Defining Operating Limits of Inertial Profilers with Single-Axis Accelerometer

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Single ***A***xis ***A***ccelerometer

SAA response affected primarily by:

- Geometric tilt from vertical as is generally the case because of test vehicle roll and pitch
- Angular accelerations in horizontal and vertical curves
- Data Acquisition processes and numerical integration algorithms

1. Objectives

- Develop a procedure that will lead to the recommendation of guidelines regarding the use of road profiling equipment based on a single-axis accelerometer (SSA) to measure pavement roughness for purposes of construction acceptance, asset management, and pavement research.
- Translate the complex limitations of SSA profiling system into practical operational constraints for typical profiler platforms and measurement systems that report either the International Roughness Index (IRI) or Ride Number (RN).
- Propose a method/procedure to monitor the operating conditions during field use of SSA profiling systems to evaluate the validity of data.

2. Method 1

Focus on the need to estimate the level of error of SAA inertial profiling systems for typical vehicle platforms using linear dynamic simulations using CARSIM, given a vehicle platform, its speed profile, and the geometry of the road.

2. Method 1 (continued)

(i) Using a vehicle simulation software (CARSIM), for a desired range and combination of horizontal alignment, vertical alignment, Cross-slope, and vehicle speed, (and possibly transition areas) produce the vehicle response, including vehicle orientation and body accelerations. The simulation results will document the difference in response among the typical profiler platforms. The output of the simulation task is a look-up table for the vehicle orientation and accelerations.

2. Method 1 (continued)

(ii) Given a road geometry and vehicle speed profile, estimate error potential in profile estimate. Given a vehicle platform and its speed on a road-geometry, estimates of pitch and roll and body accelerations can be made with the look-up tables produced in (i). The level of error due to change in speed, cross-slope, grade, and horizontal curvature is quantified.

2. CARSIM Model

2. CARSIM Output

Given Vehicle type (Van), DOC (10), and grade (0%)

E	V	Roll	Pitch	Longitudinal a x	Lateral a y	Vertical a z
-0.02	20	4.4602	0.092301	-0.00028402	0.046646	2.72E-08
	30	4.8228	0.080916	-0.00046425	0.10497	-5.97E-08
	40	5.337	0.063565	-0.00034028	0.18647	-7.53E-08
	50	6.0112	0.051693	0.00067627	0.29105	-1.33E-07
	60	6.8282	0.048703	0.0034534	0.41785	-3.92E-05
	70	7.9064	0.057689	0.010817	0.57815	0.00075795
0	20	0.29516	0.070245	-0.00037579	0.046668	7.50E-11
	30	0.65894	0.06808	-0.00067289	0.10503	-3.34E-11
	40	1.1742	0.061306	-0.00076678	0.18661	1.72E-09
	50	1.8547	0.064641	-0.00020384	0.29129	-5.95E-08
	60	2.6882	0.087085	0.0017199	0.41881	-1.98E-07
	70	3.7036	0.14155	0.0060457	0.57008	-2.18E-06

Etc…. For E = 0.02, 0.04, 0.06, 0.08, 0.10

2. CARSIM Output

Given Vehicle type (Van), DOC (10), and grade (0%)

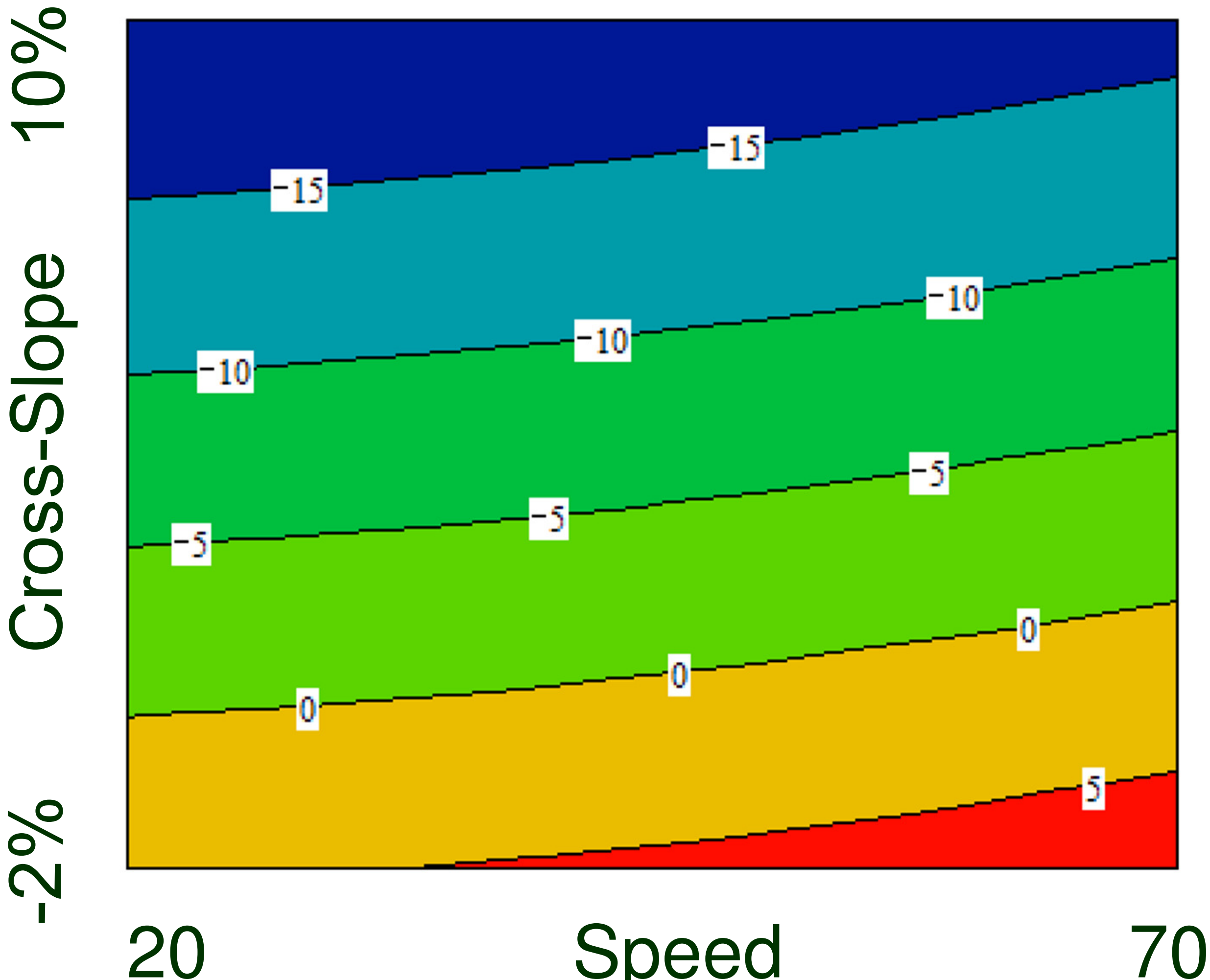
Speed

Cross-Slope

Roll	20	30	40	50	60	70
-0.02	4.460	4.823	5.337	6.011	6.828	7.906
0.00	0.295	0.659	1.174	1.855	2.688	3.704
0.02	-3.871	-3.504	-2.993	-2.317	-1.474	-0.474
0.04	-8.004	-7.632	-7.120	-6.462	-5.618	-4.613
0.06	-12.064	-11.695	-11.181	-10.528	-9.707	-8.701
0.08	-16.019	-15.657	-15.152	-14.501	-13.695	-12.706
0.10	-19.840	-19.488	-18.996	-18.358	-17.561	-16.598

2. CARSIM Output

Given Vehicle type (Van), DOC (10), and grade (0%)



2. Method 2

Develop a deployable (cost-effective and practical) solution that addresses the limitations of the SAA inertial profiling.

It requires both hardware and software modifications to existing SAA systems to estimate horizontal curvature, and vehicle roll and pitch.

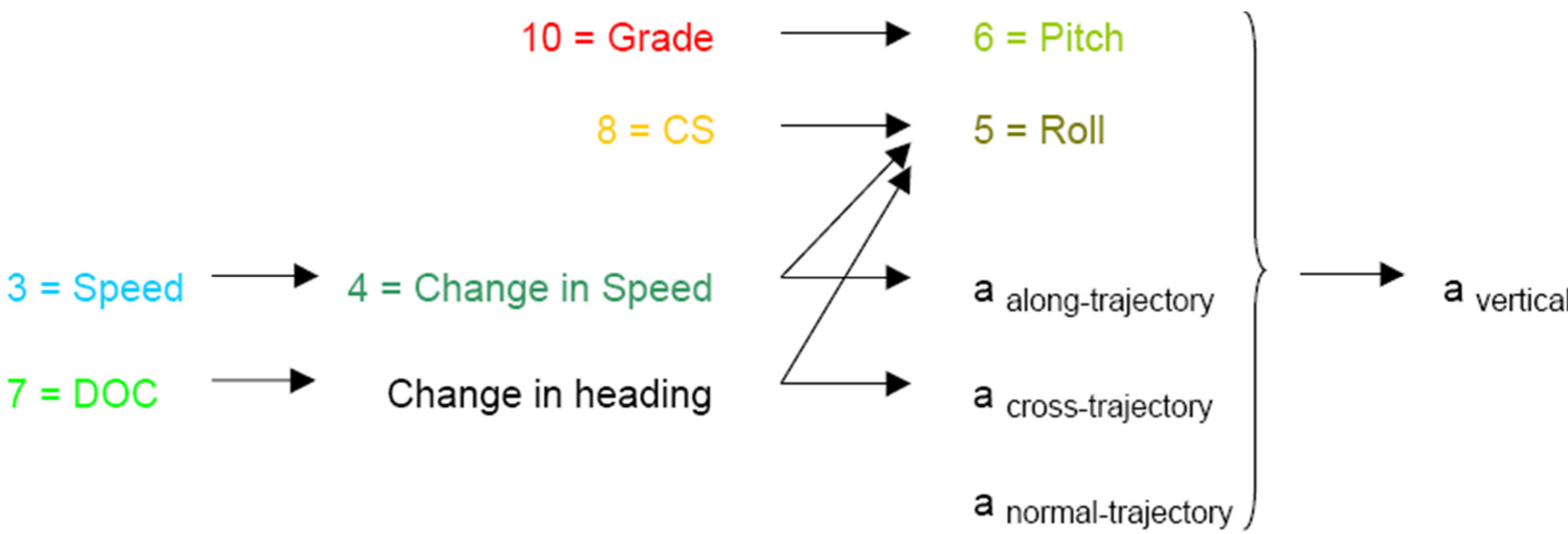
2. Method 2 (continued)

For the definition of a device that can measure 3-D effects on a SAA, a gyroscope-based solution provides the required vehicle platform data to eliminate the errors sources identified.

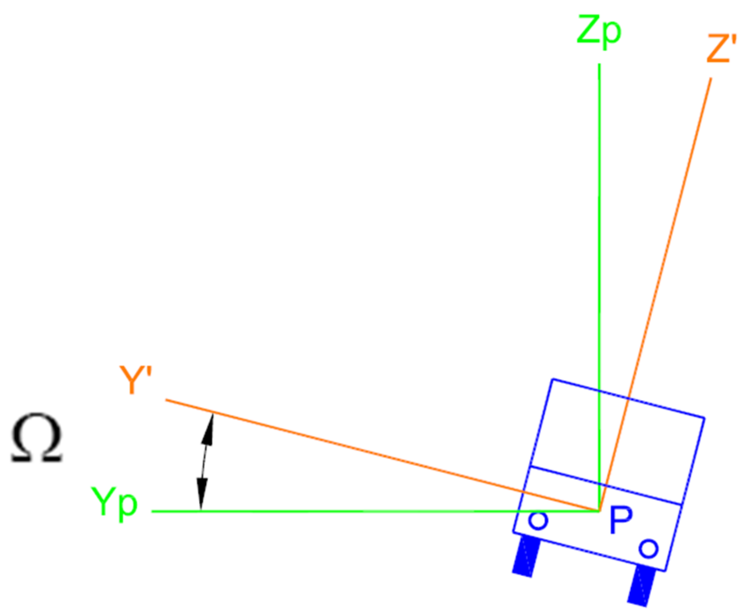
Speeds higher than 20mph limits the choice of sensor to estimate roll and pitch. Inclinometers work well at lower speeds.

3. Observations

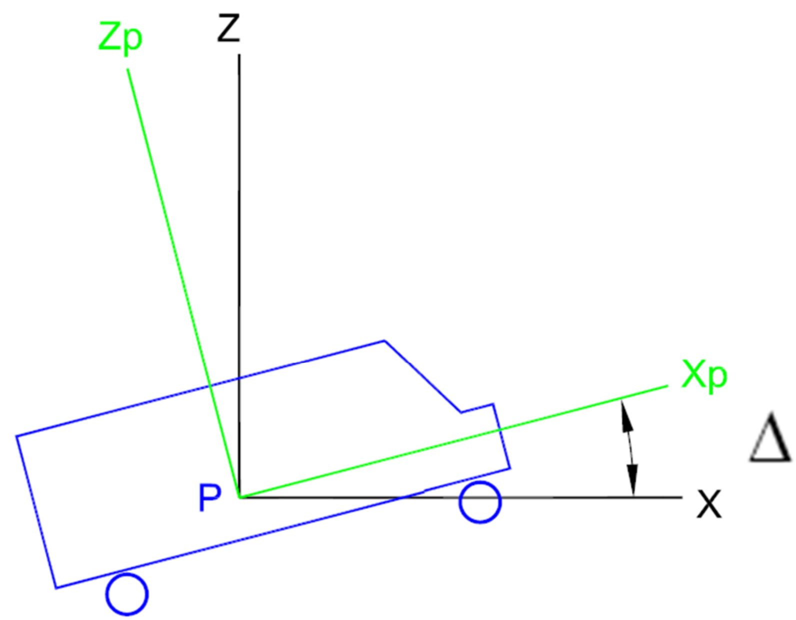
Speed and Roll are still the primary factors on the roughest segments.



3. Correction of 1-D acceleration based on 3-D solution



2) Roll



1) Pitch

3. Error Model based on 3-D Solution

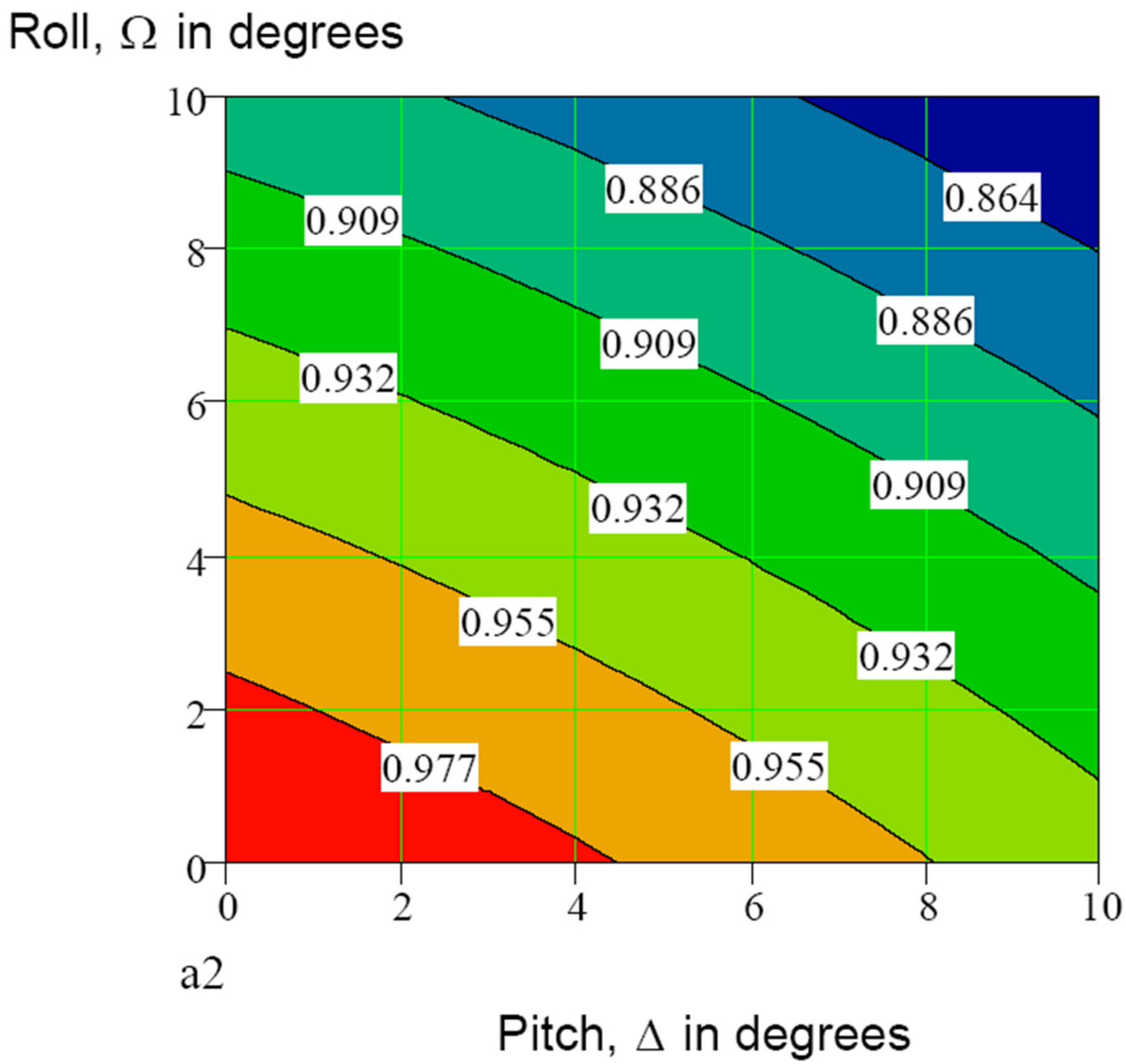
The direction cosines of interest in this study are those related to the normal vertical axis, defined in the body triad system: $\begin{bmatrix} n_{\vec{k}_1'} \\ n_{\vec{k}_2'} \\ n_{\vec{k}_3'} \end{bmatrix} = \begin{bmatrix} -\sin\Delta \\ -\cos\Delta\sin\Omega \\ \cos\Delta\cos\Omega \end{bmatrix}$

The equivalent normal acceleration, expressed in terms of the body accelerations, is equal to:

$$a_z = -\sin\Delta\, a_{x'} - \cos\Delta\sin\Omega\, a_{y'} + \cos\Delta\cos\Omega\, a_{z'}$$

3. Example 1

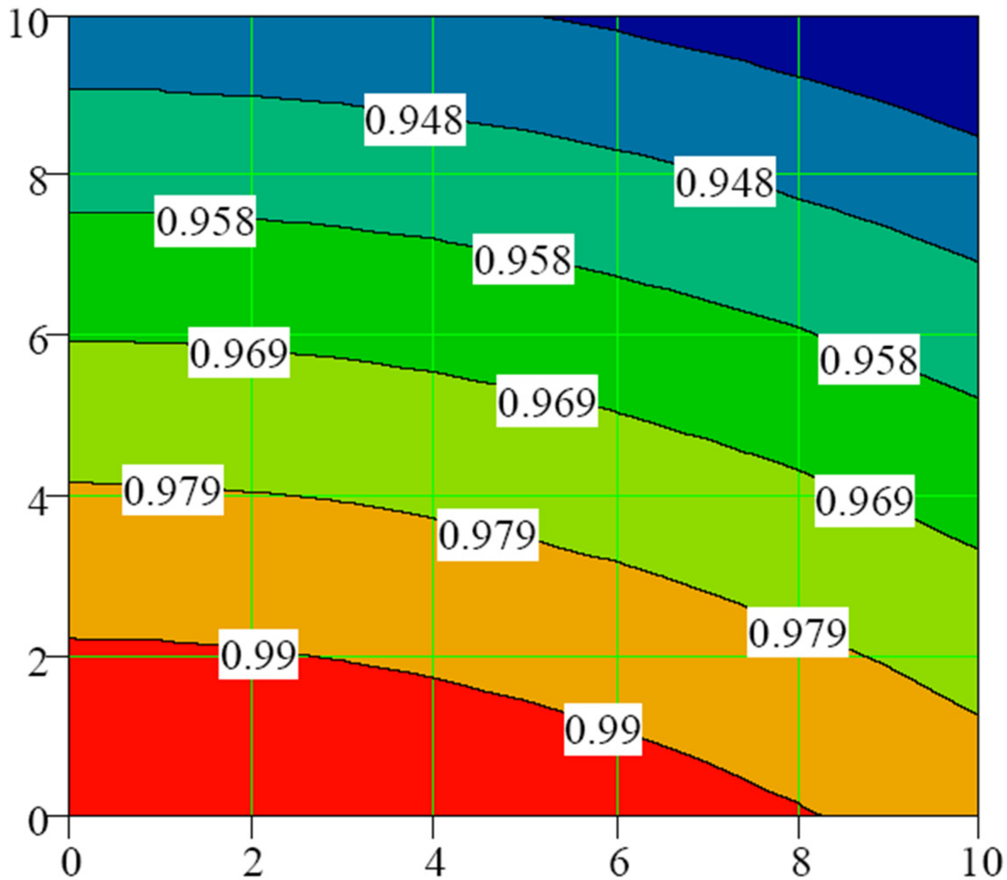
$$a2_{i,k} := -\sin(\Delta_i)\cdot 0.25 - \cos(\Delta_i)\cdot\sin(\Omega_k)\cdot(0.5) + \cos(\Delta_i)\cdot\cos(\Omega_k)\cdot 1$$



3. Example 2

$$a3_{i,k} := -\sin(\Delta_i)\cdot 0. - \cos(\Delta_i)\cdot\sin(\Omega_k)\cdot(0.25) + \cos(\Delta_i)\cdot\cos(\Omega_k)\cdot 1$$

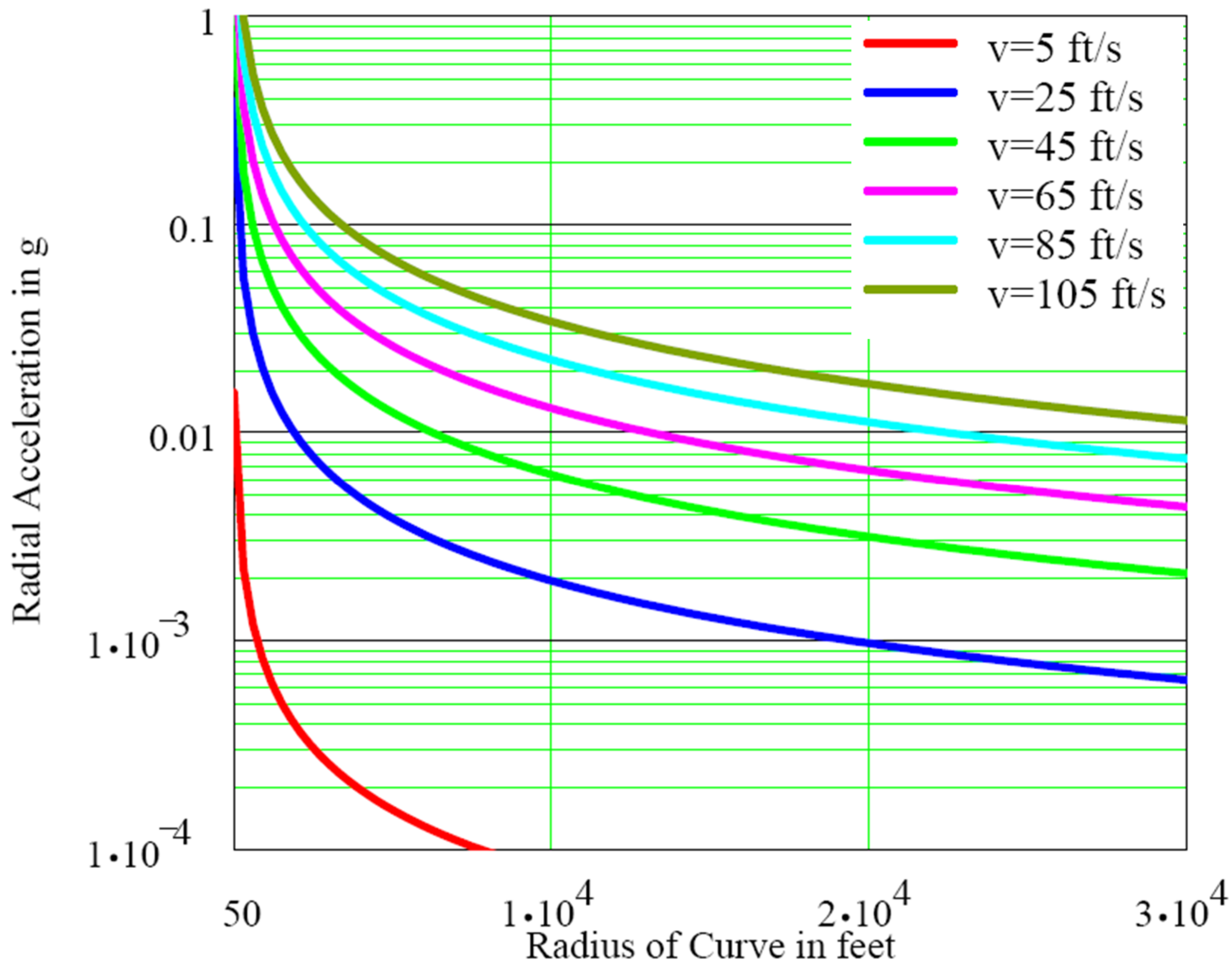
Roll, Ω in degrees



a3

Pitch, Δ in degrees

4. Speed/Curvature vs. Cross-Trajectory Accelerations



5.1. Simulation Step: Understanding differences between vehicle platforms

a. Define model for four typical SAA platforms for simulation: Pickup, SUV, Van, & ATV .

b. Define ranges of grade, cross-slope, and degree of curve combinations.

c. For speed ranges of 25mph to 70mph, perform analysis of vehicle response for conditions defined in b. and c. The analysis of vehicle response in three dimensions includes the estimation of vehicle roll, vehicle pitch, and the three vehicle body accelerations.

d. Organize simulation output as a look-up table, with grade, cross-slope, degree of curve, vehicle speed as input.

5.2. Analysis Step: Estimating level of error in vertical profile

a. For a road geometry and vehicle speed profile, generate the estimate along the vehicle path of the vehicle roll, vehicle pitch, and the three vehicle body accelerations.
b. Based on the error model, compute the estimate of accumulated error for the road geometry and the vehicle speed profile.

5.3. Synthesis Step: Collecting the right data and processing the data right

a. Collect pitch, roll, and body acceleration in three-dimensions using the proposed next-generation inertial profiling system.
b. Compute vertical profile using three-dimensional information on the vehicle platform orientation and body accelerations.
c. Estimate grade and degree-of-curve.

5.4. Validation Step: Checking simulation results and estimating level of error removed with proposed method

a. Using the degree-of-curve estimated in the synthesis step, infer level of cross-slope based on design guidelines. With vehicle speed and estimated grade in addition, look-up vehicle response from simulation results. Compare to response measured with proposed next-generation inertial profiling system.

b. Using the grade, degree-of-curve, cross-slope, vehicle speed estimated from the three-dimensional measurements, estimate the accumulated error of a SAA inertial profiler using the error model.

6. Current status of Project

- CARSIM vehicle simulation software runs in progress based on AASHTO Guidelines.
- Gyroscope-based system implemented in Ultra-Light Inertial Profiler
- Algorithm to quantify accumulation of errors based on Gyroscope output
- Validation, Verification, and Evaluation of Algorithm based on look-up tables produced with CARSIM