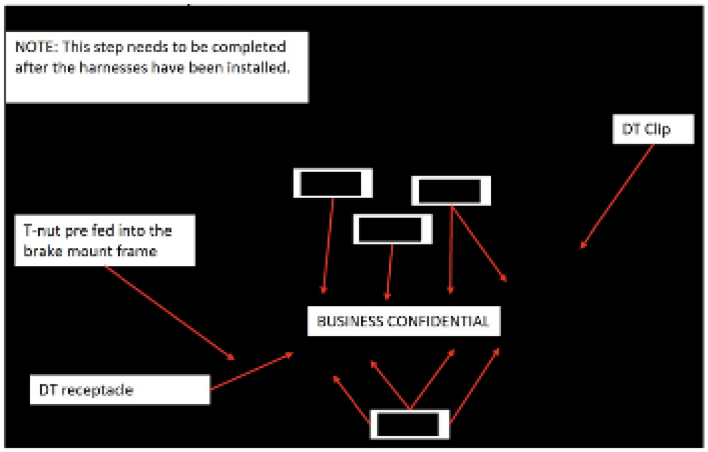
6. Connect the XXX
    - Remove the Squid plate to access XXXXX
    - Connect the XXXXX. The XXXX should already be installed XXXXXXXX



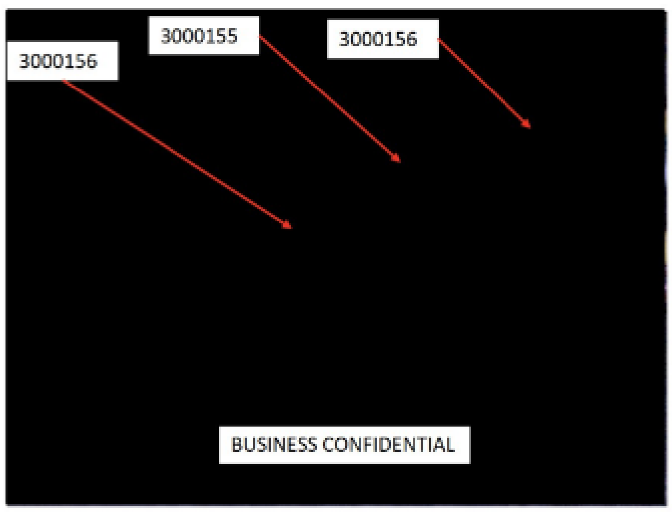
7. Connect the interior brake hoses to the bulkhead.
    - The hose lengths should be precut and labeled with pressured sensors installed. Install them in the corresponding bulkheads.



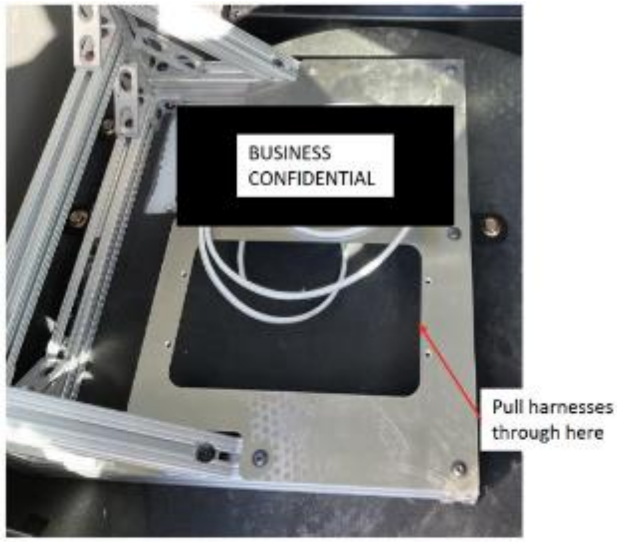
8. Attach the harness DT clips to the brake mounting bracket.
    - Slide the receptacles into the clips and install the clips into the t-nuts with the short 5/16" screws. Torque to 15 Nm
    - Connect the corresponding harnesses to the receptacles.



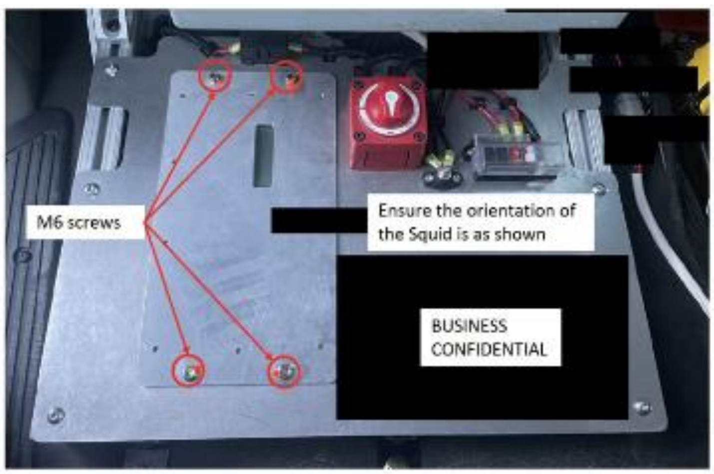
9. Connect the harness to the pass through bulkhead connectors
    - Connect the three Deutsch connectors into the bulkheads on the pass through.
    - Zip tie the harness to provide strain relief



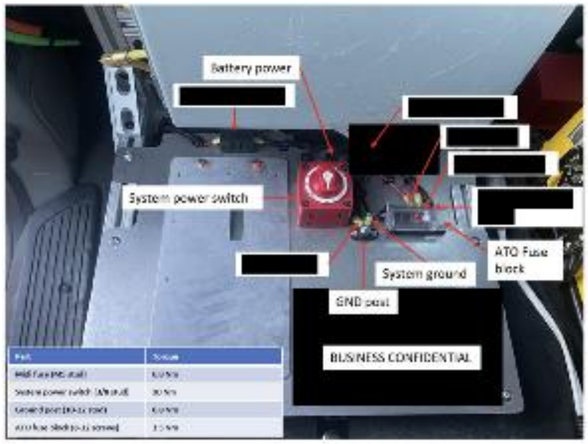
10. Connect the Squid harness.
    - Route the Squid harness through the opening in the Squid mounting plate.
    - Connect the 2 XXXs. Ensure that the caps are in place.



11. Fasten down the Squid.
    - Use the four M6s to fasten down the Squid enclosure to the Squid mounting plate. Torque to 10 Nm.



12. Complete the power wiring on the Squid mounting plate.
    - Connect the XXXX ring terminals on the harness XXXX to the Midi fuse.
    - Connect the GND ring terminal on the harness to the GND post.
    - Connect the ring terminal from the battery on harness XXX to the hot side of the system XXX witch.
    - Connect XXX to the XXXXXXXXX and to the input of the ATO fuse block.
    - Connect the XXX harness (XXX) to the ATO fuse block and GND post.
    - NOTE: refer to the wiring diagrams for more information

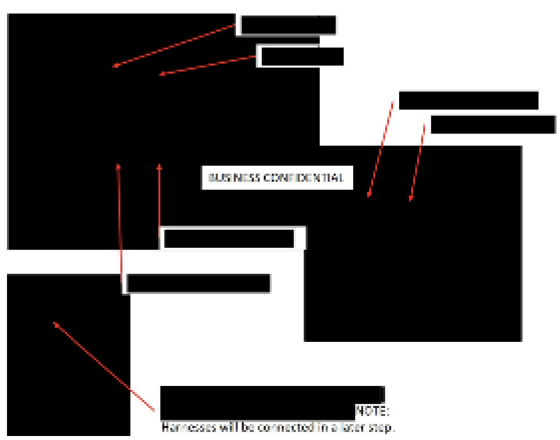


13. Fasten down the brake box.

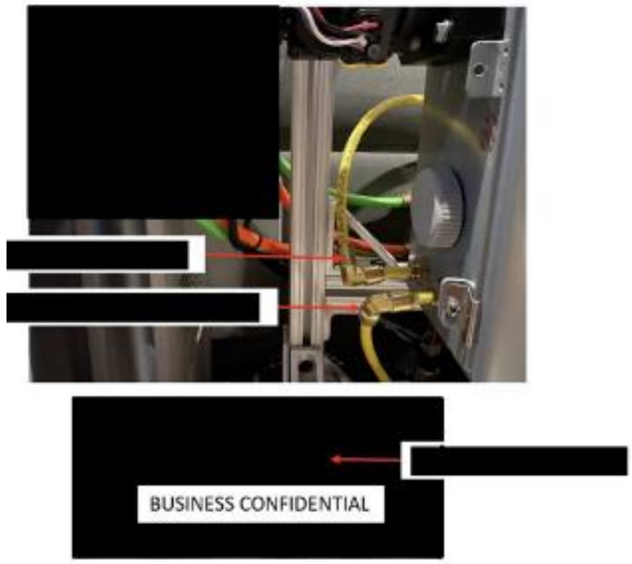
- Install the four 5/16" screws into the flange of the brake box. There are two on the top (pictured) and two on the bottom.
- The t-nuts will already be installed on the rail for the bottom two screws. The t-nuts for the top two screws will need to be installed at this time.

14. Route the interior brake hoss from the floor bulkhead to the brake box

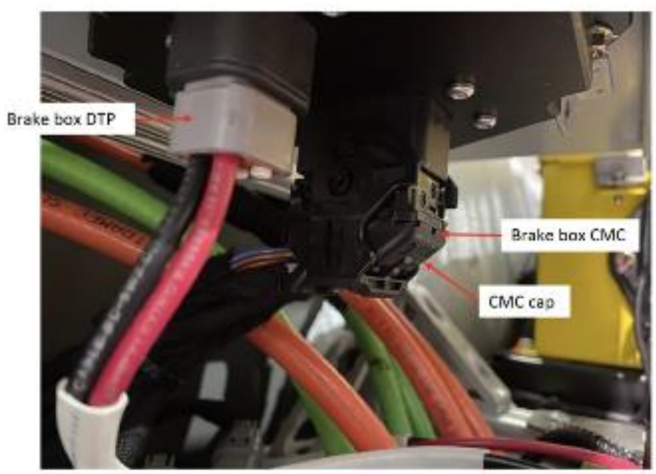
- Connect each hose to its appropriate port. The brass XXXXXXXXXXXX will already be installed.



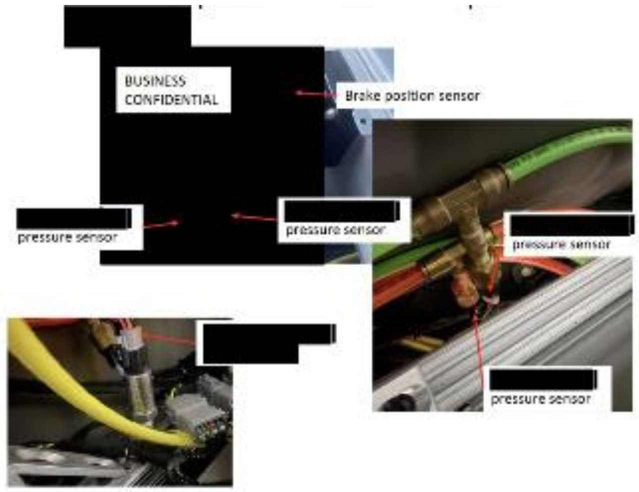
15. Connect the XXXX to the brake box.
    - Connect the XXXXXXXXXXXXXXXXXXXXXX to the bulkhead on the box.
    - Connect the XXXXXXXXXXXXXX line to the bulkhead on the box.



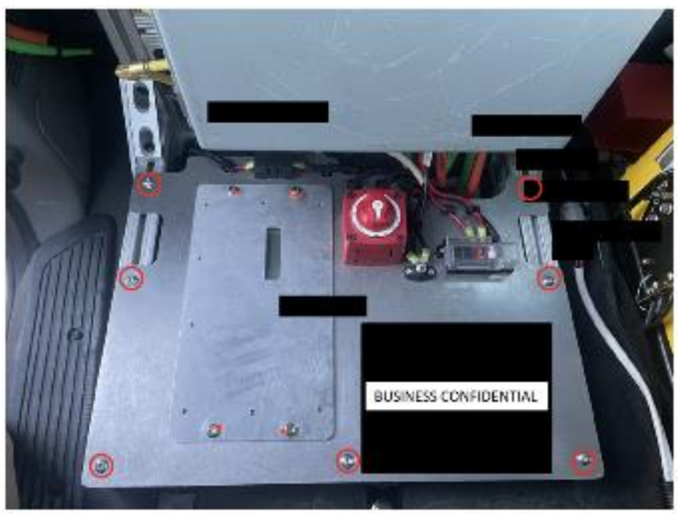
16. Connect the harness to the brake box bulkhead.
    - If the interior harnesses have not been run, please complete that section before returning.
    - Conet the CMC and the DTP. Ensure the cap is installed.



17. Connect the pressure sensor and brake position sensor harness.
    - The pressure sensors are 3 pin DT (XXX)
    - The brake position sensor is a 7 position.

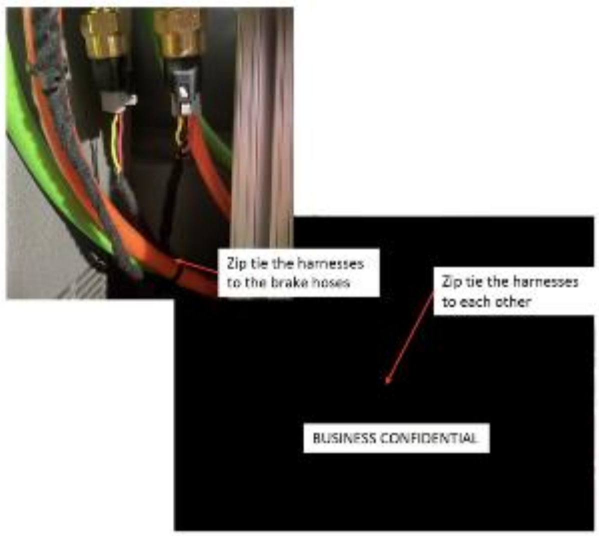


18. Fasten down the Squid mounting plate.
    - Reinstall the short 5/16” screws removed in step 6. Tighten to 15 Nm



19. Add hose protection and zip ties.
    - Where the hoss curve around the bracket, wrap them in corrugated sleeving and then tesa tape. Add zip tie brackets to the 8020 as necessary.

20. Strain relief and zip tie the brake harnesses.



Andon Light Installation

1. Prep all parts and tools.
2. Remove the trim panels.
   - The hood must be up to remove the trim panels.
   - Once the hood is up, there are 4 bolts per side. Remove it with a socket wrench or electric driver.
   - Set aside the trim panels.
3. Trim the hood.
   - The corners of the hood will interfere slightly when the Andon light brackets are installed. Mark the hood as shown and cut with a composite blade on a Sawzall. Clean the edge with a router if necessary.

4. Install the Andon mounting brackets.
   - There are two mounting brackets per side. Install them into the 4 holes that were previously securing the trim panels.
   - Use the OE screws and torque to 35Nm.

5. Install the Andon light assemblies.
   - Fasten the 6 M6 screws from the front of the truck into the pems on the first two brackets. Loctite with 243 and Torque to 10 Nm

- Return here after completing the external harness routing.

6. Connect the harness to the lights.
   - Connect all 6 lights. Take care to connect the right harness branch to the correct light. Zip tie the harness to the bracket as needed

7. Check the hood clearance.
   - Close and open the hood to check the clearance. If needed, repeat step 3, removing more material.

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8. Check door clearance.
    - Open the doors to ensure there is no interference with the lights or any other equipment. Consult Engineering if that is the case.

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