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

Chapter 5.7 ADS Road Assessment System

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Abstract

Automated Driving Systems (ADS) are set to revolutionize the transportation system. In this project, the research team led by the Virginia Tech Transportation Institute developed and documented a concept of operations (CONOPS) that informs the trucking industry, government agencies, and non-government associations on the benefits of ADS and the best practices for implementing this technology into fleet operations.

The sections of Chapter 5 provide 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.

The chapter describes a concept of a road readiness assessment system for trucks equipped with Automated Driving Systems (ADS), developed using datasets from cross-country deployments. This system distinguishes between roadways that are suitable for ADS-equipped trucks and those that may require human oversight or novel mitigations for operational stability. It integrates data on roadway infrastructure with the vehicle's assessment of road conditions through its kinematics. Considering the variations in ADS technology among different developers, a more advanced road readiness system was also developed. The assessment system is designed to be adaptable, enabling future integration with specific proprietary algorithms from ADS developers. The report illustrates how these systems have been applied to U.S. interstate highways, using data from Pronto, an ADS developer.

Government agencies can employ this system to assess their state roadway systems, which is a critical preliminary step towards implementing ADS. Moreover, the report offers recommendations and outlines next steps for stakeholders to ready U.S. roadways for ADS trucking operations.

The following chapter has been extracted from the final report. For access to the full report, see this link: https://www.vtti.vt.edu/PDFs/conops/VTTI_ADS-Trucking_CONOPS_Final-Report.pdf

5. GUIDELINES

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 1. 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

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
							& WB, I-880 EB & WB
Delaware	16					16	I-85 SB, I-295 SB
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-

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
							35W SB, I-40 EB & WB, I-44 WB, I-635 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.
1. Add a location code to the file, as described above.

2. Based on the location code, select the records representing travel in the mainline lanes of Interstate highways for analysis.
3. Add supplementary variables from the FHWA HPMS database, as described above.
4. 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.
5. Tabulate distributions of key assessment measures by distance traveled for individual routes, individual States, and all States combined.
6. Create graphs of selected distributions of key assessment variables.
7. 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 2. 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

Range of Road Lane Score	Total Length of Roadway (mi)	Percentage of Roadway Length	Cumulative Percentage of Roadway Length
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.

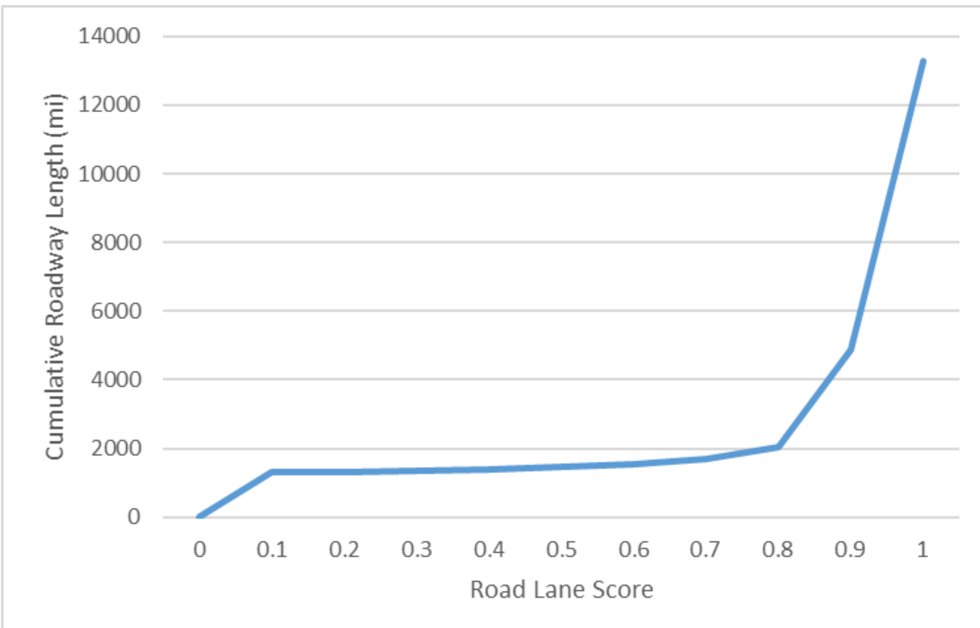

Figure 1. Graph. Cumulative distribution of road lane scores by road length based on cross-country drive data for interstate highways.

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 3. 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.

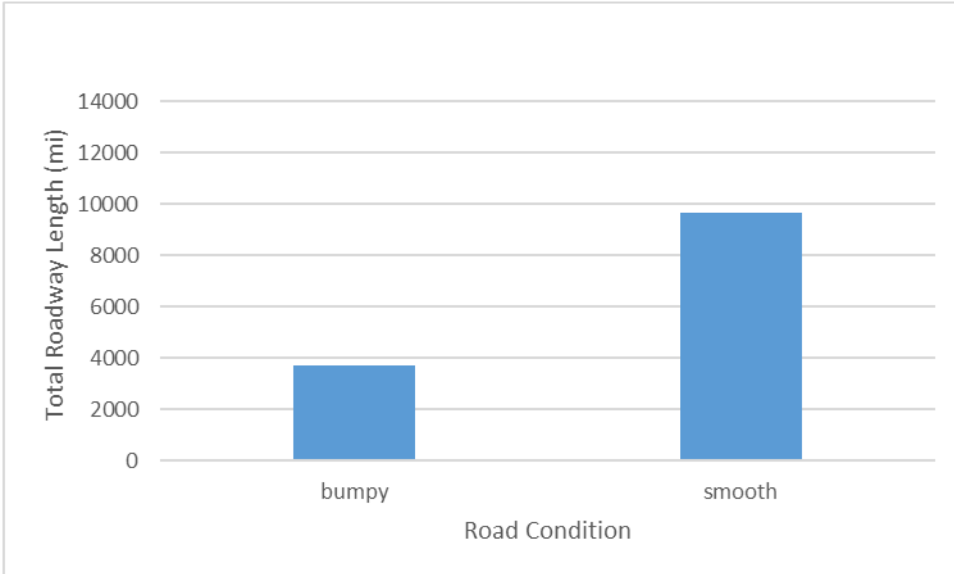

Figure 2. Chart. Distribution of road condition categories by road length based on cross-country drive data for Interstate highways.

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 4. 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)

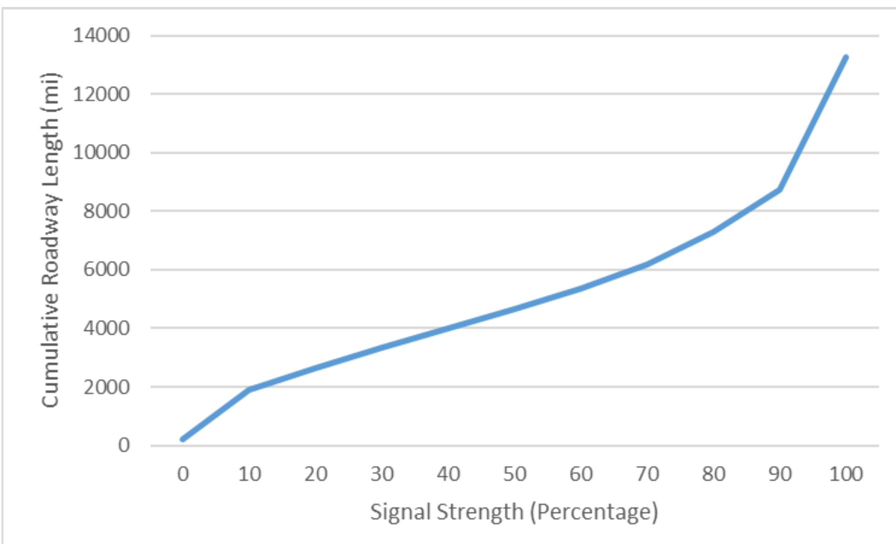

Figure 3. Graph. Cumulative distribution of cellular LTE signal strength by road length in cross-country drive data for Interstate highways.

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 5. 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
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	--

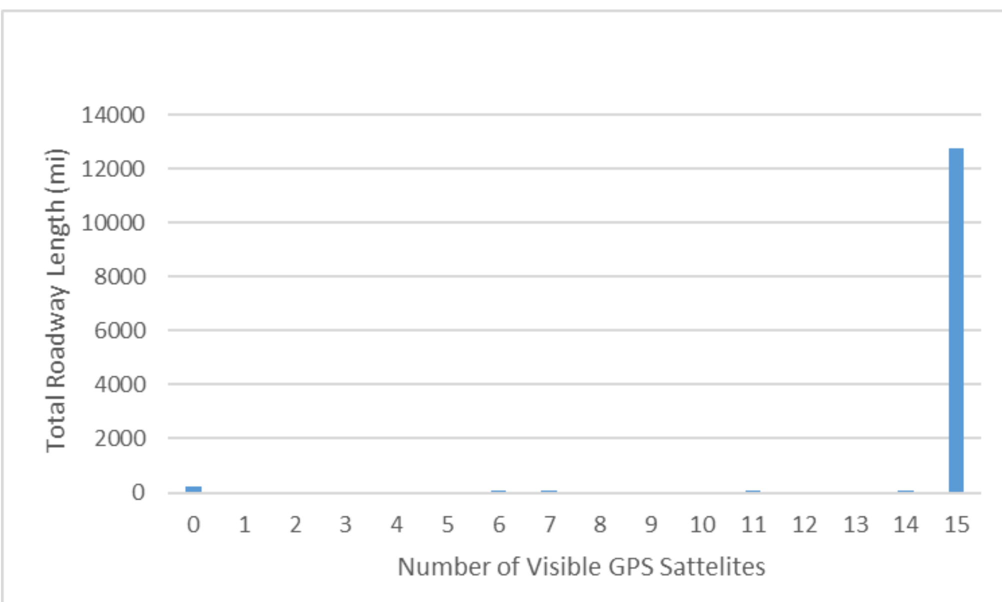

Figure 4. Chart. Distribution of number of GPS satellites visible by road length based on cross-country drive data for Interstate highways.

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 6. 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 7. 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)

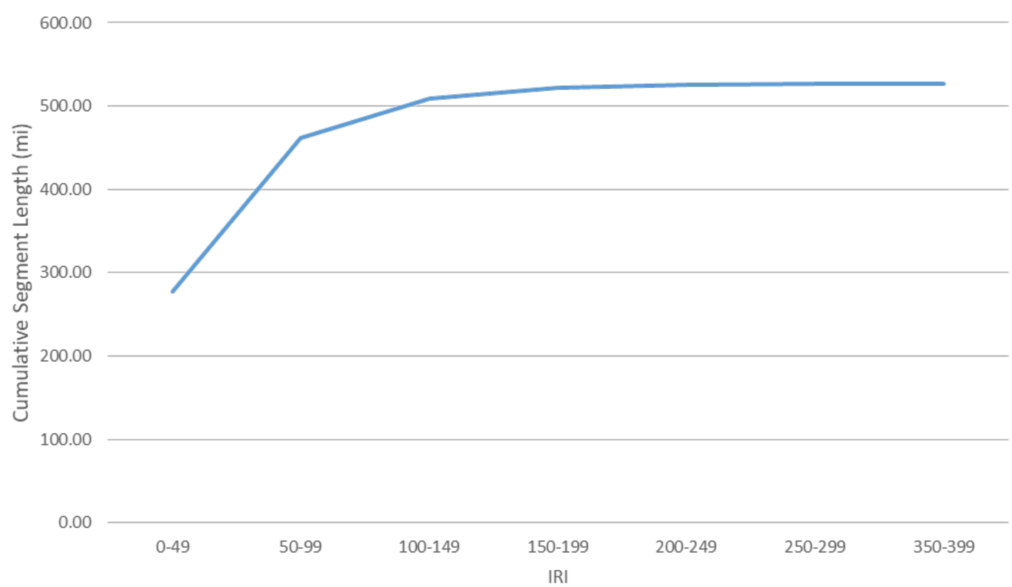

Figure 5. Graph. Cumulative distribution of IRI by road length for the Interstate highway sites included in the five cross-country drives.

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 8. 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 9. 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 10. 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 11. 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 12. 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 13. 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.

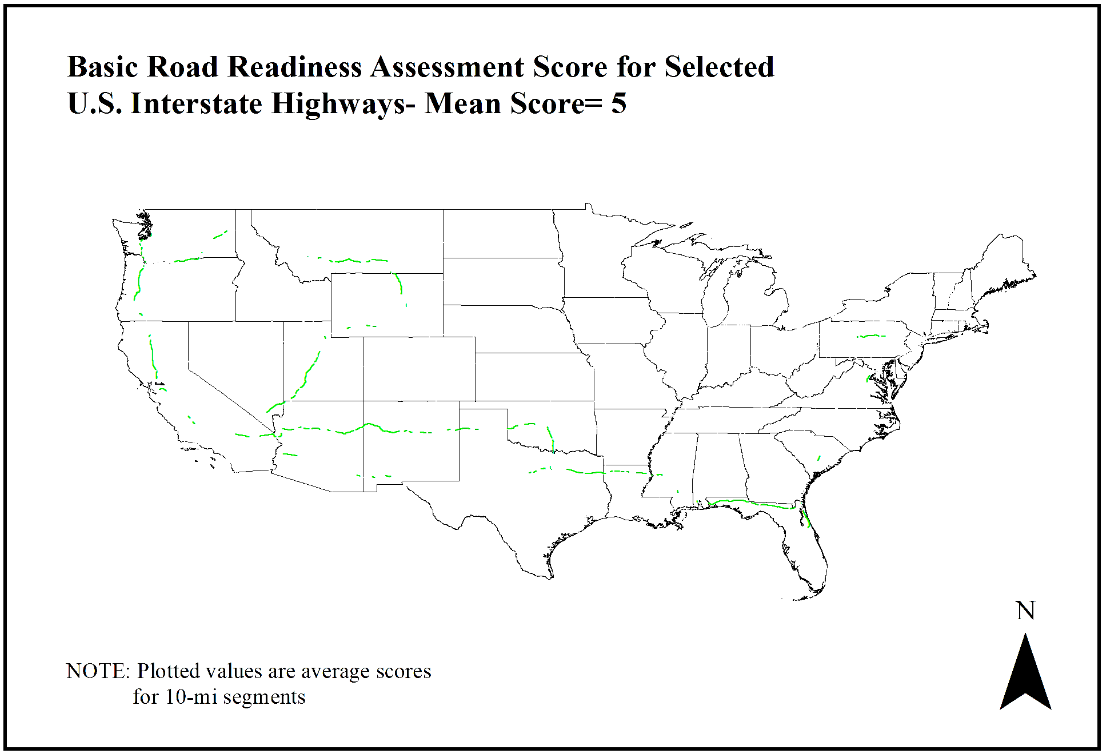

Figure 6. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean score = 5.

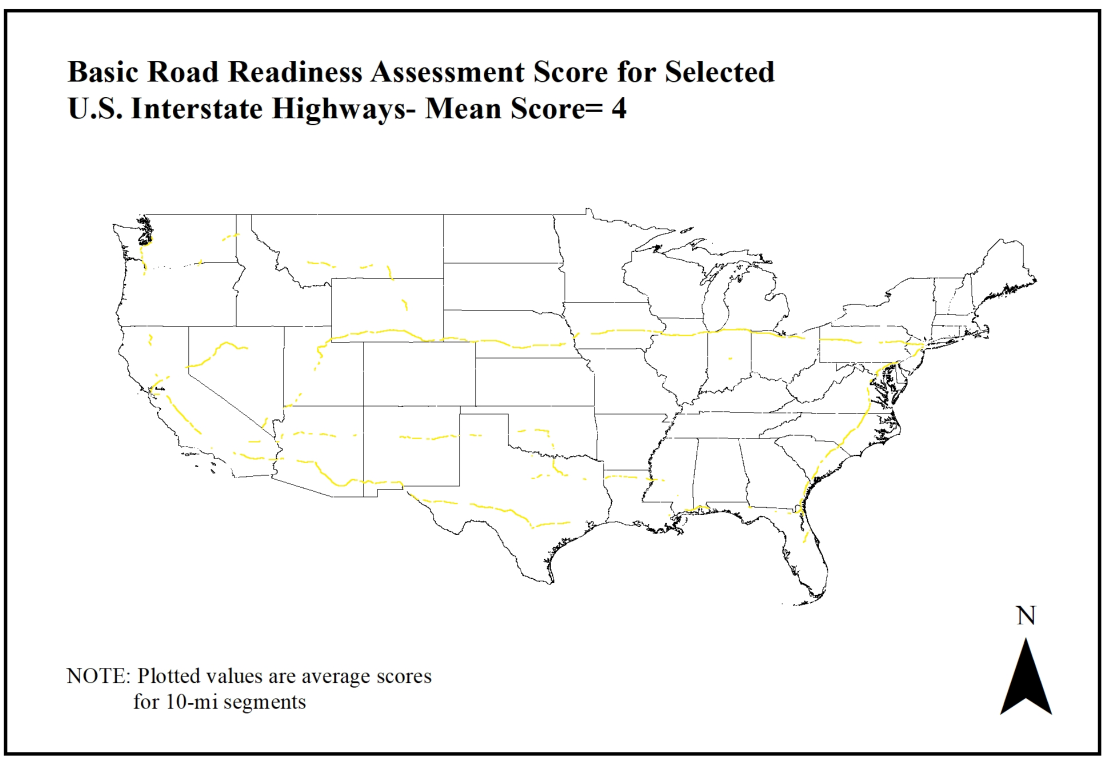

Figure 7. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean score = 4.

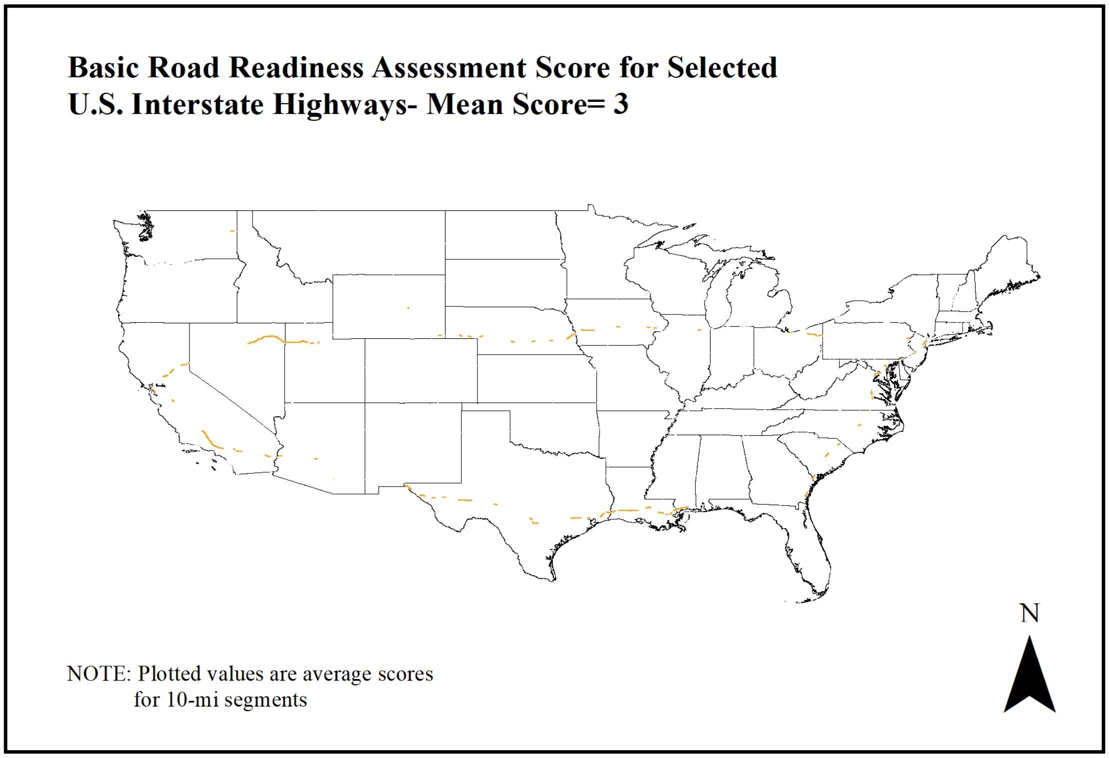

Figure 8. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean score = 3.

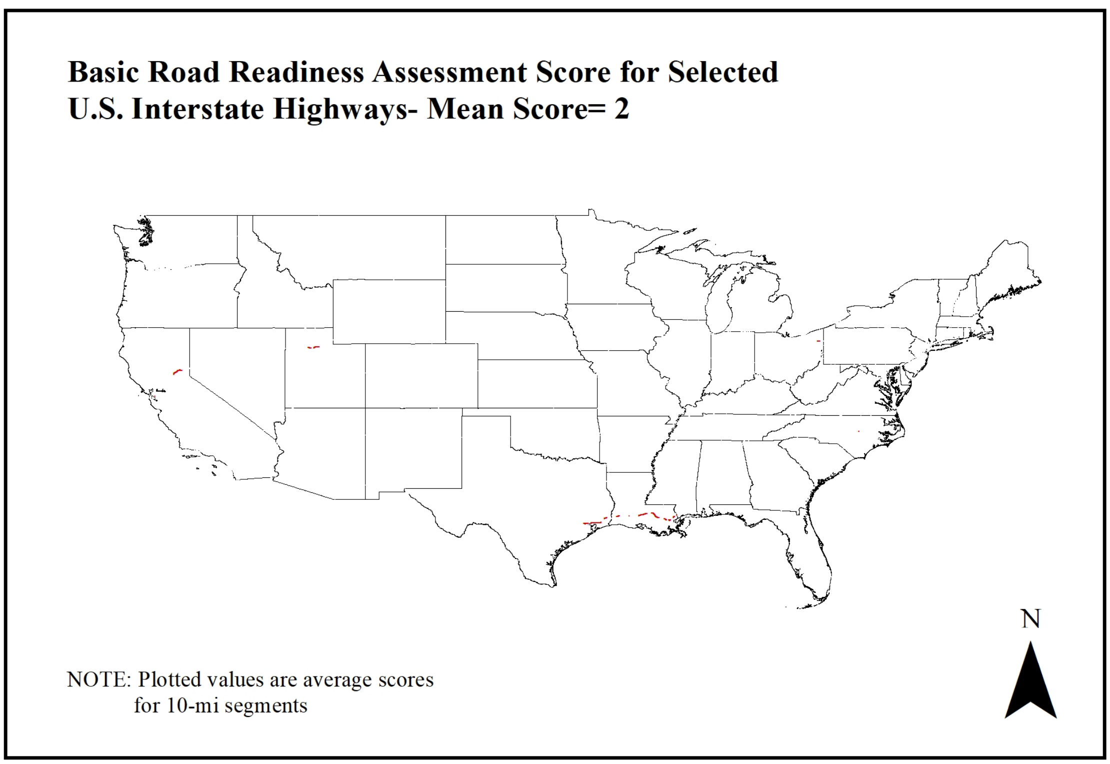

Figure 9. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean score = 2.

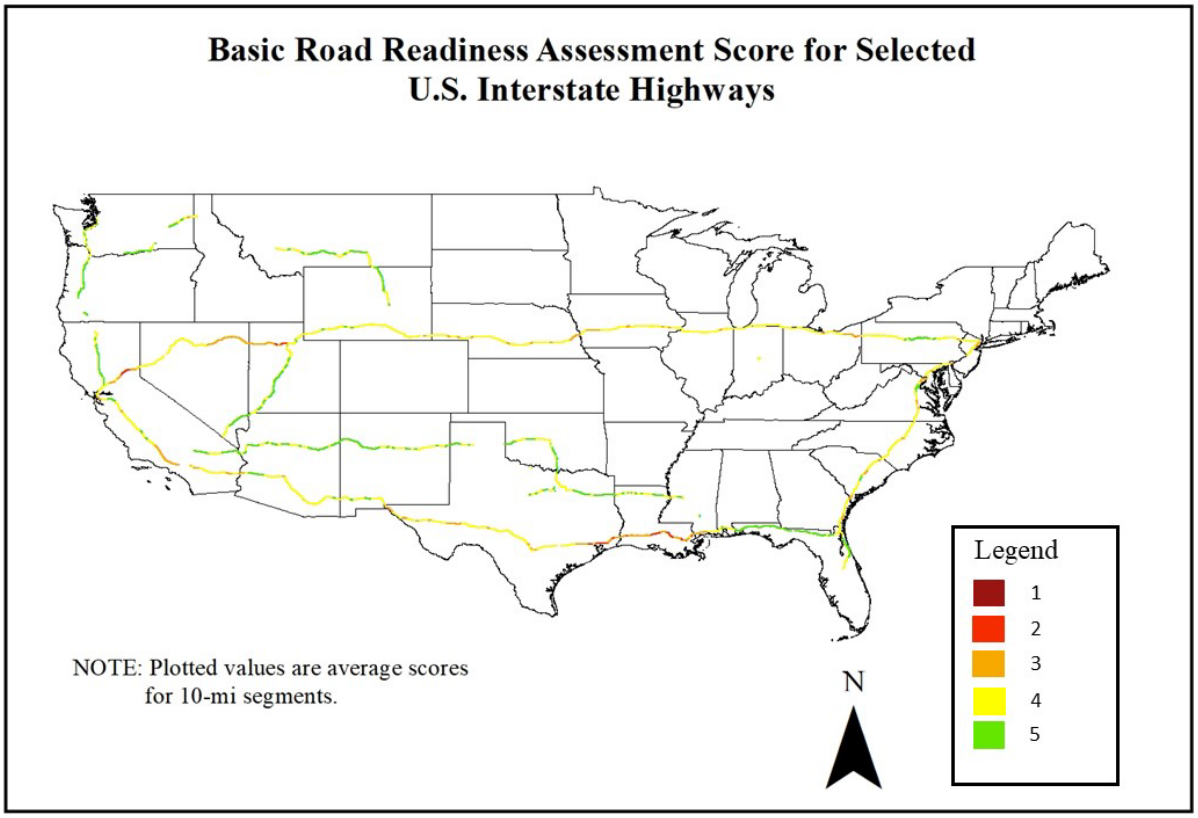

Figure 10. Map. Basic road readiness assessment score for Interstate highways (based on 10-mile averages from the cross-country drives), mean scores combined.

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 14. 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 15. 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 16. 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[(1)]) 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 11. 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[2] 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 12. 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.

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[1] Honda, H., & Uchida, Y. (2023). CLRerNet: Improving Confidence of Lane Detection with LaneIoU. arXiv preprint arXiv:2305.08366.

[2] Honda, H., et. al. (2023).