GEORGIA DOT RESEARCH PROJECT 25-01

Final Report

AN ENHANCED NETWORK-LEVEL CURVE SAFETY ASSESSMENT AND MONITORING USING MOBILE DEVICES – REFINEMENT AND FIELD EVALUATION

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16. Abstract:

Horizontal curves represent a small portion of the roadway network yet account for nearly one-quarter of fatal crashes, most of which involve vehicles running off the road due to excessive speed. Installing advisory speed signs before horizontal curves is a key countermeasure used by safety engineers to reduce curve-related fatalities, and identifying curves in need of such signs requires a proactive, data-driven approach. Recent NCHRP IDEA projects (214 and 248) introduced a low-cost, smartphone-based framework that leverages built-in GPS and IMU sensors to estimate curve superelevation and advisory speed in real time. Although these projects established the fundamental methodology, comprehensive evaluation of the framework's accuracy and repeatability under real-world conditions remains limited. This study addresses that gap through a rigorous field assessment comparing smartphone-derived measurements with high-precision 3D laser ground reference (GR) data and evaluating consistency across different vehicles and drivers. Two field sites in Georgia were selected to assess accuracy and repeatability, respectively. At the accuracy site on SR 190 (Pine Mountain), seventy test runs produced an overall superelevation RMSE of approximately 1.35 percent, and approximately 95% of advisory speed errors were within ±3 mph. Advisory speed RMSE values ranged from 1.3 to 2.1 mph across curves with varying radii. At the repeatability site on SR 136 (Cloudland Canyon), four of five vehicles produced consistent measurements, with a mean pointwise superelevation standard deviation of 0.535 percent and advisory speed standard deviation averaging 0.6 mph; one vehicle showed a systematic offset attributable to calibration or mounting issues. Overall, the findings demonstrate that the smartphone-based framework enables accurate, repeatable, and real-time curve advisory speed assessments suitable for field deployment. Real-time verification in the field reduces the need for return trips, improving efficiency and lowering costs for agencies, particularly in rural areas. As a low-cost and scalable solution, it supports more frequent curve assessments at both project and network levels, advancing proactive safety management to identify high-risk locations and implement countermeasures before crashes occur.

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GDOT Research Project No. 25-01

Final Report

AN ENHANCED NETWORK-LEVEL CURVE SAFETY ASSESSMENT AND MONITORING USING MOBILE DEVICES – REFINEMENT AND FIELD EVALUATION

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In cooperation with
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Federal Highway Administration

January 2026

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 yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
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
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 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 (2000 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)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
BBI	Ball-Bank Indicator
GDOT	Georgia Department of Transportation
GIS	Geographic Information System
GPS	Global Positioning System
GR	Ground Reference
IMU	Inertial Measurement Unit
MPH	Miles Per Hour
RMSE	Root Mean Square Error
MAE	Mean Absolute Error
ROR	Run-Off-Road
SR	State Route
SUV	Sport Utility Vehicle
NCHRP	National Cooperative Highway Research Program
IDEA	Innovations Deserving Exploratory Analysis

EXECUTIVE SUMMARY

Although horizontal curves make up only a small share of the roadway system, they account for a disproportionate number of severe and fatal crashes. Nearly one in four fatal crashes occurs on such curves, and most of those involve vehicles leaving the roadway. The main factor behind these run-off-road crashes is speed, drivers losing control when exceeding the static friction between the roadway surface and tires.

Safety engineers seek to find the roadway segments in need of countermeasures to reduce fatal crashes. Identifying such segments can be done through analyzing crash data (reactive approach) or scanning the roadway systematically to identify dangerous spots (proactive approach). Combination of Ball-Bank Indicator (BBI) and GPS measurements provides a method for determining the safe speed for horizontal curves (advisory speed), eventually identifying curves where countermeasures such as advisory speed signs are needed. However, current implementations of such systems, e.g., Rieker, require dedicated devices, are expensive, and incapable of producing results in real-time in the field. Often, inconsistencies in the data are not discovered until much later, which forces engineers to repeat costly fieldwork.

To address these problems, two NCHRP IDEA (National Cooperative Highway Research Program Innovations Deserving Exploratory Analysis) projects were developed to use low-cost mobile devices for real-time curve assessment. The NCHRP IDEA 214 project proposed using a smartphone as the main tool for assessing curve advisory speeds. Smartphones contain both GPS and IMU sensors, which can be used to record vehicle motion. Building on that foundation, the NCHRP IDEA 248 project improved the framework by moving most of the calculations onto the phone itself and adding a way to detect discrepancies as data are being collected. These refinements mean that advisory speeds can be calculated in real time, directly after a vehicle exits a curve. However, both NCHRP projects mainly focused on the development of the new method and framework. There is a lack of comprehensive and solid evaluation of the new method and framework under real-world environments.

Thus, objective of this study is to critically evaluate the accuracy and repeatability of smartphone curve measurements (i.e., superelevation and advisory speed measurements) obtained through methods developed in NCHRP IDEA 214 and 248 under real-world conditions using field tests. Accuracy was evaluated by comparing phone measurements to Ground Reference (GR) data from 3D laser imaging systems, with performance quantified using Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). Repeatability was assessed by comparing phone measurements across different cars and drivers, using pooled standard deviation to measure consistency.

Field experiments were carried out at two very different sites in Georgia for the evaluation. The first, a ten-mile segment of SR 190 near Pine Mountain, was chosen for accuracy testing because it includes forty curves with a broad mix of radii, superelevation angles, and deflection angles. We refer to this site as “accuracy site” in the following report. Seventy test runs were performed with multiple drivers and vehicle types, and the results were compared against detailed ground reference data collected with a 3D laser system and cross-referenced by manual ground reference measurements. The second site, SR 136 near Cloudland Canyon, was used to test repeatability. We refer to this site as “repeatability site” in the following report. Five vehicles of different types, each carrying the same model of smartphone and holder, made several passes in both directions. The results were then compared across vehicles to see how consistent the measurements would be.

At the accuracy site (Pine Mountain), the overall superelevation results showed an RMSE of about 1.35 percent, and approximately 95% of advisory speed errors within three miles per hour. Two-thirds of the runs were within one mile per hour of the ground reference. The superelevation accuracy ranged from an RMSE of 1.2 to 1.7 percent at different driving speeds. The accuracy of superelevation measurements varied from an RMSE of 0.894 to 2.147 percent for three of the mounting types while one of the mounting types results in an RMSE of 4.3 percent. Moreover, advisory speed accuracy ranges from an RMSE of 1.3 to 2.1 mph for different curve radii. The results were generated after analyzing more than 68,000 superelevation readings and nearly 3,000 advisory speed calculations. At the repeatability site (Cloudland Canyon), four of the five vehicles produced repeatable superelevation readings with a mean pointwise standard deviation of 0.535 (percent cross-slope). The standard deviation values ranged from 0.075 to 2.826 percent while on average, 95% of the measurements produced standard deviations below one. Advisory speed measurements resulted in a mean standard deviation of 0.6 mph ranging from around 0.2 to 1.6 mph while the 95th percentile was around 0.9 mph.

The advisory speed error levels (being within three miles per hour) are more than adequate for setting advisory speed signs. This is because advisory speed signs are normally rounded down to the nearest five miles per hour. The experiments also showed that the method works at normal driving speeds, unlike older GPS-BBI methods that require engineers to drive at relatively slow speeds. The type of holder was found to be of great importance for obtaining high accuracy measurements. Secure holders with metal joints produced accurate results, while one plastic mount type produced much larger errors and had to be discarded. At the repeatability site (Cloudland Canyon), the results confirmed that the superelevation and advisory speed measurements are repeatable, showing that the method is stable across different drivers and vehicles. One vehicle, however, consistently gave offset values due to a calibration or mounting issue. Advisory speed values also lined up with existing signage on sharp curves. Some discrepancies between advisory speed values for one of the curves were traced back to errors in curve identification (caused by the computation method and poor roadway shapefile) rather than the measurements themselves, highlighting the importance of checking the quality of curve inventories.

The findings from the two experiments demonstrate that a smartphone-based framework can provide accurate and repeatable curve advisory speed assessments in the field. The ability to collect and process data in real time in the field allows agencies to verify the accuracy of advisory speed measurements and perform any necessary cross-checks and corrections before returning to the office. This approach is significantly more efficient and practical than the existing method, which requires staff to return to the office to obtain results and then travel back to the field for additional data collection if corrections are needed. It will save time and reduce costs for local agencies, especially those with limited resources and long travel distances to rural areas for safety assessments.

Additionally, this project shows that smartphones can serve as a low-cost, scalable solution that enables more frequent curve safety assessments at both project and network levels in a technically and financially feasible manner. This supports proactive safety management practices by helping agencies identify high-risk locations and implement countermeasures before crashes occur.

Future studies could encompass broadening the testing to include heavy vehicles such as freight trucks, garbage collection vehicles, or school buses, which would allow agencies to gather continuous data more efficiently since these vehicles are already on the road on a regular basis.

Experiments are needed to validate the framework in such setups. With these expansions, the smartphone framework has the potential to transform how roadway safety assessments are carried out at the national scale.

CHAPTER 1. INTRODUCTION

Although horizontal curves make up only a small share of the roadway system, they account for a disproportionate number of severe and fatal crashes. Nearly one in four fatal crashes occurs on such curves, and most of those involve vehicles leaving the roadway. The main factor behind these run-off-road crashes is speed, drivers losing control when exceeding the static friction between the roadway surface and tires. Employing proactive methods to monitor roadway network and find potential hazardous curves, is crucial for planning and designing safety countermeasures, such as advisory speed signs (Tsai et al., 2025).

Current methods for assessing curve safety are labor-intensive, time-consuming, and often dangerous. Current methods have technical challenges related to the consistency of the outcomes under diverse driving speeds, driving behavior, and vehicle types. The GPS-BBI method (such as Rieker CARS) requires dedicated equipment and services that are too expensive for many transportation agencies, especially local agencies with limited resources. Moreover, the GPS-BBI method cannot provide in-field advisory speed results. Engineers have to travel back to the transportation agency's office to process the data and determine the advisory speeds (Tsai et al., 2025). This was identified critical for local transportation agencies based on discussions with our local community partners. For example, Paulding & Bartow counties are both rural counties in Georgia with limited resources. They need to cover large areas with long driving hours with limited staff and money. Therefore, it is crucial that they know if the collected data is valid and that they do not have to redo data collection due to low-quality data.

A low-cost, scalable methodology using smartphones was proposed in the NCHRP IDEA 214 project to determine advisory speed in a more efficient way (Tsai et al., 2021). The NCHRP IDEA 248 project refined the previous project by adding on-edge computation and advisory speed discrepancy detection. The ability to collect and process data in real time in the field allows agencies to verify the accuracy of advisory speed measurements and perform any necessary cross-checks and corrections before returning to the office. This enhanced framework enables transportation agencies to perform more frequent curve safety assessments using a low-cost, scalable smartphone device at both project and network levels in a technically and financially feasible manner. This supports proactive safety management practices by helping agencies identify high-risk locations and implement countermeasures before crashes occur.

This methodology leverages the built-in GPS and Inertial Measurement Unit (IMU) sensors for collecting data, identifying curves, computing superelevation, and determining the advisory speed. The framework automatically collects GPS and IMU data while traversing roadway curves. Curve identification is achieved by analyzing GPS trajectories and comparing them with the curve inventory cached on the smartphone (Tsai et al., 2023). Then, superelevation is computed by processing the IMU data. Finally, advisory speed is determined by following the equation from the AASHTO Green Book using the computed curve radius and superelevation (AASHTO, 2018). By shifting computational tasks to the smartphone, this framework can compute advisory speed upon exiting each curve. This capability will enable the identification of inconsistent advisory speed results during field assessments, allowing engineers to investigate and verify before returning to the office (Tsai et al., 2025).

The objective of this study is to evaluate the accuracy and repeatability of smartphone curve measurements (including both superelevation and advisory speed) obtained through methods developed in NCHRP IDEA 214 and 248 using field tests. Accuracy was evaluated by comparing phone measurements to Ground Reference (GR) data from 3D laser imaging systems, with performance quantified using Root Mean Square Error (RMSE) and Mean Absolute Error

(MAE). Repeatability was assessed by comparing phone measurements across different cars and drivers, using pooled standard deviation to measure consistency.

To conduct field tests, validate and refine the proposed framework, the following tasks were carried out to achieve the objectives:

1. Task 1: Design field-testing methodology to cover the accuracy and repeatability evaluation of smartphone measurements (i.e., superelevation and advisory speed).
2. Task 2: Conduct comprehensive field tests with GDOT engineers to capture the smartphone data needed to generate superelevation and advisory speed measurements. During these tests, gather feedback from GDOT engineers to inform and improve future implementation of the method.
3. Task 3: Analyze the collected data to evaluate the accuracy and repeatability of measurements obtained by smartphones.

Report organization

This report is organized into the following sections.

CHAPTER 1. INTRODUCTION presents background on horizontal curves safety including the limitations of current advisory speed assessment methods, and introduces the framework based on smartphones. **CHAPTER 2.** BACKGROUND KNOWLEDGE details the background of the framework and the data collection process. **CHAPTER 3.** METHODOLOGY AND FIELD TESTS summarizes the evaluation methods, the description of field tests and the data collected for accuracy and repeatability assessments. **CHAPTER 4.** RESULTS AND DISCUSSION presents the results of the accuracy evaluation at GA SR 190 and repeatability evaluation at GA SR 136. It also interprets the results and examines influencing factors such as mounting stability.

CHAPTER 2. BACKGROUND KNOWLEDGE

Two NCHRP IDEA (National Cooperative Highway Research Program Innovations Deserving Exploratory Analysis) projects were developed to use low-cost mobile devices for real-time curve assessment. The NCHRP IDEA 214 project proposed a methodology using a smartphone as the main tool for determining curve advisory speeds. Smartphones contain both GPS and IMU sensors, which can be used to record vehicle motion. Building on that foundation, the NCHRP IDEA 248 project improved the framework by moving most of the calculations onto the phone itself and adding a way to detect discrepancies as data are being collected. These refinements mean that advisory speeds can be calculated in real time, directly after a vehicle exits a curve. The following sections introduce the advisory speed determination workflow and data collection process developed in the two projects.

Advisory speed determination workflow

The proposed framework in the NCHRP IDEA 248 study (Tsai et al., 2025) is illustrated in **Figure 1.** This framework enables full edge computation of advisory speed on smartphones. The components that require data retrieval from online servers can be cached on smartphones to allow offline computations on the phones. Such components include retrieving an inventory of curve geometry data, and historical advisory speed data. As the smartphone collects IMU and GPS data, different processes run in the background continuously calculating superelevation and advisory speed data. The superelevation calculation process requires IMU readings along with the driving speed recorded by the GPS module. The GPS location data is continuously monitored to detect if the vehicle is traversing any of the curves inventoried in the cached curve geometry data. Upon exiting a curve, the superelevation data and curve radius are used to calculate the advisory speed for that curve. The calculated advisory speed is compared against the historical data cached on the phone to identify any discrepancies.

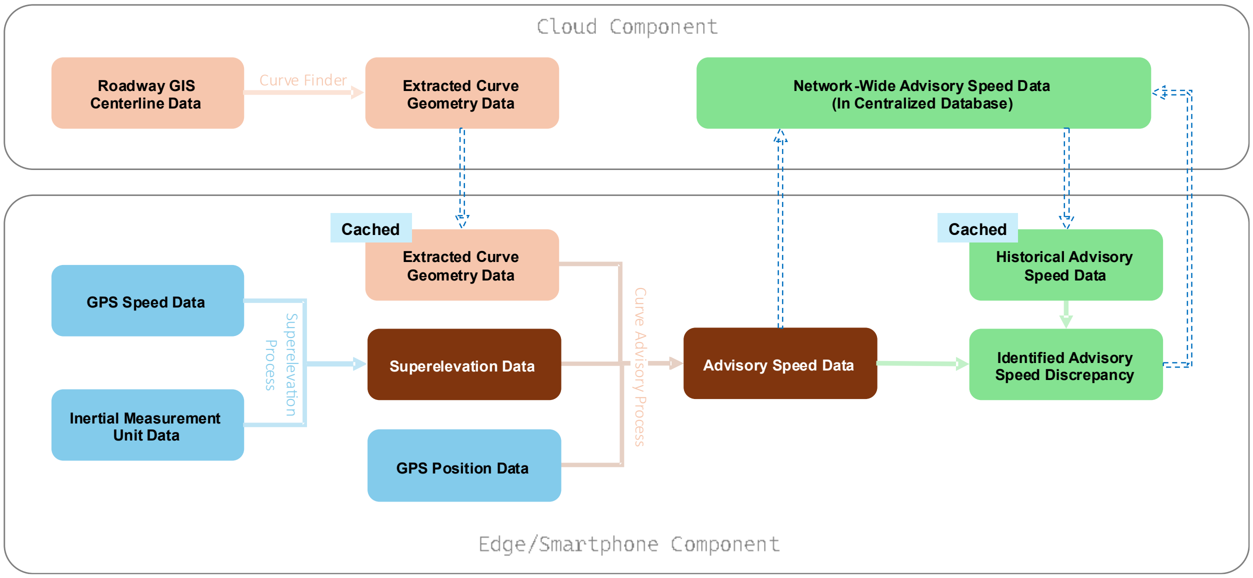


Figure 1. Flow Chart. Full edge computing with cloud connection framework layout

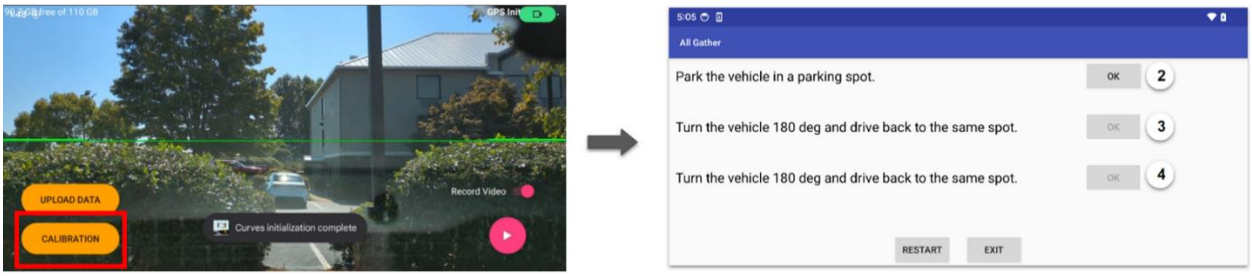
Data collection process

The mobile application can determine and display advisory speed for roadway curves in real time. By combining locally cached curve geometry with live sensor readings, the application provides immediate feedback to the driver on curve advisory speed upon exiting each curve (Tsai et al., 2023; Tsai et al., 2025). The process of data collection by mobile application is listed below:

- **Device Setup and Mounting:** Properly securing the smartphone within the vehicle is the first step to Ensure a stable and consistent orientation. **Figure 2** shows an example of the mounting setup for the smartphone.

Figure 2. Photo. Example smartphone mounting setup

- **Calibration of Reference Frame:** Before initiating data collection, the operator must follow the in-app calibration procedure, as shown in **Figure 3**, to set an accurate reference frame.



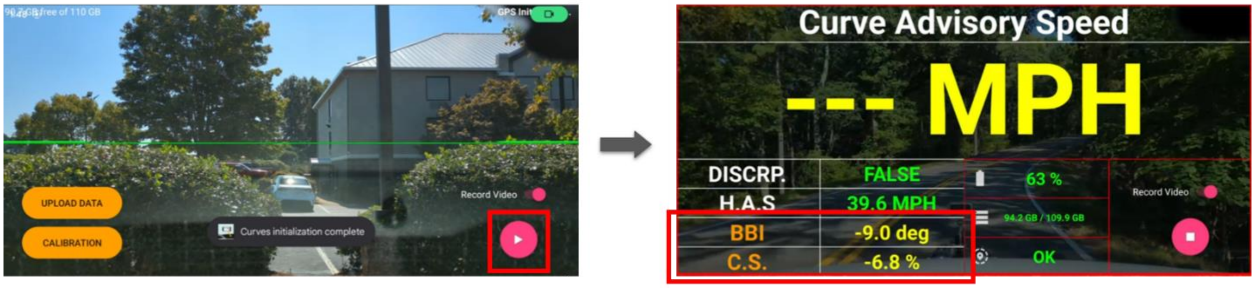
Park the vehicle in a parking spot. 2

Turn the vehicle 180 deg and drive back to the same spot. 3

Turn the vehicle 180 deg and drive back to the same spot. 4

Figure 3. Photos. Developed mobile application main interface and calibration interface

- **Data Collection Run:** As shown in **Figure 4**, during data collection, important information, such as BBI and superelevation, are displayed in real time.



Curves initialization complete

DISCRP. FALSE
H.A.S 39.6 MPH
BBI -9.0 deg
C.S. -6.8 %

Figure 4. Photos. Developed mobile application main interface and data collection interface

- **Real-Time Sensor Data Processing:** During data collection, the BBI and superelevation data are processed in real time from the speed and motion data captured by GPS and IMU sensors.
- **In-Field Advisory Speed Computation:** Prior to the field data collection, the curve geometry data is stored on the smartphone. Once the vehicle exits a curve, the computed superelevation values are combined with the stored curve geometry data to estimate the advisory speed.

Figure 5 shows an example of the combined views of in-cabin view, smartphone view, and map view. After the vehicle exits the curve, the advisory speed for the previous curve is reported, and shown on the screen (39.8 mph).

(a) (b)

Figure 5. Photos. In-field advisory speed computation (a) before and (b) after curve exit

More detailed information about the data collection procedure and in-field demonstrations are available in the NCHRP IDEA 248 final report (Tsai et al., 2025).

CHAPTER 3. METHODOLOGY AND FIELD TESTS

The NCHRP IDEA 214 and 248 projects mainly focused on the development of the new method and framework. There is a lack of comprehensive and solid evaluation of the new method and framework under real-world environments. In this study the accuracy and repeatability of smartphone curve measurements (i.e., superelevation and advisory speed measurements) were evaluated under real-world conditions using field tests. This section summarizes the evaluation methods, the description of field tests, and the data collected for accuracy and repeatability assessments.

Evaluation methodology

Two different aspects of the proposed framework were evaluated in this study: accuracy and repeatability of the superelevation and advisory speed measurements. Different evaluation methods, criteria, and plots were used depending on the purpose of the analysis.

Accuracy assessment methodology

For the accuracy site (Pine Mountain), phone measurements (observations) were compared to the Ground Reference (GR) data to capture their accuracy. To ensure that the proposed curve advisory speed assessment framework was thoroughly evaluated under realistic conditions, the research team considered a variety of factors during the test design: horizontal geometry (gentle and sharp curves), superelevation (different superelevation angles), vehicle types (sedan, SUV, pickup truck, and van), driver behavior and speed (about 25 mph to 65 mph), and smartphone mounting equipment (**Figure 6** shows four main types of smartphone mounts explored) (Tsai et al., 2025). This approach allowed the research team to comprehensively assess the accuracy of the proposed method under varied operational conditions. The correlation between the observations and reference measurements was examined on a scatter plot and the differences were quantified as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). Histogram plots were employed to show the distribution of advisory speed errors. The accuracy values were reported overall, as well as by smartphone mounting type, by driving speed, and by curve radius to evaluate the impact of each on the accuracy of the measurements.

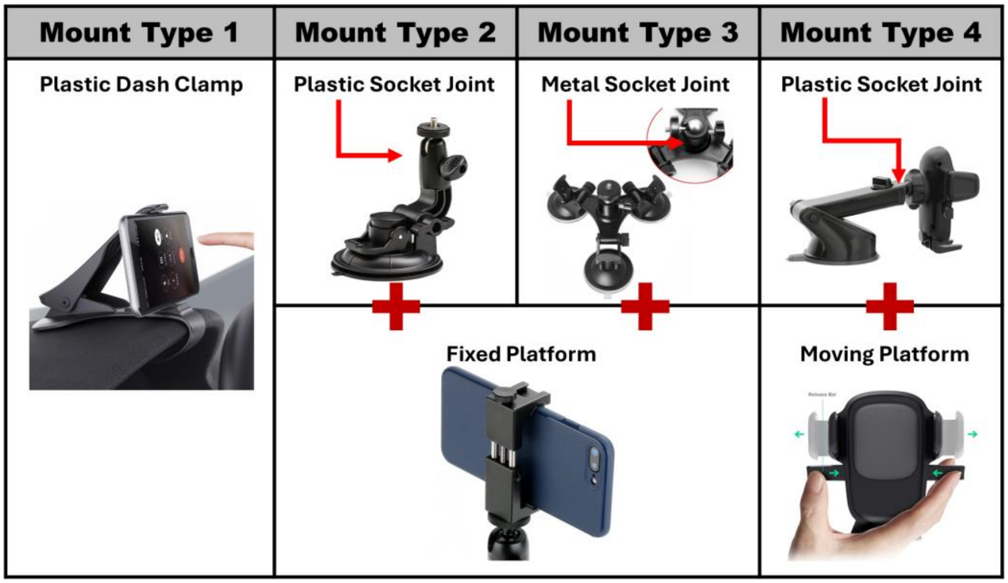


Figure 6. Figure. Smartphone mounting equipment used in validation tests

Repeatability assessment methodology

For the repeatability site (Cloudland Canyon), phone measurements (observations) were compared against each other by plotting cross-slope profiles separated by the direction of travel which shows the superelevation of different points along the road. The differences were quantified as pooled standard deviation across different cars/drivers, to evaluate the impact of different cars and drivers.

Moreover, real-time superelevation and advisory speed measurements were done in the field to assess the feasibility and practicality of such an approach to make sure the results are shown once the vehicle exits a horizontal curve with no latency.

Data sources and field test setup for accuracy assessment

Site description (GA SR 190 Pine Mountain)

To capture the complexity of real-world curve geometry, the research team evaluated the framework on a 10-mile segment of GA SR 190. This stretch of roadway spans mountainous terrain and includes a wide variety of curve geometries and superelevation angles. This segment includes 40 different curved sections, with radius ranging from 370 ft to 2300 ft, deflection angle ranging from 17 to 141 degrees, and superelevation ranging from -15% to +15%. In total, 70 runs of data, 35 in each direction, were collected using multiple vehicle types and drivers of varying experience levels. Speeds and driving behaviors varied among participants, reflecting realistic conditions more closely than a controlled test track. This diversity in geometry, driver style, and vehicle type provided a comprehensive dataset to validate the framework's accuracy across a broad set of real-world scenarios. **Figure 7** shows the layout of the test segment (Tsai et al., 2025).

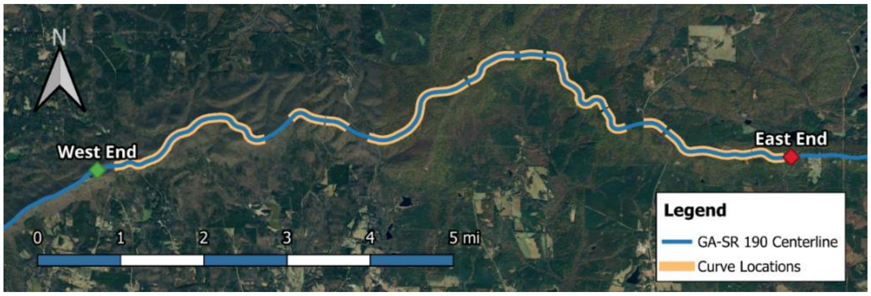


Figure 7. Map. GA SR 190 test segment layout

Collected data

The data used for this validation test were collected using the "AllGather" smartphone application developed by the research team. The application records comprehensive sensor data, including GPS trajectories and Inertial Measurement Unit (IMU) readings. Prior to data collection, all smartphones were securely mounted to the windshield or dashboard of the vehicle, and the IMU sensor reference frames were calibrated according to the Appendix E of the NCHRP IDEA 248 report. In addition, the suspension properties of all vehicles used in the test were estimated following the vehicle suspension calibration methodology detailed in the NCHRP IDEA 214 report. These calibration methods ensure that vehicle dynamics are accurately captured and reflected in the computation of superelevation and advisory speed (Tsai et al., 2025).

Curve characteristics data

Curve locations and geometric properties, such as radii and deflection angles, were extracted from GIS centerline data using the Curve Finder algorithm developed by the research team's lab, which was also detailed and used in the Phase I IDEA 214 project. This automated process provided consistent identification of roadway curves across the test section (Tsai et al., 2025).

Ground reference data description

Reference superelevation data were obtained using two complementary methods, **Figure 8** shows the equipment used in each method. On GA SR 190, cross-slope data were collected with a 3D laser imaging system, and these measurements were validated using manual measurements collected on a sub-section of GA SR 190. The comparison between manual and 3D laser measurements is documented in Appendix F of the NCHRP IDEA 248 report. This approach establishes a robust ground reference to evaluate the accuracy of the 3D laser-derived cross-slope measurements for use in superelevation assessment (Tsai et al., 2025).

(a)

(b)

Figure 8. Photos. Reference cross-slope data collection, (a) manual, (b) 3D laser imaging

Analyzing the data collected at Pine Mountain allows us to validate accuracy of the framework by comparing the smartphone-based measurements against the ground reference data.

Data sources and field test setup for repeatability assessment

Site description (GA SR 136 Cloudland Canyon)

A field data collection was conducted on Georgia State Route 136 (SR 136), on a 6-mile segment, close to Cloudland Canyon State Park. This stretch of roadway has a mountainous geography, including a wide variety of curve geometries and superelevation angles. In total, 24 horizontal curves were identified automatically along with the geometric properties such as radius, deviation angle, and curve length. The curves in this segment of the road have radii ranging from 76 ft to 1690 ft, deflection angle ranging from 26 to 216 degrees, and superelevation values ranging from -12% to +12%. In total, 20 runs of data, 10 in each direction, were collected using multiple vehicle types. Multiple runs of data were collected with different vehicles, using smartphone IMU and GPS data and processed on the smartphone in real-time to obtain BBI, superelevation, and advisory speed values. The smartphone operation was demonstrated to GDOT safety engineer and GDOT District 6 traffic engineers. **Figure 9** illustrates the selected travel directions within the study area. The trajectory from Cloudland to Trenton was chosen as the increasing direction, while the trajectory from Trenton to Cloudland was chosen as the decreasing direction.

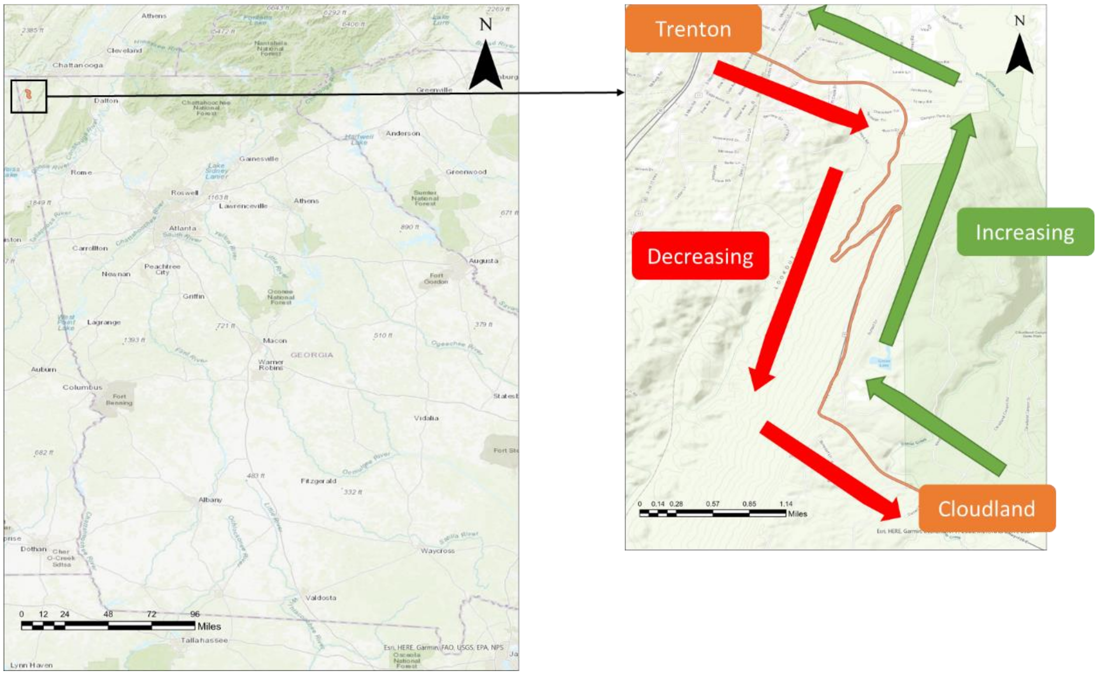


Figure 9. Maps. GA SR 136 repeatability assessment site (Increasing vs. Decreasing direction)

Figure 10 shows a map of part of the area illustrating the horizontal curves that were extracted from the centerline shapefile. The curve inventory was loaded on the phone for advisory speed calculations in the field.

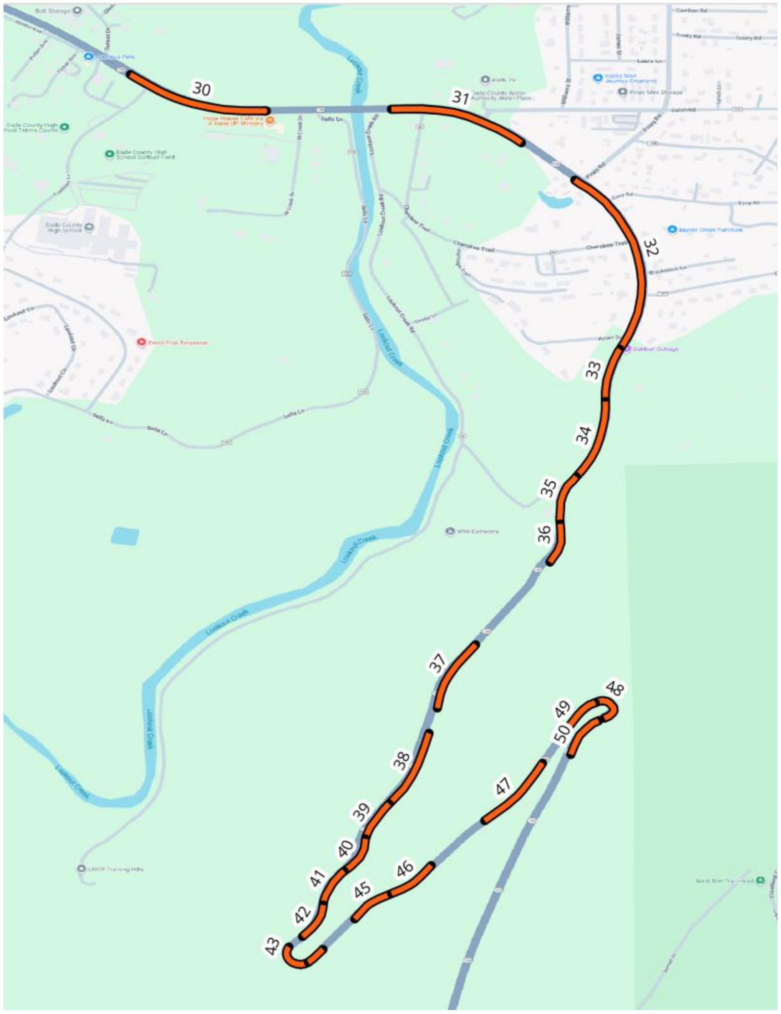


Figure 10. Map. Study area map showing curves in orange and labeled by their curve IDs

Collected data

The data were collected using 5 android phones of the same model (Pixel 8a) mounted to windshield of 5 different vehicles (including two SUVs, a sedan, a compact SUV, and a van). The selected route included diverse curves with different curve radii (sharp and gentle).

Table 1 presents comprehensive details of the collected data, including the specific vehicles used, the number of trips recorded in each direction within the study area, and the model of smartphone employed for data collection. Each car was driven by a different driver.

Table 1. Summary of data collected at GA SR 136 Cloudland Canyon

Vehicle	**Driver**	**Number of trips (increasing direction)**	**Number of trips (decreasing direction)**	**Phone**
Toyota Prius (sedan)	Driver 1	2 times	2 times	Pixel 8a
Ford Escape (compact SUV)	Driver 2	2 times	2 times	Pixel 8a
Honda Passport (SUV)	Driver 3	2 times	2 times	Pixel 8a
Tahoe (SUV)	Driver 4	2 times	2 times	Pixel 8a
Ford Transit 350 (Van)	Driver 5	2 times	2 times	Pixel 8a

The collected data was processed and analyzed to validate the effectiveness of the proposed framework in a real-world setting. The purpose was to evaluate the repeatability of superelevation and advisory speed measurements in a more controlled environment (same holder, same phone, same route, but different cars and drivers).

CHAPTER 4. RESULTS AND DISCUSSION

GA SR 190 Pine Mountain (accuracy site)

Overall accuracy

Figure 11 shows a scatter plot comparing smartphone-based superelevation measurements (y-axis) against ground reference values (x-axis) for GA SR 190. With most of the measurements being close to the 1:1 line, this figure shows that they align well with the ground reference values. The overall accuracy results show an RMSE of 1.35, demonstrating good accuracy for the purpose of determining advisory speeds for road safety assessment.

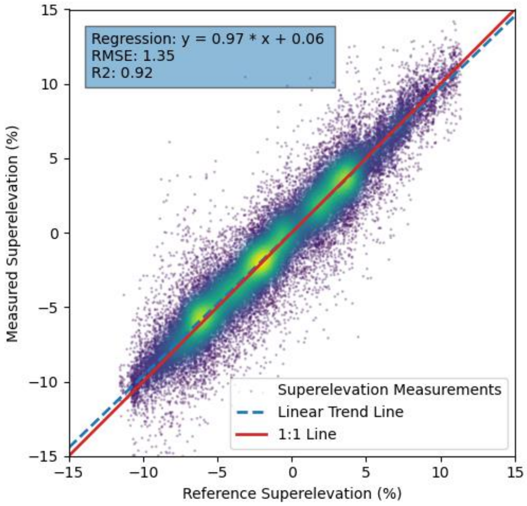


Figure 11. Plot. GA SR 190 Superelevation Validation Results

Approximately 65% of the runs had advisory speed errors below 1 mph, and 95% were within 3 mph, according to **Figure 12**. Posted advisory speeds are generally rounded down to the nearest 5 mph. Therefore, correct advisory speed value can be determined for signage given this level of accuracy (Tsai et al., 2025).

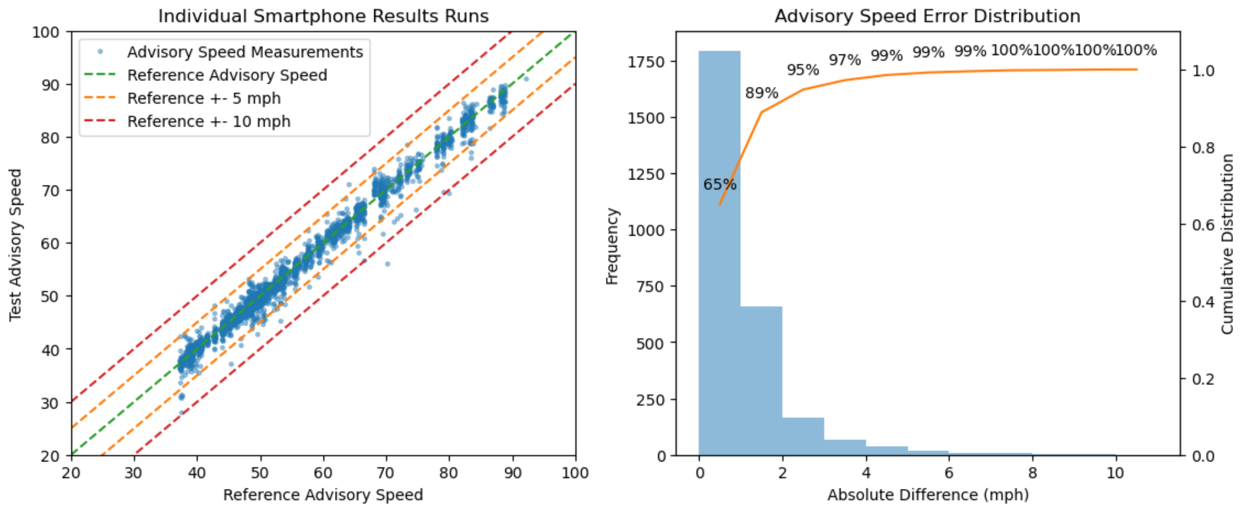


Figure 12. Plots. GA SR 190 Individual Advisory Speed Validation Results

Impact of holders

Table 2 shows the accuracy results of the superelevation measurement by the mounting type (Pine Mountain data). It is obvious that one of the mounting types, mount type 4, a plastic socket joint with a moving platform, performs worse than the others with an RMSE of 4.3. This finding highlights the importance of a stable mounting platform that has metal socket joint connections, performing better than plastic mounts. All data collected using Mount Type 4 were excluded from the validation results (Tsai et al., 2025).

Table 2. GA SR 190 superelevation accuracy by smartphone mounting type

Mount Type	RMSE	MAE
Type 1	1.079	0.763
Type 2	2.147	1.649
Type 3	0.894	0.709
Type 4	4.300	3.013

Advisory speed accuracy can also be significantly impacted by the mounting type, according to **Table 3**. Mount Type 2 results in almost double the error compared to Mount Type 1. This highlights the importance of securely mounting the smartphone with sturdy equipment (Tsai et al., 2025).

Table 3. GA SR 190 advisory speed accuracy and consistency by mounting types

Mount Type	MAE	RMSE	Standard Deviation
Type 1	0.816	1.209	1.208
Type 2	1.759	2.413	2.318
Type 3	0.752	0.960	0.953

Impact of driving speed

Table 4 shows the accuracy of superelevation measurements at different driving speeds. The RMSE ranges from 1.203 to 1.716 for different ranges of driving speeds. This shows minimal impact on superelevation accuracy no matter how fast the vehicle travels. Slightly higher impact is observed at very high speeds (65 mph or above). Existing GPS-BBI method recommend slower driving speeds to achieve results with higher accuracy. These findings indicate that the proposed method is more robust to different vehicle speeds, allowing engineers to drive at normal speeds.

Table 4. GA SR 190 superelevation accuracy by driving speed

Speed Ranges	RMSE	MAE
0-25 mph	1.503	0.903
25-35 mph	1.459	0.883
35-45 mph	1.203	0.855
45-55 mph	1.424	1.000
55-65 mph	1.421	0.992
65+ mph	1.716	1.220

Impact of curve radius

Table 5 shows the accuracy of advisory speed measurements at different curve radii, with RMSE values ranging from 1.329 to 2.100. Horizontal curves with larger radii tend to have higher error in advisory speed calculation. However, inaccuracies in advisory speed calculations on a large-radius curve are less critical. This is because higher radius typically corresponds to higher advisory speed which pose lower roadway departure risks.

Table 5. GA SR 190 advisory speed accuracy and consistency by curve radius

Curve Radius (ft)	Median Advisory Speed	MAE	RMSE	Standard Deviation
0-500	39.1	0.853	1.360	1.359
500-750	46.1	0.889	1.329	1.319
750-1000	52.3	0.940	1.333	1.314
1000-1500	64.3	1.003	1.516	1.495
1500-2000	70.6	1.401	2.100	2.077
2000+	82.6	1.238	1.848	1.809

The experiments done on Pine Mountain roads demonstrated the accuracy of the proposed methodology with superelevation error of around 1.35% and advisory speed error of less than 3 mph. The measurements are not highly sensitive to different driving speeds or different curve radii. However, a stable and sturdy smartphone holder is required to achieve accurate results.

GA SR 136 Cloudland Canyon (repeatability site)

Superelevation profiles by direction

Figure 13 and **Figure 14** illustrates the recorded superelevation across different vehicles in the study area of Cloudland Canyon in the increasing and decreasing directions, respectively. In the increasing direction plot, left turning curves are given positive superelevation values (negative superelevation values are associated with right turning curves). The superelevation values in the decreasing plot were multiplied by -1 to generate a figure which could be directly compared with the increasing direction. Both directions use the same start and end points to allow visual comparison between the two figures. The recorded superelevation values among different vehicles appear generally consistent. The smartphone data collected in Tahoe, Ford Escape, Honda Passport, and Ford Transit 350 produce consistent superelevation measurements. However, the data from Toyota Prius appears to have produced different superelevation values which is probably due to phone misalignment. As a result, the data from this vehicle was excluded from the analyses.

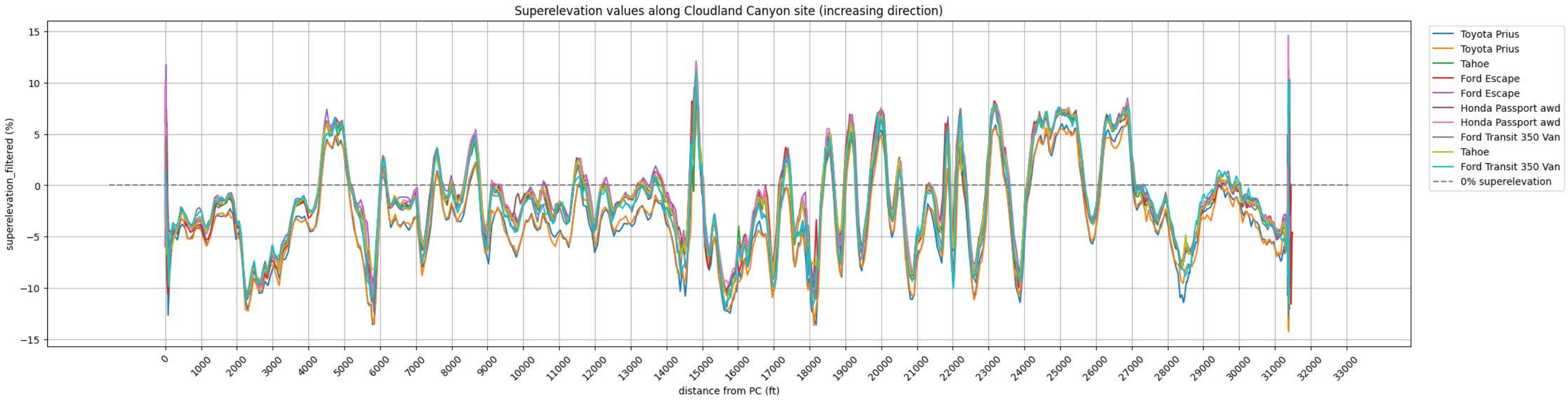


Figure 13. Plot. Cross-slope profile (increasing direction)

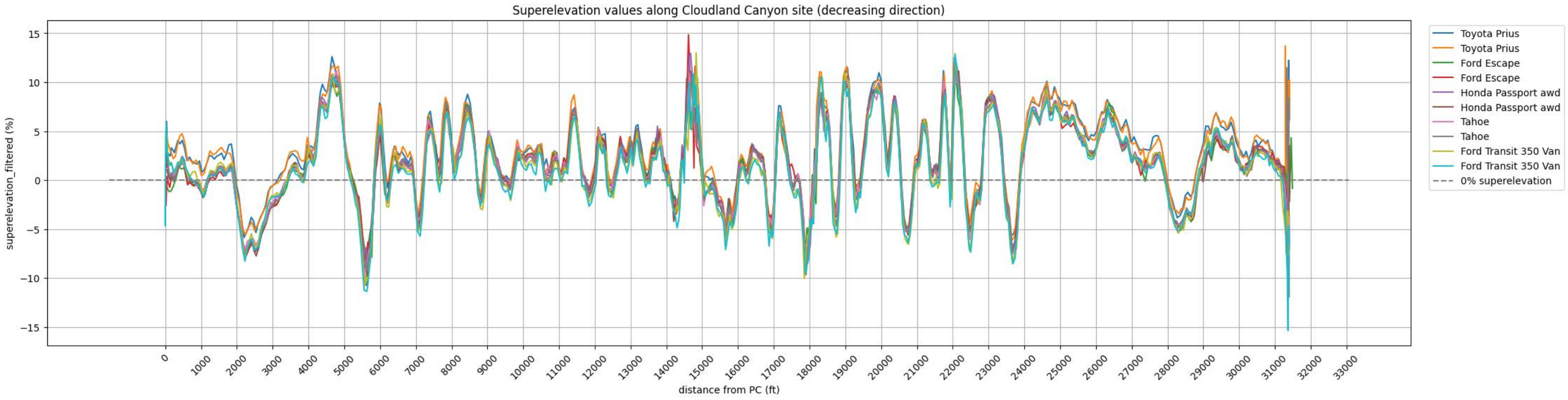
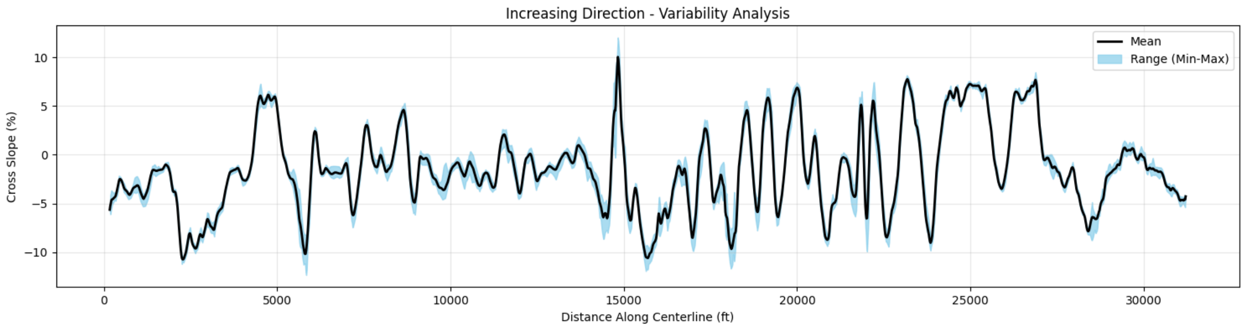


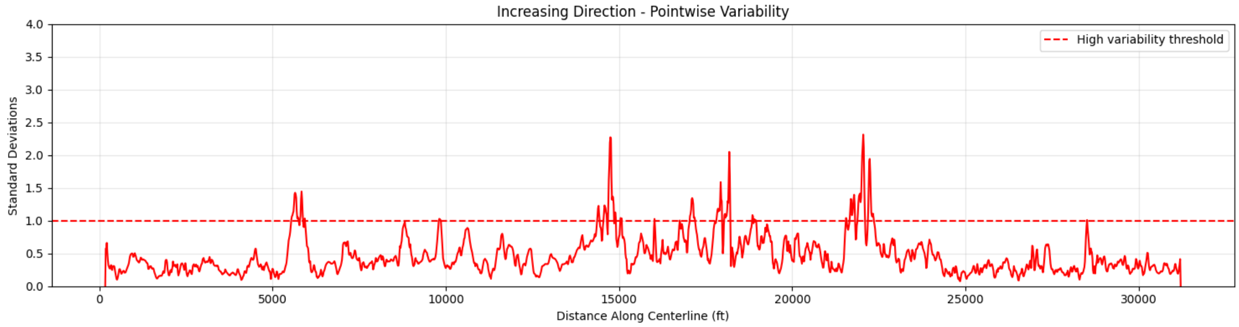
Figure 14. Plot. Cross-slope profile (decreasing direction)

Cross-slope variability analysis

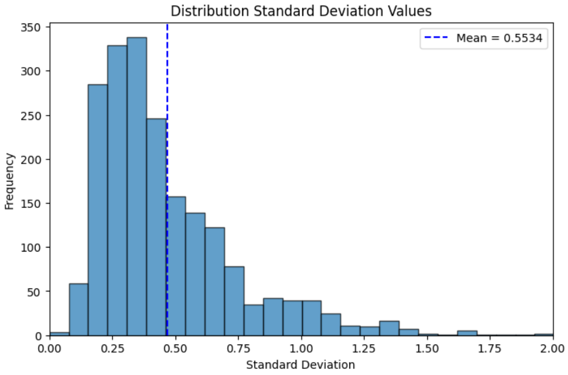
Figure 15 shows the variability analyses of the cross-slope measurements by different vehicles in the increasing direction. **Figure 15(a)** shows the superelevation profile with the y-axis showing the cross-slope in percentage and the x-axis showing the distance along the centerline in feet. The cross-slope is the average of the values captured by various cars while the minimum and maximum captured value is also shown in the figure. **Figure 15(b)** shows the pointwise variability analysis of the cross-slope measurements demonstrating the standard deviation of cross-slope measurements among different cars at each point along the centerline. It can be observed that 93.5% of the measurements fall below the 1 standard deviation threshold (same unit as cross-slope measurements – percentage) indicating satisfactory performance for road safety assessment purposes. The distribution of the standard deviation values is shown in **Figure 15(c)** with the values ranging from 0.075 to 2.314 percent and a mean standard deviation of 0.55 percent for the increasing direction.



(a) Superelevation profile



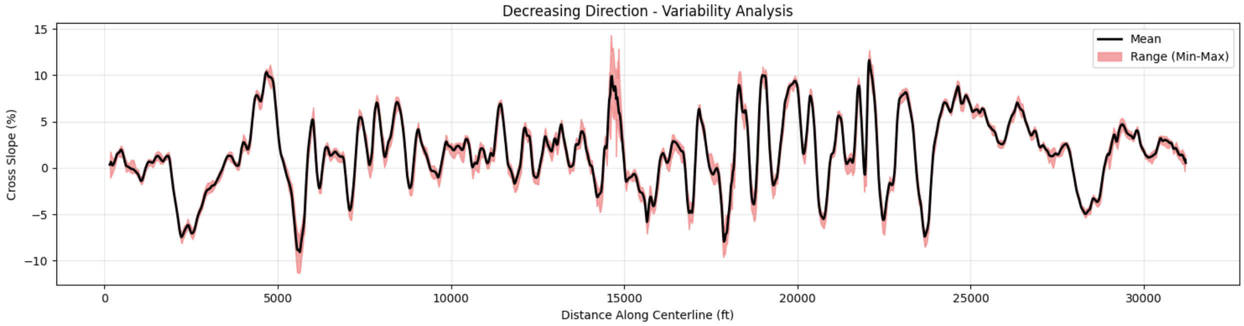
(b) Pointwise variability along the centerline measured in standard deviation of superelevation values in percentage



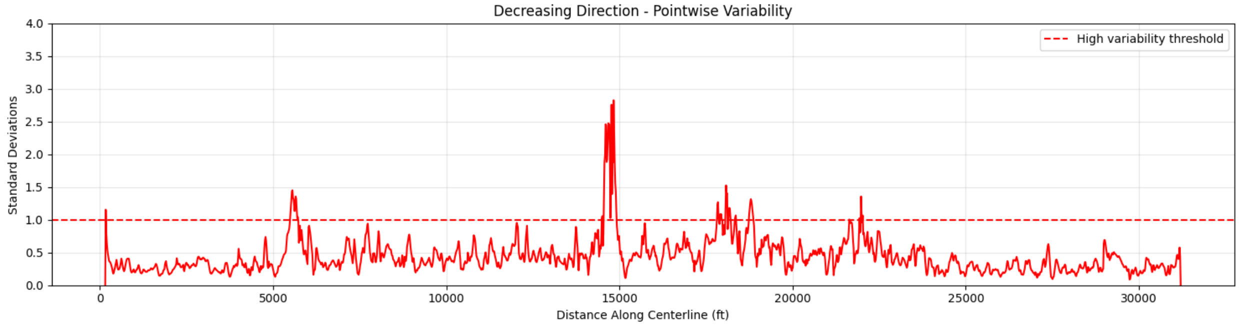
(c) Distribution of the pointwise standard deviation values

Figure 15. Plots. Cross-slope variability analysis (increasing direction)

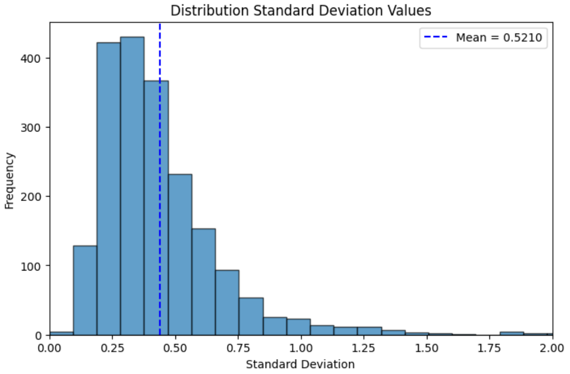
Figure 16 shows the variability analyses of the cross-slope measurements by different vehicles in the decreasing direction. **Figure 16(a)** shows the superelevation profile, **Figure 16(b)** shows the pointwise variability analysis of the cross-slope measurements showing that 96.3% of the measurements fall below the 1 standard deviation threshold, and The distribution of the standard deviation values is shown in **Figure 16(c)** with the values ranging from 0.088 to 2.826 percent and a mean standard deviation of 0.52 percent for the decreasing direction.



(a) Superelevation profile



(b) Pointwise variability along the centerline measured in standard deviation of superelevation values in percentage



(c) Distribution of the pointwise standard deviation values

Figure 16. Plots. Cross-slope variability analysis (decreasing direction)

Analyzing both directions yielded a mean standard deviation of 0.535 (percent cross-slope) ranging from 0.075 to 2.826 while around 95% of measurements had a standard deviation of one.

Even though the measurements were captured in different vehicles driven by different drivers, the variability analysis shows that repeatable superelevation measurements are obtained, suitable for the purposes of road safety assessment.

Advisory speed repeatability results by curve

The advisory speed measurements for each of the curves are shown in **Figure 17**. The x axis represents the curve ID (as introduced in Figure 10) and the y axis shows the advisory speed values in miles per hours. Each line corresponds to data collected by a specific vehicle (average of two runs). **Figure 18** shows the same type of plot but for the decreasing direction. The advisory speed observations from the phone in four cars are consistent (similar to superelevation measurement which is expected as advisory speed directly depends on superelevation). The results from the phone in Toyota Prius are not consistent as expected due to the readings being invalid (detailed explanation provided in the superelevation repeatability section. The measurements from Toyota Prius and the measurements related to curve id 44 (explained in the next section) were excluded from the analyses thereafter.

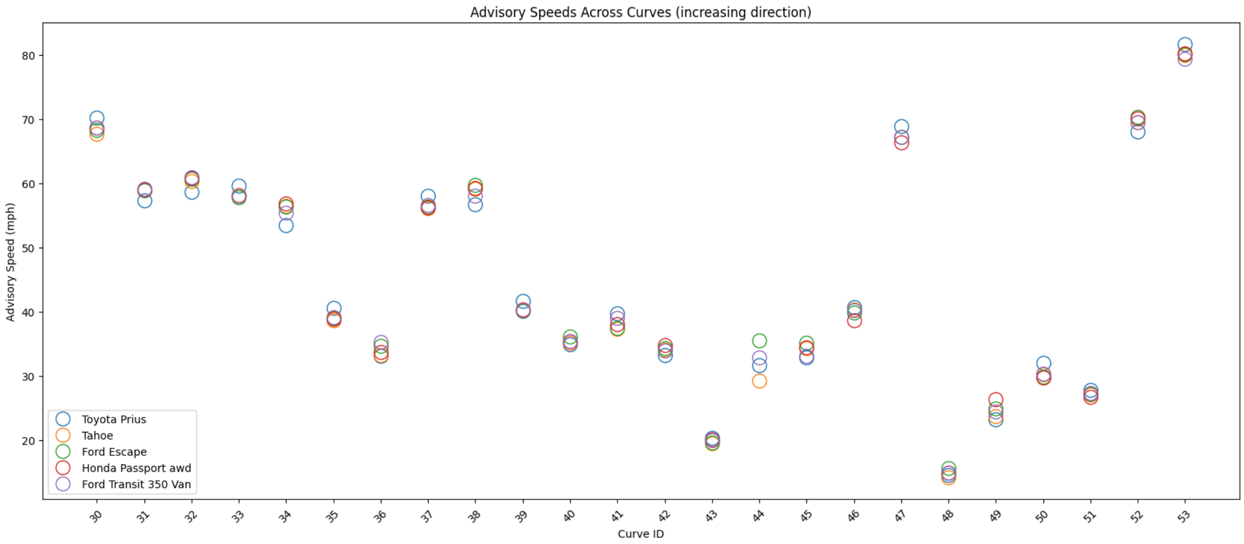


Figure 17. Plot. Advisory speeds for Cloudland Canyon curves (increasing direction)

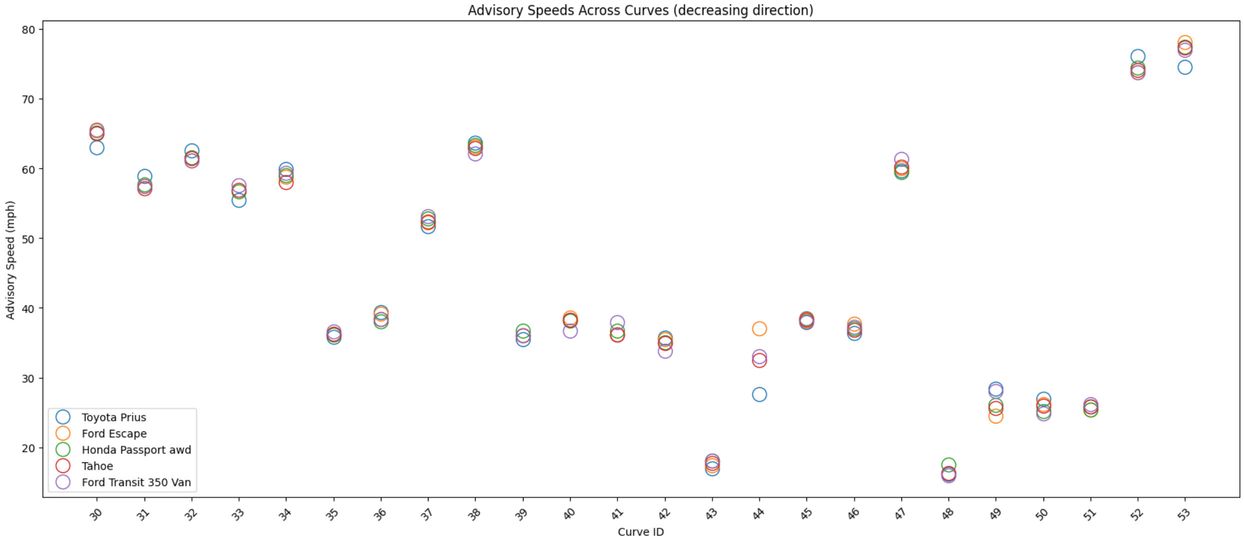


Figure 18. Plot. Advisory speeds for Cloudland Canyon curves (decreasing direction)

The standard deviation of advisory speeds was calculated for each curve separated by the direction of travel. For the increasing direction, the standard deviation of advisory speeds ranged from 0.19 to 1.13 mph with an average of 0.60 mph. The 95th percentile of standard deviation of advisory speeds was 0.98 mph. For the decreasing direction, the standard deviation of advisory speeds ranged from 0.26 to 1.59 mph with an average of 0.61 mph. The 95th percentile of standard deviation of advisory speeds was 0.80 mph.

Analyzing both directions (average of increasing and decreasing) yielded a mean standard deviation of advisory speeds of 0.6 mph ranging from around 0.2 to 1.6 while the 95th percentile was around 0.9 mph. Considering that the advisory speeds are usually rounded down to the nearest 5, an standard deviation of around 1 mph from measurements captured in different vehicles driven by different drivers indicates great performance, suitable for the purposes of road safety assessment.

Comparison with posted advisory speeds

The speed limit for this part of SR 136 is 55 mph (as observed in 2024). So, the curves with an advisory speed lower than 45 mph would probably be a candidate for further investigation and probably installing advisory signs. Some of the curves were already signed, allowing the comparison with smartphone measurements. For example, the curve with ID 48 is a very sharp curve with a posted advisory speed of 15 mph. As shown in Figure 17, phone measurements record consistently low advisory speed values around 15 mph which align with the already posted advisory speed sign (shown in **Figure 19**).

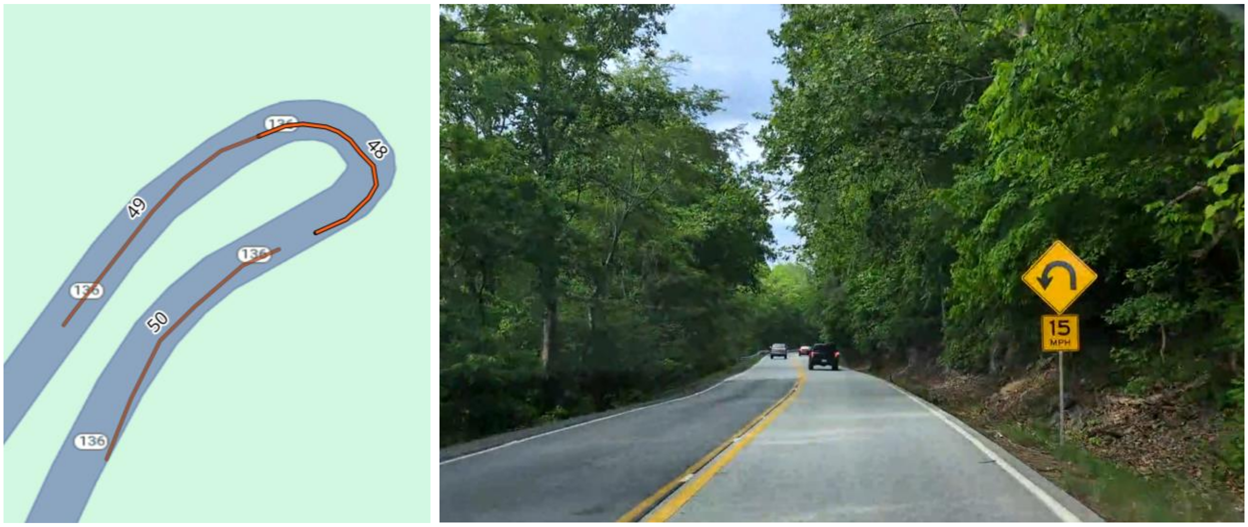


Figure 19. Multiple elements. Map of curve with ID 48 and the posted advisory speed for it

As another example, the curve with ID 43 is also a very sharp curve with a similar posted advisory speed of 15 mph. As shown in Figure 17, phone measurements record consistently low advisory speed values under 20 mph, around 15 mph which align with the already posted advisory speed sign (as shown in **Figure 20**).

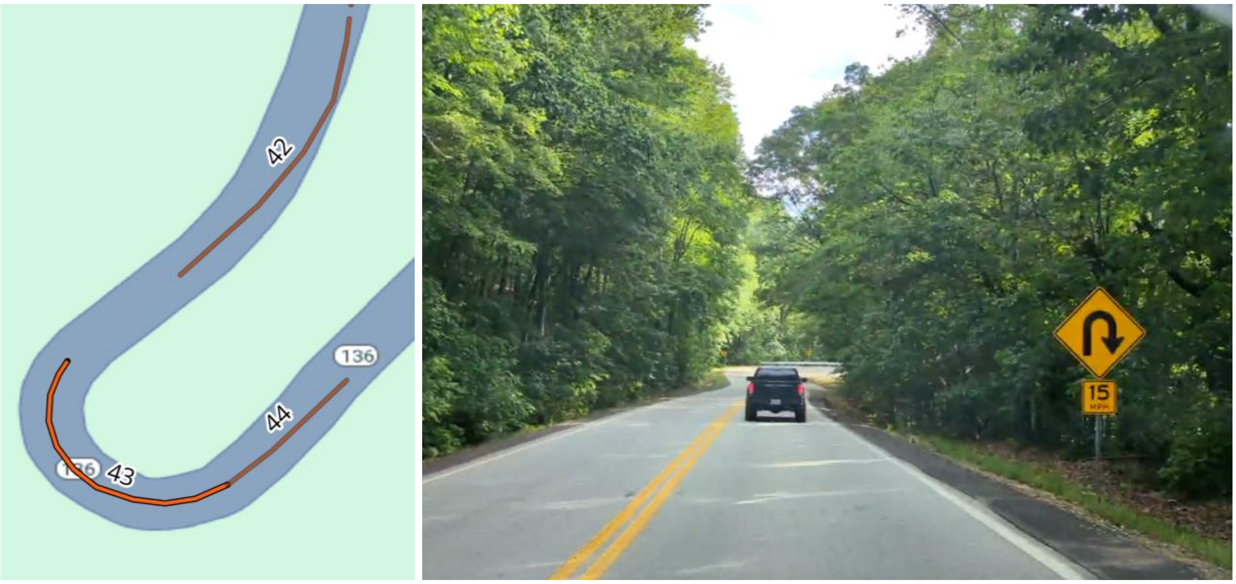


Figure 20. Multiple elements. Map of curve with ID 48 and the posted advisory speed for it

Curve ID 44 shows large discrepancy among the data collected from different vehicles as shown in Figure 19. Looking at the map in **Figure 21**, the reason behind the lower repeatability for this specific curve can be understood. Curve ID 44 was falsely identified as a curve whereas it is located in a straight section of the road and should have never been considered a horizontal curve. That explains the inconsistent advisory speed measurements for curve 44. This is because a straight section of a road does not have the gradual increase and decrease in cross slope values (superelevation). Moreover, horizontal curves have a single maximum cross slope value (full superelevation). The advisory speed is calculated based on this superelevation value. However, a straight segment of the road only follows the normal crown for its cross slope (lacking the high variance of cross slope values seen along a horizontal curve).

Figure 21. Map. Map of curve with ID 44

CONCLUSIONS AND RECOMMENDATIONS

This study validated the smartphone-based framework which was introduced in NCHRP IDEA 214 and enhanced in NCHRP IDEA 248 for real-time curve advisory speed assessment. Horizontal curves, while representing a small portion of the roadway system, account for a disproportionate number of severe and fatal crashes; nearly one in four fatal crashes occurs on curves, with most involving vehicles leaving the roadway. The developed smartphone-based framework provides a practical, low-cost framework to enable faster and more frequent data collection. This allows agencies to proactively perform roadway safety assessments such as identifying curves needing countermeasures, e.g., advisory speed signs.

Multiple experiments were done at SR 136 near Cloudland Canyon and GA SR 190 near Pine Mountain to evaluate the accuracy and repeatability of the superelevation and advisory speed measurements. Accuracy was evaluated by comparing phone measurements to Ground Reference (GR) data from 3D laser imaging systems, with performance quantified using Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). Repeatability was assessed by comparing phone measurements across different cars and drivers, using pooled standard deviation to measure consistency. The experiments confirmed that the smartphone-based framework can achieve high accuracy and produce repeatable results across multiple runs and vehicles.

The accuracy site (GA SR 190) demonstrated the methodology achieves overall superelevation RMSE of around 1.35% and 95% of advisory speed errors were within 3 mph of the ground reference. This is an acceptable limit for designing advisory speed signs, considering that they are typically rounded down to the nearest 5 mph. Two-thirds of the runs were within 1 mph, indicating excellent agreement with high-precision laser-based ground reference data. Such low superelevation and advisory speed errors support the fact that this framework meets accuracy requirements for traffic engineering applications. Results also showed that driving speed had minimal impact on measurement accuracy, with superelevation accuracy ranging from an RMSE of 1.2 to 1.7 percent across different speeds. The same observation was made about curve radii, with advisory speed accuracy ranging from an RMSE of 1.3 to 2.1 mph for different curve radii. On the other hand, the type of holder was identified as a critical factor. Secure mounts with metal joints produced reliable results (superelevation RMSE values from 0.894 to 2.147 percent), whereas one plastic mount type resulted in lower accuracy (superelevation RMSE of 4.3 percent).

The repeatability tests at Cloudland Canyon (GA SR 136) delivered highly consistent superelevation and advisory speed measurements across multiple runs of the same vehicle and across different vehicles. One vehicle, although producing repeatable measurements across multiple runs, consistently produced offset readings due to a mounting or calibration issue. The measurements from this vehicle were excluded from the analyses. The other four vehicles produced repeatable superelevation readings with a mean pointwise standard deviation of 0.535 (percent cross-slope). The standard deviation values ranged from 0.075 to 2.826 percent while on average, 95% of the measurements produced standard deviations below one. Repeatable advisory speed measurements were also obtained with a mean standard deviation of 0.6 mph ranging from around 0.2 to 1.6 mph while the 95th percentile was around 0.9 mph. Advisory speed values also lined up with existing signage on sharp curves. Some discrepancies between advisory speed values for one of the curves were traced back to errors in curve identification (caused by the computation method and poor roadway shapefile) rather than the measurements themselves, highlighting the importance of checking the quality of curve inventories. The tests confirmed that the framework achieves repeatable superelevation and advisory speed measurements. They also highlighted the importance of properly mounting the equipment, following calibration procedures, and not moving the smartphone afterwards.

The findings from the two experiments demonstrate that a smartphone-based framework can provide accurate and repeatable curve advisory speed assessments in the field. The ability to collect and process data in real time in the field allows agencies to verify the accuracy of advisory speed measurements and perform any necessary corrections before returning to the office. This approach will save time and reduce costs for local agencies, especially those with limited resources and long travel distances to rural areas for safety assessments.

Overall, this project shows that smartphones can serve as a low-cost, scalable solution that enables more frequent curve safety assessments at both project and network levels in a technically and financially feasible manner. This supports proactive safety management practices by helping agencies identify high-risk locations and implement countermeasures before crashes occur.

Recommendation:

To assess a larger area of the roadway network in a shorter amount of time, data collection can be integrated into vehicles that already travel on a regular basis, such as maintenance crew vehicles (local agencies), freight trucks, garbage collection vehicles, school buses, or police cars. It is worth noting that the proposed framework in NCHRP IDEA 214 and 248 projects has been evaluated using passenger vehicles, such as sedans, SUVs, pickup trucks, and vans. Future experiments and validation are needed to evaluate the accuracy and repeatability of measurements for when the smartphone is used in larger vehicles.

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