IDAHO TRANSPORTATION DEPARTMENT

RESEARCH REPORT

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RP 264

Evaluation of Mobile Apps for Pavement Smoothness Measurement

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16. Abstract

Measuring the surface roughness of freshly constructed pavements is common practice to ensure that the appropriate agency specifications are met. Contractors as well as state and local transportation agencies commonly use laser-based profilers to quantify the surface roughness for newly constructed pavements. However, these laser-based profilers are expensive, and require specialized training for operators. Moreover, state agencies usually own a limited number of such profilers which means they cannot be simultaneously used to test pavements being constructed in different parts of a state. In such cases, state agencies are often left with no other choice than accepting contractor-reported roughness values. Identifying lower-cost and easy-to-access alternatives for pavement roughness measurement will benefit state agencies with their Quality Control/Quality Assurance (QC/QA) protocols. One possible alternative for lower-cost pavement roughness measurement involves using data from accelerometers built into mobile devices. This research project focused on (1) review of published literature; and (2) field testing efforts to evaluate the validity, accuracy and repeatability of pavement roughness measurement using applications developed for mobile devices. A certain mobile application, RoadBump Pro, developed for the Android platform was evaluated in this study. Field testing efforts involved roughness measurement along roadway sections identified across four different districts in the state of Idaho. The collected data was compared against standard pavement roughness measurement devices such as high-speed inertial profilers and light-weight profilers. Results from the analysis indicated that pavement roughness values measured using mobile devices are significantly affected by factors such as mobile device type, vehicle type, driving speed, etc. Careful calibration efforts for certain device-vehicle combinations resulted in measured roughness values that were reasonably close to those established using inertial profilers. However, these calibration factors also showed variations while testing along different roadway segments. Findings from this research effort indicated that the technology of pavement roughness measurement using mobile devices is not sufficiently developed to be adopted into agency QC/QA programs.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.3048	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles (statute)	1.61	kilometers	km	km	kilometers	0.621	miles (statute)	mi
		AREA					AREA		
in^2	square inches	645.2	millimeters squared	cm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.0929	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C	°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

Acknowledgements

This study was sponsored by the Idaho Transportation Department (ITD) and FHWA. The authors would like to acknowledge the financial and technical support of these organizations. Several individuals from ITD contributed significantly towards ensuring successful completion of this research project; some of these individuals served officially as on the project Technical Advisory Committee (TAC), whereas others helped with the research work even though they were not officially a part of the study. Names of the TAC committee members are listed in the next section. In this section, the authors have attempted to list those individuals who volunteered their time to ensure success of this project; any omission is purely accidental. The authors greatly acknowledge the contributions of: Sandra Alberti, Dorothy Aydelotte, Darrin Johnson, Greydon Wright, Dan Harelson, Bryon Breen, Daris Bruce, and Shawna King.

Technical Advisory Committee

Each research project is overseen by a technical advisory committee (TAC), which is led by an ITD project sponsor and project manager. The Technical Advisory Committee (TAC) is responsible for monitoring project progress, reviewing deliverables, ensuring that study objective is met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

Project Sponsor – Devin Rigby, P.E.

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Executive Summary

Pavement roughness has been identified as one of the most critical factors affecting road user comfort and satisfaction. Pavement management programs implemented by most transportation agencies require peordic roughness measurements along the roadway network. This network-level roadway roughness measurement is usually carried out using state-of-the-art pavement condition assessement equipment such as inertial profilers. Significantly high purchasing costs associated with inertial profilers limits the number of such units that a particular state transportation agency can procure. Therefore, mobilizing the equipment to different parts of a state on short-notice becomes particularly challenging. This limitation becomes particularly significant when roughness measurements are required for surface smoothness assurance along freshly constructed pavements. State transportation agencies are often forced to accept the contractor-provided roughness measurement values as verification using inertial profilers poses significant logistical challenges. In such cases, alternative, relatively inexpensive pavement roughness measurement approaches can be particularly beneficial.

Modern mobile devices such as smartphones and tablets are equipped with numerous sensors such as accelerometers that can be leveraged for pavement roughness measurement. These mobile devices can be mounted to the dashboard of vehicles used by engineers, and data from the accelerometers within the mobile devices can be utilized for pavement roughness measurement. The current research study, sponsored by the Idaho Transportation Department (ITD), evaluated the accuracy of pavement roughness measurement using mobile devices. The ultimate objective was to assess whether or not this measurement approach can be adopted into agency quality assurance specifications for roadway surface smoothness. A commercially available mobile application (RoadBump Pro®) developed for the Android platform was used in this study. Roadway surface roughness was quantified using the universally used International Roughness Index (IRI).

The first step in the study involved conducting several pilot tests to compare the mobile device-measured road roughness values against those measured using reference measurement units such as inertial profilers and lightweight profilers. During the pilot testing it was observed that significant variations in the IRI values measured by the mobile devices can be observed depending on the vehicle type used for testing. Generally, it was observed that measurements using passenger cars yielded significantly higher IRI values compared to those using Sports Utility Vehicles. Comparing the average IRI values measured using mobile devices and the reference measurement units for a particular roadway section, the research team developed certain Modification Factors (MFs) that can be used to 'shift' the mobile-measured IRI values so that they are comparable to those established using inertial profilers.

The next step in the research effort involved selecting representative roadway sections from different parts of Idaho for roughness measurement using mobile devices. The research team coordinated with ITD engineers to select roadway sections for which surface roughness data from inertial profilers were readily available. Mobile device-based roughness measurements were carried out along all selected

roadway sections using multiple vehicle-device combinations. The collected data was analyzed for accuracy, repeatability, as well as for effects of different factors such as vehicle operational speed, terrain, etc.

Extensive analysis of the collected data established that pavement roughness measurement using mobile devices was significantly affected by the type of vehicle used, the type of mobile device used, the speed of operation of the vehicle, the quality of mounting of the mobile device inside the vehicle, etc. Even for the same vehicle-device combination, it was observed that the MF values changed from one roadway segment to another. This indicated that data collected using mobile devices may not be easily transformed to obtain values comparable to those established using inertial profilers. Mobile device-measured IRI values were found to be affected by the operational speed of the vehicle, but no consistent trend was observed in the variation. Moreover, two identical devices were observed to yield significantly different IRI values when used inside the same vehicle. This indicates that variabilities associated with device manufacturing can also affect the measured roughness data significantly. Based on these findings, it was concluded that pavement roughness measurement using mobile devices is not sufficiently developed for implementation into agency specifications. Although the measured values do correspond to the level of roughness along a particular roadway, the collected data lacks sufficient accuracy and precision to justify incorporation into agency specifications.

In summary, testing during the current study indicated that mobile device-based roughness measurements were not repeatable enough to be part of agency QC/QA protocols. However, data collected from the mobile devices was found to “respond” to undulations on the roadway surface. Therefore, it may be possible for agency engineers to use these devices to identify whether a particular roadway section has a localized “bump” or not or if the roughness significantly changes from one section to another. Note that the current study did not focus on evaluating this particular hypothesis. Therefore, the research team cannot make a “confident claim” regarding the success of such an approach.

Chapter 1
Introduction

Pavement condition assessment is the process of monitoring the structural and functional condition of a pavement section [1]. Structural condition refers to the ability of a pavement structure to support current and future loadings, whereas the functional condition refers to its ability to provide a smooth ride to users. Periodic field surveying and testing efforts are carried out by transportation agencies to assess the overall "health" of the pavement network. The goal of periodic pavement condition assessment programs is to develop and maintain a detailed record of pavement conditions. This condition data is used in Pavement Management Systems (PMSs) to prioritize projects for maintenance/rehabilitation, allocate budgets, and estimate future funding needs. Additionally, pavement performance data collected over time can be used to develop pavement performance models that are subsequently utilized for predicting pavement condition throughout the design life. Frequent data collection, and utilization of reliable pavement performance models can help agencies "plan ahead of time", thus resulting in significant cost savings [2].

The primary focus of a pavement functional evaluation effort is to assess whether a particular section of pavement is adequately satisfying its functional requirements, or not. This is accomplished through quantification of different distresses along the roadway surface, as well as computation of indices representing the surface roughness and rideability. Surface roughness, according to ASTM E867, can be defined as *"the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality"* [3]. Roughness, also conversely referred to as smoothness, is a crucial pavement property since it affects not only the ride quality, but also fuel consumption, vehicle delays, and maintenance costs [4]. Similarly, rideability refers to how comfortable it is to ride on a given roadway segment. In addition to passenger discomfort, rough roads often cause damage to vehicles, lead to increased fuel consumptions and increased greenhouse gas emissions. Depending on the roughness of a road and several other factors, maintenance and reconstruction activities are selected for implementation.

Research Objective

Upon construction, the roughness of a pavement section is measured to ensure it meets agency specifications for the particular roadway type. For quality control purposes, contractors commonly use laser-based profilers to quantify the pavement roughness. One of the most commonly used methods to quantify the roughness of freshly constructed pavements involves computation of the International Roughness Index (IRI) value. State and local transportation agencies often conduct "independent checks" as a part of their quality assurance program to verify the results reported by the contractors. Newly constructed pavement surfaces are checked against pre-established IRI threshold values to ensure they meet agency-adopted smoothness criteria. Laser-based profilers used for pavement roughness measurement are expensive and require specialized training for operators. Accordingly, the number of laser-based profiler vehicles available to state/local transportation agencies for pavement smoothness inspection after paving is usually limited. Availability of low-cost alternatives for pavement smoothness verification testing can help state/local transportation agencies with their quality assurance programs. To address this need, researchers have recently explored the possibility of using applications developed for mobile-devices for pavement roughness measurement.

A research study was recently undertaken by Boise State University in collaboration with the Idaho Transportation Department (ITD) to evaluate the performance of mobile devices for pavement roughness measurement. The primary objective of this project was to determine the validity, accuracy and repeatability of pavement roughness measurements obtained using mobile devices mounted inside passenger vehicles (passenger cars, sports utility vehicles, or pick-up trucks). The ultimate objective was to equip ITD construction engineers with tools to "quickly" verify the surface roughness values reported by contractors immediately after construction. The project also aimed to establish best practical protocols for implementation of this roughness measurement approach in standard practices.

Methodology

Several different tasks involving review of published literature, field-testing to establish pavement surface roughness values, and analysis of collected data were undertaken towards fulfilment of the project objectives. A recently developed mobile application, named "RoadBump Pro", was used for this study. An extensive review of published literature was first carried out to collect all available information concerning pavement roughness measurement approaches, and how mobile-based applications can be used as low-cost alternatives for the same. The next task involved pilot testing the RoadBump Pro app at selected roadway segments. The pilot testing effort involved comparing data collected using RoadBump Pro app against those collected using standard measurement units, such as inertial profilers and/or light-weight profilers. Note that the high-speed inertial profiler and the lightweight profiler are both generally referred to as "standard measurement units" throughout this report. The pilot testing effort was carried out using different mobile devices mounted inside different vehicle types to assess the effects that different vehicle-device combinations may have on the measured roughness values. Data analyses were carried out to evaluate the significance of the difference between different vehicle-device combinations. Comparing the data against those collected using standard measurement approaches helped establish calibration factors for different vehicle-device combinations that may be used by ITD engineers. Finally, a "best-practices manual" was developed to follow and maintain consistency among pavement roughness measurement efforts using mobile devices (in case such efforts are undertaken by ITD engineers in the future). Details of all tasks carried out under the scope of this study have been documented in this research report.

Report Organization

This report is divided into six Chapters. Chapter 2 summarizes findings from a review of published literature concerning (1) the use of mobile devices and other measurement methods to determine the IRI values for pavements, and (2) best practices and implementation recommendations concerning the use of mobile devices for pavement roughness measurement.

The principle of IRI calculation using mobile devices is discussed in Chapter 3. The key factors that affect the data collection are also discussed in this chapter, providing the reader a solid theoretical background for operating the RoadBump Pro app.

Calibration of the mobile devices was conducted prior to using the RoadBump Pro app in road tests. A detailed discussion describing the approaches adopted for conducting the test is provided in Chapter 4. This chapter developed a modification factor-based calibration process. The method of calculating the modification factor to apply to the raw data from mobile devices is described in Chapter 4.

Chapter 5 provides a summary of all the road tests. Pavement roughness measurements were carried out along selected pavement segments in ITD districts 3, 4, 5, and 6. In total, pavement smoothness measurements were carried out along 20 (twenty) different roadway segments. In total 178 pavement roughness datasets were recorded from the road tests. IRI data collected from these road tests were analyzed, and relevant inferences have been provided in Chapter 5.

Chapter 6 summarizes all research tasks undertaken during this study, and presents relevant conclusions drawn from the collected data.

At the end of Chapter 6, four appendices are provided.

Appendix A shows the correspondence with the research engineer in Arkansas DOT and excerpts from communications with the developer of the RoadBump Pro app, Mr. David Grimmer. Appendix B provides the modified results to show the effectiveness of the modification factor to increase the accuracy of the IRI measured using the mobile devices. Appendix C provides instructions to operate the RoadBump Pro app, and documents procedures needed to be followed during pavement roughness measurements using this app. This procedure is developed and provided in order to demonstrate the data collection methodology adopted during this study and maintain consistency in case similar data collection efforts are ever undertaken by ITD engineers in the future. Finally, Appendix D provides additional theories on signal processing.

Chapter 2
Literature Review

Background

This chapter presents findings from an extensive review of published literature carried out under the scope of this research study. The primary objective of this literature review effort was to identify the state of the art and state of practice with respect to pavement roughness measurement. Different indices developed over the years by researchers and practitioners to quantify pavement roughness are listed along with discussions on the advantages and disadvantages associated with each.
Generally, roughness measurement falls into the following three categories [5]:

- A profile numeric defined directly by mathematical functions derived from the absolute profile of road surface elevations along one or two-wheel paths;
- A summary numeric measured through “response-type” systems calibrated to a profile or other numeric by correlation (usually the cumulative axle body relative displacement averaged over a given distance and expressed as a slope);
- Subjective ratings of riding quality or pavement serviceability, usually made by a panel of raters within a scale defined by subjective descriptors.

Devices for quantifying the wheelpath profiles of roadways can be traced back to the 19th century “land planes” developed in Germany and France. In the United States (US), land planes were first introduced by the Illinois Division of Highways in the early 1920’s to be used in the Bates Road Test; this device was referred to as the Illinois Profilograph. Carey et al. [6] provided a chronological account of different devices developed for pavement profile measurement. Some of the notable devices were: (1) The California Profilograph, (2) The Bureau of Public Roads – Roughometer, (3) The Midwest Research Institute Profile Equipment, (4) the AASHO Road Test Profilometer, and (5) The CHLOE Profilometer.

Several instruments ranging from rather simplistic ones to more sophisticated instruments were available during 1982 [7]. However, in spite of the availability of the instruments, the difficulty was the correlation and transferability of measured results from various instruments and the calibration to a common scale. Therefore, developing a common scale and fitting the results from all the devices to that scale became desirable. In order to seek a solution for the problem, a project was started by the US National Cooperative Highway Research Program (NCHRP) to assist state agencies in improving their use of roughness measuring equipment. The results from this study were summarized in NCHRP Report 228 [8]. The World Bank continued the work to determine how to compare the data obtained from different countries involved in their projects. In 1982, the World Bank initiated a correlation experiment in Brazil with a view to establish a calibration standard. Findings from those experiments suggested that by standardizing the equipment it was possible to characterize the results on a standardized scale. Ultimately, the roughness scale that was tested and defined was accepted as International Roughness Index (IRI) [7]. The IRI is used for quantifying the roughness of existing pavements and is one of the contributing factors for maintenance and rehabilitation activities. IRI is also used to ensure that newly constructed pavement surfaces meet agency standards as far as smoothness is concerned. The following sections introduce different pavement roughness indices that have been developed by researchers and practitioners over the years. This is followed by in-depth discussion on the concept of IRI, and different methods to measure the IRI value for a pavement section.

Roughness Indices

Several different roughness indices have been developed over the years to describe the surface quality of a pavement section. Some of the commonly used indices are: (1) Present Serviceability Rating (PSR); (2) Present Serviceability Index (PSI); (3) Ride Quality Index (RQI); (4) Ride Number (RN); (5) Profile Index (PI); (6) Half-car Roughness Index (HRI); (6) Mean Roughness Index (MRI); and (7) International Roughness Index (IRI). Brief discussions on the most commonly used roughness indices are presented below.

Present Serviceability Rating (PSR)

The Present Serviceability Rating (PSR) system was one of the earliest approaches to quantify the roughness of a pavement surface. The PSR system is based on the concept of serviceability or the ability of the pavement to serve traffic [6], and was developed through several road tests conducted by the American Association of State Highway Officials (AASHO). ASTM E867 defines PSR as *"… a mean rating of the serviceability of pavement (traveled length of road) established by a rating panel under controlled conditions."* The PSR scale ranges from 0 (very poor serviceability) to 5 (very good serviceability) and requires a panel of raters to ride in an automobile over the pavement under observation. PSR mainly gives an idea of passenger comfort. Ride comfort depends on the following elements: (1) Human response to vibration; (2) Vehicle response to vibration; and (3) Road roughness. Among these three elements, road roughness is the one that controls the other two; accordingly, lower road roughness leads to greater riding comfort.

Today, for road health monitoring throughout the country, the Federal Highway Administration (FHWA) still requires state transportation agencies to report the PSR data for their pavement networks.
lists descriptions of pavement sections that typically correspond to different PSR ranges as defined by FHWA [9].

Table 1. Descriptions of Pavement Conditions Corresponding to Different PSR Levels [9]

PSR Range (Verbal Rating)	Description
5.0 to 4.0 (Very Good)	Only new, superior (or nearly new) pavements are likely to be smooth enough and distress free (sufficiently free of cracks and patches) to qualify for this category. Most pavements constructed or resurfaced during the data year would normally be rated very good.
3.9 to 3.0 (Good)	Pavements in this category, although not quite as smooth as those described above, give a first class ride and exhibit few, if any, visible signs of surface deterioration. Flexible pavements may be beginning to show evidence of rutting and fine random cracks. Rigid pavements may be beginning to show evidence of slight surface deterioration, such as minor cracks and spalling.
2.9 to 2.0 (Fair)	The riding qualities of pavements in this category are noticeably inferior to those of new pavements and may be barely tolerable for high-speed traffic. Surface defects of flexible pavements may include rutting, map cracking, and extensive patching. Rigid pavements in this group may have a few joint failures, faulting and cracking, and some pumping.
1.9 to 1.0 (Poor)	Pavements in this category have deteriorated to such an extent that they affect the speed of free-flow traffic. Flexible pavement may have large potholes and deep cracks. Distress includes raveling, cracking, rutting, and occurs over 50 percent, or more, of the surface. Rigid pavement distress includes joint spalling, faulting, patching, cracking, scaling, and may include pumping and faulting.
0.9 to 0.0 (Very Poor)	Pavements in this category are in an extremely deteriorated condition. The facility is passable only at reduced speeds and with considerable ride discomfort. Large potholes and deep cracks exist. Distress occurs over 75 percent or more of the surface.

Present Serviceability Index (PSI)

The primary disadvantage of the PSR system is that it relies on human interpretation of ride quality, and is therefore highly subjective in nature. Unlike PSR, the Present Serviceability Index (PSI) does not solely rely on human interpretation of ride quality. However, it is important to note that the PSI value is not completely independent of PSR; it can be thought of as an index that was developed by statistically correlating PSR values for different pavement sections with certain measures of surface profile, and pavement distresses. To develop the PSI, a panel of raters first evaluated various road segments across the states of Illinois, Indiana, and Minnesota, and established the corresponding PSR values. This information was then statistically correlated to certain measures of surface profile and pavement distresses. Equations listed in **Figure 1** show the expressions used to calculate the PSI values for flexible and rigid pavements, respectively [10].

$$PSI = 5.03 - 1.91 \times \log(1 + SV) - 1.38\,(RD)^2 - 0.01\sqrt{C + P} \text{ (Flexible pavement)}$$
$$PSI = 5.41 - 1.78 \times \log(1 + SV) - 0.09\ \sqrt{C + P} \text{ (Rigid Pavement)}$$

Figure 1. Equations for Calculating PSI Values for Flexible and Rigid Pavements

Here, PSI is Present Serviceability Index, SV is slope Variance, RD is mean rut depth (in.) and C+P is cracking and patching ($ft^2/100ft^2$)

Note that the PSI value calculated using the above equations is a statistical estimate of the mean of the Present Serviceability Rating (PSR) values assigned to a particular pavement section by the rating panel. The Slope Variance (SV) value is measured using a CHLOE profilometer, an electro-mechanical device that needs to be towed by a vehicle [6]. The CHLOE profilometer detects the following three statistical measures for every pavement section being rated: (1) number of sampling points, (2) sum of the deviations of the slopes from an assumed reference, and (3) sum of the squared deviations of the slopes from the same reference. These numbers are then combined to establish the SV value. The Rut Depth (RD) is the mean rut depth (in.); C is cracking (ft/100 ft^2), and P is patching (ft^2/100 ft^2). Note that the PSI value for a particular pavement does not remain constant with time, and decreases in value as the pavement surface deteriorates. **Figure 2** graphically illustrates how the PSI value for a pavement section changes with time. Vertical bumps in the PSI curve represent maintenance and rehabilitation events. Notice that the PSI value achieved after maintenance (second peak in the graph) is not as high as the initial peak. This is because even through maintenance, the serviceability of the road cannot be restored to the same level as a newly paved section.

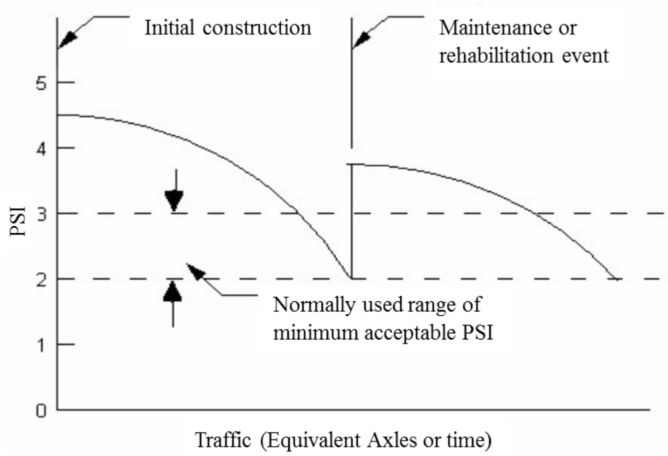


Figure 2. Schematic Representation of a Pavement Performance Curve [11]

The only difference between PSR and PSI is that the “Index” is a statistical estimate of the panel’s mean “Rating”. However, PSI calculation is a highly time-consuming process as it requires significant amounts of data collection. Moreover, it is conceptually derived from PSR, which is highly subjective in nature. Accordingly, PSI is not the most effective approach for quantifying pavement roughness in modern practice.

Ride Number (RN)

Ride Number (RN) is an index that is conceptually similar to PSI, with a scale ranging from 0 to 5; 0 represents an un-rideable road and 5.0 represents a perfectly smooth surface. The concept of RN was developed under the scope of a National Cooperative Highway Research Program (NCHRP) sponsored research study [12], and was published as NCHRP Report 308. The objective of the research was to identify the link between road profiles and subjective opinion. The RN value is obtained through nonlinear transformation of the Profile Index (PI) value, which is obtained from pavement profile data. To get RN, at first, Power Spectral Density (PSD) functions are generated for two longitudinal profiles, and then further reduced to get the summary statistics generally called Profile Index (PI). The PI values for the two profiles are then combined by Root Mean Square (RMS) method to obtain and estimate the mean PI value. The mathematical process introduced to determine RN is described in NCHRP Report 275. At first, PI is computed from the left and right PIs by the following equation [13]:

$$PI = \sqrt{\frac{PI_L^2 + PI_R^2}{2}}$$

Figure 3. Equation for Calculating the Profile Index (PI) Value Based on Measurements along Left and Right Wheelpaths

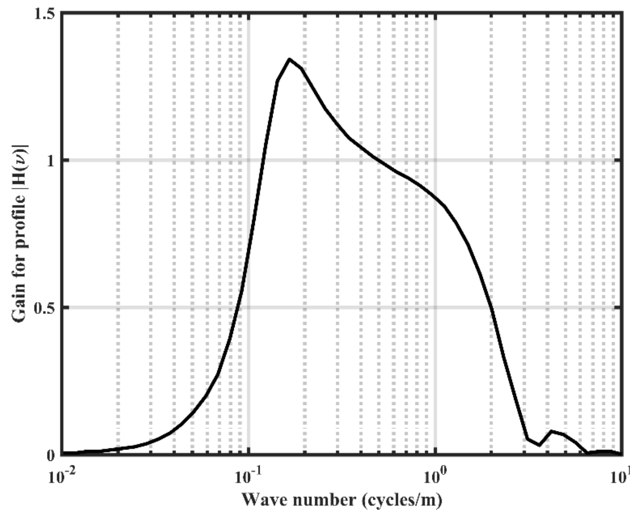
The PI values calculated using the equation presented in **Figure 3** can subsequently be used to calculate the RN value (see **Figure 4**).

$$RN = 5e^{-160 \times PI}$$

Figure 4. Formula for Calculating the Ride Number (RN) Value Based on Calculated Profile Index (PI) Values

In cases where collecting two profiles is difficult, the RN value can be computed from only one profile; however, RN values calculated from profiles along two wheelpaths are different from that calculated along one-wheel path. Before starting the calculation, the surface profile is filtered using a moving average filter with a base length of 250 mm (9.85 in.) [11]. The system for calculating RN is linear, so this profile index filter produces a signal similar to the input signal (please refer to the section on **Frequency Response Analysis** for details).

Depending on the wave number of the input sinusoid, the amplitude of the output sinusoid will be modified. The modification factor is called gain. Considering that roadway profiles can be treated as waveforms resulting from superposition of multiple sinusoidal waves, the gain is highly dependent on the wavelengths. The dependence of gain on wavelengths is often represented by plotting it against the wave number (inverse of wavelength) (see **Figure 5**). As seen from the figure, the system exhibits a maximum sensitivity for a wave number of 0.16 cycle/m (0.05 cycle/ft.).



Note: The horizontal axis represents Wave Number, which is Inverse of the Wave Length.

Figure 5. Sensitivity of RN to Wavelength [11]

Quarter-Car Model

Response-type roughness systems were popular since 1940 and numerous research were being done to develop the roughness scale. The profile index was tailored to correlate well with the output of these systems. In order to calibrate the response-type systems, engineers were trying to develop an ideal system for the computer.

The idea was a mathematical model which could simulate the vehicle and the road meter. The mathematical model is named as quarter-car computerized response system. It was also called as "The Golden Car". This name was assigned since this simulation was a calibration reference. For example, a meter bar made of gold is kept isolated inside a vault and brought out when calibration of other length measures is needed. A schematic diagram of Quarter-Car Model is shown in **Figure 6**.

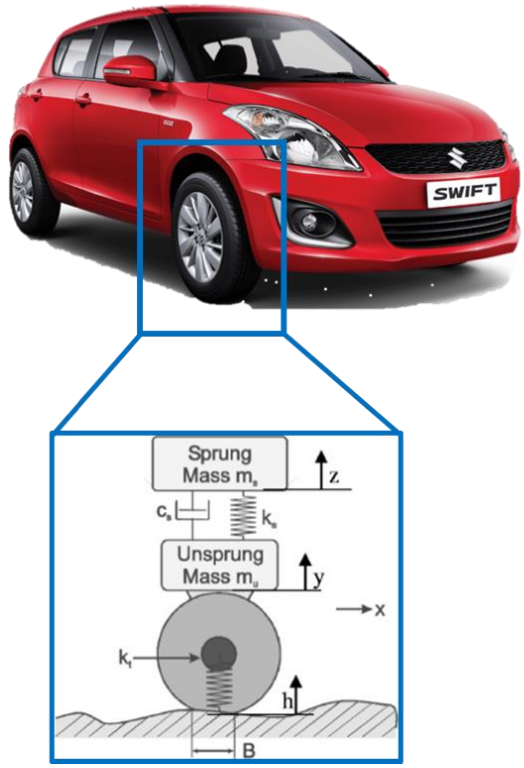


Figure 6. Schematic Representation of a Quarter Car Model [14]

This mathematical simulation uses the quarter car system to generate an imaginary profile. As shown in **Figure 6**, the quarter car is made up of two parts: a sprung mass m_s, which represents the vehicle body and an unsprung mass m_u, which represents the set of wheel and suspension. The sprung and unsprung masses are connected by the suspension, which is emulated by a spring k_s and a damper c_s. The system is in contact with the real pavement surface by another spring k_t [15].

Half-Car Roughness Index

Before IRI was widely accepted, the response-type systems were used for roughness measurement. Because of calibrating those systems, vehicle simulation was used with measured profiles. One of the popular response type systems is the Half-car model. The quarter-car model equations can be used for estimating its response. Essentially, by half car model, two data points are gathered for every single point along the road profile. Therefore, to get the value at a point the numbers were averaged for every point and fed in the quarter car model.

The half-car model has an advantage over the quarter-car model. It closely resembles the road experience, since it is collecting information from both sides of the car. A schematic diagram of the Half-car roughness index is shown in **Figure 7**.

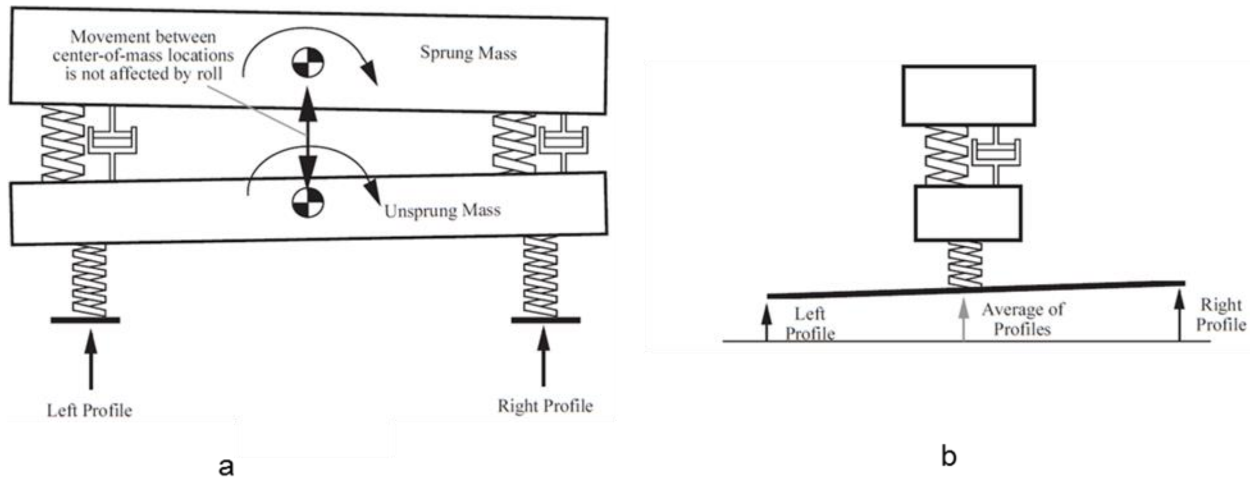


Figure 7. (a) A Half-Car Model, (b) A Quarter-Car Model [16]

Figure 7 shows a half-car model **(a)** and a quarter-car model **(b).** It is evident from the figure that the half-car model is quite similar to the quarter-car model except for the connection between the sets of two quarter-car models. These two sets are joined together by the axle of the vehicle. During operation, the half car model reads two profiles at a time shown in the figure by the left and right profile. However, the quarter car model is unable to analyze two profiles at a time. The profiles are averaged and fed into the quarter-car model to get the result. **Figure 7 (b)** shows this process.

The HRI value is calculated by applying the IRI algorithm to the average of the left and right wheel path profiles. Researchers in the past have observed that pavement roughness calculated using the HRI is less than or equal to that from IRI analysis; a correlation of HRI = 0.89 IRI has been reported (NHI Course 131100). It has also been argued that "little or no additional information is provided by the HRI over the IRI".

International Roughness Index

Each state in the United States is required to report the IRI of their road network to the Federal Highway Administration (FHWA) in the annual Highway Performance Monitoring System (HPMS). According to ASTM, "IRI is an index computed from a longitudinal profile measurement using a quarter-car simulation at a simulation speed of 50 mph (80 km/h)" [3]. It is recorded in inches per mile (in/mile), or meters per kilometer (m/km).

IRI was chosen as the standard reference roughness index of the HPMS, a national database of roadway information kept by the FHWA. Reported road segment IRI is compared with the standards developed by FHWA. Deviations from the standards indicate the requirement for repair and maintenance. Higher IRI values indicate higher roughness of the pavement and vice versa. The HPMS Field Manual lists the following advantages associated with the use of IRI for quantifying pavement roughness [17]:

- It is a time-stable and reproducible index calculated through mathematical processing of the known pavement profile;
- It is broadly representative of the effects of roughness on vehicle response and user's perception over the range of wavelengths of interest and is thus relevant to the definition of roughness;
- It is a zero-origin scale consistent with the roughness definition;

- It is compatible with profile measuring equipment available in the U.S. market;
- It is independent of section length and amenable to simple averaging;
- It is consistent with established international standards and can be related to other roughness measures.

The FHWA recommended threshold is 170 in/mile (2.7 m/km) for acceptable ride quality in its 1998 strategic plan for the National Highway System. **Table 2** provides the pavement condition criteria for all functional road classifications in the national highway system [17].**Figure 8** shows how to interpret the IRI scale with driving quality.

Table 2. FHWA Pavement Condition Criteria [17]

Category	IRI (in/mile)		Interstate and NHS Ride Quality
	Interstate	Non-Interstate	
Very good	<60	<60	Acceptable 0-170
Good	60 - 94	60 - 94	
Fair	95 - 119	95 - 170	
Poor	120-170	171-220	Less than acceptable > 170
Very Poor	>170	>220	

IRI is a summary of the roughness quality of the road. These roughness qualities affect vehicle response. It also gives an overall idea of operating cost, ride quality, dynamic wheel loads and overall surface condition. **Figure 8** demonstrates IRI ranges comparing different classes of roads. It shows the IRI in both m/km and in/mile scales. The figure shows what should be the IRI of the road for a targeted speed of the road. For instance, on a road with IRI of 200 in/mile, the maximum speed can be 62 mph. Therefore, if the road is intended to serve a traffic speed of more than 62 mph, the roughness has to be less than 200 in/mile. The figure also shows the range of expected roughness of different types of roads. For example, the IRI of a rough unpaved road is between 500 in/mile and 1200 in/mile.

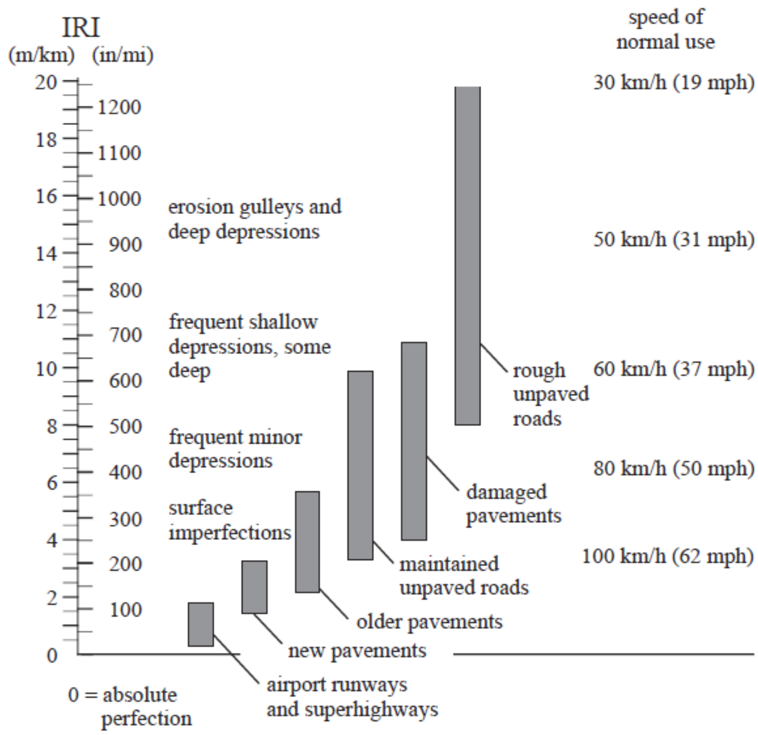


Figure 8. IRI Interpretation Scale [11]

IRI is a statistical index that summarizes the surface deviations for just one-wheel track. Similar to HRI, IRI calculation also relies on the Quarter-Car Model. However, unlike HRI, IRI used only one profile to quantify the roughness. According to ASTM [3] equations for calculating the IRI are expressed in the state-space form. The state-space form of motion is shown in **Figure 9**.

$$\dot{x} = Ax + Bz$$
$$y = Cx + Dz_{road}$$

Figure 9. Equation of Motion in State-Space Form

In matrix form, the equations shown in **Figure 9** can be rewritten in terms of the Quarter-Car Model parameters, as shown in
Figure 10.

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\dfrac{k_s}{m_s} & -\dfrac{c_s}{m_s} & \dfrac{k_s}{m_s} & \dfrac{c_s}{m_s} \\ 0 & 0 & 0 & 1 \\ \dfrac{k_s}{m_u} & \dfrac{c_s}{m_u} & -\dfrac{k_t + k_s}{m_u} & -\dfrac{c_s}{m_u} \end{bmatrix} \begin{bmatrix} x_s \\ \dot{x_s} \\ x_u \\ \dot{x_u} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{k_t}{m_u} \end{bmatrix} [z_{road}]$$

$$y = [-1 \quad 0 \quad 1 \quad 0] \begin{bmatrix} x_s \\ \dot{x_s} \\ x_u \\ \dot{x_u} \end{bmatrix} + [0][z_{road}]$$

Figure 10. Equation of Motion in State-Space Matrix Form

The parameters (normalized to m_s=1) for the golden car are [18] c_s = 6.0 [1/s], k_t = 653 [1/s^2], k_s = 63.3 [1/s^2], and $\mu = \frac{m_u}{m_s}$ =0.15.

Similar to RN, IRI is sensitive to smaller wavelengths. The range of wavelengths that influences it lies between 1.2 and 3.0 meters [11] The wave number sensitivity of the IRI quarter-car filter is shown in **Figure 11**. The calculation procedure is same as described in RN. The output wave is multiplied by a factor (gain), which is a dimensionless number and varies depending on the wave number of the input wave. For instance, if the input is a sinusoid with an amplitude and wave number of 10 and 0.0065 cycle/m then the output amplitude will be $10 \times 1.46 = 14.6$. Here 1.46 is a factor, called gain, which is shown in **Figure 11.**

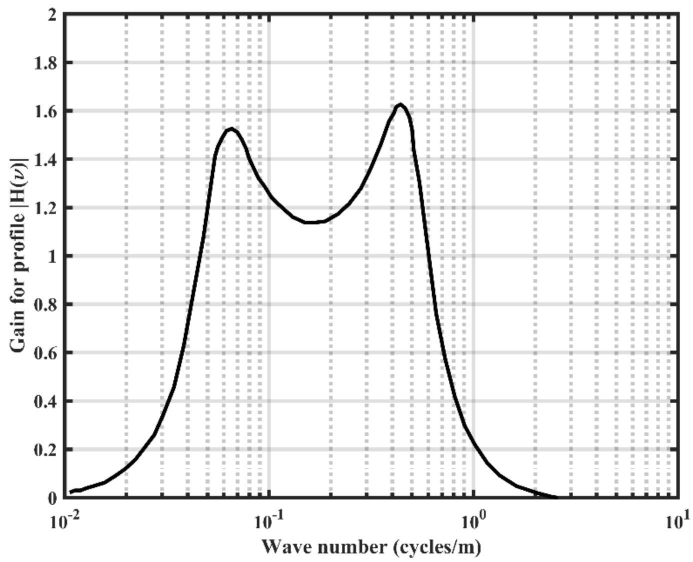


Figure 11. Sensitivity of IRI to Wave Number [11]

Existing Methods for Measuring Pavement Roughness

With the above review of a few major roughness indices, we move forward and discuss different methods that can measure these indices. State DOTs conduct the measurement of IRI on a regular basis. A number of devices and methods are available to evaluate pavement roughness. However, most are not currently utilized because of low accuracy and measurement inefficiencies. A review of pavement roughness measurement technology and devices are summarized below.

- In early 1900s engineers began to use road and level surveys to get the pavement profile [19].
- A response-type road roughness measurement system named the Bureau of Public Roads (BPR) Roughometer was developed in the 1940s. This device involved a single-axle trailer with a single tire towed by a vehicle. Another response-based system is Mays Ride Meter. This system was developed in 1960.
- The profilograph is a device used to measure the deviation of pavement surface from a flat reference. California profilograph and Rainhart profilograph fall into this category. These emerged in the 1960s and have been available for many years and existed in a variety of different forms, configurations, and brands [20].
- The first high-speed inertial profiler was developed by Elson Spangler and William Kelley at the General Motors Research Corporation [21]. The Automatic Road Analyzer (ARAN), Dynatest, SSI, Ames

Engineering, and International Cybernetics Corporation (ICC) inertial profilers are now widely used. ITD uses a 2017 Pathway Services PathRunner van for automated road and pavement condition surveys (South Dakota Profiler Class 1 - ASTM E950).

The devices typically used for measuring pavement smoothness in the U.S. can be divided into four categories:

- Calibration and construction control systems
- Response-type systems
- Manual devices
- Non-contact profile measurement systems

Among all the roughness parameters listed above, IRI is a common roughness indicator. IRI is used to measure roughness in 47 states within the US; however, at least 10 different approaches have been used to collect IRI [19]. Not only do variations exist among the tools used to collect pavement profile, but also different analysis methods are also used (choice of wheel path data, averaging techniques). A brief description of different roughness measuring methods is provided below.

Roughness Measurement Methods

Depending on the working principle, the roughness measurement methods can be divided into two types, static and inertial measures. The method, in which the instruments are not moving or at least measures different elevations while the instrument is standing in the same place is called static measures. For measuring profiles, “Rod and level” and “Dipstick” are both considered as static measuring devices. On the other hand, inertial profiler, profilographs and Response-type road roughness meters are used in inertial methods.

Typically, inertial profilers are faster and measure roughness automatically. In contrast, static profiling methods are slower and do not offer automation. Following are the methods/equipment that can be used for calculating surface profiles and/or roughness:

Rod and Level

Level surveying is a common topic in surveying and this is the most basic instrument used for road profiling. The level delivers the elevation reference, the readings from the road produces the height relative to the reference. A tape measures the location of the particular elevation measuring point. Although, it seems that the working procedure will be same for difference devices, the requirements for obtaining a profile that is valid for computing roughness are different from ordinary procedure. The resolution of intervals for taking elevation measures should be fine enough to represent the actual profile as close as possible. The individual measures have to be accurate within 0.02 in. or less. From the description of acquiring the reading, it is clear that the requirements are much more rigorous than conventional surveying. **Figure 12** shows a rod-level profile measurement setup.

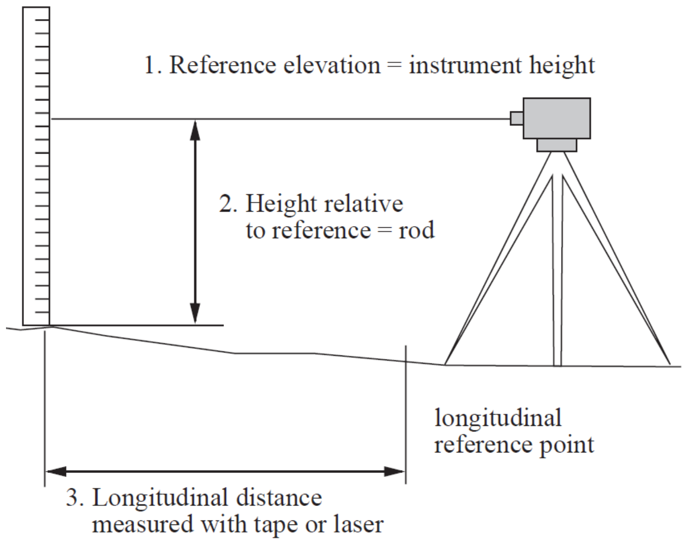


Figure 12. Rod and Level Profile Measurement Setup [11]

Dipstick Profiler

The Dipstick Profiler is a semi-automated device developed by Face Company. It has automatic data collection and processing system in its battery-powered on-board computer. This instrument can record the pavement profile measurement very accurately and comparatively faster than rod and level measurements. The device can record 10 to 15 readings per minute. Software analysis provides a profile accurate to ± 0.127 mm. As measurements by Dipstick are time-consuming and are generally used to measure a profile for calibration of more complex instruments. **Figure 13** shows a Dipstick Profiler.

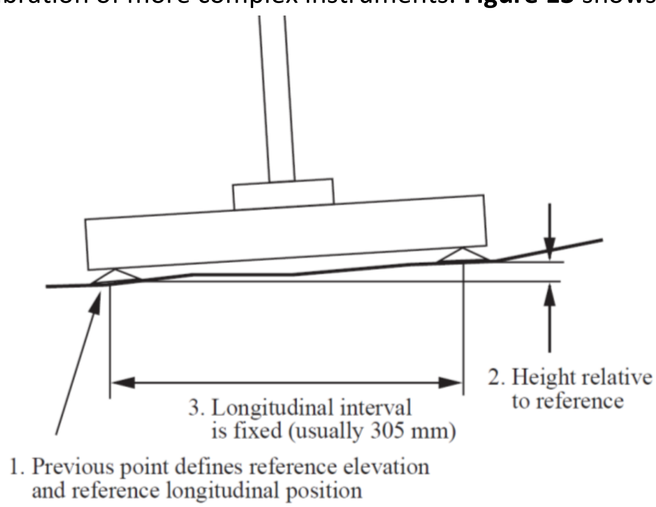


Figure 13. Dipstick Profiler [4]

Working with Dipstick is rather simpler compared to the Rod-Level profiling method. The device is moved along the line of interest of which the profile is required. It contains a built-in inclinometer, the function of which is measuring the difference in height between the two supports. Normally the supports are spaced 305 mm apart. To profile a line along the ground, the device is leaned forward so that all of its weight is on the leading foot. This causes the rear foot to be slightly off of the ground. In this position, the device is rotated 180 degrees about the front foot, bringing the rear foot in front. The process is repeated till the end of the line is reached. During the process, the onboard computer monitors the sensors at some time intervals. It automatically records the change in elevation. It beeps to indicate when it has successfully recorded the data and is ready for the next recording. **Figure 14** shows a dipstick profiler in action.

At every data collection point, it changes its reference elevation. Elevation determined for the previous point becomes the reference for the next reading. The height relative to the reference is calculated using the angle of the device with respect to surface normal, together with the spacing between its supports. The longitudinal distance is determined by multiplying the number of measures made with known spacing.

Rod-Level and Dipstick Profilers both will yield same profile if the initial reference is same for both setups.

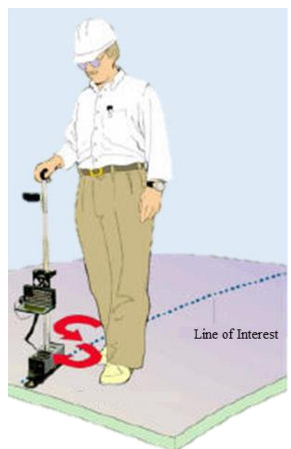


Figure 14. Dipstick Profiler in Action [22]

Profilographs

Profilograph is a low-speed device. It measures the road by sensing the height of the wheel attached to it. The wheel is located at its center and it can move in the vertical direction. By using this free vertical movement, it senses the deviations in the road profile. The deviation is recorded on graph paper from the motion of the sensing wheel. Although the sensitivity of a profilograph can go up to 6 m in length it can detect very slight deviations in the profile. Nevertheless, due to its low speed, it is impractical for using is road network evaluation. A profilograph is shown in **Figure 15**.

Figure 15. Photograph Showing a Profilograph [23]

Inertial Profiler

An inertial profiler concept implemented at General Motors Research (GMR) laboratories in the 1960 and later developed in 1966, has been widely used for highway evaluation. Inertial Profilers are capable of accurately measuring the wavelengths present on the roadway without amplification or attenuation. The measurements obtained from inertial profilers can provide a basis for smoothness specifications for new and rehabilitated pavements, and for providing a roughness index for monitoring pavement smoothness throughout the pavement's service life. The inertial profiler needs a dedicated vehicle that can drive at or above 60 mph. It should have a GPS attached to it. The collected roughness data is attributed to a point along the road to mark the road condition at that location. For assigning data to an accurate location the coordinates need to be as accurate as possible. Therefore, a GPS with fine resolution is required for this case. If a GPS with lower resolution is used, then the roughness data is allotted to a false position. For safety purposes, the profiler vehicle should have a flashing light. A standard inertial profiler vehicle is shown in **Figure 16**.

Figure 16. Photograph Showing an Inertial Profiler [24]

According to Woodstrom [25], modern inertial profilers require four basic sub-systems:

- Accelerometers to determine the height of the vehicle relative to an inertial frame of reference
- Height sensors to measure the instantaneous riding height of the vehicle relative to a location on the road below the sensor
- Distance or a speed sensor to determine the position of the vehicle along the length of the road (nowadays combined with GPS)
- Computer hardware and software for computation of the road profile

From the four main components of inertial profilers, the accelerometer is used on high-speed profilers to establish an inertial reference. Relative height measurements are made with the reading from height sensor data and the accelerometer data. The vertical acceleration reading from the accelerometer is integrated twice to establish its vertical position. This is used as a floating reference height and the height sensor measurement is subtracted from it to obtain the road elevation. All these calculations are done in a central computer. A brief description of the accelerometer and its working principle is provided in Appendix D.

Current Pavement Roughness Measurement Practices

Currently, IRI has been a widely accepted as the standard reference roughness index of the roadway information kept by the FHWA. According to the IRI measurement practices, inertial profilers testing vehicles are suitable for pavement roughness data collection at a high speed of approximately 50 mph. This speed is relatively high compared to the usual operating speed of urban roadways (usually 30-35 mph). In contrast, a lightweight profiler is a viable option operating at low speed. The advantages with lightweight profilers are: (1) Weight of lightweight profilers is significantly less than a typical high-speed profiler. This allows them to be used on newly paved concrete pavements; (2) Lightweight profilers operate at lower speeds (not more than 20 mph). This makes lightweight profilers better suited for operating in constrained conditions, such as behind barriers or between shorter sections of non-continuous pavements. Furthermore, an ongoing research study sponsored by the National Cooperative Highway Research Program (NCHRP; Project 10-93: Measuring, Characterizing, and Reporting Pavement Roughness of Low-Speed and Urban Roads) is focusing on identifying/developing a means for measuring, characterizing, and reporting pavement roughness on low-speed and urban roads.

Merritt et al. [26] synthesized a state-of-the-practice for IRI-based specifications to help the contractors, who are familiar with the profilograph-based specifications, and understand the IRI-based specifications. They provided a summary of current practices used by different states. A summary of methods used for calibrating the profilers for using in the field is listed in the report titled "Improving the Quality of Pavement Profiler Performance", a work conducted under Transportation Pooled Fund Study TPF-5(063). This report also summarizes the procedures for calibrating reference devices against which the accuracies of standard profilers are verified. Merritt et al. [26] also presented results from a survey conducted on practices concerning the use of IRI as a pavement roughness indicator. Several significant findings from the survey have been listed below.

- 66 percent responding agencies reported using IRI-based specifications for asphalt pavement,

- 21 percent responding agencies reported using IRI-based specifications for concrete pavements, whereas 69 percent reported using profilograph-based specifications; the remaining states reported not having a concrete pavement smoothness specification.
- States use 0.1 mile section lengths for reporting pavement smoothness.
- 28 percent responding agencies reported collecting the profile data internally, 42 percent reported requiring the contractor to collect profile data, whereas the remaining 30 percent reported requiring data collection by both agency as well as contractors.
- 85 percent responding agencies reported having a verification process to evaluate contractor results.
- 60 percent of the responding agencies reported having a profiler certification program for state owned profilers, and 51 percent reported having a certification program for contractor-owned profilers.

According to the authors, IRI is “tuned” to a speed of approximately 50 mph, which is relatively high compared to the usual speed of operation along urban roadways. NCHRP Project 10-93 titled “Measuring, Characterizing, and Reporting Pavement Roughness of Low-Speed and Urban Roads” focused on overcoming this obstacle, and developing a low-speed IRI measuring tool. Additionally, a prototype for a low-speed profiler called “urban profiler” was under development that is able to better roughness measurement at lower-speed urban roadways. A lightweight profiler is a viable option in this case. The advantages with lightweight profilers are:

- The weight of a lightweight profiler is significantly less than a typical high-speed profiler. This allows the lightweight profiler to be driven on freshly poured concrete pavements even before full strength has been attained.
- Lightweight profilers operate at relatively lower speeds. This leads to easier operation in constrained conditions such as those behind barriers or between shorter sections of non-continuous pavements.

Utilizing Mobile Devices to Measure Surface Roughness

As stated in the review, modern inertial profilers can provide a fast and accurate measure of surface roughness. An inertial profiler requires four basic sub-systems: (1) accelerometers, (2) height sensors, (3) distance or speed sensors, and (4) computer hardware and software. Usually, such a well-integrated inertial profiler system is expensive, and has limited availability as the profiler owned by a particular state agency is shared by all local districts and construction projects. With the recent advancement in the mobile technology, engineers and researchers are developing new tools that are based on mobile devices (such as cellphones and tablets) with built-in sensors to measure surface roughness. Applications developed for the purpose can collect data from sensor built-in to the mobile devices, and subsequently quantify the pavement roughness.
The built-in accelerometers can be directly used to collect data associated with the ride quality on a pavement surface. Mobile devices such as smartphones and tablets have 3-axis accelerometers that can be used to collect vehicle vertical acceleration data in three orthogonal directions [27]. **Figure 17** shows a schematic of a mobile device with three orthogonal directions for acceleration measurement.

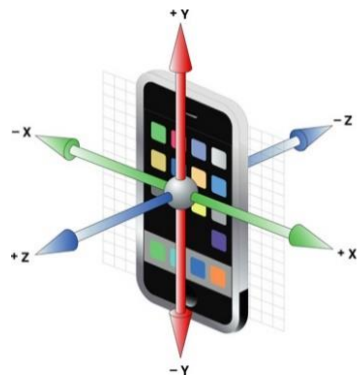


Figure 17. Mobile Accelerometer Axes [28]

The Roughness Capture application collects acceleration data in three orthogonal directions, along with the timestamp, and corresponding GPS coordinates; the data is stored in an ASCII text file. Data collection rate is specified by the app, generally in the range of 40 - 100 Hz, with higher sampling rates usually resulting in higher accuracies. Note that the device needs to have adequate hardware backup to support a higher sampling frequency. It is noteworthy that the application of mobile devices for pavement smoothness measurement is still in its early age as far as practical implementation is concerned; only a limited number of publications and case studies have focused on this application. The following section presents a summary of the limited number of mobile device-based case studies found in the literature.

Integration of Smart-Phone-Based Pavement Roughness Data Collection

Researchers at the University of Illinois at Urbana-Champaign (UIUC) made an effort to measure pavement roughness using smartphone accelerometer data [4] and assess the effects of vehicle suspension on IRI estimation. An Android-based app called “Roughness Capture”, capable of collecting accelerometer data at different frequencies, was developed during this study. The user interface of the app and mounting procedure of the phone is shown in
Figure 18**.**

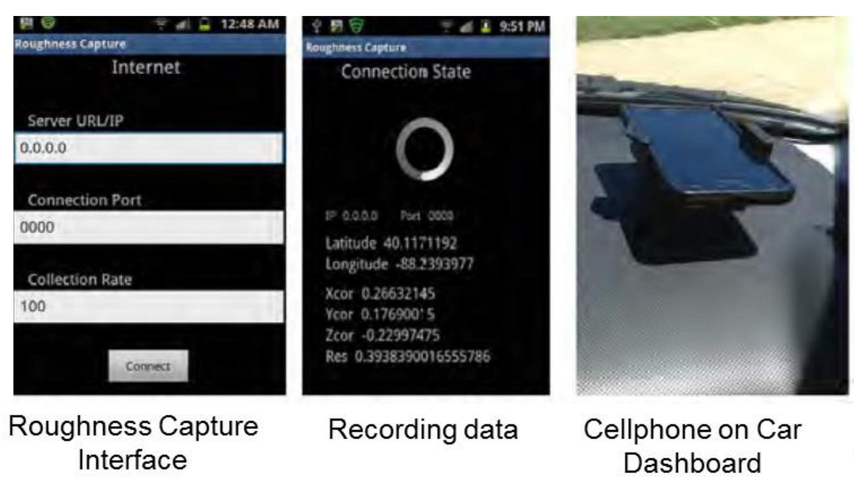


Figure 18. App Interface and Mounting Procedure [4]

The researchers used an inertial profiler for validating the results. The device was mounted on the dashboard of the profiler. Data was collected at two different frequencies: 100 Hz and 156 Hz. Data was also collected using a passenger car to investigate the effect(s) of vehicle suspension on IRI estimation using the app.

Analysis of the data collected by the app was done initially to estimate a surface profile. A MATLAB® code was developed to double-integrate the accelerometer data to obtain the surface profile. After this step, the profile is fed into the profile viewing and analysis (ProVAL) program to obtain the roughness information of the traversed path. After getting the data from ProVAL program, researchers attempted to validate the program by comparing the app data with inertial profiler data. Initially, they found that higher data collection rate will yield close estimation of surface roughness measured by the profiler. Afterward, they attempted to correlate the vehicle speed with roughness measure. However, conclusion of this study did not coincide with the previous ones. Previous researchers found that higher speed (i.e. 50 mph) helps to improve the data quality [29]. On the contrary, the researchers at UIUC compared data collected at a speed of 40 and 50 mph, and observed that better result was obtained at 40 mph speed. This gives a conflicting conclusion that lower speed being better for IRI approximation using mobile devices. The suspension of the car also has an effect on the data collection. For all pavement sections tested, passenger cars produced higher IRI values compared to the inertial profiler. ***Tool Developed: Roughness Capture***

DataProbe (A Project Funded by Michigan DOT)

DataProbe [29] is an Android-based smartphone application developed at the University of Michigan Transportation Research Institute (UMTRI). This app collects data from accelerometers built-in to mobile devices. The data is subsequently uploaded over the internet to centrally located servers. It is noteworthy that the data is located on a server, and a computer is required for further analysis of the data. The data analysis approach does not use the accelerometer data directly, but rather uses the variance of accelerometer data as calculated using equation shown in **Figure 19**.

$$\sigma^2 = \sum_{i=1}^{100} \frac{\left(x_i - x_{avg}\right)^2}{n-1}$$

Figure 19. Equation of Variance

where, i is the index of reading, x_i is the i'th accelerometer reading from each second, x_{avg} is the average of 100 readings for each second and n is the total number of readings (in this case 100).

In order to get desired data from the accelerometer, the phone has to be perfectly flat or in landscape orientation. **Figure 20** shows a photograph of a mobile phone in landscape orientation displaying the DataProbe interface.

Figure 20. Photograph Showing a Smartphone with DataProbe App [29]

Belzowski [29] studied the correlation between the variance of the accelerometer data and IRI, and observed that the relationship was significantly nonlinear shown in **Figure 21**.

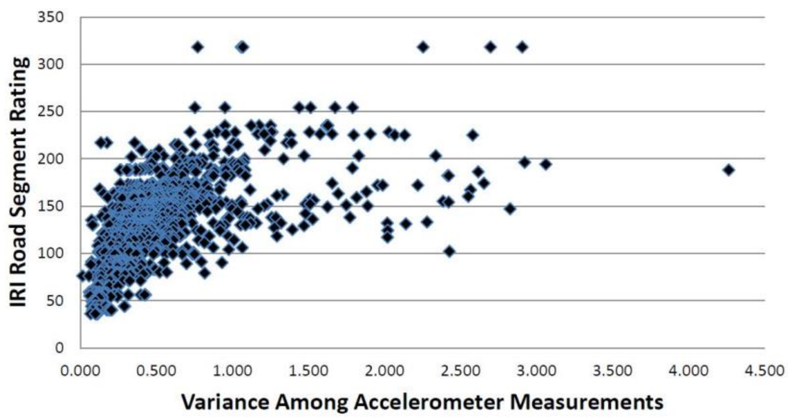


Figure 21. Relationship Between Variance of Accelerometer Data and IRI of the Road Segment Under Consideration [29]

Moreover, the researchers also attempted to identify variables that may impact IRI estimation. Speed of the vehicle was found to have a significant effect on the collected road roughness data; the researchers reported that an average speed of 57 - 60 mph is suitable for data collection with the app. Finally, they surmised that multiple trips over the same road segment tend to increase the accuracy of DataProbe app to predict IRI. In conclusion, smartphone based IRI computation can be used as an inexpensive means of rough estimation of IRI. ***Tool Developed: DataProbe***

AndroSensor (A Project Conducted by Tokyo Metropolitan University, Japan)

A research group in Tokyo Metropolitan University (TMU) worked with the devices for roughness measurements [30]. The main idea of this project was to provide a low-cost roughness measuring device to the area where high-tech roughness measuring devices are still unavailable rendering a manual approach unavoidable. From the conclusion of AndroSensor project, researchers know that for obtaining a close estimation of roughness measure with mobile devices a road needs to be traversed a couple of times. This idea of data collection was utilized in the project pursued by TMU but in a different fashion. The researchers tried to use crowdsourcing, a method of data collection where participation of mass population is required, for data collection. They collected a lot of data for analysis, then uploaded the processed data to the cloud (in their case Road Management System) where it is available to everyone. Concept map of their work is shown **Figure 22**.

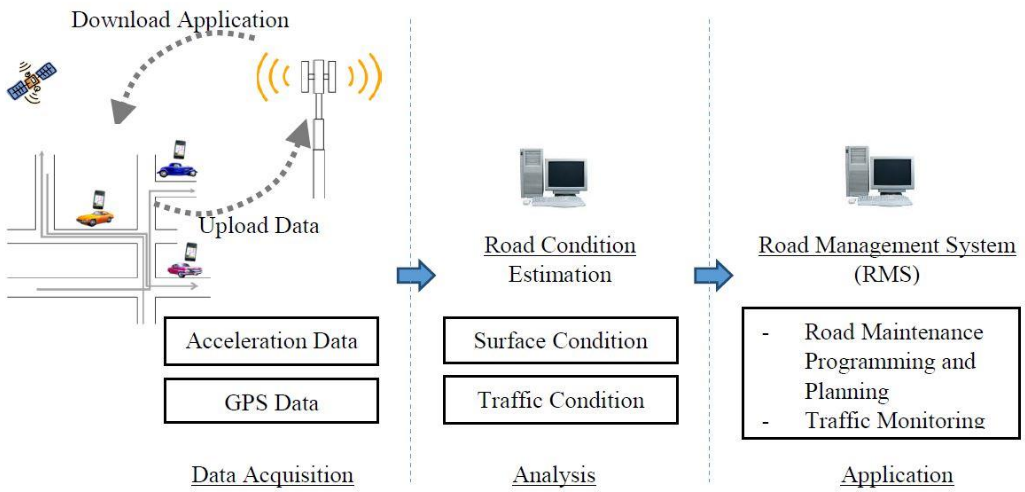


Figure 22. Conceptual Workflow of Road Condition Monitoring System [30]

The research team used smartphones for accelerometer, Global Positioning System (GPS) logger for reading location information and a video camera to capture video for future reference. The smartphones were installed with AndroSensor app for collecting accelerometer data. Furthermore, this app can collect data from all the available sensors in a smartphone. The frequency of data collection of the accelerometer is 100 Hz. The Vehicle Intelligent Monitoring System (VIMS) is used to get a reference roughness data to calibrate the computation procedure. VIMS was developed by University of Tokyo, Japan. VIMS is unable to capture data when the speed is lower than 20 km/h while accelerometer data is collected continuously. This requires a preprocessing of data before starting computation. Preprocessing was also done for filtering the accelerometer data with a high pass filter before analysis. This is a standard method used for Android devices [31]. After preprocessing, the researchers tried to correlate accelerometer data and pavement roughness. They found that there is a linear correlation between them. They also investigated the effect of speed on the quality of accelerometer data collection. It was found that when the speed is less than 60 km/h, the speed has a significant effect on data collection. ***Tool Developed: AndroSensor***

Comparative advantage and disadvantages of these available tools to measure pavement surface roughness are listed in **Table 3**. Note that, although RoadBump Pro is not a part of literature review, it is included in this table to draw attention on its advantages and disadvantages along with comparing it with others.

Table 3: Advantage and Disadvantages of Available Methods

Roughness Capture	AndroSensor Project	DataProbe Project	RoadBump Pro app
Advantages: a. Can work with all modern smartphones. b. Accelerometer reading has good correlation with IRI	**Advantages:** a. Makes use of accelerometers that are built into all modern mobile devices. So, the availability is very good. b. Accelerometer reading has good correlation with IRI	**Advantages:** a. Data is kept safe in a server and the data is available for analyzing immediately after it is uploaded. b. Offers data collection by crowdsourcing	**Advantages:** a. Very cheap compared to the price of an inertial profiler. b. Data is stored in the respective device in which the data was collected. c. Visualize the road roughness data on a map. d. It can perform both data collection and analysis in a single platform.
Disadvantages: a. This is not a standalone method, rather a three-step process. The users must download the recorded accelerometer data from the mobile device in a computer, and then run a MATLAB® script on the collected accelerometer data to estimate the pavement profile. Finally, the estimated profile is used as an input in ProVAL to calculate the IRI.	**Disadvantages:** a. Calibration required before using. b. Quality of collected data depends on a lot of factors, including frequency of data acquisition by the accelerometer, speed of operation, human errors. c. Further analysis is done with a computer, which needs another layer of labor after gathering data.	**Disadvantages:** a. Calibration required before using. b. Further analysis is done with a computer, which needs another layer of labor after gathering data.	**Disadvantages:** a. Calibration required before using. b. Sensitive to the location in the car at which the device is placed, vehicle suspension system, tire pressure etc.

Best Practices and Recommendations from Literature Review

Through extensive review of the published case studies and preliminary testing, the research team has summarized the following recommendations to facilitate accurate collection of pavement roughness data using mobile applications and subsequent analyses for roughness quantification.

Data Collection:

- The vehicle should start driving at a certain distance from the starting point of the data collection. This distance should be far enough to gain at least 40 mph when the vehicle reaches the starting point of pavement section of interest. The user should let the app start when the vehicle is at rest. After finishing the data collection, the operator should stop the vehicle and terminate the data collection [32].
- Placement of device is important. The device should be placed firmly in the center of dashboard of the car. This is required to mitigate unwanted reading coming from false vibration [29].
- A constant speed (between 40 to 60 mph) should be maintained during data collection, as variation in horizontal speeds is found to be a source for error [11,33]. If possible, use of cruise control is recommended.
- All information regarding data collection should be recorded for future reference. For example, Date and time of every test run, type and condition of the road, information about any device malfunctions, etc [29].
- When working with mobile devices, the vehicle mounted with the mobile devices needs to be driven several times along the same road to acquire reliable data. The same wheel path should be maintained, as much as possible, while collecting data for the second time [11]. Multiple vehicles may be employed to test the conformance of the data with the standard result from inertial profiler or lightweight profiler [29].

Data Analysis:

- Mobile devices can perform well in a category-based classification system[29]. For example, following the analysis of pavement condition based on accelerometer data, the pavement under study can be classified in a predefined category i.e. good, bad, worst etc.

Summary of Literature Review

In summary, with recent advancement of mobile device, new tools (hardware and software) have been developed with built-in sensors to help improve the user experience in measuring surface roughness. The mobile devices applicable include cellphones and tablets. The application of mobile devices in measuring pavement smoothness is a pretty new development, and therefore has much room for growth. There are several published applications and case studies for research purpose only. Researchers and engineers have developed mobile apps to collect data and subsequently calculate the surface roughness along the roadway. From the literature review it was observed that the driving speed, device placement within the vehicle, and vehicle conditions are factors that need to be specified for a particular testing vehicle. The following chapters of this report present details of testing and data analyses carried out under the scope of the current project to assess the applicability of mobile applications for pavement roughness measurement.

Chapter 3
Principle of Road Roughness Measurement using Accelerometer Data from Mobile Devices

This chapter discusses the basic principles associated with road roughness measurement using accelerometer data extracted from mobile devices (cellular phones or tablets). As described in the previous chapter, laser-based profilers calculate pavement profiles that are used as input for quarter-car model to measure the pavement roughness. However, in these profilers there are several different sensors that helps producing a relatively accurate pavement profile. In contrast, pavement roughness measurement using mobile devices primarily relies on the data from accelerometer(s) built-in to these devices. Accordingly, pavement roughness measurement using mobile devices can be classified as a "Response Type Road Roughness Measurement System (RTRRMS)". Acceleration (in three directions) magnitudes recorded by the mobile devices can be integrated to establish the pavement profile, which is subsequently subjected to established mathematical analysis procedures to quantify the pavement roughness (often through the calculation of International Roughness Index or IRI). The following sections present the theoretical background associated with this pavement roughness measurement approach. Based on basic kinematic relationships, acceleration (a) is defined as the rate of change of velocity (v) with time (t) . Similarly, velocity (v) is defined as the rate of change of displacement (z) with time (t). The corresponding equations are presented in **Figure 23 and Figure 24.**

$$\boldsymbol{a = \frac{dv}{dt}}$$

Figure 23. Equation of Acceleration in Differential Form

$$\boldsymbol{v = \frac{dz}{dt}}$$

Figure 24. Equation of Velocity in Differential Form

As already mentioned, accelerometers record the acceleration time-history for a given object, which can be integrated to obtain the velocity (v) and displacement (z) time histories. The corresponding equations (in integral form) are presented in **Figure 25** and
Figure 26.

$$\boldsymbol{v = \int_0^t a dt}$$

Figure 25. Equation of Velocity in Integral Form

$$\boldsymbol{z = \int_0^t v dt}$$

Figure 26. Equation of Displacement in Integral Form

It should be noted that Equations listed in **Figure 23** through

Figure 26 represent the acceleration, velocity, and displacement as one-dimensional quantities. However, these are vector quantities and should have three components in three directions in a 3-D space. A concept image of vector in 3-D space is provided in **Figure 27**. As shown in the figure, vertical movement of a vehicle suspension due to irregularities in the pavement surface will be recorded as displacements in the z direction. Similarly, transverse (with respect to the direction of travel) movements will be registered along the x-direction, and any movements in the direction of travel (forward or backward) will be registered along the y-direction.

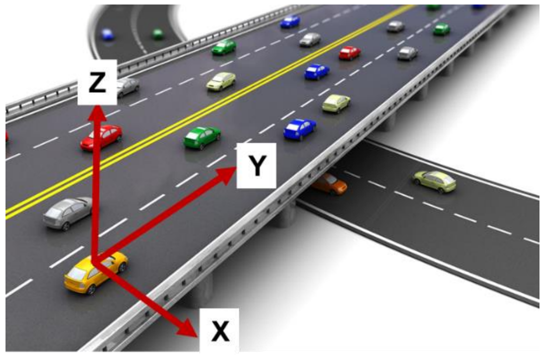


Figure 27. Concept Image of Vector in 3-D Space

Based on this representation, it is clear that irregularities (such as bumps and dips) in the pavement profile will lead to predominant movements along the z direction. Please note that this is possible only in the case of perfectly horizontal plane pavements. Perfectly horizontal plane pavement surfaces will have the normal (z) axis perfectly aligned in the vertical direction. However, this is practically impossible because of variabilities associated with terrains and superelevated roadway sections. In circumstances where the axes of a mobile device mounted inside a vehicle do not coincide with the global coordinate system, movements of the vehicle suspension system due to irregularities in the pavement surface will not register along the z direction only. Accordingly, the resultant acceleration vector *a* should be calculated by considering acceleration components along the x, y, and z directions (a_x, a_y, *and* a_z; see **Figure 28**).

$$\boldsymbol{a} = \sqrt{\boldsymbol{a}_x^2 + \boldsymbol{a}_y^2 + \boldsymbol{a}_z^2}$$

Figure 28. Equation for Calculating the Resultant Acceleration from Individual Components along the X, Y, and Z Directions

It is important to note that the procedure of calculating the resultant acceleration vector by considering the three orthogonal components can potentially introduce another source of error into this approach. For example, any change in the speed of the vehicle (increase or decrease) will register as accelerations (positive or negative) along the direction of travel (Y direction in **Figure 27**), and will lead to a change in the magnitude of the resultant acceleration vector. The same is true for sudden lateral movements (along the X direction in **Figure 27**). Therefore, for the resultant acceleration vector to represent the vertical (Z) direction only, it is important for the vehicle to move at a constant speed along a straight line, therefore, eliminating any accelerations in the X and Y directions.

In contrast, sophisticated pavement profile measurement equipment, such as the inertial profiler van, which is equipped with a set of standard measurement devices does not have these problems. These vehicles are equipped with advanced instruments, for example, line laser, height sensor, distance measuring Instrument (DMI), and high-end accelerometer that has a frequency superior than the accelerometers embedded in mobile devices. Images of these instruments are shown in **Figure 29**.

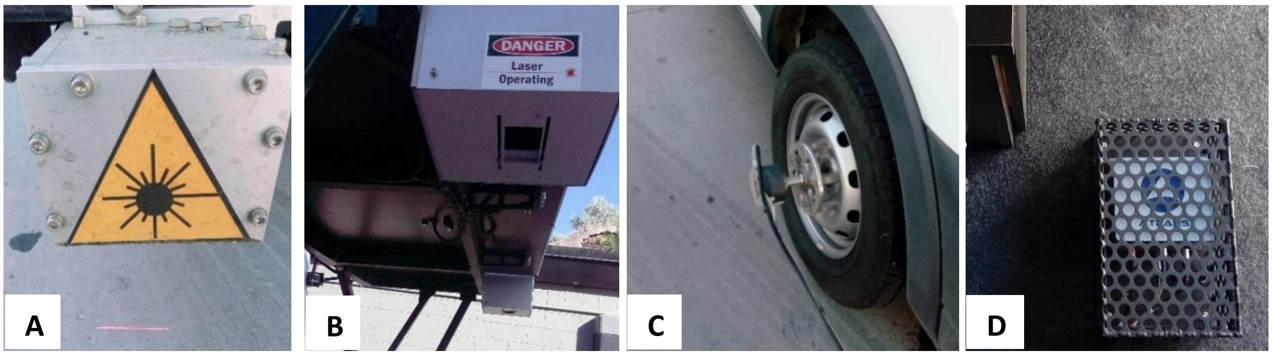


Figure 29. Photographs Showing: (A) Line Laser; (B) Height Sensor; (C) Distance Measuring Instrument; and (D) Inertial Measurement Unit (IMU)

Height sensors, installed in inertial profilers, determine the height of the sensor from the pavement surface. It uses triangulation technique for calculating the height of pavement surface from its location. Triangulation is a land surveying technique that determines a single point in space with reference to the measurements taken from two other distinct points. A method showing how triangulation method works for calculating height is shown in **Figure 31**. At first, a light beam is emitted from the source that is reflected from a plane located at position 1, the primary focus point located at a known height. Reflected light beam from position is captured by receiver located near image plane shown in **Figure 31**. The reflected light creates and internal angle, θ, with the incident light and an internal angle, ϕ, with the image plane. There is a lens located in between the image plane and position 1. The distance between position 1 and the lens is a and the distance between the lens and the image plane is b. After that, the same light beam is reflected from the surface of interest, position 2 in **Figure 31**. This reflected light beam is captured by the same receiver located at the image plane. Reflected light from position 2 creates an internal angle, Ψ, with the reflected light from position 1. The two reflection beams reflected from position 1 and 2 are located at a distance of, δ, on the image plane. Using the known angles, θ, ϕ, and distances $\delta, a, and\ b$ one can calculate the distance, d, between position 1 and 2 using equation shown in **Figure 30**.

$$\delta = \frac{dbsin\theta}{dsin(\theta + \phi) + asin\phi}$$

Figure 30. Equation for Measuring Distance, $\boldsymbol{\delta}$.

Distance of position 2 from the sensor can be calculated by adding the distance, d, calculated using equation shown in **Figure 30**. This will represent the height of surface from the sensor.

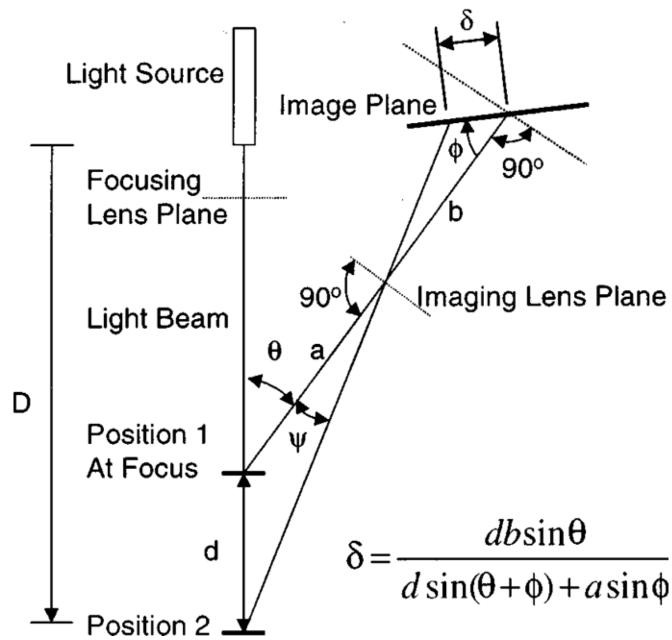


Figure 31. Triangulation Method Used for Determining Height Using Height Sensor [34]

For calculating the profile, an inertial profiler uses the data from the accelerometer to calculate the inertial reference value. Then, the inertial reference value is combined with the height sensor data to produce a complete profile using a central computer located inside the inertial profiler van. A schematic of height sensor and accelerometer placed in an inertial profiler is shown in **Figure 32**.

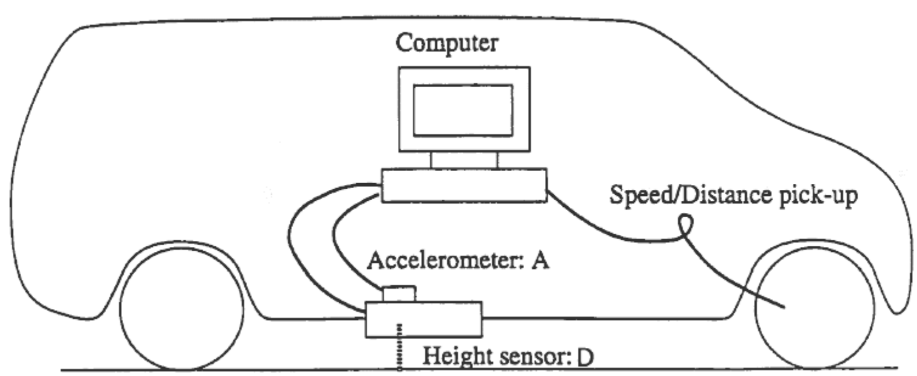


Figure 32. Schematic of Height Sensor and Accelerometer Placed in an Inertial Profiler [15]

The height sensor calculates the height from the sensor to the pavement surface. At the same time, the reference height is computed using the vertical acceleration data collected from the accelerometer using the equations shown in **Figure 25**. The laser determined height, D, is subtracted from the inertial height computed using the accelerometer data to get the pavement profile. All these computational operations are conducted in the central computer located inside the inertial profiler van. The actual profile can be calculated using the equation shown in **Figure 33.**

$$Z_{road} = \int_0^t \int_0^t (adt)dt - D$$

Figure 33. Equation for calculating the profile elevation through double integration of acceleration

Here, a is the vertical acceleration collected using the accelerometer and D is the vertical distance detected from the height sensor. After conducting these calculation on a series of points, a continuous data points are generated representing the surface profile. A sample pavement profile is shown in **Figure 34**.

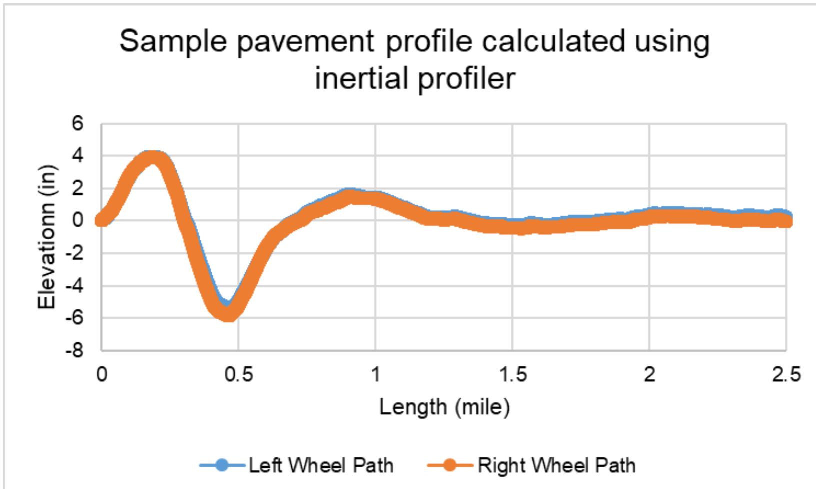


Figure 34. Sample Pavement Profile Calculated Using Inertial Profiler

The distance measuring unit determines the actual distance travelled by the vehicle using the number of revolution of the wheel with which it is attached. Using all these sensors and devices, an inertial profiler is able to determine true pavement profile. Roughness computed using the profile will represent the actual pavement roughness.

Following the calculation of pavement profile, a quarter-car model described below is used to compute the roughness of the pavement under study. According to ASTM [3] the equations of motion are expressed in the state-space form of which is shown in **Figure 35** and **Figure 36**.

$$\dot{x} = Ax + Bz_{road}$$
$$y = Cx + Dz_{road}$$

Figure 35. Equation of Motion in State-Space Form

In matrix form, the equations shown in **Figure 35** can be rewritten in terms of the quarter car model parameters. Matrix form of these equations are listed in **Figure 36**.

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\dfrac{k_s}{m_s} & -\dfrac{c_s}{m_s} & \dfrac{k_s}{m_s} & \dfrac{c_s}{m_s} \\ 0 & 0 & 0 & 1 \\ \dfrac{k_s}{m_u} & \dfrac{c_s}{m_u} & -\dfrac{k_t + k_s}{m_u} & -\dfrac{c_s}{m_u} \end{bmatrix} \begin{bmatrix} x_s \\ \dot{x_s} \\ x_u \\ \dot{x_u} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{k_t}{m_u} \end{bmatrix} [z_{road}]$$

$$y = [-1 \quad 0 \quad 1 \quad 0] \begin{bmatrix} x_s \\ \dot{x_s} \\ x_u \\ \dot{x_u} \end{bmatrix} + [0][z_{road}]$$

Figure 36. Equation of Motion on State-Space Form

Details of the relevant parameters were presented in **Chapter 2**.

Compared to high precision measurement from the inertial profiler, a mobile device uses only accelerometer data to produce information on pavement roughness. As stated earlier the sensitivity of the accelerometer sensors in mobile devices are significantly lower than that of inertial profiler. Based on our selected mobile devices, the most advanced accelerometer sensor in mobile devices has a sensitivity of up to 200 Hz. Position of the vehicle is determined using and Global Positioning System (GPS) data. Furthermore, the mobile devices are also entirely dependent on the suspension system of the vehicle used to collect pavement roughness data. Thus, the testing vehicle's suspension system will create a source of variance for estimating the pavement roughness.

At the same time, the accelerometer sensor is an electronic device. It produces electronic signal based on voltage difference generated by the vibration. Electronic signals always have an inherent source of error that is called noise. There are several different reasons that can introduce noise in an electronic signal. Since, this is beyond the scope of the subject under study, this topic will not be documented in detail in this report. However, these noises are added to the actual signal and recorded as acceleration at that point. This will eventually result in an erroneous pavement roughness.

Sensor built into mobile devices can render them as viable tools for pavement roughness measurement application. As reported by Douangphachanh [30] accelerometer readings and pavement roughness are strongly correlated with a correlation coefficient (R^2) of up to 72 percent. However, proper attention needs to be paid while calibrating the device. Also, the vehicle suspension system plays a significant role in roughness measurement using mobile devices. Subtle difference in suspension system of the vehicles will cause vibration of different magnitude. Thus, calibrating only mobile devices cannot promise an accurate result, rather the combination including one mobile device and one vehicle needs to be calibrated prior to field application. The following chapters describe a series of methods used in the current study to calibrate the devices; recommendations have been presented for best practices and specifications have been provided for onsite application.

Summary

The primary focus of this chapter was to describe the theoretical background of the profile estimation and roughness calculation using mobile devices. Differences in data collection mechanisms inherent to mobile devices and inertial profilers were highlighted. Compared to low-cost mobile devices, the inertial profilers are equipped with ultra-modern devices and sensors with high-level of precision and accuracy to calculate the actual pavement profile. On the other hand, since the mobile devices only have several low-cost sensors built-in, their accuracy and sensitivity are not as good as those found in inertial profilers. This creates a room for unexpected errors in profile estimation and finally roughness calculation.

Chapter 4
Pilot Testing and Initial Comparisons

As summarized in previous chapter, pavement roughness measurement using mobile devices primarily relies on data from low-cost accelerometers built into the mobile devices. Accordingly, IRI values reported by these mobile devices may not always match those reported by reference pavement profile measurement units, such as inertial profiler vans or lightweight profilers. Such differences in the reported roughness values can be somewhat eliminated through directed calibration efforts. In an effort to establish calibration factors for different vehicle-device combinations being used in the current research study, several pilot tests were conducted along a pre-selected pavement section in Boise, Idaho. Pavement roughness along the same pavement section was measured using multiple mobile devices (running the RoadBump Pro app), as well as two commonly used reference pavement roughness measurement units: (a) inertial profiler van; and (b) a lightweight profiler. Detailed descriptions of the features of these two devices have been provided later in this chapter. Pavement roughness data collected by these two vehicles were used as reference values; modification factors were calculated to "shift" the data collected by the mobile devices to ensure a close match with the reference datasets. Another objective of this pilot testing effort was to assess the precision and repeatability of the RoadBump Pro mobile application.

Five different mobile devices (two smart phones, and three tablets) were used during this research effort. Accordingly, the pilot testing effort also included measurements using these five devices. The objective was to identify low-cost mobile devices that could produce reliable pavement roughness measurements. As already mentioned, the RoadBump Pro app was developed for the Android platform, and therefore, only mobile devices running the Android operating system could be used in this study. The pilot testing was carried out using different vehicle types. This was primarily because ITD engineers working on different projects may have access to different vehicles and studying the inter-vehicle variation in roughness measurements using mobile devices would provide useful information that may help the implementation of this technology into practice. A large number of datasets were generated during the pilot tests to facilitate the calibration process. Mobile devices were also placed inside the inertial profiler van to compare the device sensitivities by eliminating any variabilities associated with vehicular suspension systems. This chapter discusses all details concerning the pilot testing effort along with in-depth discussions of the adopted calibration methods and mathematical procedures adopted for data analysis.

Vehicle Types Used during Pilot Testing

As already mentioned, one of the primary limitations associated with pavement roughness measurement using mobile devices concerns the variability introduced by the suspension system of the vehicle being used. A study focusing on evaluating the feasibility of this technology must therefore assess the extent of variabilities introduced into the results by different vehicles. Four different vehicles were used to collect pavement roughness data during the pilot testing effort. The pavement section used for pilot testing was a standard pavement section used by ITD for inertial profiler calibration efforts. Note that selection of the vehicles for this measurement effort was based on no particular engineering selection approach. These were personal vehicles belonging to research team members and presented a wide-enough spectrum to study inter-vehicle variability. **Figure 37** through **Figure 40** show photographs of the vehicles used during the pilot testing effort.

Figure 37. Photograph Showing a 2002 Honda Civic Sedan Used for Pavement Roughness Measurement Using Mobile Devices during the Pilot Testing Effort

Figure 38. Photograph Showing a 2015 Jeep Cherokee Used for Pavement Roughness Measurement Using Mobile Devices during the Pilot Testing Effort

Figure 39. Photograph showing a 2013 Nissan Altima Sedan Used for Pavement Roughness Measurement Using Mobile Devices during the Pilot Testing Effort

Figure 40. Photograph Showing a 2005 Kia Rio Sedan Used for Pavement Roughness Measurement using Mobile Devices during the Pilot Testing Effort

Pavement Section Used for Pilot Testing

The roadway segment selected for pilot testing was a particular section of Hill road between N. Harrison Blvd and 36th Street in North-East Boise, Idaho. This roadway section is regularly used by ITD for inertial profiler calibration purposes. A snapshot (from Google Maps) of this 1.25-mile (one-way) long roadway segment has been presented in **Figure 41**.

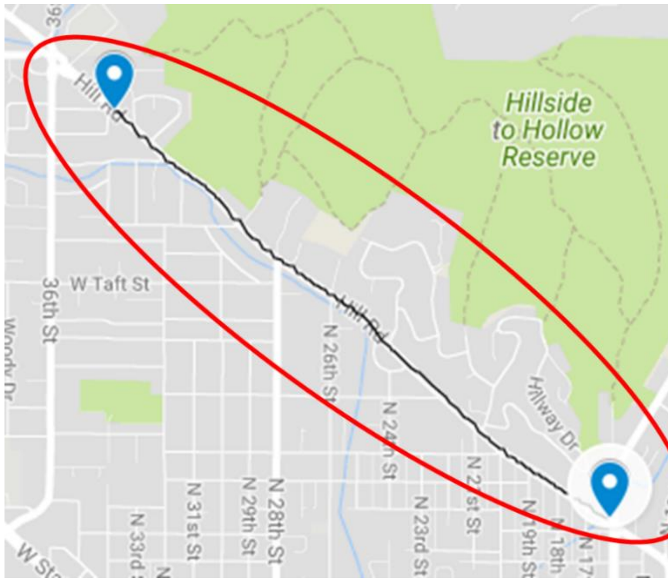


Figure 41. Map of Section of Hill Road

Devices Selected for Pilot Testing

Five different mobile devices were used to measure pavement surface roughness throughout this study. A list of mobile devices used in the current study is provided below along with the code names used in this refer to refer to these devices.

1. Tab-1: Samsung Galaxy Tab 4
2. Tab-2: Samsung Galaxy Tab 4
3. Note 3: Samsung Galaxy Note 3
4. Note 4: Samsung Galaxy Note 4
5. Note 101: Samsung Galaxy Note 10.1

All mobile devices used in this study were manufactured by Samsung®, were running on the Android® platform. Note that all Samsung devices were selected as they are one of the most common device types currently used. The research team does not intend to make any recommendation regarding whether one device type is better than others or not. As seen from the above list, two of the devices (Tab-1 and Tab-2) were identical. The objective behind using two identical devices was to study whether they consistently recorded identical pavement roughness values or not. By using all five devices throughout the study, five different datasets (per vehicle) were generated for each roadway segment tested. It was important to generate sufficient number of datasets to study inter-vehicle and inter-device variabilities under different testing conditions. Photographs of the devices used in this study are presented in **Figure 42**.

(a) (b)

(c) (d)

(e)

Figure 42. Photographs Showing the Mobile Devices used for Pavement Roughness Measurement in the Current Study: (A) Samsung Galaxy Tab 4 (Tab-1 and Tab-2); (B) Samsung Galaxy Note 3; (C) Samsung Galaxy Note 4; and (D) Samsung Galaxy Note 10.1

During pavement roughness measurement using mobile devices, it is important to ensure that the devices are not subjected to excessive vibrations other than that originating from movements of the vehicle suspension system while traversing along the roadway. It is therefore important for the mobile device to be mounted firmly inside the testing vehicle. A device that is not mounted firmly, will record excessive vibrations that may be misinterpreted as pavement surface roughness. After exploring different alternatives, a type of non-slip rubber pad was selected by the research team to firmly hold the mobile devices on the vehicle dashboards. The devices were mounted on the dashboard to ensure ease of access. The pads used for mounting were made of high-elastic polymer materials and attached to the pavement dashboard through suction; the pads can endure high-temperatures, and are non-toxic and odorless. A photograph of the sticky pad used for placing the mobile devices on the dashboard is shown in **Figure 43**. Note that the particular model of rubber pad used in the current study was purchased from an online vendor; the research team does not intend to advocate the use of one particular pad type. The primary objective behind the use of these pads is to ensure that the mobile devices are held firmly on the vehicle dashboard. Any pad achieving this objective should work well as far as similar testing efforts are concerned.

Figure 43. Photograph Showing the Sticky Rubber Pad Used in the Current Study for Mounting the Mobile Devices to the Vehicle Dashboards

Pavement roughness data collected using the mobile devices were compared against data from two reference roughness measurement units: (1) inertial profiler van, and (2) lightweight profiler. Inertial profilers are capable of collecting pavement condition data at normal traffic speeds and are commonly used by state transportation agencies for network-level pavement condition assessment efforts. Light-weight profilers on the other hand, have maximum operating speeds of approximately 20 mph, and are used for measuring the pavement roughness along short pavement sections. Due to their light weight, they are particularly suited for pavement roughness measurements along a freshly paved concrete surface (they can be driven on fresh-poured concrete in 24 hours or less). These devices are commonly used by contractors for pavement roughness quality control for freshly paved surfaces.

The inertial profiler van used by ITD (also used in this research study) was manufactured by Ford. The measurement system was assembled in 2017 by Pathway Services for automated road and pavement condition surveys. This measurement system was built according to South Dakota Profiler Class 1 - ASTM E950. **Figure 44** shows a photograph of the rear end of the inertial profiler van used in this study. The laser-based crack measurement system as well as the rear-facing camera are visible in this picture.

Figure 45 shows a photograph of the lightweight profiler used for roughness data collection in this research study.

Figure 44. Photograph Showing ITD's Inertial Profiler Van Used as a Reference Data Source in this Study

Figure 45. Photograph of the Lightweight Profiler Used in This Study

Data Analysis from Pilot Testing Effort

Two pilot tests were conducted to collect pavement roughness data along the pre-selected calibration roadway (Hill Road between 36th street and N. Harrison Blvd). The research team worked closely with

ITD engineers to collect data for comparison and calibration purposes. The first pilot test, using a Boise State Sedan, was made on June 12, 2017. The primary objective of this preliminary run was to ensure the workability of the selected devices and the mobile app. Two types of reference measurement units: a high-speed inertial profiler van and a lightweight profiler were used to collect pavement roughness data to establish reference values against which the data from mobile devices can be compared. This roadway section has a posted speed limit of 35 mph; therefore, the speed of the inertial profiler van was restricted to 30 mph to ensure a constant driving speed. The devices were also placed on top of working platform built in the middle of the inertial van. This was done to observe if the mobile devices can replicate the roughness data when they are placed inside an inertial profiler van. **Figure 46** shows photographs of the mobile devices mounted on the working platform built into ITD's inertial profiler van. Pavement roughness data was also collected using the inertial profiler van system throughout these pilot testing runs. A snapshot of the workstation inside the inertial van is shown in **Figure 47**.

Figure 46. Photographs Showing Placement of the Mobile devices inside Inertial Profiler Van

Figure 47. Photographs Showing the Workstation inside the Inertial Profiler Van

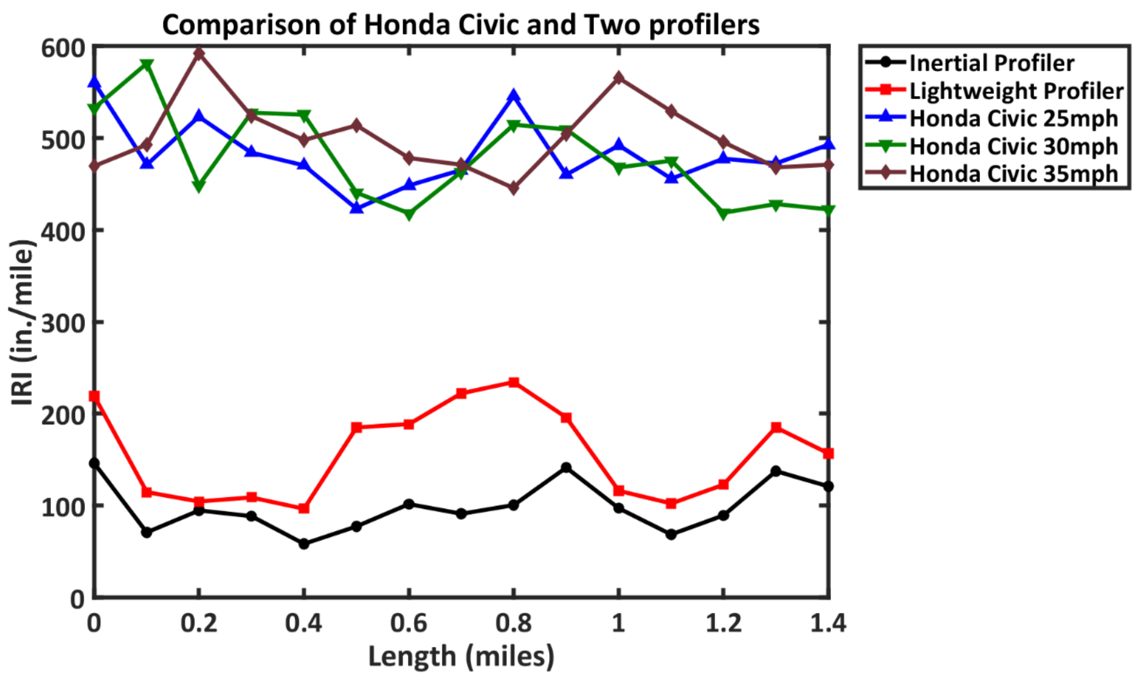
This particular test, where the mobile devices were mounted inside the inertial profiler van, was intended to compare the data collected using the Inertia Measurement Unit (IMU) mounted inside the profiler van and the accelerometers built into the mobile devices. The inertial profiler was driven for five times along the same direction of Hill road. All five mobile devices were used to collect pavement roughness data during each run. The following sections present results collected during the pilot testing effort. Note that measurements along the calibration roadway section were conducted on two different occasions. Findings from both sections are presented below.

Pilot Testing Effort # 1 (Date: June 12, 2017)

The mobile device-based pavement roughness measurements were taken using the 2002 Honda Civic sedan. Measurements using the inertial profiler as well as the lightweight profiler were also carried out on the same day. To study the effect of operating speed on mobile-based roughness measurements, the three different sets of measurements (data was collected using all five mobile devices on each occasion) were taken using the 2002 Honda Civic sedan: operating speeds were set to 25 mph, 30 mph, and 35 mph. **Figure 48** shows a photograph of four of the mobile devices mounted on the dashboard of the 2002 Honda Civic sedan.

Figure 48. Photograph Showing Four Mobile Devices Mounted on the Dashboard of the 2002 Honda Civic Sedan

Data collected using the mobile devices and the 2002 Honda Civic Sedan at three different speeds (25 mph, 30 mph, and 35 mph) were compared against data obtained using the reference measurement systems (inertial profiler and light weight profiler). **Figure 49** shows such comparative plot using data obtained from one of the mobile devices (Tab-2). Note that only two of the mobile devices (Tab-1 and Tab-2) functioned properly during this particular test run. Therefore, data from one of the two devices (chosen for the sake of representation) has been presented here.



Note: Data from only one Mobile Device: Tab-2 has been shown in this plot

Figure 49. Comparing the Roughness Data Collected using the Reference Measurement Units against those Collected using a 2002 Honda Civic Operated at Three Different Speeds

As seen from the figure, a large degree of variation was observed between data collected using the two reference measurement units. This was not expected, because both the inertial profiler van and the lightweight profiler operate based on the same principles, and differences between collected data can indicate one of the following possibilities: (1) the calibration settings for the sensors on one of the vehicles were incorrect; (2) measurements using the two units were not carried out along the same wheel paths. Considering that the inertial profiler van is calibrated annually for network-level measurement efforts, the research team therefore decided to verify the calibration settings for the light weight profiler. Another set of pilot tests would be conducted once the calibrations for the light weight profiler were verified. Comparing the mobile-based roughness values plotted in **Figure 49**, it can be seen that significant differences were observed between the IRI values for the three different runs (corresponding to three different driving speeds).

Another important thing to note from **Figure 49** is that the roughness values recorded by the reference measurement units were significantly lower (99 in./mile for the inertial profiler van; 157 in./mile for the lightweight profiler) than those recorded by the mobile device. This significant difference can most likely be attributed to differences in the suspension systems for the sedan and the reference measurement units. Different suspension system can cause the vehicle to vibrate at different frequencies affecting the vibration readings coming from pavement roughness. To verify this hypothesis, and to improve the measurements taken by the lightweight profiler, a second round of pilot testing efforts were carried out on July 27, 2017. Findings from this second round of pilot testing are discussed below.

Pilot Testing Effort # 2 (Date: July 27, 2017)

During the second pilot testing effort, three different personal vehicles were used for mobile-device based pavement roughness measurement. The three vehicles used were: (1) A 2015 Jeep Cherokee, (2) a 2013 Nissan Altima, and (3) a 2005 Kia Rio. Measurements were also conducted using the reference measurement units, such as ITD's inertial profiler van and lightweight profiler, for comparison purposes. Measurements using the inertial profiler van were taken five times in both directions; this produced 10 sets of data (five in each direction) from the inertial profiler van. Moreover, all five mobile devices were placed inside the profiler van during each of the runs, producing $5\ (devices) \times 5(runs) \times 2(directions) = 50$ datasets. Thereafter, each of the vehicles, mounted with all five mobile devices, were driven along the same road for three times (in both directions), thus producing $5(devices) \times 3(vehicles) \times 3(runs) \times 2(directions) = 90$ datasets. Extensive analysis of these datasets allowed the research team to study the factors of interest; results from the analysis of these datasets have been presented in the following sections.

Analysis of Data from Pilot Testing Effort # 2

In this section, IRI values calculated using the mobile devices placed in different vehicles are analyzed. First, data from the mobile devices were compared against those from the reference measurement units. **Figure 50** shows one such comparative plot; this data is an average of three runs traversed using a 2015 Jeep Cherokee driving at an average speed of 30 miles per hour.

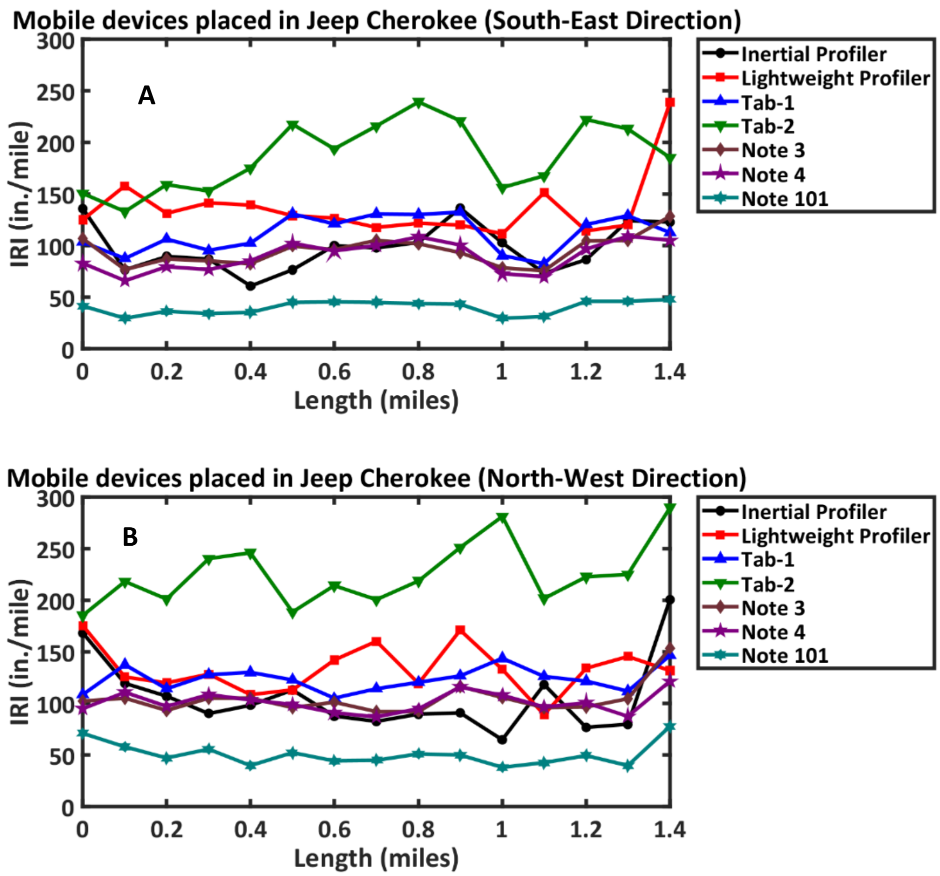


Figure 50. Comparing the Roughness Data Collected using the Reference Measurement Units against Those Collected using a 2015 Jeep Cherokee Along (a) South-East Direction (b) North-West Direction

The first thing to be noticed from **Figure 50** is that the IRI values recorded by the mobile devices were significantly lower than those plotted in **Figure 49**. This clearly indicates the effect of vehicle suspension system on mobile-based roughness measurements; values recorded using a 2002 Honda Civic (see **Figure 49**) were significantly higher than those recorded using a 2015 Jeep Cherokee (see **Figure 50**). It can also be seen from **Figure 50** that all the mobile devices, except Tab-2 (replicate # 2 of the Samsung Galaxy Tab 4 model) and Note 101, produced IRI values that were within ± 60 in./mile (at every 0.1 mile) to the values recorded using the inertial profiler. Values recorded by Tab 2 were significantly higher than all other measured values. One probable reason responsible for this might be inadequate mounting of the device to the vehicle's dashboard. It is also important to note that a recognizable difference was still observed between the IRI trends from the inertial profiler van and the lightweight profiler. Apparently, even after calibration, the two units did not produce identical results. Mean IRI values calculated by the different devices from this pilot testing effort have been listed in **Table 4** along with values recorded by the two reference measurement units. The percent difference values have been calculated by taking the inertial profiler as the reference value.

Table 4. Comparing the Mean IRI Values Calculated by Different Measurement Devices/Units (All Mobile Devices Placed in a 2015 Jeep Cherokee).

Source of data	Mean IRI (South-East Direction) (in/mile)	% difference	Mean IRI (North-West Direction) (in/mile)	% difference
Inertial profiler	99	NA	105	NA
Lightweight profiler	136	- 38.9%	133	-25.82
Tab-1	111	-13.73	123	-17
Tab-2	186	-90.22	225	-113.17
Note 3	95	3.14	104	1.3
Note 4	89	8.39	101	4.36
Note 101	40	59.17	50	52.05

Note that a negative difference in **Table 4** indicates that the roughness value from a particular device/unit is higher than the IRI from reference source. As seen from the table, three of the mobile devices (Tab-1, Note 3, and Note 4) reported IRI values that were within ±5 percent of the IRI value reported by the inertial profiler.

Figure 51 shows pavement roughness data collected using the mobile devices mounted inside the 2013 Nissan Altima sedan. As seen from the figure, the values were significantly (often more than 5 times) higher than those recorded using the reference measurement units. Changing the vehicle type (from a Sports Utility Vehicle to a Sedan) resulted in significant increase in the measured IRI values. It can also be seen from **Figure 51** that IRI values recorded by Tab-1 were significantly higher than those recorded by Tab-2. This is the exact opposite of the trend observed in **Figure 50**. Therefore, it is evident that the roughness values recorded by two identical mobile devices can differ significantly from one measurement to another. **Table 5** lists the mean IRI values recorded for the calibration roadway section by placing the five mobile devices in a 2013 Nissan Altima. Comparing the values reported in **Table 5** against those in **Table 4** clearly indicates that suspension systems in sedan-type vehicles lead to significantly less vibration dampening compared to SUV-type vehicles. Similar data for measurements carried out using a 2005 Kia Rio have been presented in Error! Reference source not found. and **Table 6**.

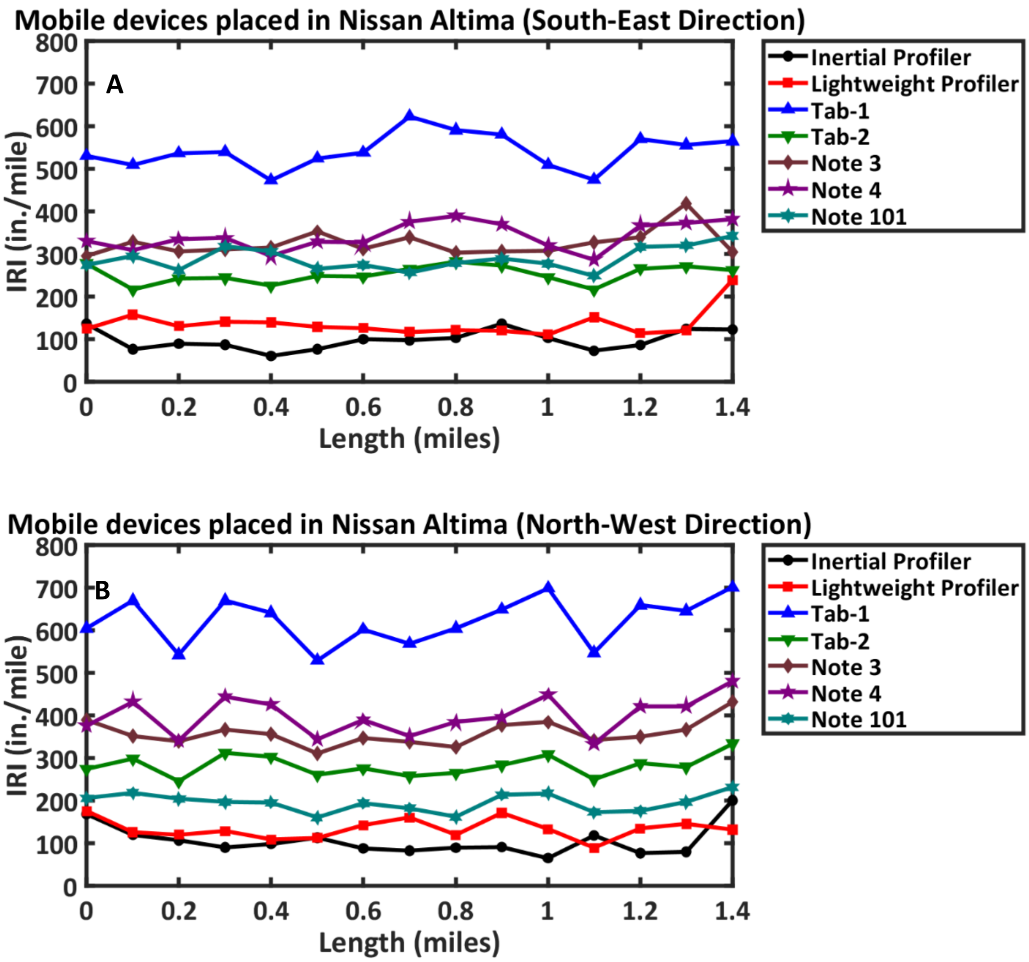
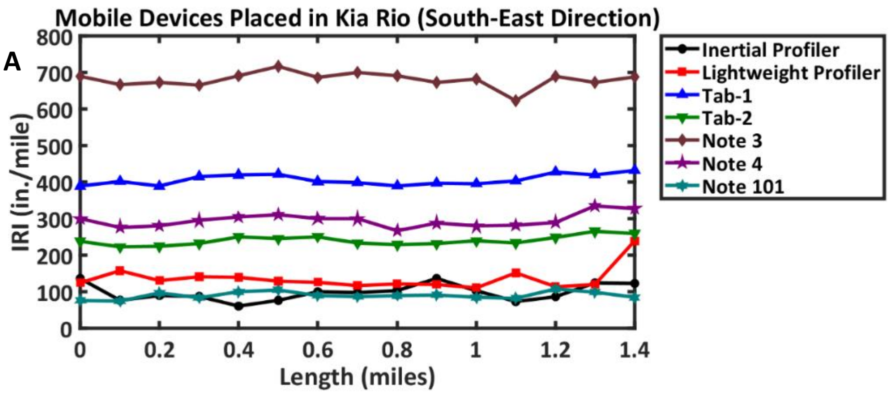


Figure 51. Comparing the Roughness Data Collected using the Reference Measurement Units against Those Collected using a 2013 Nissan Altima (a) South-East Direction (b) North-West Direction

Table 5. Comparing the Mean IRI Values Calculated by Different Measurement Devices/Units (All Mobile Devices Placed in a 2013 Nissan Altima)

Source of data	Mean IRI (South-East Direction) (in/mile)	% difference	Mean IRI (North-West Direction) (in/mile)	% difference
Inertial profiler	99	NA	105	NA
Lightweight profiler	136	- 38.9%	133	-25.82
Tab-1	541	-451.55	622	-487.48
Tab-2	252	-156.65	282	-166.61
Note 3	324	-230.23	358	-238.69
Note 4	341	-248.08	399	-277.25
Note 101	288	-193.588	195	-84.27



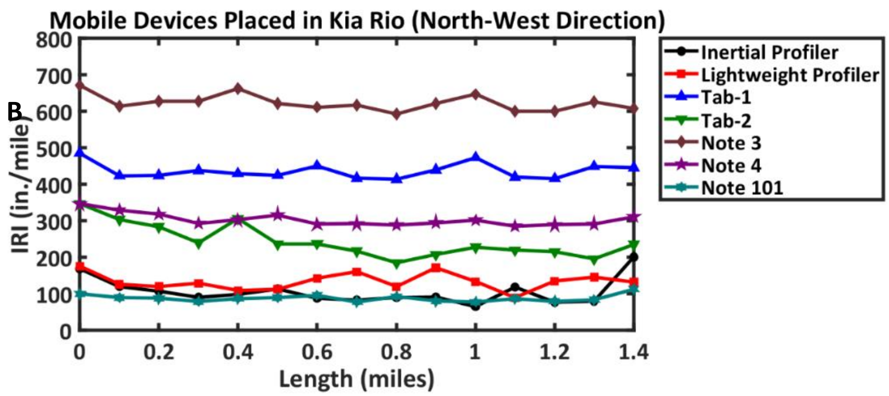


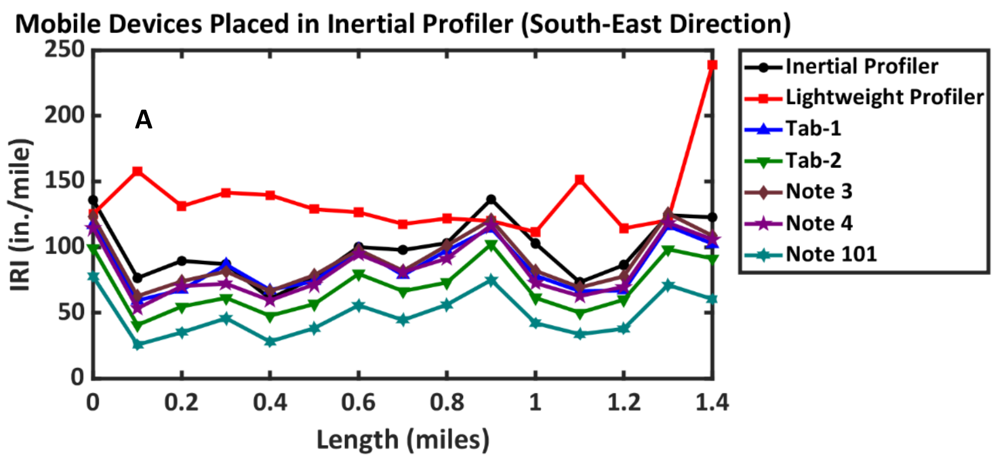
Figure 52. Comparing the Roughness Data Collected using the Reference Measurement Units Against Those Collected using a 2005 Kia Rio (a) South-East Direction (b) North-West Direction

Table 6. Comparing the Mean IRI Values Calculated by Different Measurement Devices/Units (All Mobile Devices Placed in a 2005 Kia Rio)

Source of data	Mean IRI (South-East Direction) (in/mile)	% difference	Mean IRI (North-West Direction) (in/mile)	% difference
Inertial profiler	99	NA	105	NA
Lightweight profiler	136	- 38.9%	133	-25.82
Tab-1	78	20.14	79	24.51
Tab-2	104	-6.25	106	-0.44
Note 3	106	-8.33	106	-0.58
Note 4	96	1.85	997	7.82
Note 101	102	-4.24	103	2.27

As seen from Error! Reference source not found. and **Table 6**, the roughness values measured using the 2005 Kia Rio were significantly higher than those recorded using ITD's inertial profiler van and a lightweight profiler. The lowest IRI is produced by Note 101 which is 96 percent of the reference IRI by inertial profiler. Even for measurements carried out using the Kia Rio sedan, a significant difference between the values recorded by Tab-1 and Tab-2 (two devices of the exact same model) were observed. This clearly establishes that mobile-based measurement systems may not be very consistent even when multiple pieces of the same device are used. It is recommended to be considered as independent devices even the devices are identical models.

Finally, to eliminate variabilities associated with vehicle suspension systems, a set of measurements were conducted by placing the mobile devices inside the inertial profiler van. This enabled comparison between the IRI values, recorded by the IMU (integrated into the profiler van), and the mobile devices. Note that the IRI values calculated by the IMU uses the laser unit to compensate for the difference in elevation between the pavement system and the vehicle suspension. The mobile devices, on the other hand, do not compensate for this distance.
Figure 53 presents the datasets collected by the mobile devices placed inside inertial profiler van.



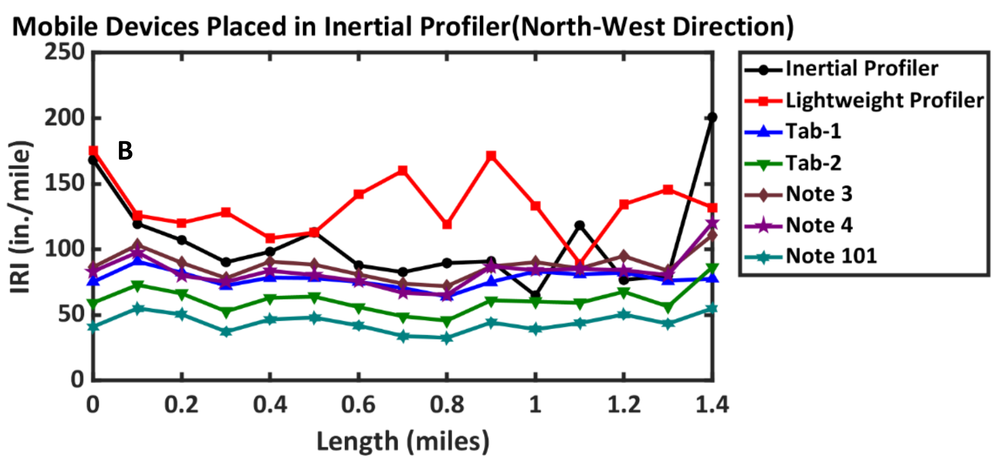


Figure 53. Comparing the Roughness Data Collected using the Reference Measurement Units against Those Collected by Placing the Mobile Devices inside the Inertial Profiler Van (a) South-East Direction (b) North-West Direction

As seen from the
Figure 53, IRI values recorded using each of the devices share a general trend of IRI variation along the roadway section. Unlike measurements using other vehicles, the mobile-measured and IMU-measured IRI values are reasonably close to each other. The mean IRI values from each device, and the corresponding percent difference values with respect to the inertial profiler van have been listed in **Table 7**.

Table 7. Comparing the Mean IRI Values Calculated by Different Measurement Devices/Units (all Mobile Devices Placed inside the Inertial Profiler Van)

Source of data	Mean IRI (South-East Direction) (in/mile)	Percent Difference (%)	Mean IRI (North-West Direction) (in/mile)	Percent Difference (%)
Inertial profiler	99	NA	105	NA
Lightweight profiler	136	- 38.90	133	-25.82
Tab-1	86	12.38	77	26.79
Tab-2	69	29.28	61	42.01
Note 3	90	8.28	87	17.11
Note 4	83	14.89	83	21.32
Note 101	48	50.72	44	58.27

As seen from the above table, the best match of average value (taking the inertial profiler as the reference unit) was obtained for Tab-1. A significant difference was again noticed between data recorded by Tab-1 and Tab-2, indicating that identical mobile devices may not always lead to the same measured roughness values.

Calibration Procedure

Analysis results presented in the previous section clearly established that pavement roughness values measured by mobile devices are significantly affected by the device type, as well as the suspension system of the vehicle. Therefore, data collected using this approach needs to be “shifted” to compensate for device and vehicle-related effects. This “shifting” process is termed in this document as “calibration”. After calibration, the mobile devices are expected to produce IRI values close to those measured by reference measurement units. It is important to note that the lightweight profiler used in this study reported values that were significantly different from those recorded using the profiler van, therefore raising questions about the calibration of the unit. The research team, therefore, decided to use IRI values recorded by the inertial profiler van as the reference point for all further analyses. The following paragraphs illustrate a simple, yet efficient approach used to scale the data collected using mobile devices to match values from the reference measurement units. Data collected by placing the mobile devices inside the 2013 Nissan Altima sedan has been used as an example during this illustration.

Average IRI values per 0.1-mile segments of the roadway as measured by placing the mobile devices inside a 2013 Nissan Altima sedan have been listed in **Table 8**. As is common during pavement roughness measurement efforts, data collected using the mobile devices are broken up into 0.1-mile long segments. The value reported corresponding to each segment is essentially the average of all values recorded by the device as the vehicle traverses 0.1 miles along the roadway. For example, if the accelerometer has a sensitivity of 150 Hz, it will record 150 accelerometer data per second. Now, if the vehicle speed is 50 mph then it will take 7.19 seconds to travel 0.1 mile. During that time the device will generate 1080 roughness data points. Therefore, to report one IRI value for the 0.1-mile long segment of roadway, 1080 data points are averaged.

Table 8. Average IRI Values Calculated per 0.1-Mile Long Segments by Tab-1 Mounted inside a 2013 Nissan Altima (Data from First of Five Runs Presented)

From Mile	To Mile	Inertial Profiler van (in/mile)	Lightweight profiler (in/mile)	IRI Avg (in/mile)
0	0.1	146	125	500
0.1	0.2	71	158	498
0.2	0.3	95	131	496
0.3	0.4	88	141	499
0.4	0.5	58	140	431
0.5	0.6	77	129	531
0.6	0.7	102	127	500
0.7	0.8	91	117	573
0.8	0.9	101	122	546
0.9	1.0	141	120	560
1.0	1.1	97	111	527
1.1	1.2	69	151	453
1.2	1.3	89	114	577
1.3	1.4	137	120	503
1.4	1.4	121	239	492
Average		99	136	513

The last row of the table shows the average of all the IRI's from 0 to 1.4 mile is 513 in/mile. The mean IRI value for this section of the roadway (ITD's calibration roadway) was established as 98.89 in/mile using the inertial profiler van. Accordingly, average IRI values measured using the 2013 Nissan Altima and Tab-1 combination was $\frac{513}{99} = 5.181$ times higher than that established using the inertial profiler. Therefore, IRI values recorded using the mobile device needs to be multiplied by a factor of $\left(\frac{1}{5.181} = 0.19\right)$ to match the inertial profiler values. This multiplicative factor (referred to in this document as the Modification Factor or MF) can be used to scale the mobile device-measured IRI values to the reference values and can be greater or smaller than unity depending on the sensitivity of the vehicle suspension system and the accelerometer of the mobile device used. **Table 9** lists the same numbers as **Table 8**, with an added column demonstrating the modified IRI values.

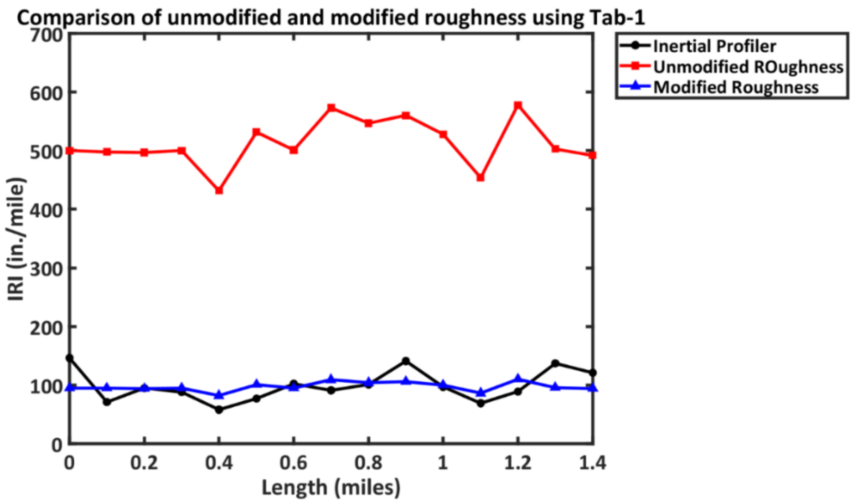
Table 9. Modified and Unmodified IRI Values (Tab-1 Mounted inside a 2013 Nissan Altima)

From Mile	To Mile	Inertial Profiler van (in/mile)	Lightweight profiler (in/mile)	Unmodified IRI (in./mile)	Modified IRI (in./mile)
0	0.1	146	125	500	95
0.1	0.2	71	158	498	94
0.2	0.3	95	131	496	94
0.3	0.4	88	141	499	94
0.4	0.5	58	140	431	82
0.5	0.6	77	129	531	101
0.6	0.7	102	127	500	95
0.7	0.8	91	117	573	108
0.8	0.9	101	122	546	103
0.9	1.0	141	120	560	106
1.0	1.1	97	111	527	100
1.1	1.2	69	151	453	86
1.2	1.3	89	114	577	109
1.3	1.4	137	120	503	95
1.4	1.5	121	239	492	93
Average		99	136	513	97

It should be noted that by applying the MF, the final mean IRI is calculated to be 97 in./mile, which is close to the average value (99 in./mile) obtained from the inertial profiler. A plot showing the modified and unmodified IRI along calibration roadway section (data corresponding to Tab-1 mounted inside a 2013 Nissan Altima) is shown in

Figure 54. For comparison purposes, the IRI values recorded using the inertial profiler have also been included in

Figure 54.



Note: Measurements Carried out using Tab-1 Mounted inside a 2013 Nissan Altima

Figure 54. Effect of MF on Mobile-Measured IRI Values

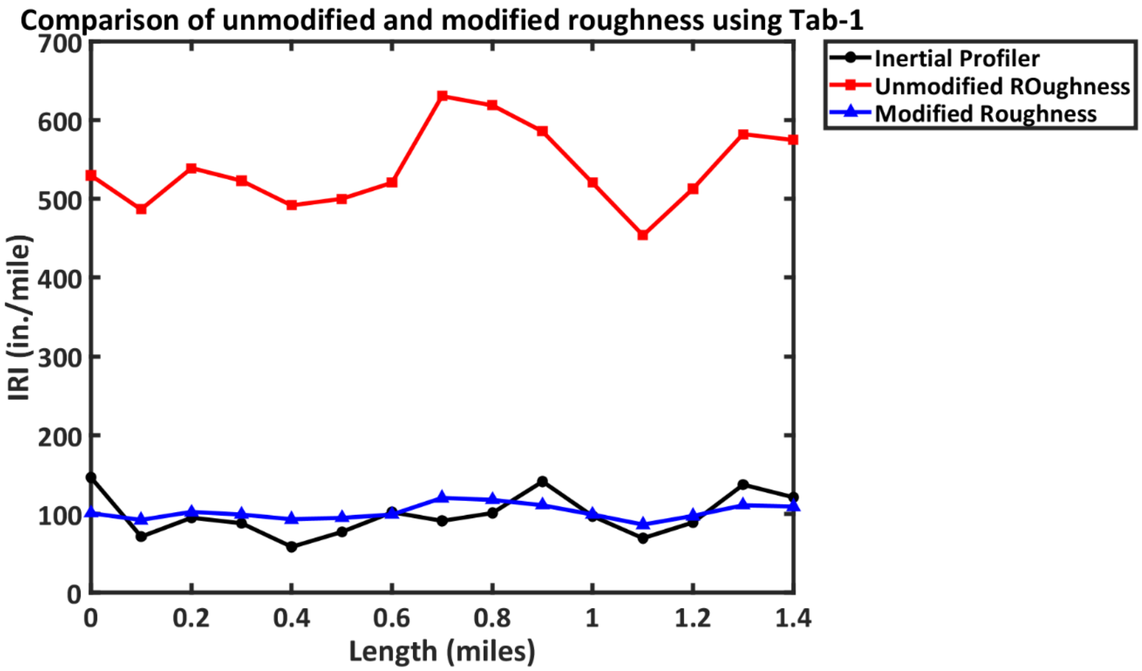
Testing the Modification Factors

To test the repeatability of this modification approach, the same calculated value was applied to data recorded using the same vehicle-device combination (2013 Nissan Altima and Tab-1) during a second run. The data from this second run has been presented in **Table 10**. As seen from **Table 10**, the average IRI value for the roadway section was calculated to be 102 in./mile after application of the MF. This value is close to the inertial profiler-established value (99 in./mile); this illustrates the applicability of this modification approach, as long as the same vehicle-device combinations are used. Note that the MF is calculated based on the average IRI of the entire roadway segment. Therefore, the modified IRI values for individual 0.1-mile segments may not closely match the corresponding values using the reference measurement units.

Table 10. Modified and Unmodified IRI Values (Tab-1 Mounted inside a 2013 Nissan Altima; Run # 2)

From Mile	To Mile	Inertial Profiler van (in/mile)	Lightweight profiler (in/mile)	Unmodified IRI (in/mile)	Modified IRI (in/mile)
0	0.1	146	125	530	100
0.1	0.2	71	158	486	92
0.2	0.3	95	131	538	102
0.3	0.4	88	141	522	99
0.4	0.5	58	140	492	93
0.5	0.6	77	129	499	94
0.6	0.7	102	127	521	99
0.7	0.8	91	117	630	119
0.8	0.9	101	122	619	117
0.9	1.0	141	120	586	111
1.0	1.1	97	111	521	99
1.1	1.2	69	151	453	86
1.2	1.3	89	114	512	97
1.3	1.4	137	120	582	110
1.4	1.45	121	239	575	109
Average		99	136	538	102

Figure 55 presents a plot of the modified and unmodified IRI trends along the calibration site from the second run using the 2013 Nissan Altima. For comparison, IRI trends established using the inertial profiler are also plotted on the same graph.



Note: Measurements Carried out using a Tab-1 Mounted inside a 2013 Nissan Altima; Run # 2

Figure 55. Effect of MF on Mobile-Measured IRI Values

The MFs for all vehicle-device combinations (4 different vehicles; 5 different devices) were established using a similar approach and have been listed in **Table 11**.

Table 11. MFs Established for Twenty Different Vehicle-Device Combinations through the Pilot Testing Effort

Device/Vehicle	2015 Jeep Cherokee	2013 Nissan Altima	2005 Kia Rio	2017 Inertial Profiler
Tab-1	0.88	0.19	0.25	1.13
Tab-2	0.55	0.4	0.4	1.41
Note 3	1.03	0.34	0.26	1.08
Note 4	1.09	0.29	0.32	1.17
Note 101	2.38	0.58	1.1	2.07

As seen from **Table 11**, the MFs corresponding to some of the vehicle-device combinations were greater than unity, whereas the values for some others were less than unity. As is evident, a MF magnitude close to unity indicates a good match between the particular vehicle-device combination and inertial profiler results. From **Table 11**, the MF closest to unity was 1.03, and corresponding to data recorded using a Samsung Galaxy Note-3 mounted inside the 2015 Jeep Cherokee. This indicates that IRI values calculated using the Note-3 and 2015 Jeep Cherokee are likely to show the closest match with inertial profiler measurements. However, it is noted that this inference is derived based on measurements from the pilot testing effort only, and the consistency of this hypothesis needs to be verified for different roadway conditions.

Summary

This chapter discussed findings from two different pilot testing efforts undertaken under the scope of this research project. A particular roadway section used by ITD for inertial profiler calibration purposes was selected, and roughness measurements were carried out using different vehicle-device combinations; reference measurements were also taken using ITD's high-speed inertial profiler, as well as a lightweight profiler. Four different vehicles were used to test the effect of vehicle suspension system on pavement roughness. Finally, Modification Factor- (MF-) based calibration method was developed and tested against pavement roughness data collected using an inertial profiler. The research team observed that scaling the raw data collected by mobile devices using MF resulted in close approximation of pavement roughness values measured using the reference measurement units. As already mentioned, the MF is calculated based on the average IRI of the entire roadway segment. Therefore, the modified IRI values for individual 0.1-mile segments may not closely match the corresponding values established using the reference measurement units. Some vehicle-device combinations resulted in MFs closer to unity than the others. Results from pavement roughness measurement efforts carried out along different pavement sections selected across different ITD districts will be presented in the next chapter.

Chapter 5
Roughness Measurement along Selected Roadway Segments across Idaho

Chapter 4 presented findings from the pilot testing efforts undertaken during the current study to assess the suitability of mobile devices for pavement roughness measurements. Based on the results, it was concluded that IRI values, reported by the mobile devices, were greatly dependent on the vehicle-device combination being used. However, by comparing the results against those from reference measurement units (such as inertial profiler vans and/or lightweight profilers), certain MF's can be established to "scale" the values recorded by the mobile devices. The pilot testing efforts demonstrated that such procedure scales up or down the pavement roughness values close to the values reported by the reference measurement units. It is important to note that this MF is not vehicle or device-specific number; rather, it is unique for each vehicle-device combination. Note that, due to variabilities associated with the manufacturing of devices, Tab-1 and Tab-2 (two identical devices) yielded different MF values.

Upon completion of the pilot testing effort, the next task involved pavement roughness testing along pre-selected pavement sections from different parts of Idaho to assess the feasibility of implementing this testing approach into practice. The research team coordinated with engineers from different ITD districts to identify candidate roadway sections for pavement roughness measurements using mobile devices. Pavement sections in four different ITD districts (Districts 3, 4, 5, and 6) were tested under the scope of this project. Note that different vehicles were used to collect pavement roughness data in all four districts. This was primarily because ITD engineers in different districts have access to different vehicles, and for adequate implementation of this technology into practice, testing using available vehicles is important. Pavement roughness measurement using different vehicles, and subsequent comparison against reference measurement units will help establish the applicability of this testing approach.

Approach for Selection of Test Sections

As already mentioned, the research team worked closely with ITD engineers to select the pavement sections to be tested under the scope of this project. Special emphasis was given to newly paved or rehabilitated roadway sections during this selection process. A list of road construction projects where the research team collected the pavement roughness data using the mobile devices is given in **Table** 12. Please note that, IRI data was collected on both sides for some of the road sections and is mentioned in the table.

Table 12. List of Roadway Sections from Different ITD Districts Tested During this Research Study

Project location	Date of data collection	Route Number	Project description	Length of segment Tested (miles)	Number of Roadway Segments Tested
D3	09/11/2017	SH-67	From SH-167 to SH-51 (Covered both sides)	7.5	2
		SH-167	From SH-67 to SH-78 (Covered both sides)	16	2
		SH-78	From Grandview to river road (Covered both sides)	8	2
D4	10/04/2017	I-84	From SH-50 to Machine Pass	0.5	1
		I-84	From Machine Pass to Valley Road	5	1
		I-84	From Valley road to MP191 EBL	6.5	1
	10/11/2017	SH-25	From I-84 to Hazelton	4	1
D5	10/20/2017	I-15	Project Number: 13103 From Sand Road to South Blackfoot	2.5	1
		I-15	Project Number: 18784 From Lava Beds to Bonneville Country Line	8	1
		US-91	Project Extent: Shelly City Limits	1.5	1
		I-15	Project Number: 13550 From Arimo to McCammon (Covered both sides)	7	2
		US-30	Montpelier City Limits covered both sides	1.5	2
D6	11/03/2017	I-15	From MP 180.7 to Montana State Line (MP 180.7 to MP 196) (Covered both sides)	4	2
		SH-33	From Henry's fork snake river bridge to US-20 MP 73.40 - 77.73)	4	1
				Total number of road segments	20

Details of Testing Efforts

As already mentioned, testing in different ITD districts were carried out using different vehicles (selected from those available to ITD engineers). During each testing effort, five mobile devices equipped with RoadBump Pro app were used. If time permitted, each road was traversed several times to assess the repeatability of the test results. Special care was taken during the testing to maintain a constant driving speed; sudden acceleration or deceleration of the vehicle can lead to erroneous measurements using the mobile devices.

Vehicles Used to Collect the Pavement Roughness Data

Different vehicles were used for the pavement roughness measurement efforts based on availabilities. **Table 13** provides a list of vehicles and mobile devices used during the testing effort.

Table 13. List of Vehicles and Devices Used in Different ITD Districts during the Pavement Roughness Measurement Effort

District	Testing Date(s)	Vehicles Used	Comments	Mobile Devices Used
D3	September 11, 2017	2012 GMC Canyon	Pick-Up Truck	Tab-1, Tab-2, Note 4, and Note 101
		2015 Jeep Cherokee*	Sports Utility Vehicle (SUV)	
D4	October 4, 2017 and October 11, 2017	2010 GMC Canyon SL	Pick-Up Truck	Tab-1, Tab-2, Note 3, Note 4, and Note 101
		2015 Chevrolet Traverse	Sport Utility Vehicle (SUV)	
		2013 Chevrolet Silverado	Pick-Up Truck	
		2014 Chevrolet Colorado	Pick-Up Truck	
D5	October 20, 2017	2012 GMC Canyon SLE	Pick-Up Truck	Tab-1, Tab-2, Note 3, Note 4, and Note 101
D6	November 3, 2017	2016 Chevrolet Traverse	Sport Utility Vehicle (SUV)	Tab-1, Tab-2, Note 3, Note 4, and Note 101
		2013 Chevrolet Silverado	Pick-Up Truck	

* Same as the one used during the pilot testing effort

The first road-test was conducted in D3 on 09-11-2017. Two different vehicles were used during this test. Four mobile devices Tab-1, Tab-2, Note 4 and Note 101 was used to collect pavement roughness data, resulting in the collection of a total of $2 \times 6 \times 4 = 48$ datasets. Six different pavement sections located along SH-67, SH-167, and SH-78 in Mountain Home was used during road-test in D3. The lengths of these road sections were $7.5 \times 2 = 15$ miles, $16 \times 2 = 32$ miles, and $8 \times 2 = 16$ miles, respectively. Both sides of each road section were used for collecting roughness data.

The research team travelled to D4, near Twin falls, Idaho, twice to collect pavement roughness data on 10-04-2017 and 10-11-2017, respectively. Three vehicles were used during the first data collection effort, while two different vehicles were used on the second day of road-test in D4. Among the vehicles, GMC Canyon SL shown in **Table 13** was the only one used for both days. However, the tire pressure was different between two data collection efforts. Technically, this caused a difference in the spring constant of sprung mass of the quarter car model (Please refer to the Quarter-Car Model for details). Hence, two separate datasets collected using this vehicle by two different efforts were analyzed separately. Three pavement sections were tested during the first visit, while two pavement sections were selected during the second visit. All the five devices were used to collect pavement roughness data during both visits in D4. Thus, in total $3\ (vehicle) \times 3\ (pavement\ section) \times 5\ (device) = 45$ datasets were gathered during first attempt and $2\ (vehicle) \times 2 (pavement\ section) \times 5 (device) = 20$ datasets were gathered during the second attempt of road-tests made in D4. Length of these pavement sections varied from 0.5 mile to five miles.

Testing in ITD District 5 was conducted on 10-20-2017. Seven different pavement sections were tested in D5. Length of these pavement sections varied from half a mile to 8 miles. All five devices and one type of vehicle were used to collect pavement roughness data in D5. As a result, total number of datasets gathered in D5 was $1\ (vehicle) \times 7 (pavement\ sections) \times 5 (devices) = 35$. Finally, the research team travelled to D6 near Rigby, Idaho on 11-03-2017. Two vehicles were used to collect pavement roughness data during the visit in D6. One of the vehicles was a 2016 Chevrolet Traverse and the other was a 2013 Chevrolet Silverado. Three different pavement sections were tested in D6. Both two road segments in this district were four miles long. All five devices were used to collect pavement roughness data. As a result, in total $2\ (vehicles) \times 3 (pavement\ sections) \times 5 (devices) = 30$ datasets were gathered during the road-tests made in D6.

Observed Variation in Modification Factor

As already discussed in Chapter 4, pavement roughness measurements obtained from mobile devices mounted inside vehicles is greatly dependent on values of the Modification Factors established. Accordingly, for this particular pavement roughness measurement approach to be applicable in the field, it is important for the MF values for a particular vehicle-device combination to be relatively constant across different roadway sections. The research team studied the variation in MF values for particular vehicle-device combinations to assess the applicability of this roughness measurement approach across different roadway segments. **Figure 56** presents box plots for MF values recorded for different devices mounted inside the 2015 Jeep-Cherokee. The data presented in **Figure 56** are taken from different roadway segments tested within District 3. As seen from the figure, the MF values corresponding to Tab-2 (mounted inside the 2015 Jeep Cherokee) varied between 0.26 and 0.64, with a median value slightly higher than 0.4. Similarly, the values for Note 4 (again mounted inside the 2015 Jeep Cherokee) ranged between 0.67 and 1.11; the value for Note 101, on the other hand, ranged between 1.03 and 1.5. This indicates that even when the same vehicle-device combinations are used, the MF values (essentially relative magnitudes of the mobile device-measured IRI values in comparison with inertial profiler-measured IRI values) can change significantly from one roadway section to another. This can present a serious question in regards to the feasibility of pavement roughness measurement using mobile devices in practice. As the MF values for a given vehicle-device combination do not remain unchanged across pavement sections, identifying the appropriate device settings to produce results close to inertial profiler-measured values can be nearly impossible. **Figure 57** shows similar boxplots for four devices mounted inside the GMC Canyon pickup truck used in District 3. Once again, significant variations in the MF values are observed even for the same vehicle-device combination.

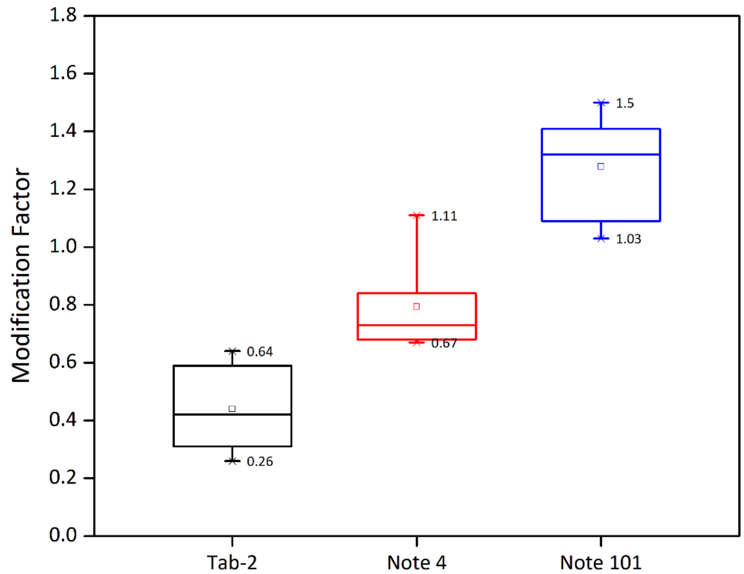


Figure 56. Variation of MF of Jeep-Cherokee along Different Roads in D3

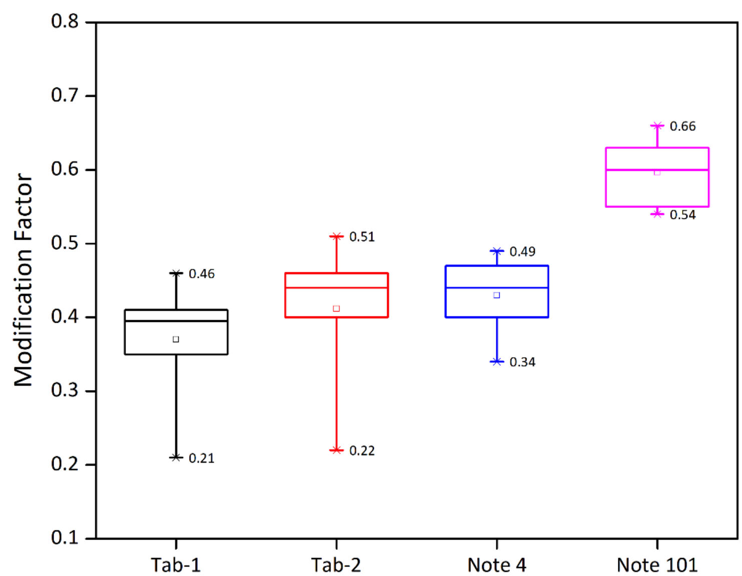


Figure 57. Variation of MF of GMC Canyon along Different Roads in D3

Analysis of Collected Data

By the end of all road testing efforts, a total of 178 data sets were collected from 20 different roadway segments. A total of 9 vehicles were used for mobile-based roadway roughness measurements. The collected data was extensively analyzed to identify significant trends, and the findings have been presented in the following paragraphs. **Table 14** lists the different roadway segments tested in different ITD districts.

Table 14. Description of Tested Pavement Sections

Project location	Reference Measurement Unit	Pavement Section Name	Project description	Average IRI Recorded by Reference Measurement Units (in/mile)
D3	ITD's Inertial profiler	SH-67	From SH-167 to SH-51 (Covered both sides)	51 and 52
		SH-167	From SH-67 to SH-78 (Covered both sides)	80 and 81
		SH-78	From Grandview to river road (Covered both sides)	66 and 71
D4	ITD's Lightweight profiler	I-84	From SH-50 to Machine Pass	33
		I-84	From Machine Pass to Valley Road	37
		I-84	From Valley road to MP191 EBL	52
		SH-25	From I-84 to Hazelton	380
D5	ITD's Inertial profiler	I-15	Project Number: 13103 From Sand Road to South Blackfoot	55
		I-15	Project Number: 18784 From Lava Beds to Bonneville Country Line	50
		US-91	Project Extent: Shelly City Limits	72
		I-15	Project Number: 13550 From Arimo to McCammon (Covered both sides)	37 on both sides
		US-30	Montpelier City Limits covered both sides	55 and 77
D6	ITD's Inertial profiler	I-15	From MP 180.7 to Montana State Line (MP 180.7 to MP 196) (Covered both sides)	36 and 35
		SH-33	From Henry's fork snake river bridge to US-20 (MP 73.40 - 77.73)	45

Comparing Mobile-Device Based Roughness Data with Reference Measurement Units for ITD District 6 (Representative Pavement Section)

For a pavement section extending from MP 180 to Montana of I-15 in D6, IRI values measured using mobile devices and the inertial profiler have been analyzed in this section. Please note that ITD engineers usually drive SUVs or Trucks in the field. **Figure 58** shows the unmodified data collected by the mobile devise mounted inside a 2016 Chevrolet Traverse vehicle.

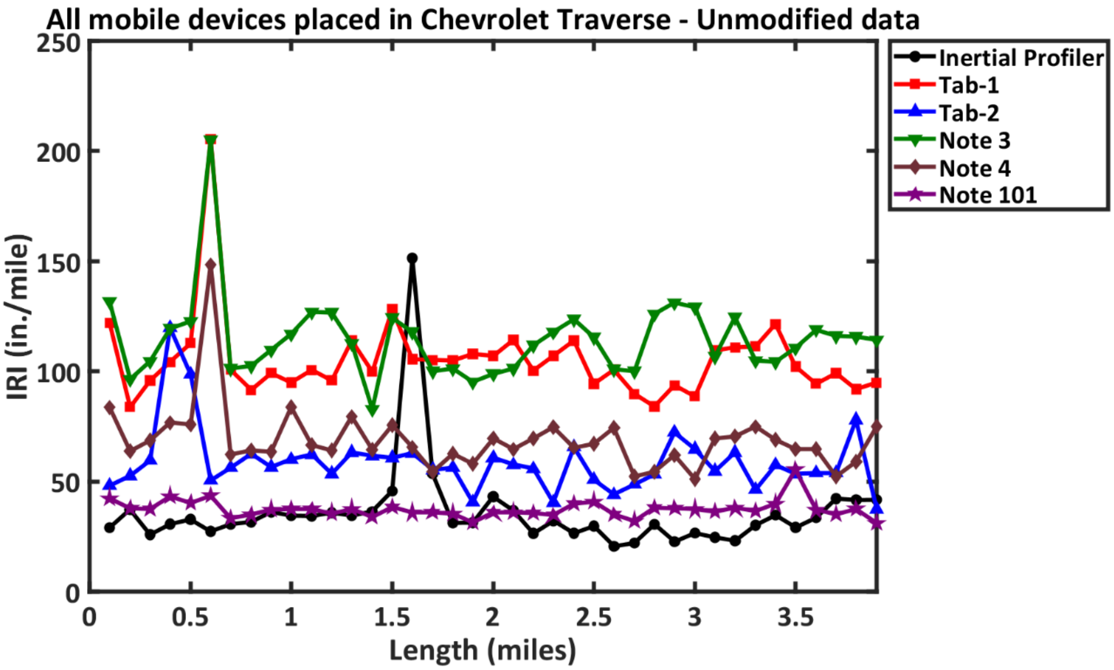


Figure 58. Unmodified Data Collected by All the Devices Placed in Chevrolet Traverse

A significant difference can be seen among the roughness datasets collected by mobile devices and the inertial profiler. As seen from the figure, the IRI value for the pavement section measured using a particular device does not change significantly from one end of the section to the other. Note that the aim of this comparison is not to establish this approach as a standard roughness measurement protocol. Rather, the objective is to compare relative magnitudes of roughness calculated by different devices for the given roadway segment. The research team does not intend to claim that roughness index (such as IRI) calculations should be conducted over the entire segment of the roadway section. Average of the datasets collected by inertial profiler, Tab-1, Tab-2, Note 3, Note 4 and Note 101 are 35, 106, 61, 115, 69, and 38 in./mile, respectively. Therefore, Note 101 mounted inside the 2016 Chevrolet Traverse recorded roughness values that were the closest to those measured using the inertial profiler (in other words a MF value of very close to unity can be expected). The largest deviation, on the other hand, was observed for Tab 1, followed by Note 3. These average IRI values along with the percentage difference of the mobile device data compared to the inertial profiler data are listed in **Table 15**.

Table 15. Comparison of IRI Data Collected Using Mobile Devices Placed inside Chevrolet Traverse against Inertial Profiler

Source of IRI data	Mean IRI (in/mile)	Percent Difference (%)
Inertial profiler	35	NA
Tab-1	106	-202
Tab-2	61	-74
Note 3	115	-228
Note 4	69	-98
Note 101	38	-9

From the averages, the MF can be calculated; the calculated MF's for Tab-1, Tab-2, Note 3, Note 4 and Note 101 are 0.34, 0.58, 0.31, 0.51, and 0.94, respectively. This indicates that although during the pilot testing effort the Note 3 – Jeep Cherokee combination was found to yield IRI values closest to those recorded using the inertial profiler, the user should not expect similar results from all the SUVs. This may either be due to: (1) differences in the vehicle suspension systems; (2) differences in mobile device mounting conditions inside the vehicles. Therefore, this is a clear indication of inconsistent roughness indices calculated for the same roadway segment under different measurement conditions.

Unity plots represent a common approach to compare and visualize two datasets representing similar measurements. The name, unity chart, was given due to the special straight line that crosses the plot area at 45 degrees and passes through the origin. Thus, the equation of this unity line is $y = x$. In reality, not all the data points will lie on the unity line because difference always occurs between the datasets from different sources. In such a case, offset lines from the unity line are useful tools to give a clear visual assessment of the extent to which the datasets differ from each other. Note that the offset lines drawn on a unity plot represent an envelope around the scattered data points and can be thought of representing a range within which the measured values can be expected to lie. **Figure 59** through **Figure 63** present unity plots for pavement roughness data collected using mobile devices mounted inside a 2016 Chevrolet Traverse. The objective is to assess the extent to which the mobile device-measured IRI values differ from those measured using an inertial profiler. Note that the offset average IRI value for this roadway segment measured using the inertial profiler was 35 in./mile. Therefore, the offset values for these plots were drawn at 35 in./mile from the unity line. Note that the research team does not intend to suggest that a variation of 35 in./mile should be used as a standard range for comparison. Instead, this value is adopted to have a basis for comparison depending on the available datasets. Essentially, data points lying within the envelop established by the offset lines will represent measurements that lie within one mean value of the corresponding reference IRI value (established using the inertial profiler). Data points lying outside the envelop represent measurements that show significant differences from the reference values.

It can be seen that all the data points collected using Tab-1 (**Figure 59**) lie outside the offset band defined based on the mean IRI of Inertial Profiler. For Tab-2 and Note 4, quite a few (8 out of 40, and

and 14 out of 40, respectively) data points lie outside the offset band. Referring to **Figure 63**, the data collected by Note 101 (placed in the 2016 Chevrolet Traverse) showed the least amount of scatter when compared against inertial profiler measurements along the same roadway section; measurements taken using Note 3 showed the second closest match (see **Figure 61**).

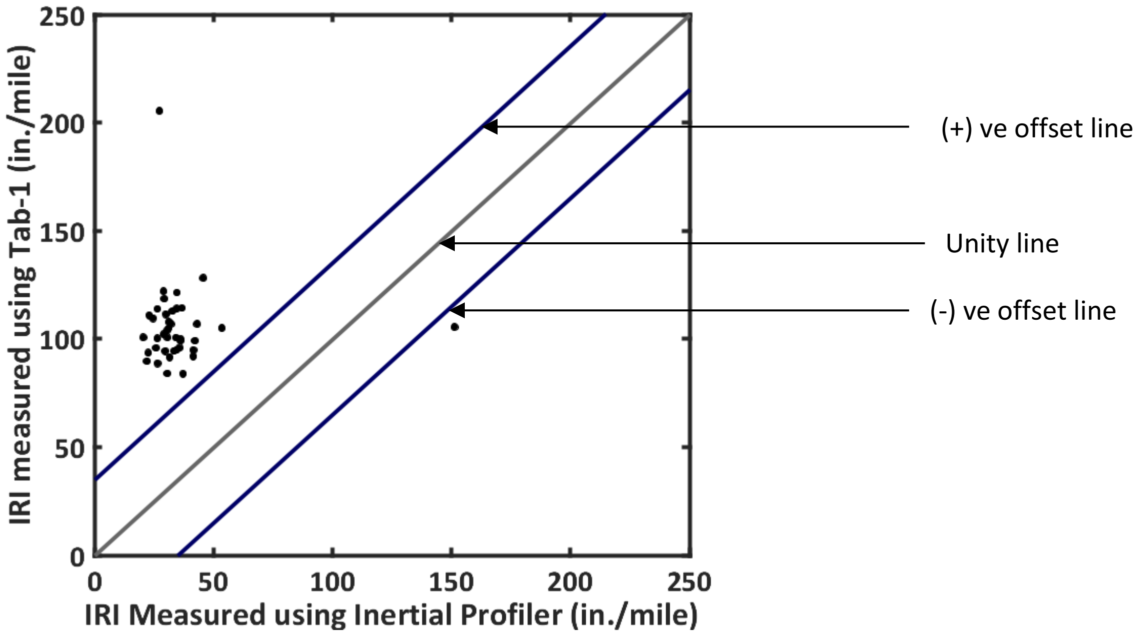


Figure 59. Unity Line Plot for Tab-1 using 2016 Chevrolet Traverse along I-15

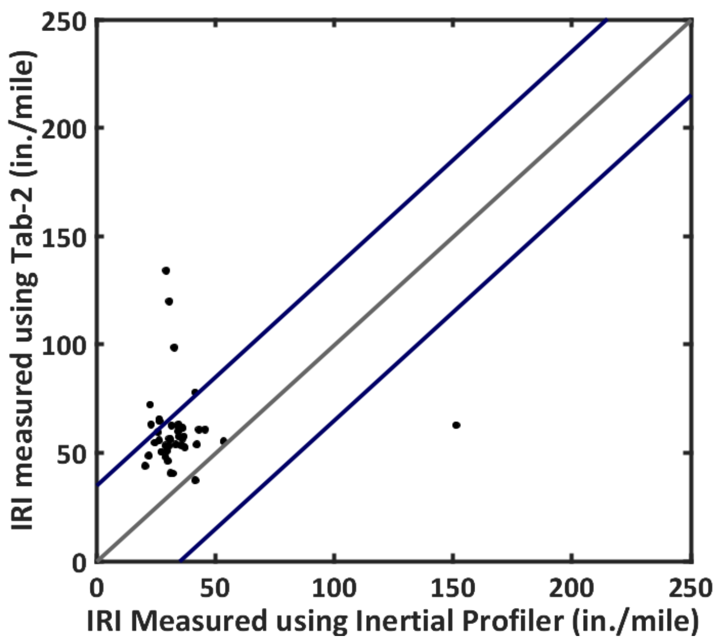


Figure 60. Unity Line Plot for Tab-2 using 2016 Chevrolet Traverse along I-15

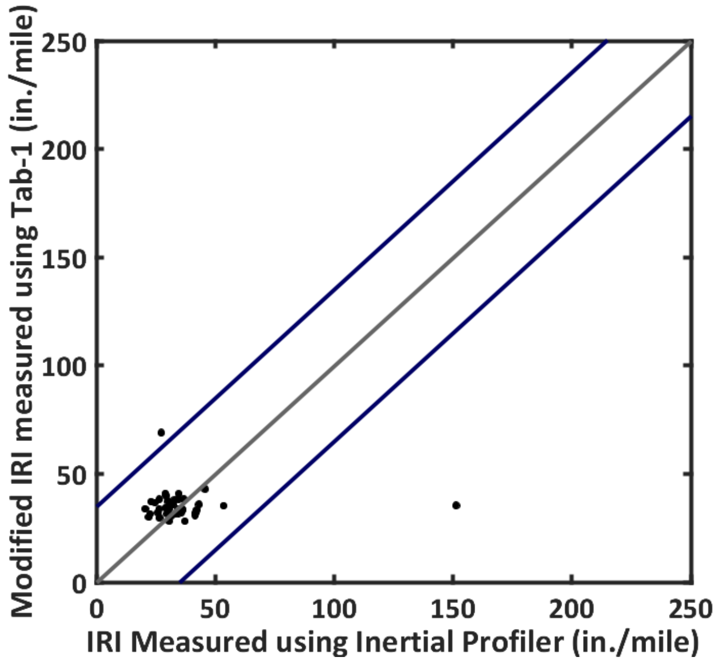


Figure 61. Unity Line Plot for Note 3 using 2016 Chevrolet Traverse along I-15

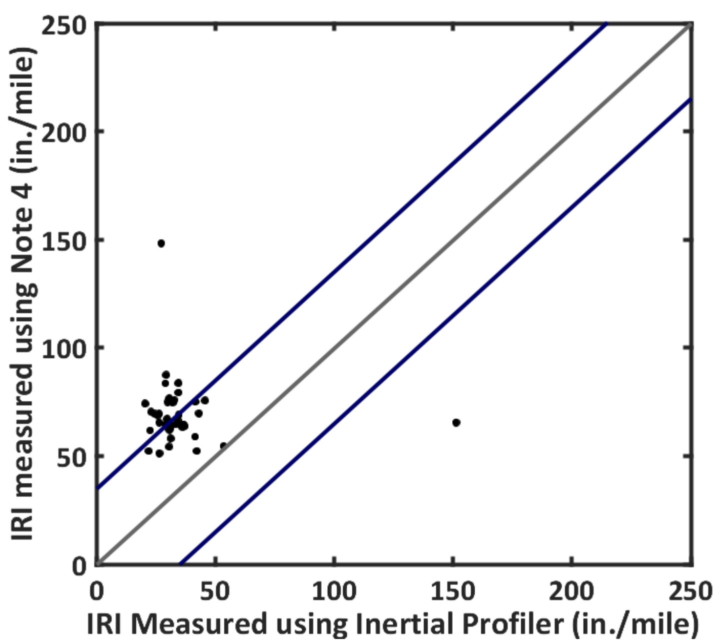


Figure 62. Unity Line Plot for Note 4 using 2016 Chevrolet Traverse along I-15

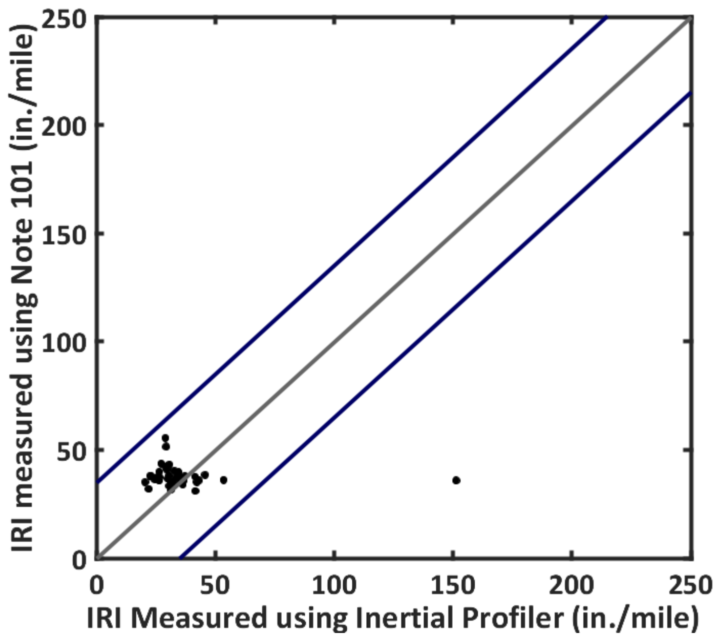


Figure 63. Unity Line Plot for Note 101 using 2016 Chevrolet Traverse along I-15

Figure 64 shows the modified (scaled) data from the five mobile devices mounted inside the 2016 Chevrolet Traverse along with the unmodified reference data (from inertial profiler).

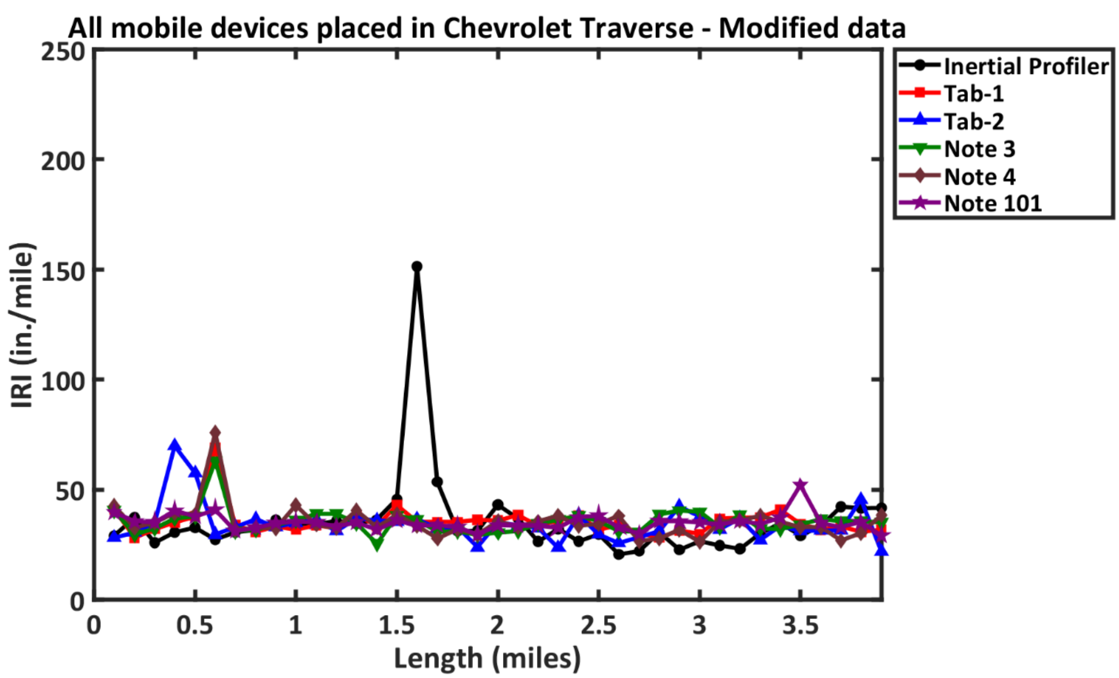


Figure 64. Modified Data Collected by All the Devices Placed in 2016 Chevrolet Traverse

It can be seen in
Figure 64, incorporation of the modification factors “shifts” the IRI values established using the mobile devices so that they lie close to the reference values.
Figure 65 through **Figure 69** show the unity plots of modified data plotted against the reference IRI data. Note that the offset lines drawn in these figures correspond to those established for the unmodified data. The objective is to illustrate the reduction in scatter for the data after incorporation of the modification factors, which is clearly evident from the very small value of data points lying outside the offset envelop.

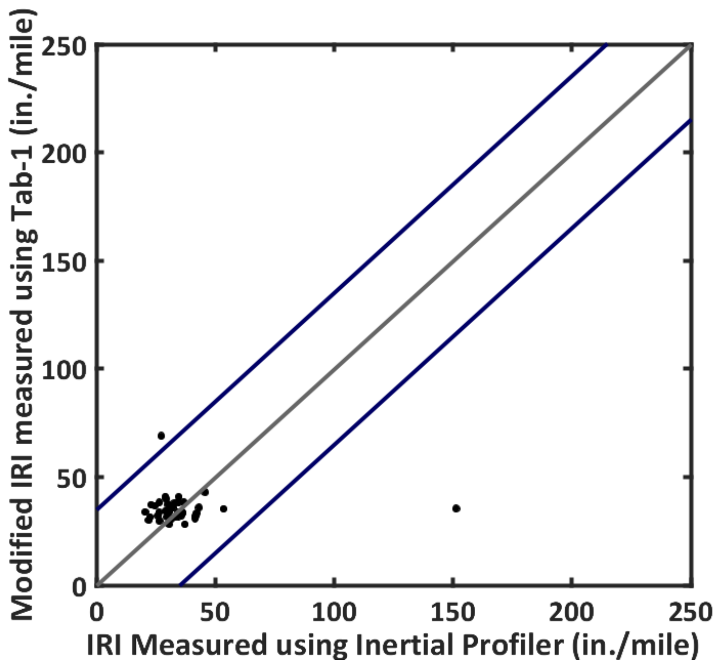


Figure 65. Unity Line Plot for Tab-1 Modified Data using 2016 Chevrolet Traverse in I-15

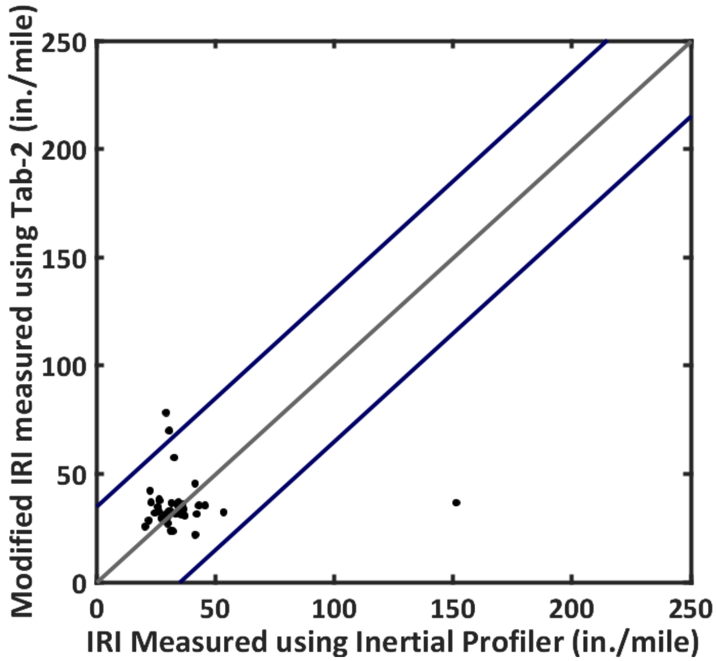


Figure 66. Unity Line Plot for Tab-2 Modified Data using 2016 Chevrolet Traverse in I-15

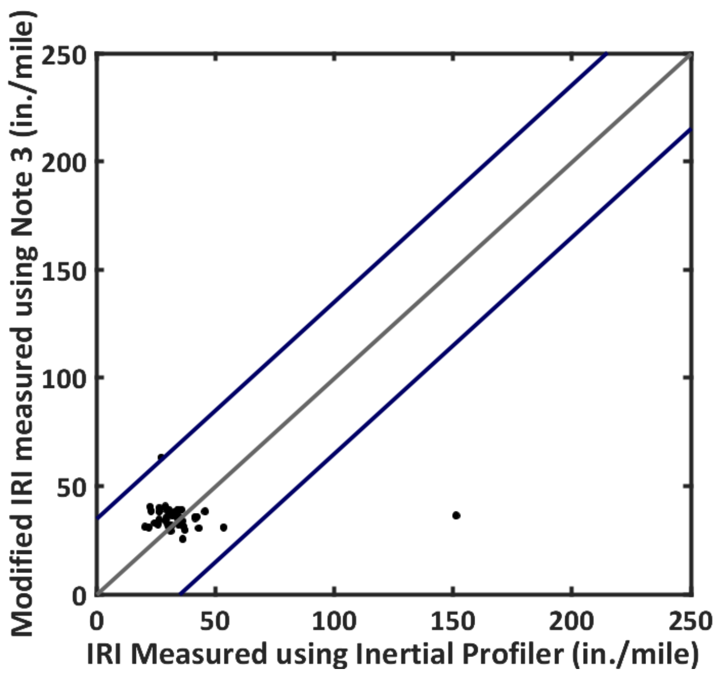


Figure 67. Unity Line Plot for Note 3 Modified Data using 2016 Chevrolet Traverse in I-15

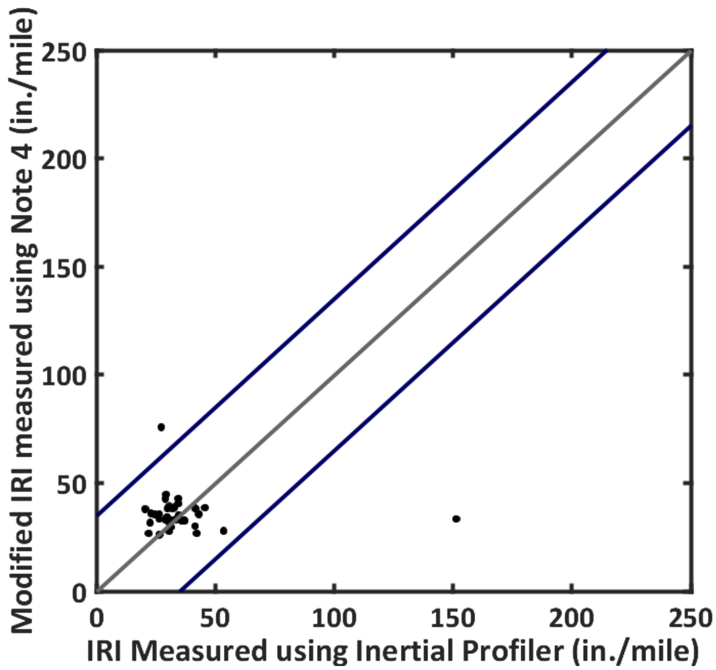


Figure 68. Unity line plot for Note 4 modified data using 2016 Chevrolet Traverse in I-15

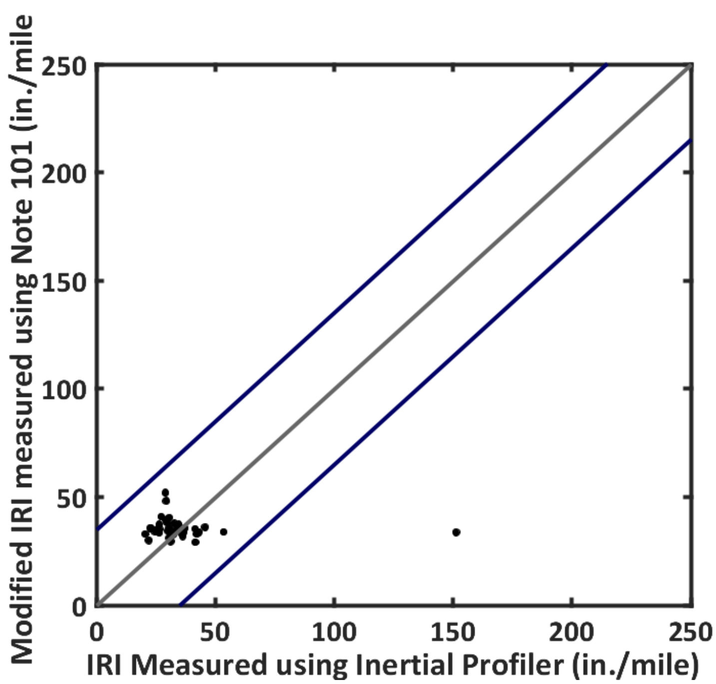


Figure 69. Unity Line Plot for Note 101 Modified Data using 2016 Chevrolet Traverse in I-15

Influence of Data Collection Speed

As already mentioned, pavement roughness data collection using mobile devices can be significantly affected by the dynamics associated with vehicle movement on the roadway surface. It is therefore important to maintain relatively uniform vehicle operational speeds to ensure the collected data is not adversely affected by speed variations. Douangphachanh [30] showed that IRI data collection using mobile devices is sensitive to the speed of the vehicle. The mobile application used in the current study for pavement roughness measurement (RoadBump Pro) recommended driving speeds between 40 and 60 mph [35]. In order for this alternative roadway roughness measurement approach to be implemented into practice, the effect of vehicle speed on the measured roughness values needs to be well-understood.

The current study attempted to assess the effect of vehicle speed on the measured roughness values by during data collection efforts along SH-25 located in D4. The posted speed limit along this particular section of SH-25 is 50 mph. The speed sensitivity study was carried out by driving a GMC Canyon pickup truck along the roadway three times at while maintain speeds approximately 40 mph, 49 mph, and 52 mph. All five mobile devices used throughout the current study were mounted on the dashboard of the vehicle for pavement roughness measurement. During subsequent data analysis it was observed that one particular mobile device (Tab-2) malfunctioned during this data collection effort. Accordingly, data collected by the remaining four devices (Tab-1, Note 3, Note 4, Note 101) was used for the speed sensitivity study. Results from this analysis effort have been presented in the following figures. Note that the average driving speed values used in the plots were extracted from the RoadBump Pro app, which in turn utilizes the GPS built into each mobile device. Therefore, depending on the sensitivity of the GPS within a particular device, the extracted speed value may differ slightly from the actual operating speed. For example, the same three driving speeds were recorded by Tab-1 as 39.9 mph, 49.8 mph, and 51.7 mph (see **Figure 70**), whereas the values recorded by Note 3 were 41.3 mph, 49.7 mph, and 51.6 mph, respectively. Although the extracted speed values do differ from each other slightly from one device to another, they can be treated as the same for all practical purposes.

Figure 70 shows box plots for the IRI values recorded using Tab-1 when the vehicle was driven at three different speeds. As seen from the figure, the median IRI value (denoted by the red horizontal line within the box) decreased as the average speed increased from 39.9 mph to 49.8 mph (median IRI value reduced from 877 in./mile to 378 in./mile). However, the median IRI value increased from 378 in./mile to 1095 in./mile as the speed was further increased to 51.7 mph. Similar trends were observed for Note 3 (**Figure 71**) and Note 101 (**Figure 73**). However, a different trend was observed for Note 4 (**Figure 72**; the highest median IRI value was observed when the operating speed was 49.7 mph. This indicates that the effect of speed on pavement IRI values measured using mobile devices is not necessarily constant and can vary from one device to another. Therefore, no over-arching conclusion can be drawn regarding the expected trends. Note that similar plots of the other side of the road (SH-25 from Hazelton to I-84) are included in Appendix B.

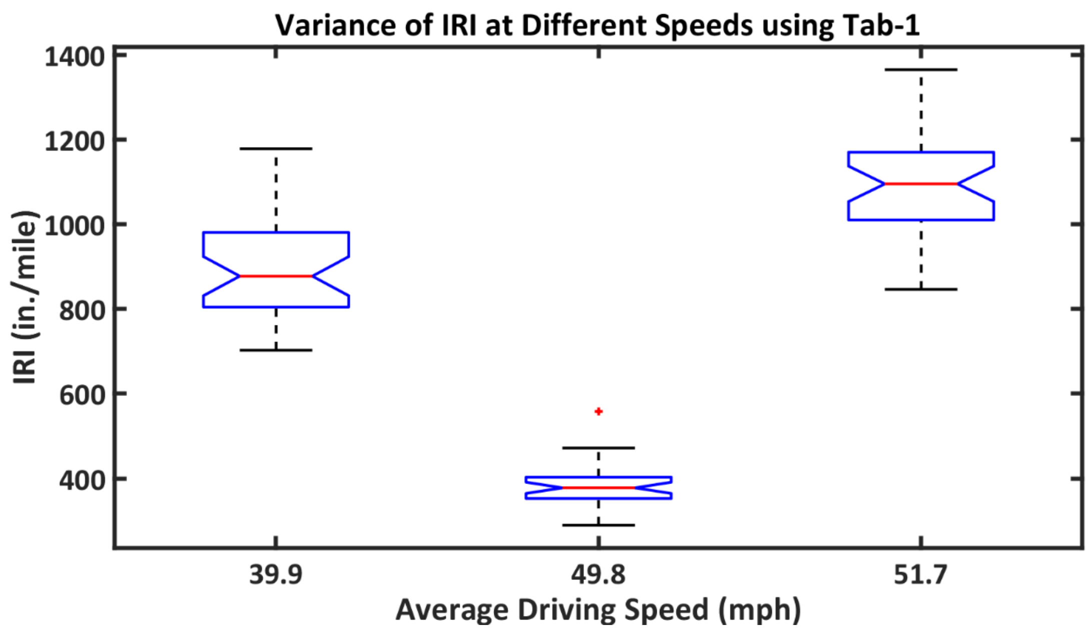


Figure 70. Variance of IRI at Different speeds using Tab-1

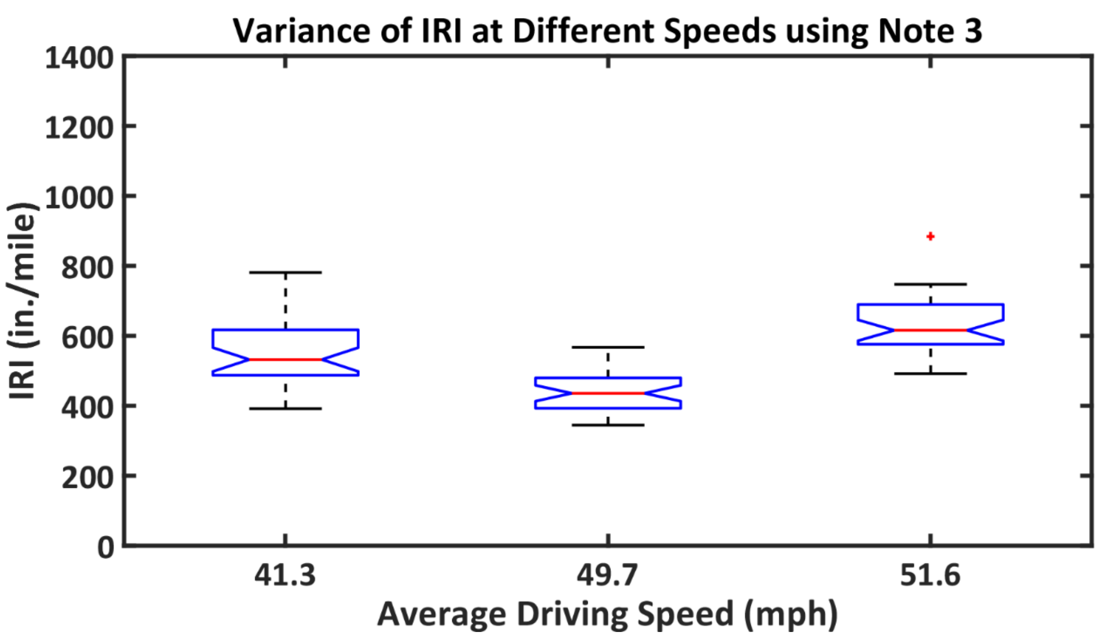


Figure 71. Variance of IRI at Different speeds using Note 3

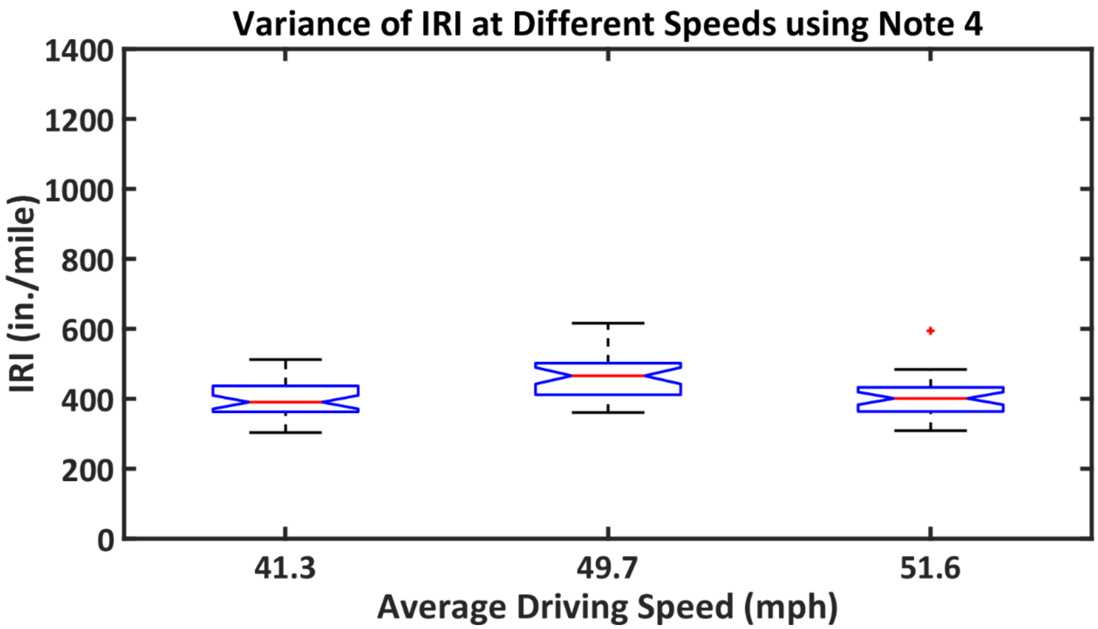


Figure 72. Variance of IRI at Different speeds using Note 4

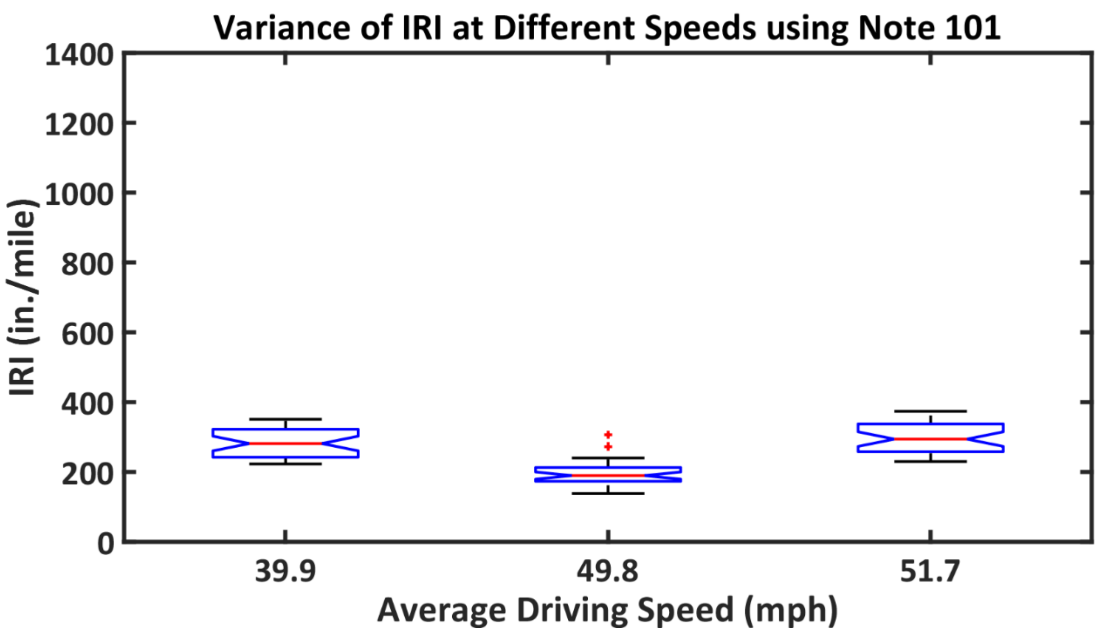


Figure 73. Variance of IRI at Different speeds using Note 101

Effect of Terrains

In order for pavement roughness measurement using mobile devices to be implement into agency specifications, it is important to first establish how the measured values are affected by different vehicle-, device-, and site-specific conditions. Therefore, it was of interest to evaluate whether the measured roughness values were affected by pavement grade or not. As already mentioned, road roughness measurement using the RoadBump Pro app utilizes data from the accelerometers built into the mobile devices to calculate the IRI values. Accordingly, factors such as longitudinal grade in the pavement that can affect the response of the accelerometer may impact the calculated IRI values. The research team attempted to identify roadway sections with noticeable longitudinal grades for testing under the scope of this study. However, due to limitations associated with availability of inertial profiler data for comparison, only roadway sections from districts 3, 4, 5, and 6 were considered for this task. All pavement sections tested in this study were visually flat and did not have any noticeable longitudinal grade. Upon comparing the vertical elevations of the start and end points of the different roadway sections tested, it was observed that a ‘small’ difference in the elevations were present in some of the roadway sections tested. Two roadway sections in D5 (US-30 between Montpelier city limits; and I-15 from Arimo to McCammon) were selected for comparison. The elevation data of the start and the end point of the selected pavement sections were acquired and compared. The initial and final elevations of the first pavement section were 5985.1 ft and 5983.68 ft, respectively. The length of this pavement section was 1.3 miles yielding a pavement slope of 0.002 percent. In contrast, the initial and final elevations of the second pavement section (I-15 from Arimo to McCammon) were 4728.11 ft and 4680.96 ft, respectively. The length of the pavement section was 7.2 miles yielding a pavement slope of 0.12 percent. It is important to note that the longitudinal grade for the pavement section (I-15 between Arimo to McCammon) with a definite elevation difference between the end points was still negligible for all practical purposes. Nevertheless, data for this pavement section was analyzed to assess whether or not any significant effect on the mobile device-measured roughness values were noticeable. For comparison the other pavement section is also chosen from D5. Two sets of MF (one with grade and another without grade) were determined for the same vehicle-device combinations. **Figure 74** shows the elevation differences between the end points for the two roadway segments, as well as the lengths for both segments.

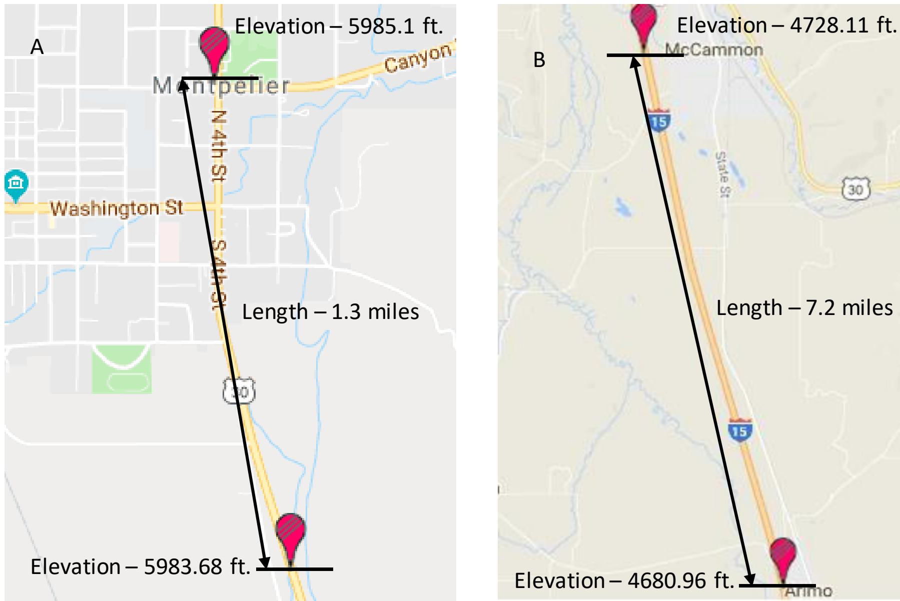


Figure 74. Elevation Difference and Length of Two Different Sections (A) Arimo to McCammon; and (B) Montpelier city limits in D5

From the length and elevation data, the longitudinal grades for the two roadway segments can be calculated as follows:

US-30 between Montpelier City Limits: $\frac{5985.1-5983.68}{1.3} = 1.09\ ft/mile\ (2 \times 10^{-2}\%)$,

I-15 between Arimo to McCamon: $\frac{4728.11-4680.96}{7.2} = 6.54\ ft/mile\ (0.12\%)$.

As seen from these numbers, both roadway segments can be considered to be flat for all practical purposes. Nevertheless, the I-15 segment has a more defined grade compared to the US-30 section. The same vehicle (GMC Canyon SLE) was driven along both roadway segments at 50 mph. The average reference IRI values for these two sections using the inertial profiler were 54 and 37 in./mile, respectively. MF values for the mobile devices placed in GMC Canyon SL on these two pavement sections were calculated, and have been listed in **Table 16**.

Table 16. Modification Factors for GMC Canyon SLE driven along Two Different Sections in D5 with Different Grade

Mobile device	Section 1 (level)	Section 2 (Definite Grade)	Percent Difference (%)
Tab-1	0.56	0.62	9.6
Tab-2	0.20	0.18	-11.1
Note 3	0.36	0.36	0
Note 4	0.33	0.47	29.8
Note 101	0.57	0.65	12.3

From the values listed in **Table 16**, no particular trend can be observed. Although the MF values for section 2 (roadway segment with a definite longitudinal grade) are generally higher than those for section 1, it is not clear whether this was due to the effect of the terrain, or because of inherent differences in surface roughness for the two roadway segments. Note that none of the pavement sections tested during this study had a significant definite grade. Therefore, this research effort could not definitively conclude whether the mobile device-measured roughness values are affected by pavement longitudinal grade or not. Further testing along roadways with significant grades, as well as along roadway segments with similar surface roughness characteristics, but different longitudinal grades, need to be carried out to accurately answer this research question.

Performance Analysis for Vehicles and Devices

As already mentioned, the current study utilized several vehicle types and mobile devices for measuring roadway surface roughness using the RoadBump Pro app. The collected data should be analyzed to identify whether or not a particular mobile device or vehicle type produced consistently better IRI values (close to those established by the reference measurement units) compared to others. Although several different approaches can be adopted to answer this question, the current research team utilized multiple regression analysis for this purpose. Multiple regression analysis is a statistical tool that predicts the relationship between one series of dataset to one or more series of datasets. It is used to predict the value of a variable depending on the value of two or more variables. The variable to be predicted is named the 'criterion variable' or the 'dependent variable'. The variables used to predict the value of the dependent variable are named 'predictor variables'. The objective of this analysis is to determine the reference IRI data (collected by inertial/lightweight profiler) based on the data collected by the mobile devices. In this case, the roughness data collected by mobile devices constitute the predictor variables. The roughness data generated by the inertial profiler is considered as the criterion (or dependent) variable. Note that in cases where mobile-based roughness measurements are carried out using multiple vehicles, a similar regression analysis approach can be used to predict the reference (established by inertial profilers or lightweight profilers) IRI values from average IRI values measured using individual vehicles.

After completing this analysis, a regression equation is generated. This equation has equal number of predictor variables as the number of vehicles used to produce the IRI generated by the standard roughness collection vehicles. The formula shown in **Figure 75** is developed after conducting this regression analysis.

$$IRI_{IP} = I + n_1 \times IRI_{V1} + n_2 \times IRI_{V2} + \ \dots$$

Figure 75. Typical Regression Equation

The equation shown in **Figure 75** is a typical regression equation showing the relationship among IRI from inertial profiler (IRI_{IP}), vehicle 1 (IRI_{V1}) and vehicle 2 (IRI_{V2}). In this equation, I is called the intercept. Physically it can be conceptualized as a base value. If there is no contribution from other variables, then it will represent a horizontal straight line. In contrast, n_1 and n_2 are coefficients describing the contributions of respective predictor variables on predicting the IRI calculated using the inertial profiler. Please note that these coefficients are not 'constrained', and can have both positive and negative values. A positive value for a regression coefficient indicates a positive correlation between the dependent variable and that particular predictor variable. Similarly, a negative coefficient value indicates a negative correlation between the predictor and dependent variables. Additionally, a higher magnitude for a coefficient indicates that particular predictor variable has a greater contribution towards the calculated value for dependent variable. The procedure for calculating the coefficients and the intercepts for a regression equation are described in **Appendix E**.

Multiple regression analyses were carried out the mobile-based roughness measurement data to assess whether the mobile-measured data can be used to predict the results obtained through inertial profiler (or lightweight profiler) measurements. This procedure is illustrated in the following paragraphs by selecting a randomly picked representative roughness dataset collected in D3 using Jeep-Cherokee and the GMC Canyon. The same regressive magnitude of the coefficients will reveal which vehicle has better accuracy in predicting the reference IRI. For illustrative purpose, a segment of roughness dataset collected by Tab-2 placed in Jeep Cherokee and GMC Canyon are is presented in **Table 17**; the data was collected along SH-67 in D3. Note that the table also lists IRI values measured using the inertial profiler. The complete dataset is provided in appendix B **Table 20**.

Table 17. Pavement Roughness Measured by Inertial Profiler and Tab-2 placed in Jeep Cherokee, and GMC Canyon along SH-67

Segment No.	From Mile	To Mile	Inertial profiler (in/mile)	Jeep Cherokee (in/mile)	GMC Canyon (in/mile)
1	0	0.1	143	45	117
2	0.1	0.2	43	50	122
3	0.2	0.3	49	69	110
4	0.3	0.4	42	101	107
5	0.4	0.5	40	77	99
6	0.5	0.6	48	44	100
7	0.6	0.7	42	62	117
8	0.7	0.8	51	89	123
9	0.8	0.9	47	69	115
10	0.9	1.0	49	49	111
	…	…	…	…	…

After completing the regression analysis, a regression equation given in **Figure 76** is produced. From the equation, it can be seen that the coefficients for Jeep Cherokee and GMC Canyon are -0.13 and 0.13 respectively. Please note that the coefficients have opposite sign. This means that the predictor variables, in this case Jeep Cherokee and GMC Canyon, are both inversely correlated. Moreover, note that this regression equation produced a Coefficient of Determination (R^2) value of 0.03. This indicates that only 3 percent of the variance in the dependent variable can be predicted using the independent (or predictor) variables. The fact that the coefficients for the two vehicles have opposite signs, indicates that data collected from the inertial profiler has a direct linear correlation (although with a very small correlation coefficient) with that collected using the GMC Canyon, but has an inverse linear correlation with data from the Jeep Cherokee. In other words, as the vehicle type changes, the correlation between the mobile-measured and reference data changes as well. This poses a significant problem as far as accurately predicting the inertial profiler data from the mobile device data is concerned. Finally, the intercept is calculated to be 46.88. It denotes that the difference between mean reference IRI and the weighted means of the IRI from the devices is 46.88 in./mile.

$$IRI_{IP} = 46.88 - 0.13 \times IRI_{Jeep} + 0.13 \times IRI_{Truck}$$

Figure 76. Regression Equation of Dataset Listed in Table 17

Just like the measurements from two different vehicles (using the same mobile device) were compared above, a similar exercise can compare the data collected using different devices mounted in the same vehicle. This has been illustrated by randomly picking a particular dataset: data from a section of I-84 extending from Valley Road to MP 191 in D4; data collected using the Chevrolet-Traverse was used for this purpose. It is important to note that some of these analysis approaches have been discussed in this report for randomly picked datasets for the sake of brevity. The research team conducted similar analysis for several other datasets, but the results have not been included in this report as their inclusion would not contribute towards the primary conclusions drawn in this report.

Table 18 lists the data collected using different mobile devices mounted in the Chevrolet Traverse along with reference data collected using the lightweight profiler. Please note that for demonstration purposes, roughness data for only a one-mile section of the roadway is presented in this table. The complete dataset can be found in Appendix B **Table 21**. IRI data calculated by the mobile devices constitute the predictor variables, whereas that from the lightweight profiler constitute the dependent variable.

Table 18. Pavement Roughness Calculated by Lightweight Profiler and Five Mobile Devices Mounted in a Chevrolet Traverse

From (mile)	To (mile)	Lightweight profiler (in/mile)	Tab-1 (in/mile)	Tab-2 (in/mile)	Note 3 (in/mile)	Note 4 (in/mile)	Note 101 (in/mile)
0	0.1	44	95	64	45	71	44
0.1	0.2	36	77	44	40	58	33
0.2	0.3	33	75	46	46	61	45
0.3	0.4	32	74	39	38	60	45
0.4	0.5	32	69	45	41	53	33
0.5	0.6	25	79	50	38	56	45
0.6	0.7	30	73	39	32	50	25
0.7	0.8	38	59	34	35	57	27
0.8	0.9	26	107	57	56	82	29
0.9	1.0	32	93	45	38	56	23

After completing the regression analysis, a regression equation given in **Figure 77** was produced. The regression coefficients for Tab-1, Tab-2, Note 3, Note 4, and Note 101 were calculated to be -0.25, 0.46, -0.24, 0.39, and 0.32, respectively. Similar to the observation for different vehicles, it can be seen that the regression coefficients for some of the mobile devices have a positive sign, whereas for the others the coefficients have a negative sign. This indicates, even when the mobile devices are mounted inside the same vehicle, no consistent trend is observed between the mobile-based data, and the data from reference measurement units. Once again, this observation raises a question regarding the justifiability of mobile-based roughness measurements being implemented into agency QC/QA specifications.

$$IRI_{LwP} = 8.65 - 0.25 \times IRI_{Tab-1} + 0.46 \times IRI_{Tab-2} - 0.24 \times IRI_{Note\ 3} + 0.39 \times IRI_{Note\ 4} + 0.32 \times IRI_{Note\ 101}$$

Figure 77. Regression Equation of dataset Listed in Table 18

After completion of the above regression analyses, it can be concluded that no consistent relationships can be expected between mobile-measured pavement roughness data and those from reference measurement units such as high-speed inertial profilers or lightweight profilers. IRI values collected using mobile devices change significantly due to changes in vehicles and/or device types. The following section evaluates the effect of pavement roughness (in terms of average IRI of the tested segments) on the Modification Factors (MFs) established for different vehicle-device combinations. The overall objective is to assess whether or not the MF values established for a particular vehicle-device combination remain unchanged from one pavement type to another (in terms of varying level of surface roughness).

Effect of Pavement Roughness on Modification Factor (MF)

The research team conducted extensive statistical analyses to determine whether or not the MF is a constant for a specific vehicle-device combination for a range of pavement roughness values. It was found that same vehicle-device combination produces different MF after driving the vehicle along different pavement sections which is shown in **Figure 56** and **Figure 57**. After observing this variance, the research team hypothesized that the MF may depend on the pavement roughness. In this section the sensitivity of modification factors to pavement roughness is discussed.

For this analysis, IRI data collected in D5 using GMC Canyon SLE was selected. Note that data from D5 was selected because in D5 several different pavement sections were tested using only one vehicle, producing several data points with same vehicle-device combination. **Figure 78** through **Figure 82** show the variation of MF as a function of mean IRI values for the roadway segments calculated using the inertial profiler data. Note that the six data points in the following figures correspond to mean IRI values (as established using the inertial profiler) for six of the roadway segments (different directions are counted as different segments) tested in D5.

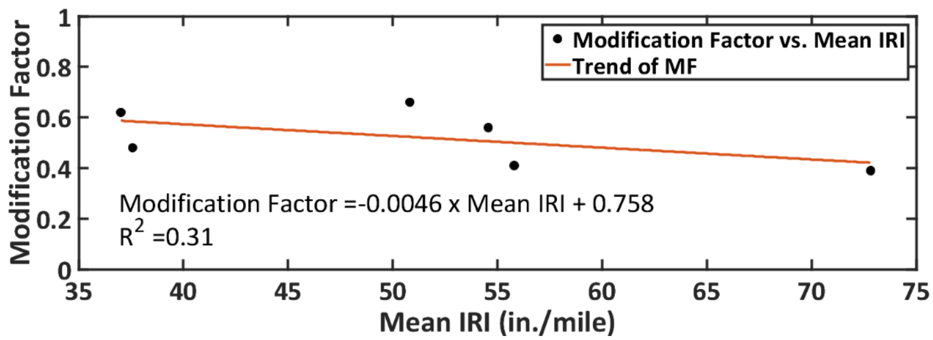


Figure 78. Variation of Modification Factor for Tab-1

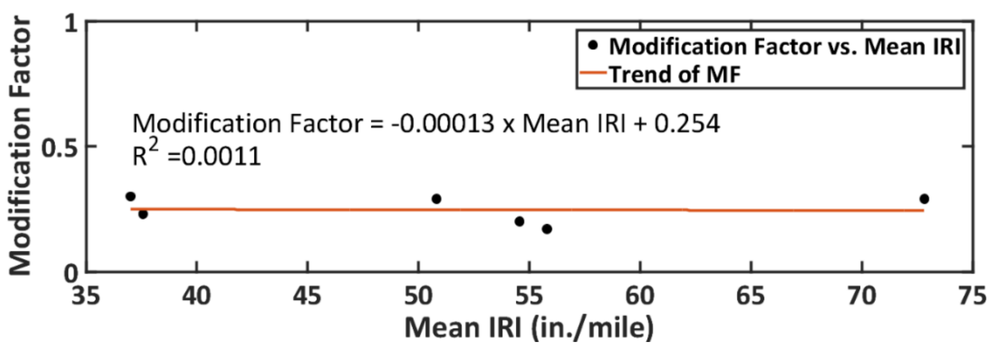


Figure 79. Variation of Modification Factor for Tab-2

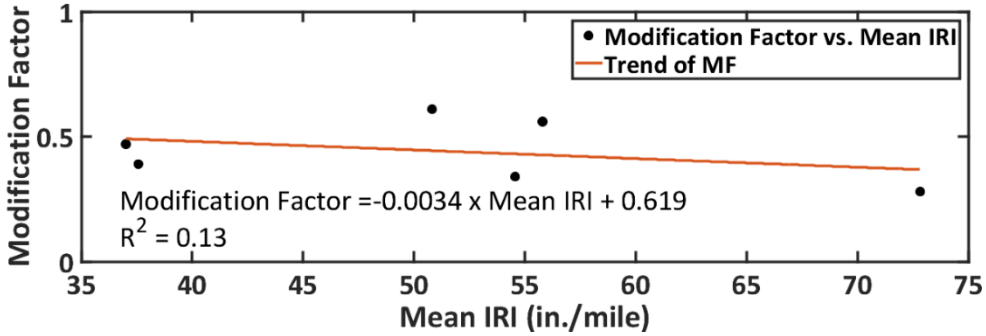


Figure 80. Variation of Modification Factor for Note 3

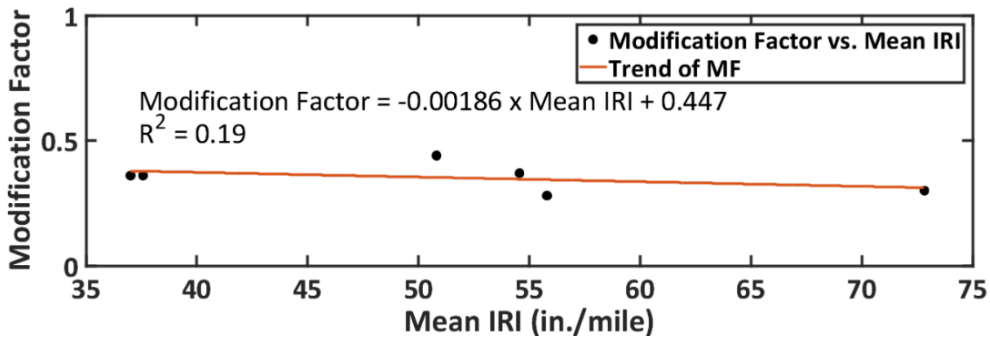


Figure 81. Variation of Modification Factor for Note 4

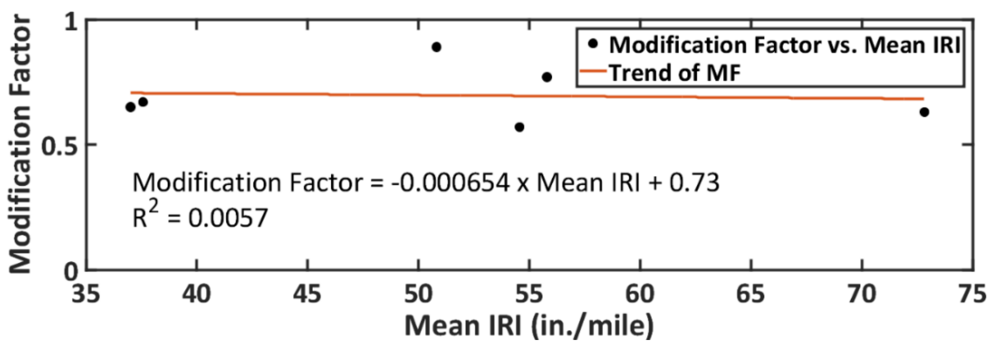


Figure 82. Variation of Modification Factor for Note 101

From these figures it can be seen that the modification factor values for the different mobile devices do not remain constant as the mean IRI of the roadway segment changes. Straight line trendlines were drawn with correlation as high as 0.31 and as low as 0.0057. It means that there is no correlation between calculated MF and pavement roughness. A MF matrix showing the factors for all the vehicle-device combinations tested during the road tests is provided in **Table 19**.

Table 19. MF Matrix Summary

District	Vehicle	Tab-1	Tab-2	Note 3	Note 4	Note 101
D3	Jeep Cherokee	0.88	0.55	1.03	1.09	2.38
	GMC Canyon	0.35	0.4	Not used	0.4	0.58
D4	Chevrolet-Silverado	0.32	0.48	0.37	0.29	0.71
	Chevrolet-Colorado[1]	0.96	0.83	1.08	0.98	2.13
	Chevrolet-Traverse	0.75	0.52	1.15	0.86	0.91
	GMC-Canyon SL (1st road test)	0.11	0.09	0.29	0.13	0.32
	GMC-Canyon SL (2nd road test)[1]	0.99	Device Malfunction	0.85	0.8	1.9
D5	GMC-Canyon SLE	0.66	0.29	0.44	0.61	0.89
D6	Chevrolet traverse	0.34	0.60	0.31	0.52	1.03
	Chevrolet Silverado	0.3	0.21	0.48	0.26	0.57

As seen from the above table, the MF values for the GMC Canyon SL in D4 changes drastically from the 1st road test to the 2nd road test. Although the same vehicle was used on both days, it is worth mentioning that the tire pressure differed significantly from one day to the other. Change in the tire pressure was found to affect the mobile-measured pavement roughness values significantly.

Effect of Other Factors on Mobile-Measured Roughness Values

It is noteworthy that the accuracy of mobile device-measured pavement surface roughness is subject to several different factors besides the ones analyzed above. For example, while the modified mobile device IRI values are comparable to the reference IRI data in terms of road section averages, the scatter in the raw data may cause a slightly larger deviation. Based on the analysis results, it was found that tire

[1] These factors are based on analysis of SH-25 from I-84 to Hazelton. SH-25 was the only rough road evaluated during the road test. This road is located in D4.

pressure has a significant impact on Pavement IRI measurement using mobile devices. However, impact of other factors such as vehicle load level could not be verified. Nevertheless, it should be kept in mind that the mobile devices are entirely dependent on the vehicle suspension system. As a result, change in vehicle load level will modify the unsprung mass, which is directly related to the quarter car model. Please recall that IRI is calculated by simulating quarter car model on pavement profile. Hence, it is understandable that vehicle weight will also have an impact on the IRI calculation using mobile device. Finally, if the mobile device mounting system is prone to vibration, the amplified vibration recorded by mobile devices is considered as pavement roughness. In other words, vibration-prone mounting systems can act as additional sources of error.

Summary of Findings

In this chapter, a description of data collection efforts was provided along with the description of the vehicles and pavement sections used to collect the pavement roughness data. It was found that the MF calculated for a given vehicle-device combination may not always remain the same while tests are being carried out along different roadway segments. It means that the roughness data collection using mobile devices is not repeatable. Analysis was presented to show the effect of terrain on pavement roughness calculation. For the sake of this analysis, two pavement sections with different slopes were chosen. Due to limited available data, the research team was unable to confirm if different terrains have any effect on the pavement roughness data collection using the mobile devices.

Multiple regression analysis was used to compare the ‘performances’ of different mobile devices and vehicles during pavement roughness measurement using mobile applications. A 2015 Jeep Cherokee and a 2012 GMC Canyon, tested in D3 were analyzed. Similar analysis was performed on five mobile devices and the coefficients for Tab-1, TAB-2, Note 3, Note 4, and Note 101 was -0.25, 0.46, -0.24, 0.39, and 0.32, respectively. From these analyses, it was concluded that the trend in pavement roughness data collected using mobile devices may vary from one device to another, as well as one vehicle to another. From statistical analysis of MF values for different mobile devices, no definitive correlation between mean pavement roughness and MF values was observed. Finally, a matrix showing the MF for all the vehicle-device combination tested during the road test was presented

Chapter 6
Summary and Conclusions

It is well known that pavement roughness is an essential factor that dramatically affects driving experience and life-cycle costs of pavements. Pavement roughness data collection is generally performed by transportation agencies. It is noteworthy that current pavement roughness measurement efforts need specialized vehicles, for instance, the inertial profiler van that is equipped with high-end sensors and electronic devices. This advanced measurement equipment is usually very expensive and requires a frequent checkup for calibration and maintenance. Additionally, these vehicles need to be driven by well-trained operators. Besides, transportation agencies own a limited number of these vehicles, which limits the number of simultaneous tests that can be made using the vehicles. Nowadays, mobile devices, such as smartphones and tablets, have numerous sensors built-in for providing the users with different types of information, such as temperature, luminance, and vibration, etc. Although these sensors are embedded into the system with a view to including additional features to the mobile devices, their readings can be recorded and used in engineering applications. One of the critical sensors used in mobile devices is the accelerometer. Accelerometers can register the vibration experienced by the mobile devices while driving along a road. Researchers observed that accelerometer data tends to indicate variations in pavement profile. However, an exact correlation between the accelerometer response and pavement roughness was not possible due to the variablities introduced by the vehicle suspension system.

Note that calculating pavement roughness is a two-step process, including pavement profiler measurement and International Roughness Index (IRI) calculation. For an inertial profiler, the pavement surface profile is calculated based on the high frequency laser scanning data. Note that the inertial profilers integrate laser height sensor reading and the accelerometer data to determine the accurate pavement profile. In contrast, mobile devices measure pavement roughness using only acceleration data collected from the built-in accelerometer in mobile devices. After the profile calculation is done, this profile is fed into the quarter car model to calculate the pavement roughness.

The RoadBump Pro app records the accelerometer data from a mobile device, and calculates the pavement profile based on the accelerometer readings. Subsequently, it simulates the quarter car model on the profile to calculate IRI. As previously mentioned, pavement surface profile measurements using mobile devices solely rely on data collected from the accelerometers. Accelerometer readings can be influenced by several factors, such as vehicle suspension system, tire pressure, driving speed, etc. This makes it difficult for the mobile devices to obtain the actual profile. However, careful calibration of the devices is supposed to improve the accuracy of roughness calculation. Keeping that in mind, the current research project was undertaken through collaboration between the Idaho Transportation Department (ITD) and Boise State University to assess the feasibility of using mobile devices for pavement roughness measurement during QC/QA as well standard pavement condition assessment practices. The objective was to evaluate this roughness measurement approach under varying conditions and to develop recommendations for settings and practices for pavement surface roughness measurement using mobile devices.

A pilot testing effort was first carried out along Hill Road, which is used by ITD for verifying the calibration of the high-speed inertial profiler. During the pilot testing effort, several different vehicles were tested, along with five different mobile devices running on Android operating system, in order to compare the mobile device data with standard results from high-speed/lightweight profilers. It was found that the mobile devices-based IRI measurement is largely dependent on vehicle suspension system. As a result, sedan-type vehicles produced slightly higher IRI compared to the inertial profiler. On the other hand, some of the SUV-type vehicles produced IRI in the same range of the inertial profiler data. Moreover, it was also observed that two identical mobile devices may not always record the same pavement roughness data owing to manufacturing-related variances.

To facilitate testing using different vehicles and devices, the RoadBump Pro app offers an option for modification factor (MF). Based on this MF, the calculated IRI value gets modified and is supposed to produce results in the same range as those from reference measurement units such as high-speed and lightweight profilers. The RoadBump Pro user guide suggests three different MFs for three different vehicle types: MF = 1 for SUV; MF = 1.2 for trucks; and MF = 0.8 for Sedan-type vehicles. However, during analysis of data collected under the scope of the current project, the research team observed that separate MF value need to be calculated for different devices as well. As a result, in this project MF values were developed for different vehicle-device combinations. If a different vehicle or a different mobile device is used during testing, a different MF needs to be calculated. A matrix showing the MFs for all the tested vehicle-device combinations was presented in Chapter 5. In total, 10 vehicles and 5 mobile devices were tested during this project. Hence, the MF matrix in chapter 5 contains 50 MFs for these combinations.

Besides being dependent on the type of device and vehicle types, it was found that driving speed has an effect on IRI values calculated from mobile-based roughness measurements. However, this dependency is not uniform across one device to another, as well as from one driving speed to another. After determining a number of MF's for different vehicle-device combinations, it was observed that these factors exhibited significant variance. Roughness measurements using mobile devices did not exhibit the desired level of repeatability that would justify their adoption into agency specifications. The effect of pavement longitudinal grade on roughness measurements using mobile devices could not be studied extensively as none of the roadway segments tested in this study had significant longitudinal grades.

During the process of pavement roughness measurement using mobile devices, the primary source of data is the vibration levels measured using low-cost accelerometers built into the mobile devices. Data from these sensors is of significantly inferior accuracy compared to those collected using high-end sensors built into inertial profilers. The current research study employed the MF approach to 'scale' IRI values measured using the mobile devices. These scaled values approached the roughness values measured by reference measurement units (e.g. high-speed profiler or lightweight profiler). However, IRI values measured using mobile devices can be affected by several factors such as such as: sensitivity of the accelerometer built-into the mobile device, vehicle speed, tire pressure, and suspension of the vehicle being used, among others. The effects of factors such as vehicle speed on the measured IRI values may not be consistent across all devices. Moreover, data collected using two identical devices (e.g. Tab 1 and Tab 2 used in this study) may differ significantly from each other indicating inherent differences in the manufacturing components. Even though the proposed MF method can increase the precision and accuracy of the IRI values calculated from mobile-based measurements, it may not be repeatable across different measurement conditions. Note that this technology is still in its infancy and intensive research is required to be able to use this in road testing. The research team could not find any evidence of mobile-based pavement roughness measurements being adopted by transportation agencies.

To conclude this research project, mobile device-based pavement roughness measurement are not accurate or precise enough to adopt into agency specifications. During this study, the pavement roughness data collected using different vehicle-mobile device combinations exhibited different levels of accuracy when compared against reference measurement units. Raw IRI data accuracy of over 90 percent was achieved when a Samsung Galaxy Note 3 device was placed inside a 2015 Jeep Cherokee during the pilot testing. However, the same level of accuracy could not be achieved while Samsung Galaxy Note 3 – 2015 Jeep Cherokee was used along different roadway segments. In contrast, the roughness data collected using mobile devices placed in sedans such as 2002 Honda Civic and 2015 Nissan Altima showed a difference of more than 500 percent. These observations raise questions regarding the reliability and repeatability of the roughness measurement using mobile devices. Therefore, adopting this technology into construction Quality Control/Quality Assurance (QC/QA) protocols is not recommended at this stage. However, it should be noted that data collected from the mobile devices was found to “respond” to undulations on the roadway surface. Therefore, it may be possible for agency engineers to use these devices to identify whether a particular roadway section has a localized “bump” or not or if the roughness significantly changes from one section to another. Note that the current study did not focus on evaluating this particular hypothesis. Therefore, the research team cannot make a “confident claim” regarding the success of such an approach.

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Appendix A
Correspondences Concerning Previous Applications of Mobile Devices for Road Roughness Measurement and Features of the RoadBump Pro Mobile Application

In this section, a summary of the e-mail conversations with personnel from Arkansas DOT and the developer of the RoadBump Pro app will be presented.

Correspondence with Arkansas DOT

With a view to getting information regarding roughness measurement using mobile devices, the research team attempted to communicate with personnel from Arkansas DOT. After contacting them it was found out that using mobile apps to measure pavement roughness is a brand-new practice for pavement industry, and no research project has been undertaken by the Arkansas DOT to try this modern approach to pavement smoothness measurement. A screenshot of the email communication is presented as **Figure 83**.

Wright, Elisha C. <Elisha.Wright-Kehner@ahtd.ar.gov> May 30 (1 day ago)
to Aminul, Deb, me

Aminul,

The AHTD Research Section did not complete a report for "Measurement of Pavement Roughness with Mobile Apps". Dave Grimmer developed an app, RoadBump, that is similar to this topic. His webpage is http://www.grimmersoftware.com/.

Let me know if you have any further questions.

Elisha Wright-Kehner, P.E.
Staff Research Engineer
System Information and Research
Arkansas State Highway and Transportation Department
elisha.wright-kehner@ahtd.ar.gov
Office: (501)569-2074

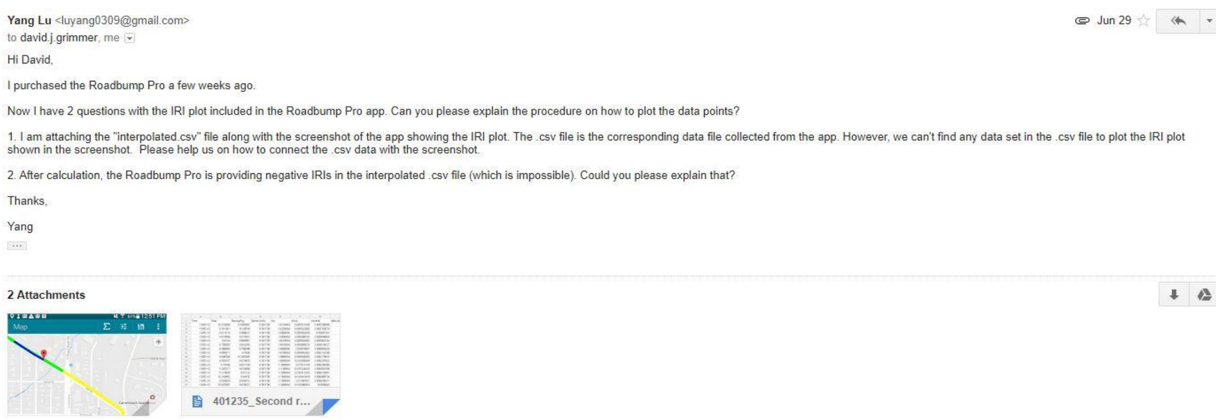
Figure 83. Screenshot of E-Mail Communication with Arkansas DOT's Staff Research Engineer

Correspondence with Developer of RoadBump Pro App

The research team also communicated with Mr. David Grimmer, developer of the RoadBump Pro app. The primary objective of this correspondence was to gather information about the settings and calibration procedures to ensure optimum performance of the app. A summary of the conversation is presented in the following paragraphs.

First, the research team tried to understand the exact approach involved in using the data collected by the app, and generating IRI plots for the pavement sections being monitored. Based on the response from Mr. Grimmer, the number of data points collected during a particular measurement is divided by 72 to decide on the window size to be used in the moving average filter; the window size is constrained to have a value between 25 and 1000. Accordingly, if dividing the number of data points by 72 yields a value less than 25, then a window size of 25 is selected for analysis. Similarly, for values greater than 1000, a window size of 1000 is selected.

Through discussions about appropriate calibration procedures, the research team learned that mounting the device on a phone holder should be avoided as it adds noise to the data. Better performance is said to be achieved when the mobile device is mounted on the vehicle's dashboard using "Non-Slip Mats". The difference between vehicle types used to collect the data is accounted for by the "Device/Vehicle Factor" in the application. Suggested values for this factor are: 0.75 for pick-up trucks, 1.0 for Sports Utility Vehicles (SUVs), and 1.2 for Sedans (suggestions provided by the app developer). Screenshots of selected email conversations are provided below in chronological order.


Yang Lu <luyang0309@gmail.com>
to david.j.grimmer, me
Jun 29

Hi David,

I purchased the Roadbump Pro a few weeks ago.

Now I have 2 questions with the IRI plot included in the Roadbump Pro app. Can you please explain the procedure on how to plot the data points?

1. I am attaching the "interpolated.csv" file along with the screenshot of the app showing the IRI plot. The .csv file is the corresponding data file collected from the app. However, we can't find any data set in the .csv file to plot the IRI plot shown in the screenshot. Please help us on how to connect the .csv data with the screenshot.

2. After calculation, the Roadbump Pro is providing negative IRIs in the interpolated .csv file (which is impossible). Could you please explain that?

Thanks,

Yang

2 Attachments

401235_Second r...

Figure 84. E-Mail from Boise State Research Team to Mr. Grimmer Regarding the Approach Used to Calculate IRI Values, and Plot the Result

David Grimmer <david.j.grimmer@gmail.com> Jul 2
to Yang, me

I took your CSV File and worked with the x(miles) and IRI (in/mile) columns. In the screen image you sent, itt's title ends "ma563 ". This means the plot displayed uses a moving average of the previous 563 readings. I added a new column to the spreadsheet to do a movin average of the last 563 values and plotted x(milesz) against the moving average - that yields the same graph as shown in the RoadBump screen image. I have attache the spreadsheet showing this.

Some negative values are OK as they are just points in time. A negative IRI makes no sense over and significant distance. The instant to instant changes are not significant - just the averages over a significant distance.

Dave

X 401235_Second r...

Figure 85. E-Mail from Mr. Grimmer to Boise State Research Team Responding to the Questions Presented in Figure 84

On Fri, Jul 14, 2017 at 10:41 AM Yang Lu <luyang0309@gmail.com> wrote:

Hi David,

Thank you very much for your answer.

It helped us figured out the data points used to plot the moving average graph. You used a window size of 563 in the excel file. Now we found that a factor of 72-75 was used to divide the number of data population to get the moving average window size. Furthermore, a condition was imposed on the window size that it cannot exceed 1000. Here are our new questions:

How to get the exact window size you are using to get the plot (not get it from looking at the data visualization window of the app). Is it possible to get the window size from a specific datasheet produced by the app?

Best regards,

Yang

Figure 86. E-Mail from Boise State Research Team to Mr. Grimmer Regarding the Procedure to Calculate the Window Size to be used in the Moving Average Filter

---------- Forwarded message ----------
From: "David Grimmer" <david.j.grimmer@gmail.com>
Date: Jul 16, 2017 7:54 AM
Subject: Re: RoadBump - determine moving average window size
To: "Yang Lu" <luyang0309@gmail.com>
Cc:

The program that displays the map looks at how many accelerometer records exist between the start and end markers. We take the numeber of accelerometer records and divide by 72 to determine how many records should make up the moving average. There is a minimum of 25 and a maximum of 1000.

Dave

Figure 87. E-Mail from Mr. Grimmer to Boise State Research Team Responding to the Questions Presented in Figure 86

Yang Lu <luyang0309@gmail.com> Aug 3 (4 days ago)
to David, me

Hi David,

I purchased the Roadbump Pro two months ago.

We need some details about calibration requirements for using the app in the field. Could you please answer the following questions:

1. We noticed that the same settings used in the app for different vehicles do not actually produce the same IRI. Could you please explain what measures you took to calibrate while you were testing the app? For example, how did you mount the mobile devices on the car? Did you start collecting IRI data immediately after starting to move the car? What is the margin of error if a driver accelerates/decelerates during data collection?

2. Is there any requirement for the vehicle to be used to test IRI?

3. It is true that 20 mph is the minimum operating speed of the app. However, what is the optimum operating speed with the app?

Thanks,

Yang

Figure 88. E-Mail from Boise State Research Team to Mr. Grimmer Regarding the Recommended Calibration Procedure

David Grimmer <david.j.grimmer@gmail.com> 9:06 PM (19 hours ago)
to Yang, me

1 - Most of my testing was with a 2011 Honda Pilot with a Galaxy S6 placed on the center shelf of the dashboard. I have tried placing it in some kind of cell phone holder so the phone could be pointed at me, but that just added more movement to the phone than what was really there.The car already has soft wheels, springs and shock absorbers. Putting the phone in a mount just adds another spring - another source of error. I have had good results in other vehicles with the non-slip pads on a dashboard. Try searching for "non slip phone pad" on Amazon.com and you will see the pads I have had good results with. Different cars will give different results because they have different suspensions and weights. Where you place the device in the vehicle makes a different also - the higher it is in the car the higher the readings will be. The Vehicle/Device Factor takes care of increasing or decreasing the values to the desired level. I generally make sure I am recording data at least a couple of seconds before I get to the point where I know I will be reporting results. I also record at least a couple of seconds past the end point. In the app you can easily zoom in and move the start and end points to exactly where you want them. Acceleration and braking should be smooth and gradual. I have not found normal speed changes to have a significant impact. A source of error that most don't consider is the ability for a human to drive the exact same path more than once. Since everything comes through the tires, you need to drive in exactly the same lane position repeatedly to get perfect results.

2 - Any 4 wheeled vehicle will work.

3 - 20 MPH is the slowest I have tested against a known IRI. I have interpolated numbers below 20 MPH and above 60 MPH.

Dave

Figure 89. E-Mail from Mr. Grimmer to Boise State Research Team Responding to the Questions Presented in Figure 88

Appendix B
Plots and Tables form Testing Efforts

In this section, all the modified IRI's will be shown for comparison against IRI data collected using inertial van. At first the raw datasets are extracted from mobile devices. Then these raw datasets are modified using appropriate MFs. IRI of the respective pavement sections were measured using inertial profiler or the lightweight profiler as standard datasets. These datasets are plotted along with the modified datasets for comparison. From the plots, it can be seen that the modified IRI datasets are comparable with the IRI from inertial profiler van.

Modified IRI Plots from D3

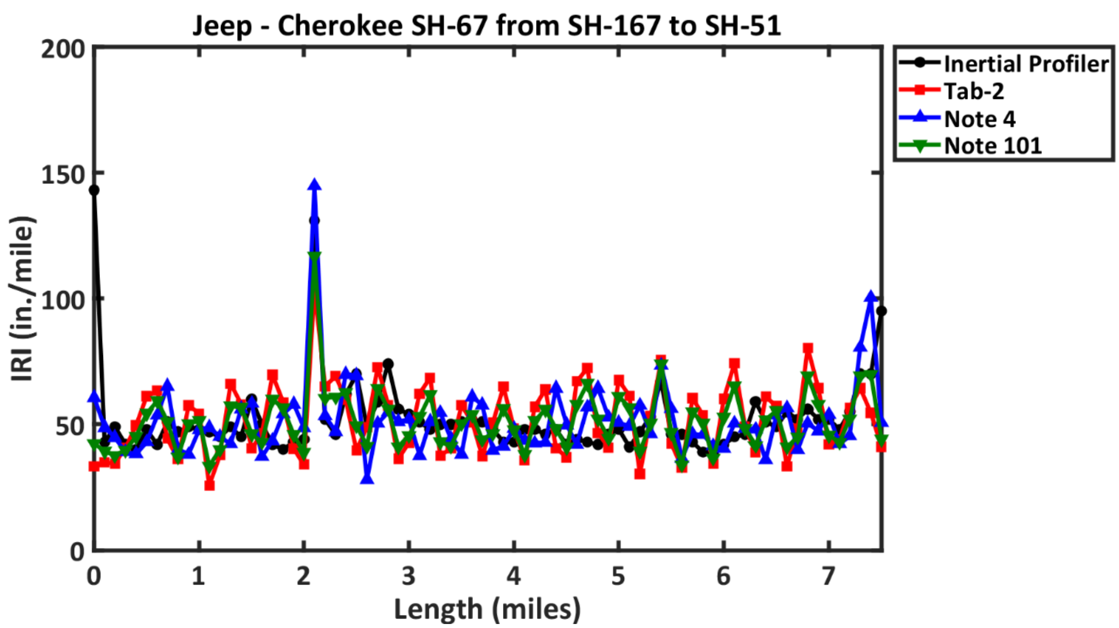


Figure 90. Modified IRI of SH-67 from SH-167 to SH-51 in D3 using Tab-2, Note 4 and Note 101 Placed in Jeep Cherokee.

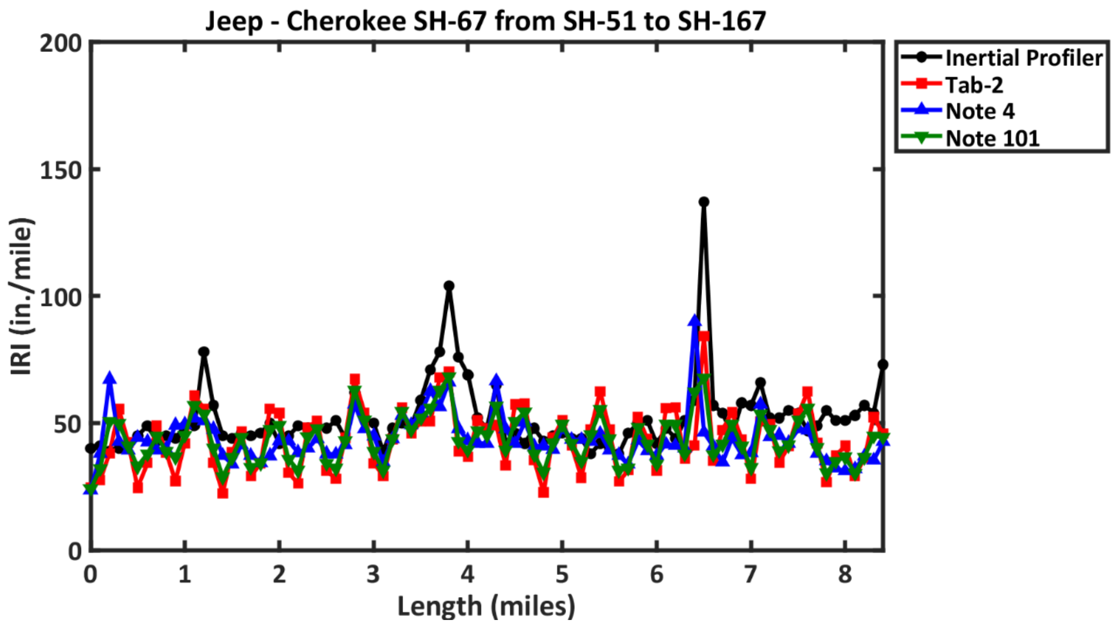


Figure 91. Modified IRI of SH-67 from SH-51 to SH-167 in D3 using Tab-2, Note 4 and Note 101 placed in Jeep Cherokee.

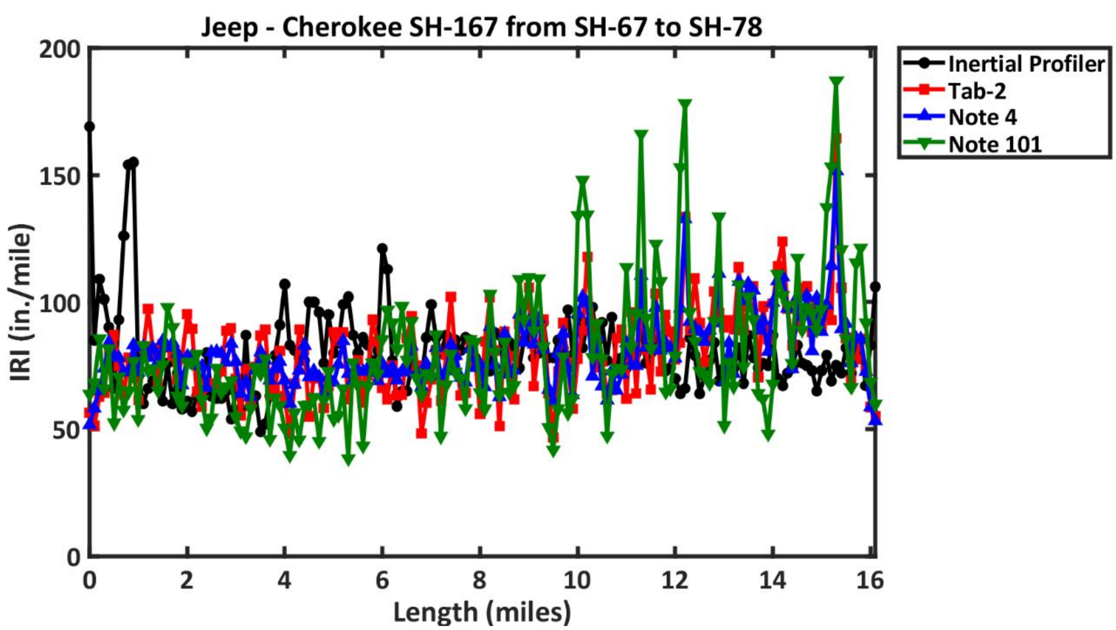


Figure 92. Modified IRI of SH-167 from SH-67 to SH-78 in D3 using Tab-2, Note 4 and Note 101 Placed in Jeep Cherokee.

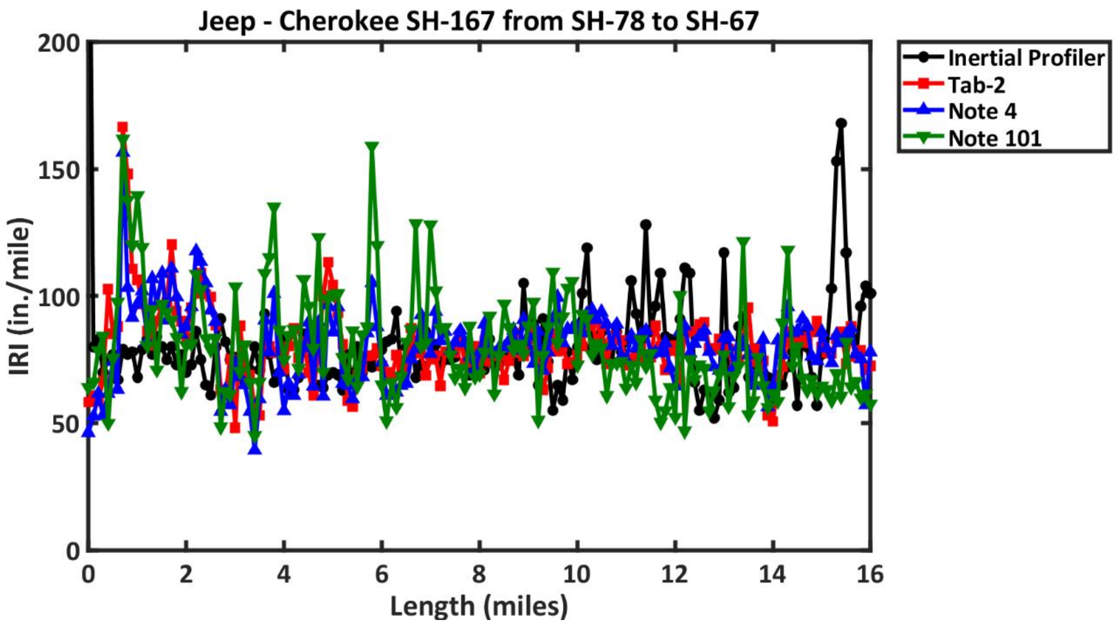


Figure 93. Modified IRI of SH-167 from SH-78 to SH-67 in D3 using Tab-2, Note 4 and Note 101 Placed in Jeep Cherokee.

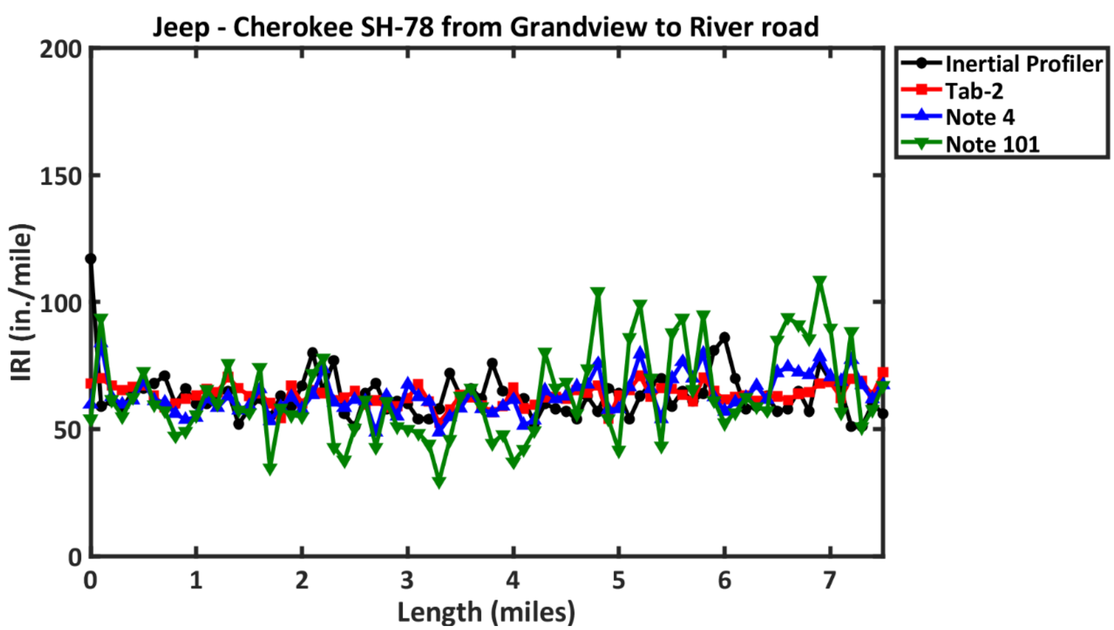


Figure 94. Modified IRI of SH-78 from Grandview to River road in D3 using Tab-2, Note 4 and Note 101 Placed in Jeep Cherokee.

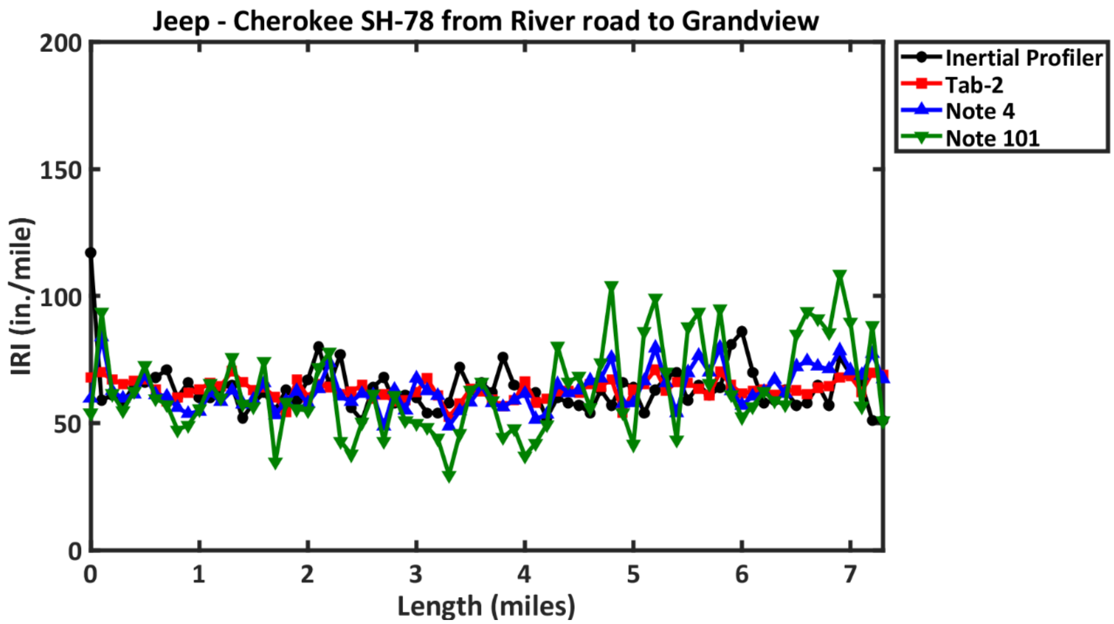


Figure 95. Modified IRI of SH-78 from River Road to Grandview in D3 using Tab-2, Note 4 and Note 101 Placed in Jeep Cherokee.

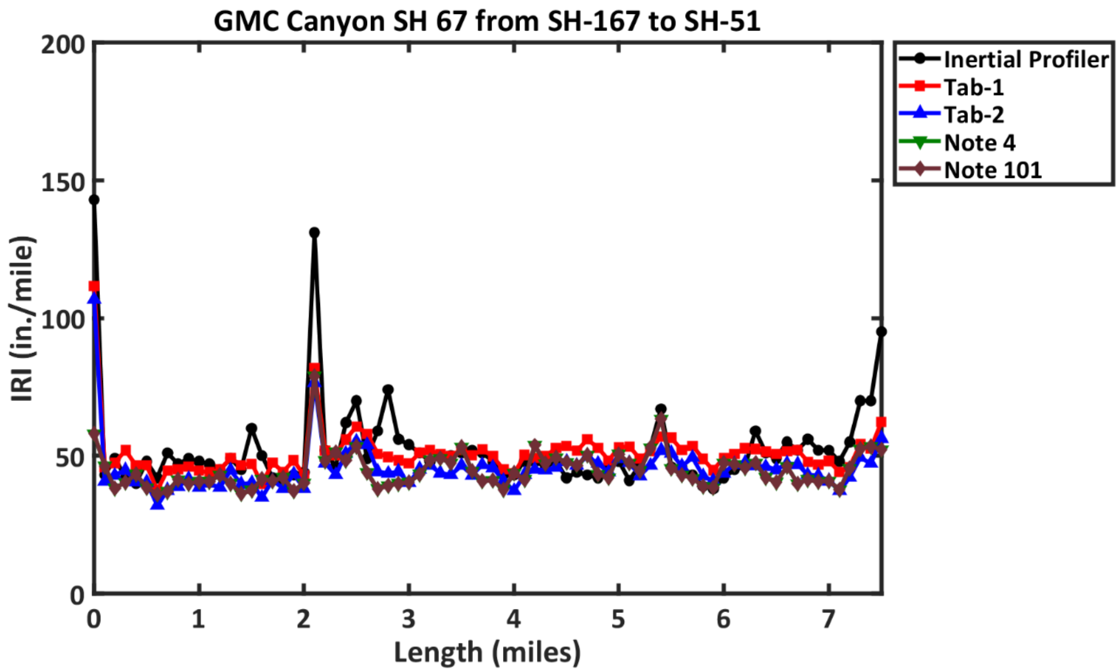


Figure 96. Modified IRI of SH-67 from SH-167 to SH-51 in D3 using Tab-1, Tab-2, Note 4 and Note 101 Placed in GMC Canyon.

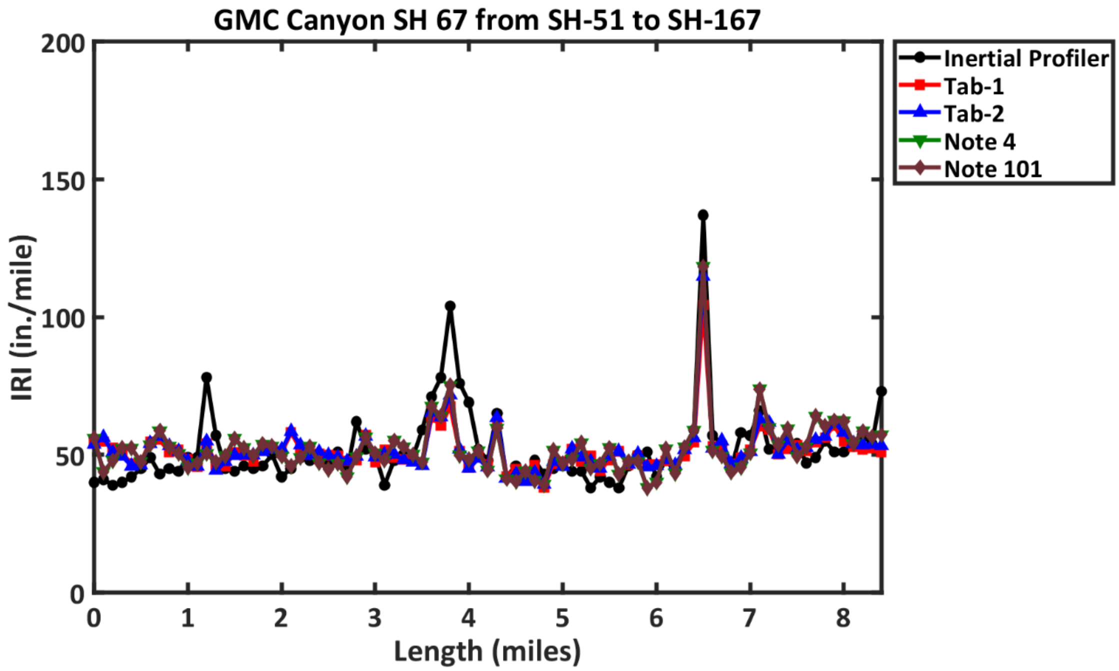


Figure 97. Modified IRI of SH-67 from SH-51 to SH-167 in D3 using Tab-1, Tab-2, Note 4 and Note 101 Placed in GMC Canyon.

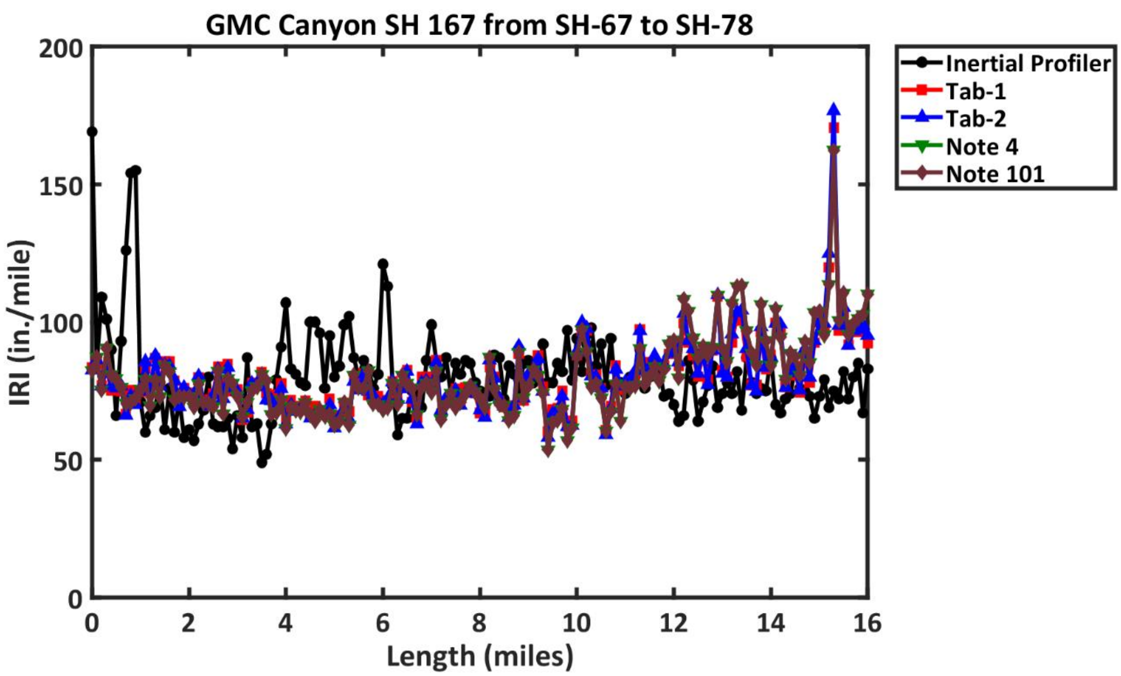


Figure 98. Modified IRI of SH-167 from SH-67 to SH-78 in D3 using Tab-1, tab-2, Note 4 and Note 101 Placed in GMC Canyon.

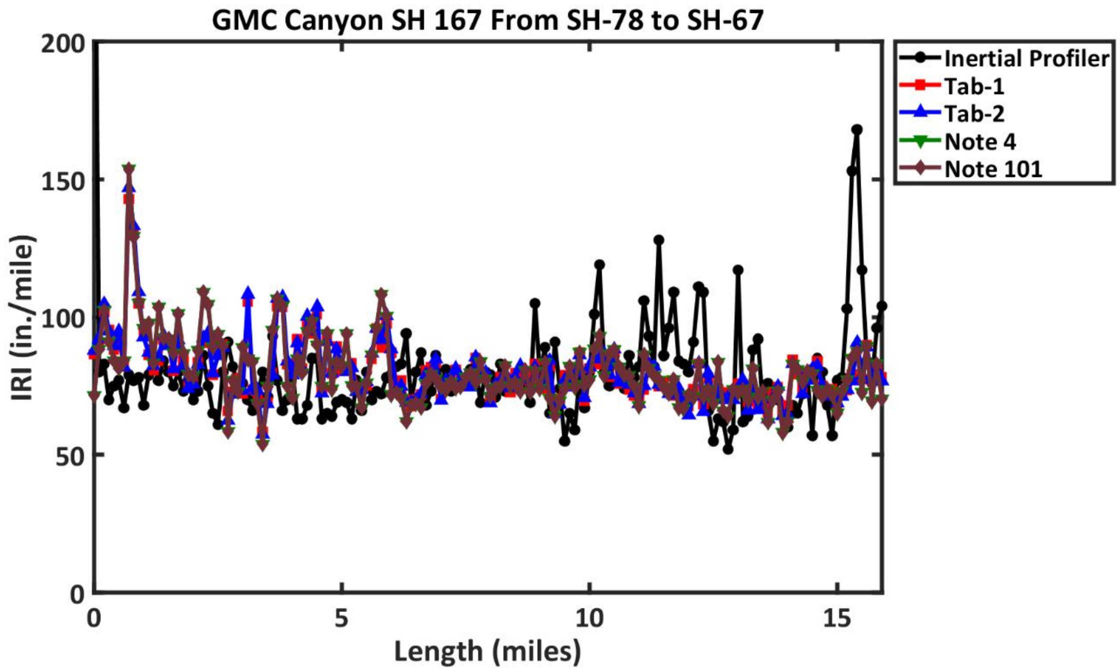


Figure 99. Modified IRI of SH-167 from SH-78 to SH-67 in D3 using Tab-1, Tab-2, Note 4 and Note 101 Placed in GMC Canyon.

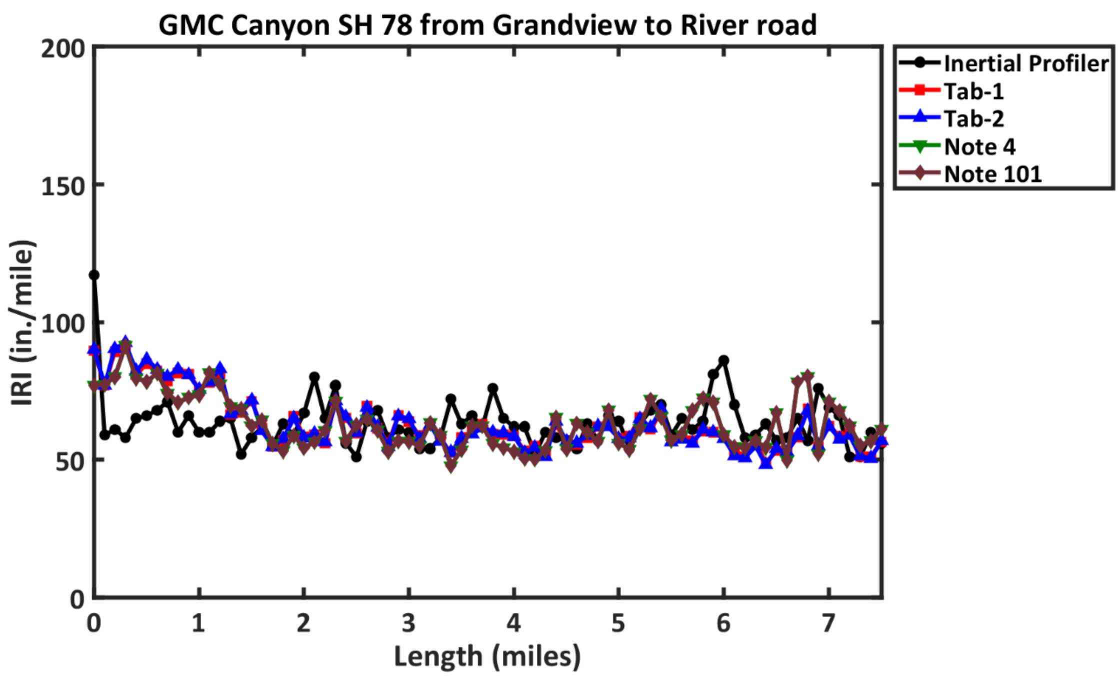


Figure 100. Modified IRI of SH-78 from Grandview to River Road in D3 using Tab-1, Tab-2, Note 4 and Note 101 Placed in GMC Canyon.

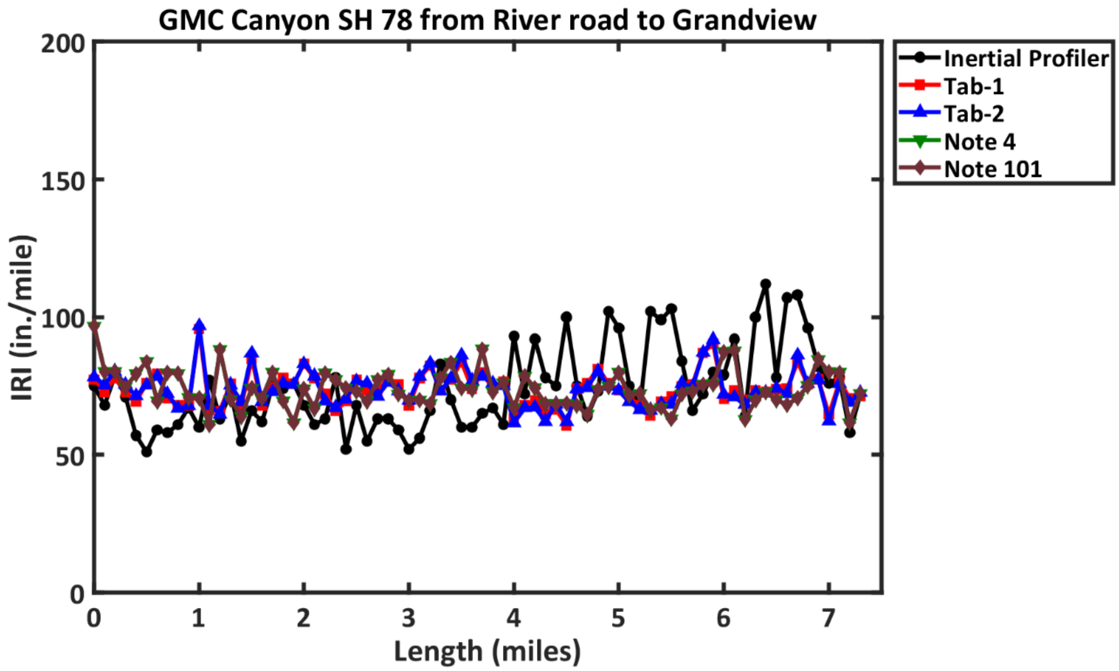


Figure 101. Modified IRI of SH-78 from River Road to Grandview in D3 using Tab-1, Tab-2, Note 4 and Note 101 Placed in GMC Canyon.

Modified IRI Plots from D4

Note that modified plots in D3 shows both sides of the roads. However, modified plots from the roads tested in D4, D5 and D6 uses only one side of the road.

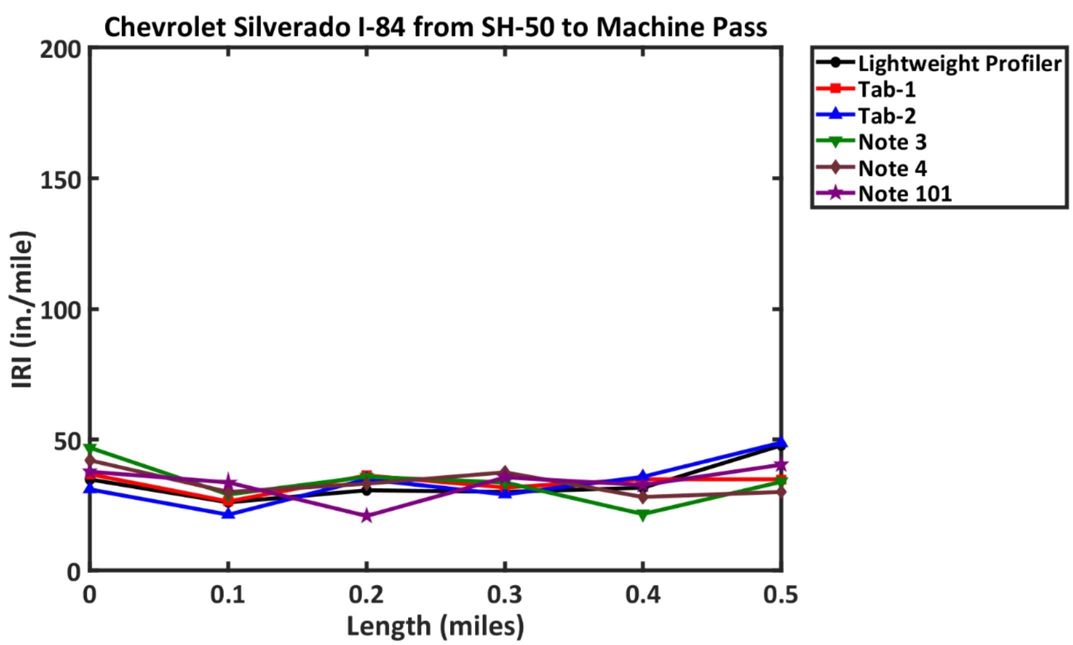


Figure 102. Modified IRI of I-84 from SH-50 to Machine Pass in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in Chevrolet Silverado.

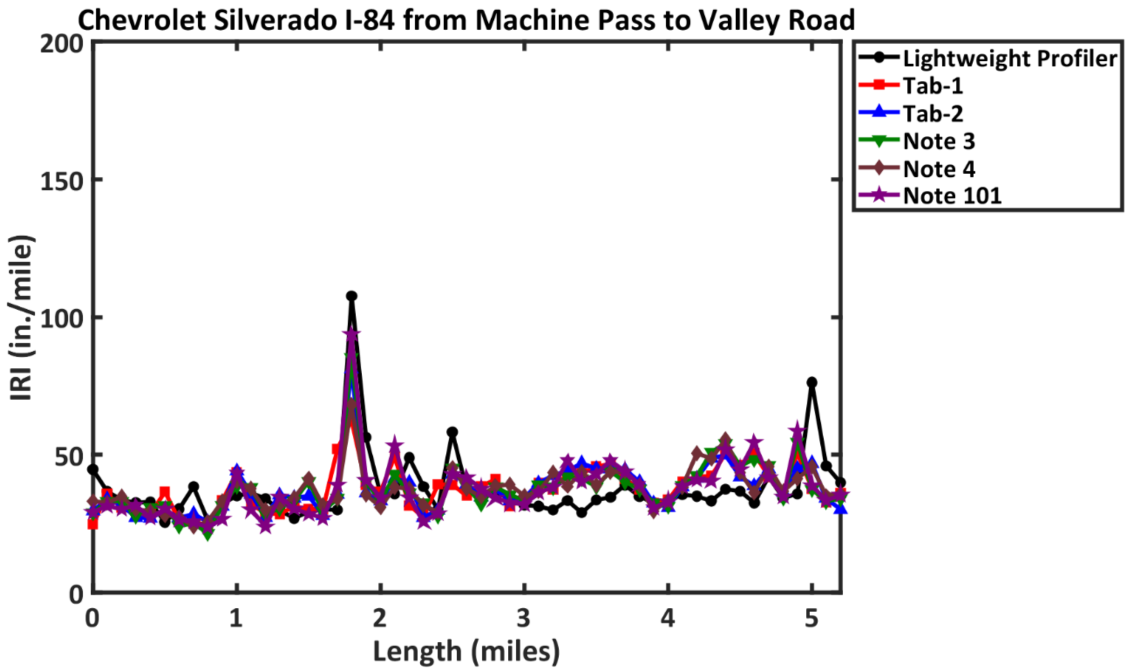


Figure 103. Modified IRI of I-84 from Machine Pass to Valley Road in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in Chevrolet Silverado.

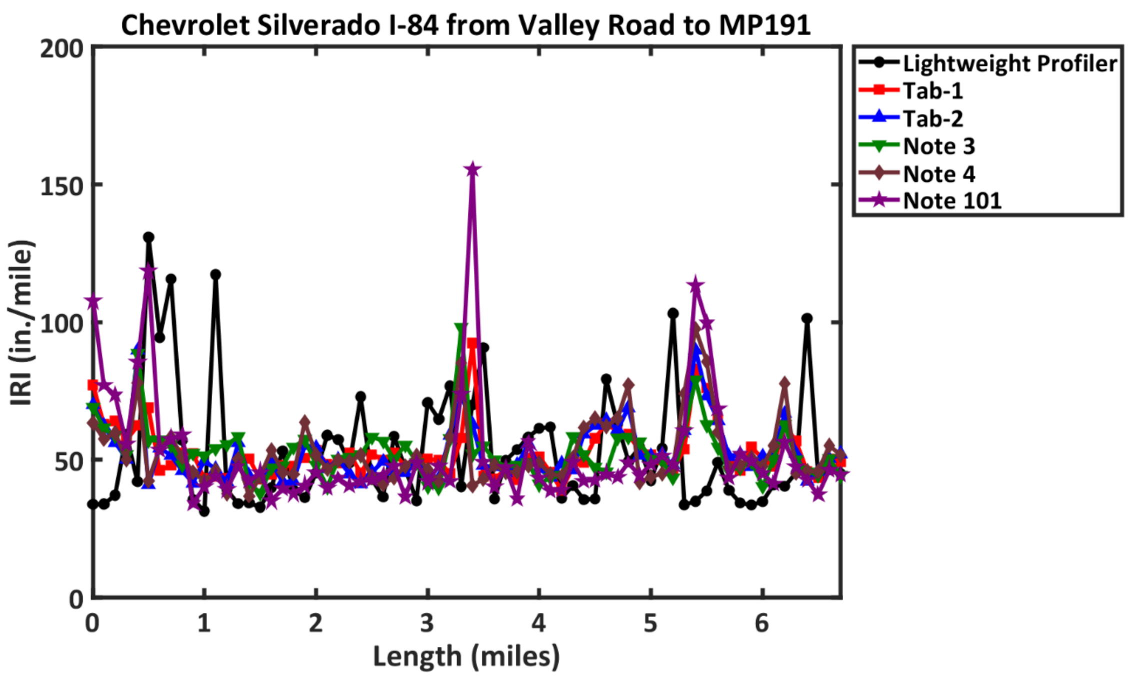


Figure 104. Modified IRI of I-84 from Valley Road to MP191 in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in Chevrolet Silverado.

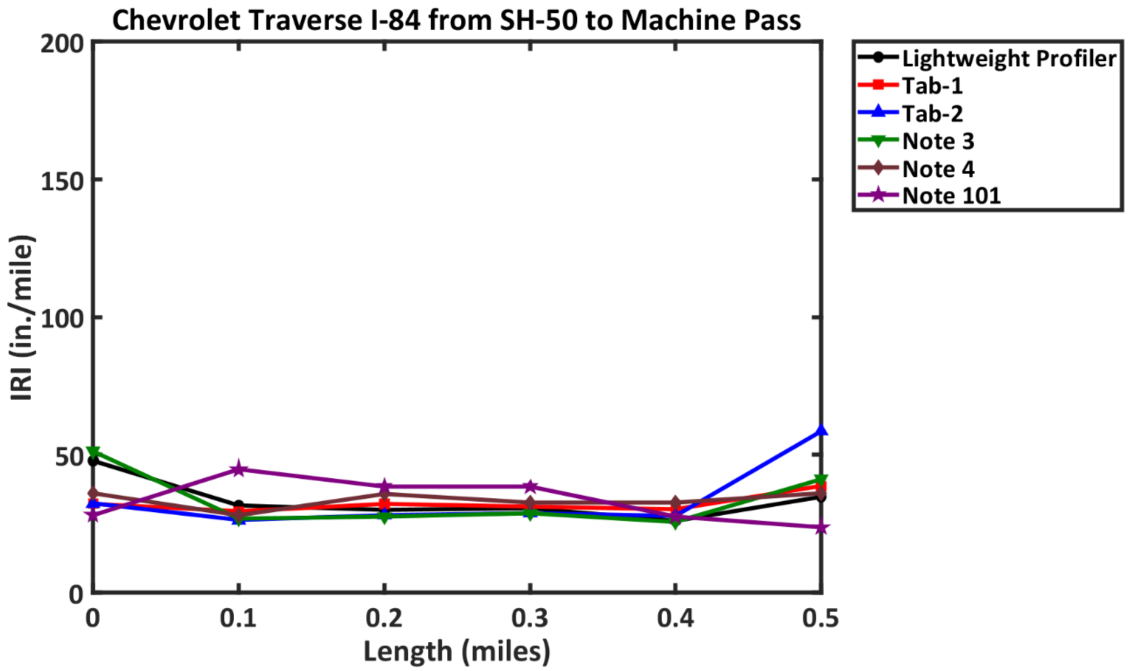


Figure 105. Modified IRI of I-84 from Sh-50 to Machine Pass in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in Chevrolet Traverse.

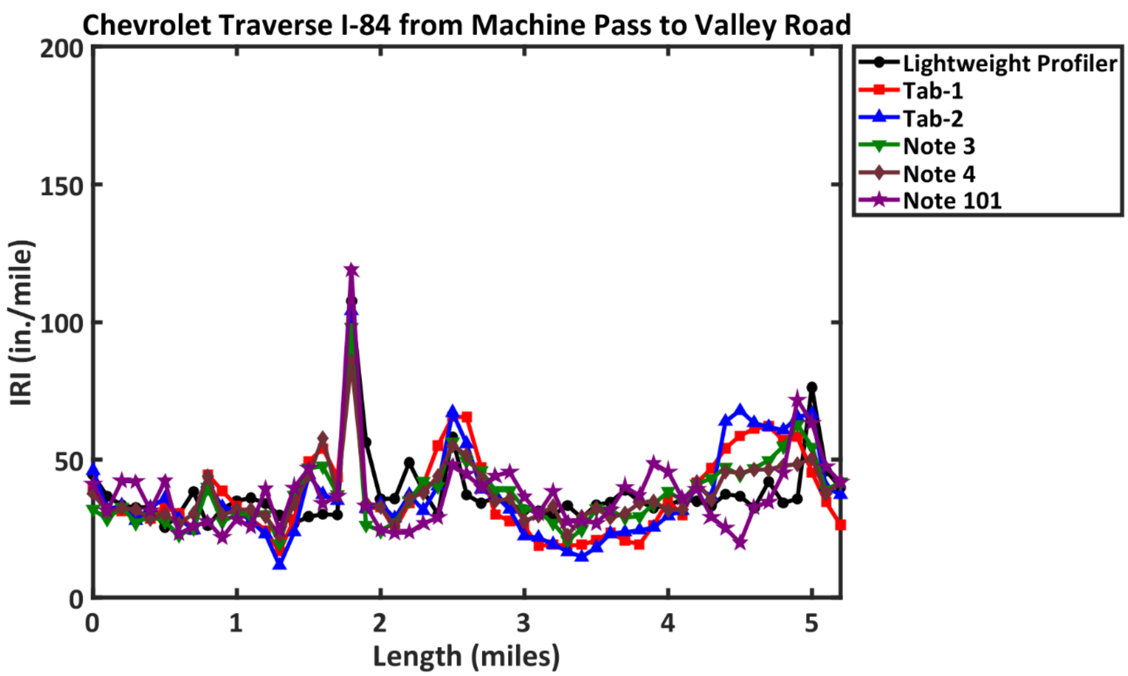


Figure 106. Modified IRI of I-84 from Machine Pass to Valley Road in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in Chevrolet Traverse.

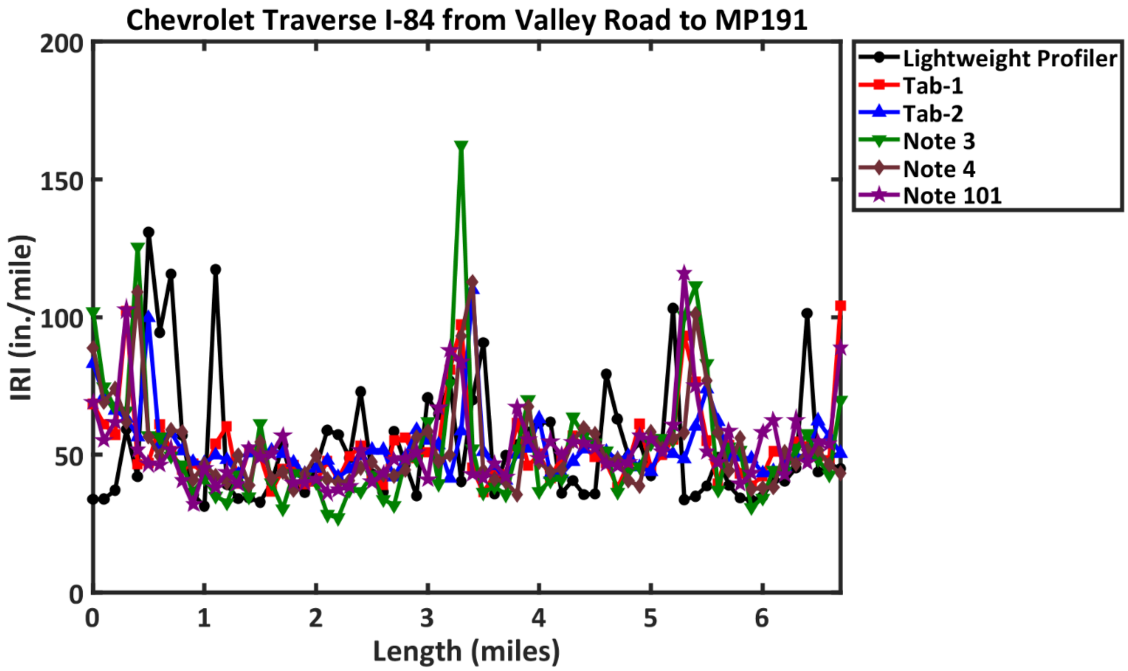


Figure 107. Modified IRI of I-84 from Valley Road to MP191 in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 placed in Chevrolet Traverse.

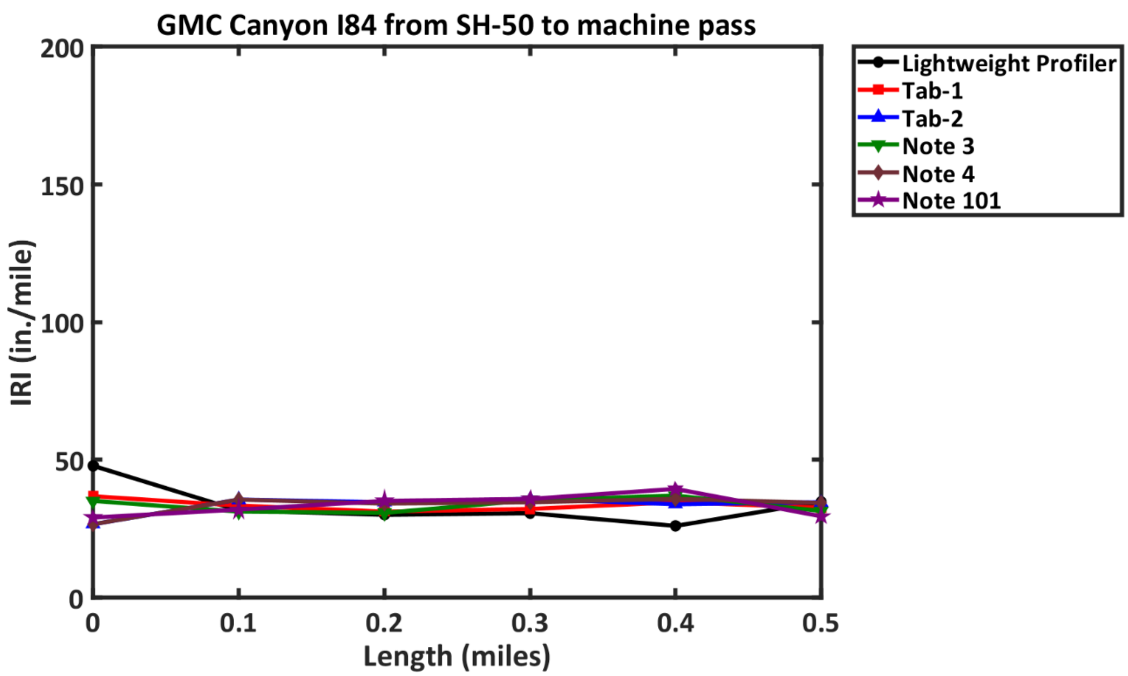


Figure 108. Modified IRI of I-84 from Sh-50 to Machine Pass in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in GMC Canyon SL.

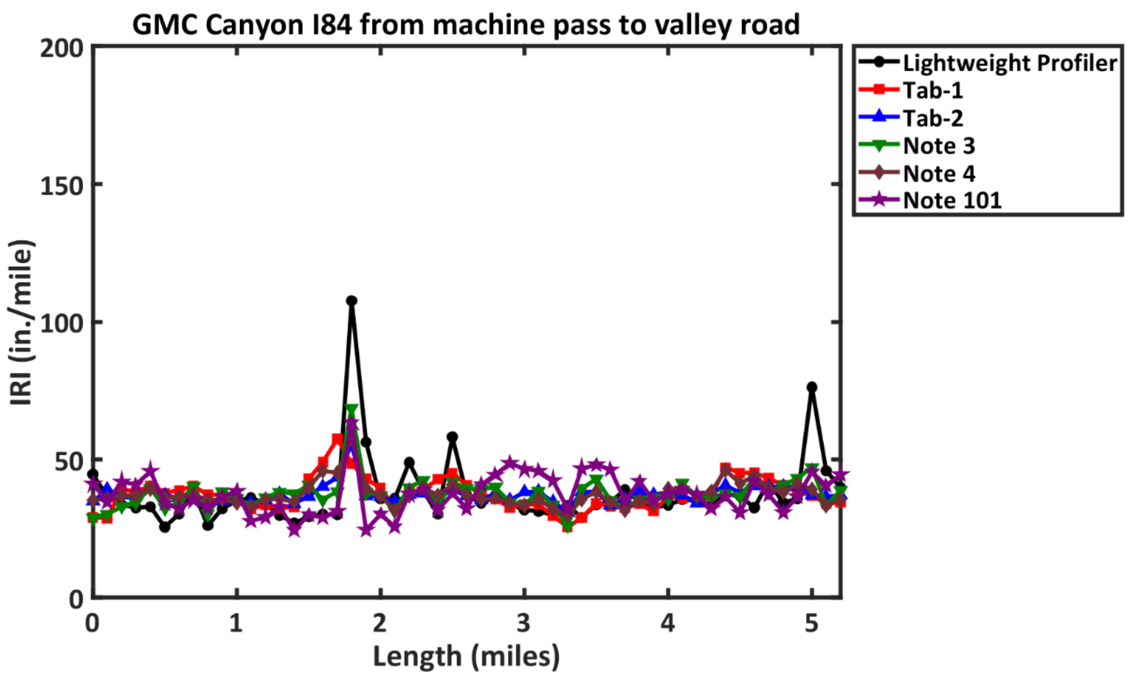


Figure 109. Modified IRI of I-84 from Machine Pass to Valley Road in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in GMC Canyon SL.

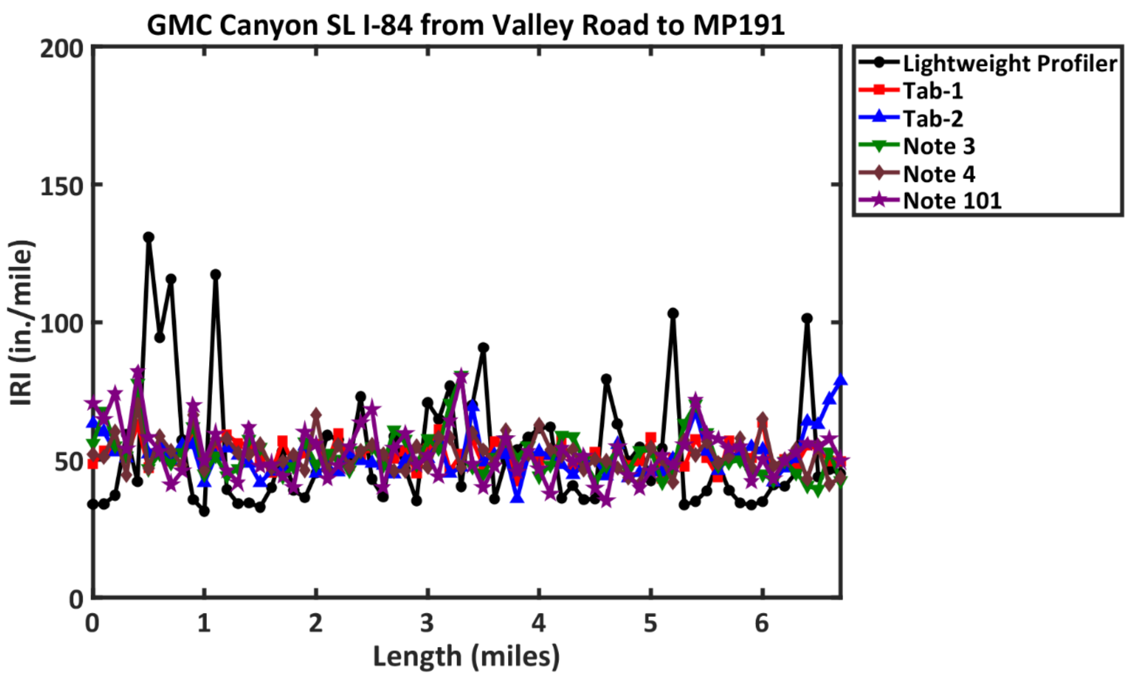


Figure 110. Modified IRI of I-84 from Valley Road to MP191 in D4 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in GMC Canyon SL.

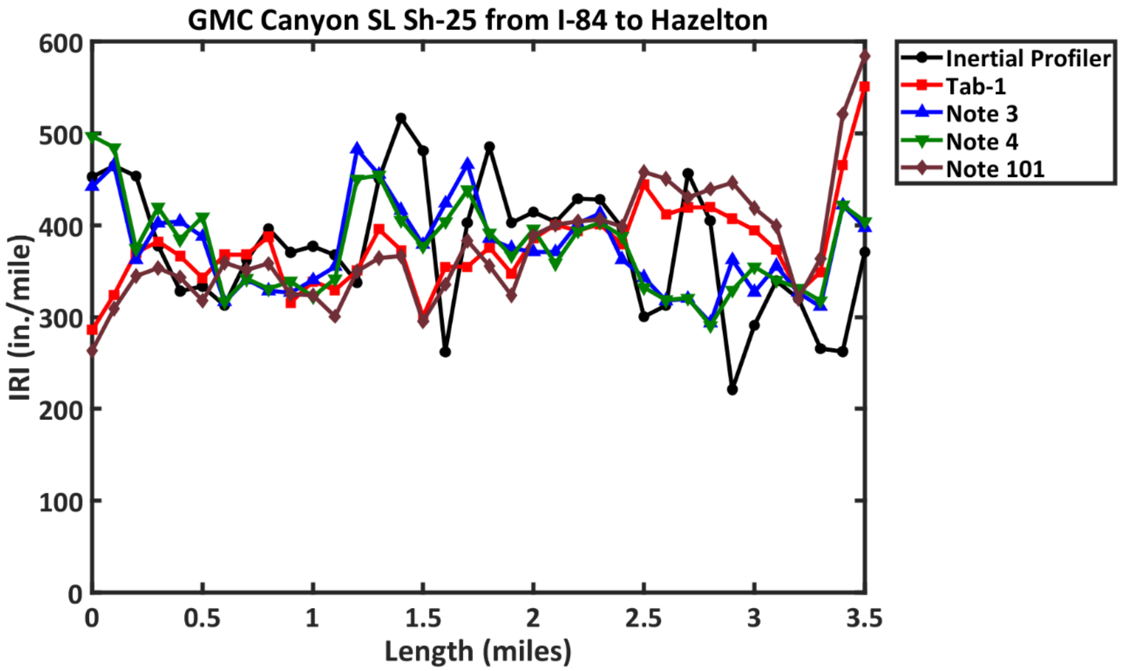


Figure 111. Modified IRI of SH-25 from I-84 to Hazelton in D4 using Tab-1, Note 3, Note 4 and Note 101 Placed in GMC Canyon SL.

Modified IRI Plots from D5

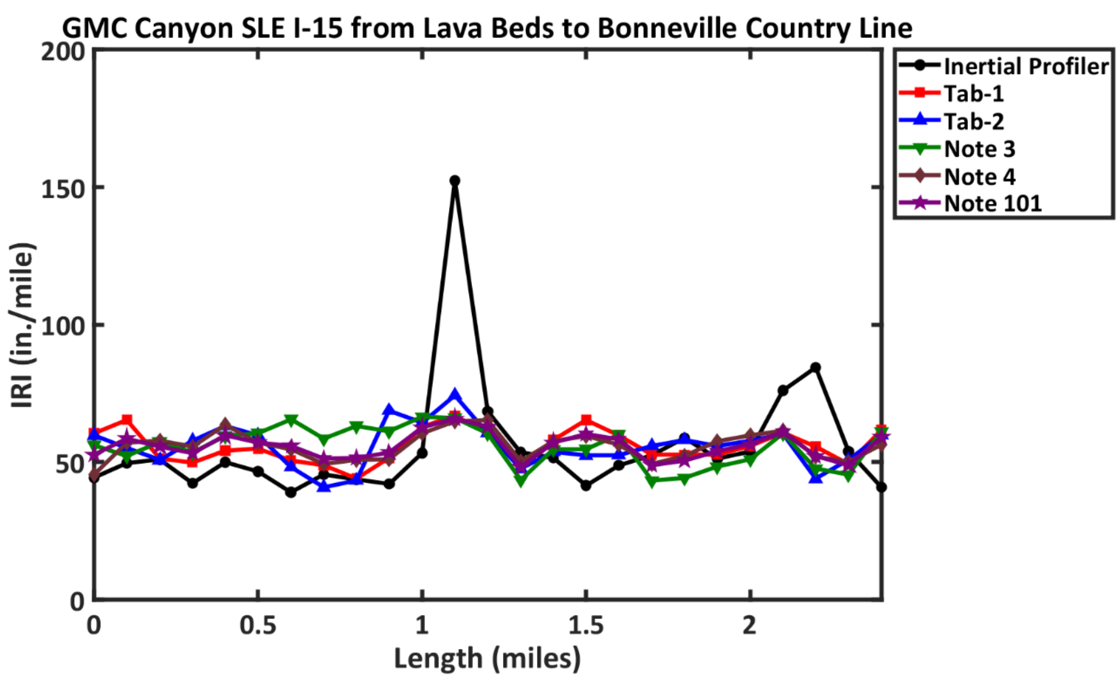


Figure 112. Modified IRI of I-15 section from Lava Beds to Bonneville Country Line D5 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 placed in GMC Canyon SLE.

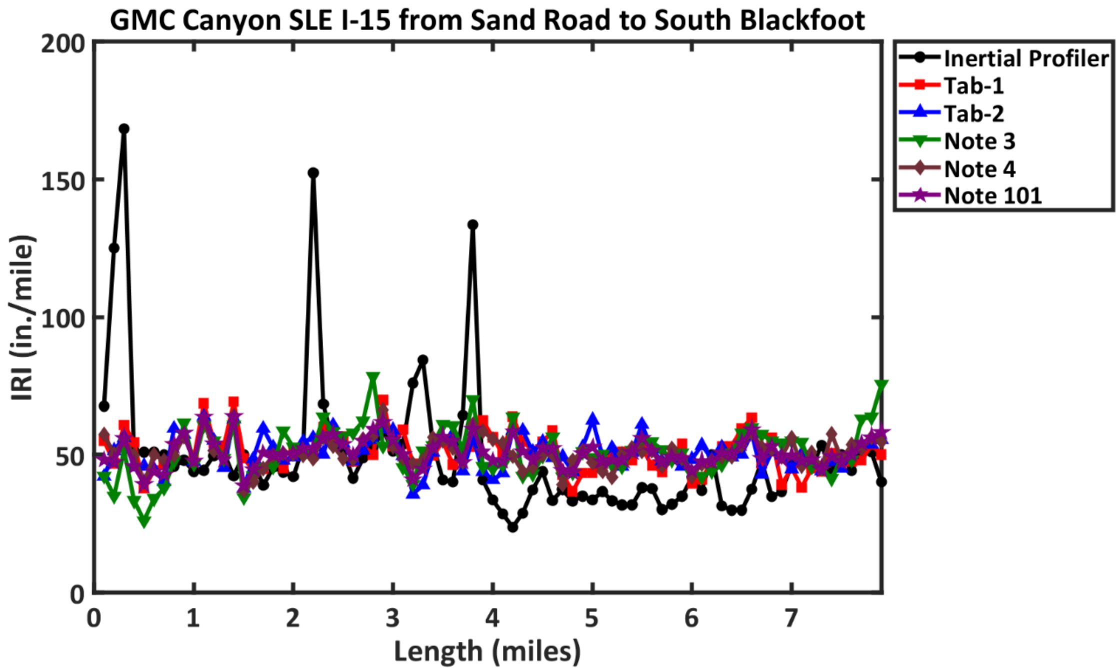


Figure 113. Modified IRI of I-15 Section from Sand Road to South Blackfoot in D5 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in GMC Canyon SLE.

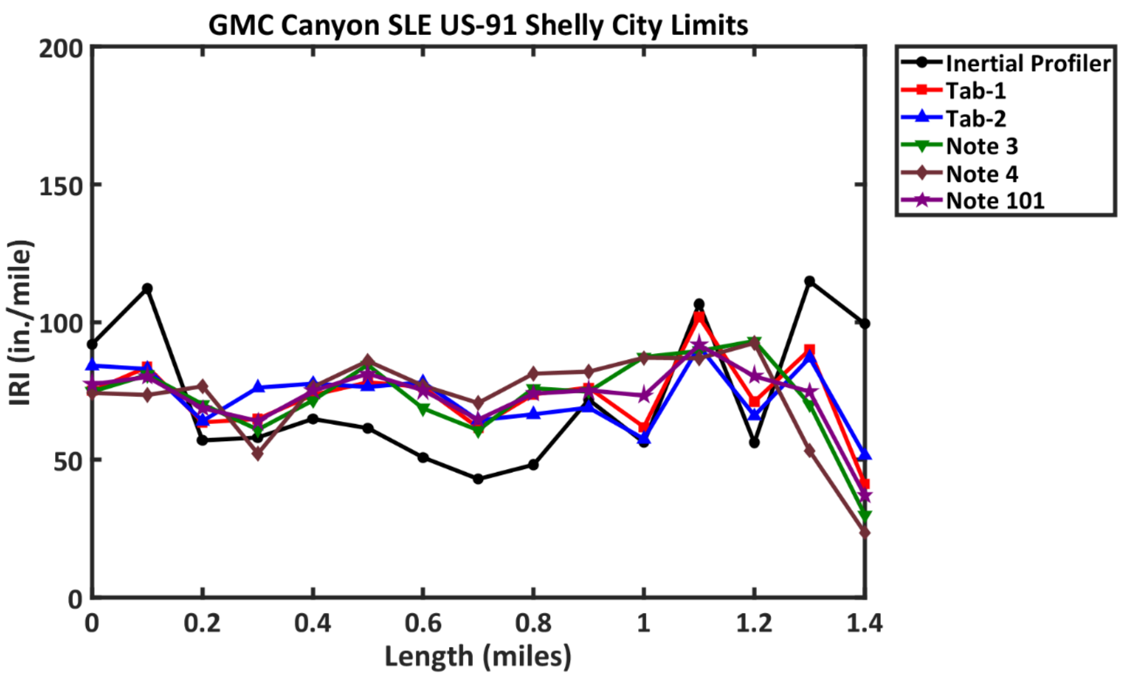


Figure 114. Modified IRI of US-91 Section Covering Shelly City Limits in D5 using Tab-1, Tab-2, Note 3, Note 4 and Note 101 Placed in GMC Canyon SLE.

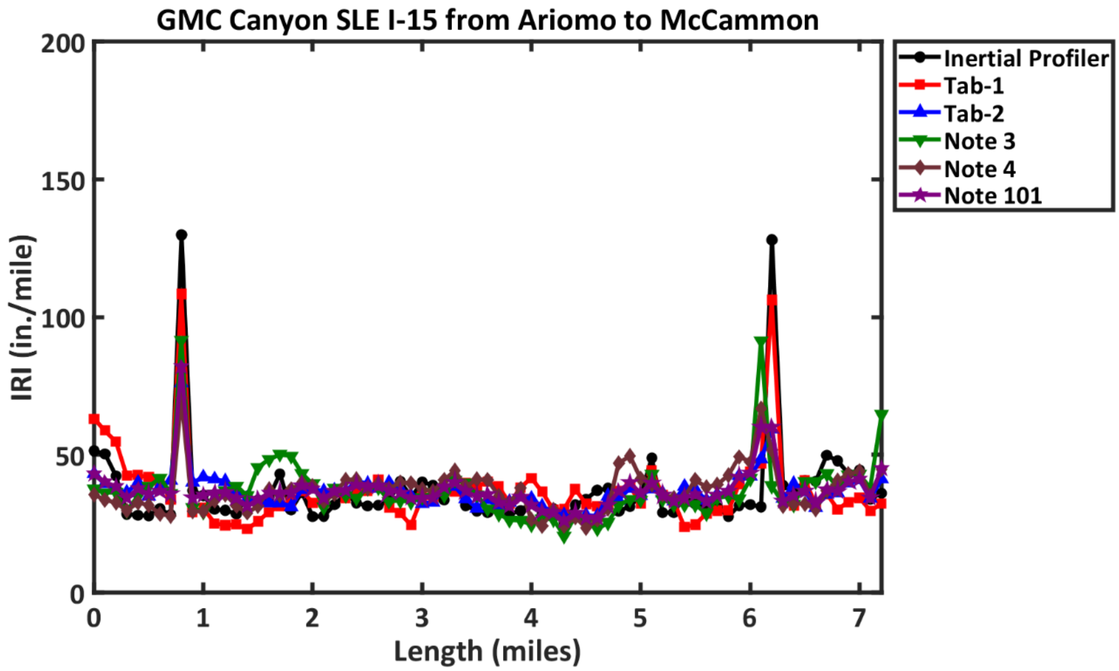


Figure 115. Modified IRI of I-15 Section from Arimo to Mccammon in D5 using Tab-1, Tab-2, Note 3, Note 4, and Note 101 Placed in GMC Canyon SLE.

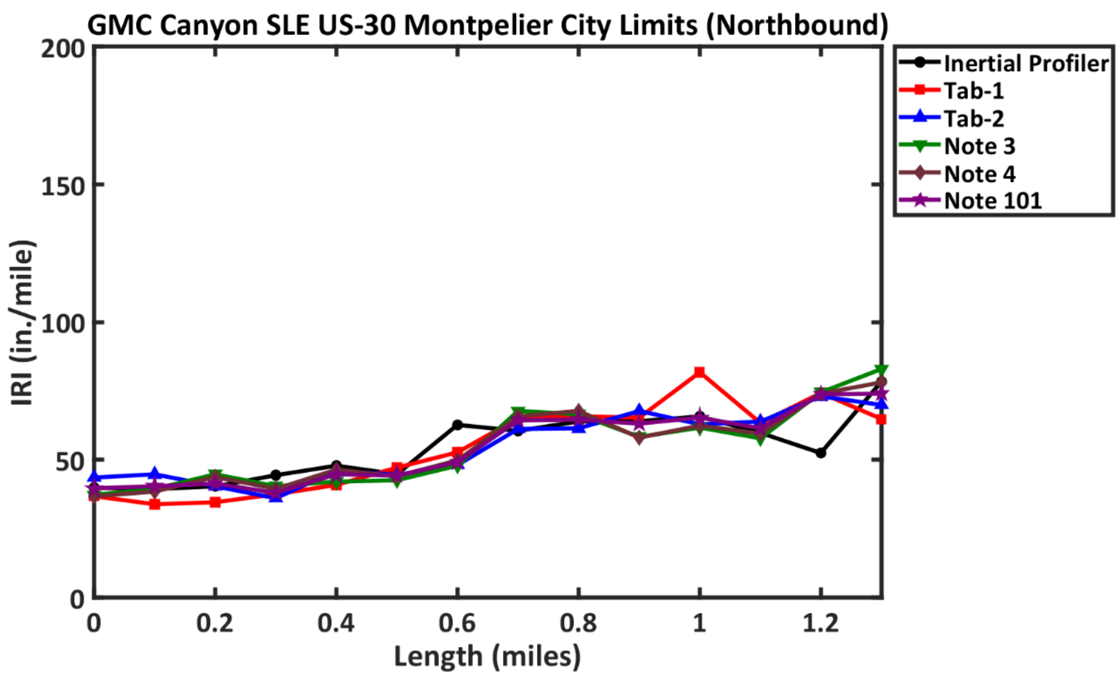


Figure 116. Modified IRI of US-30 Section covering Montpelier City Limits (Northbound) in D5 using Tab-1, Tab-2, Note 3, Note 4, and Note 101 Placed in GMC Canyon SLE.

Modified IRI Plots from D6

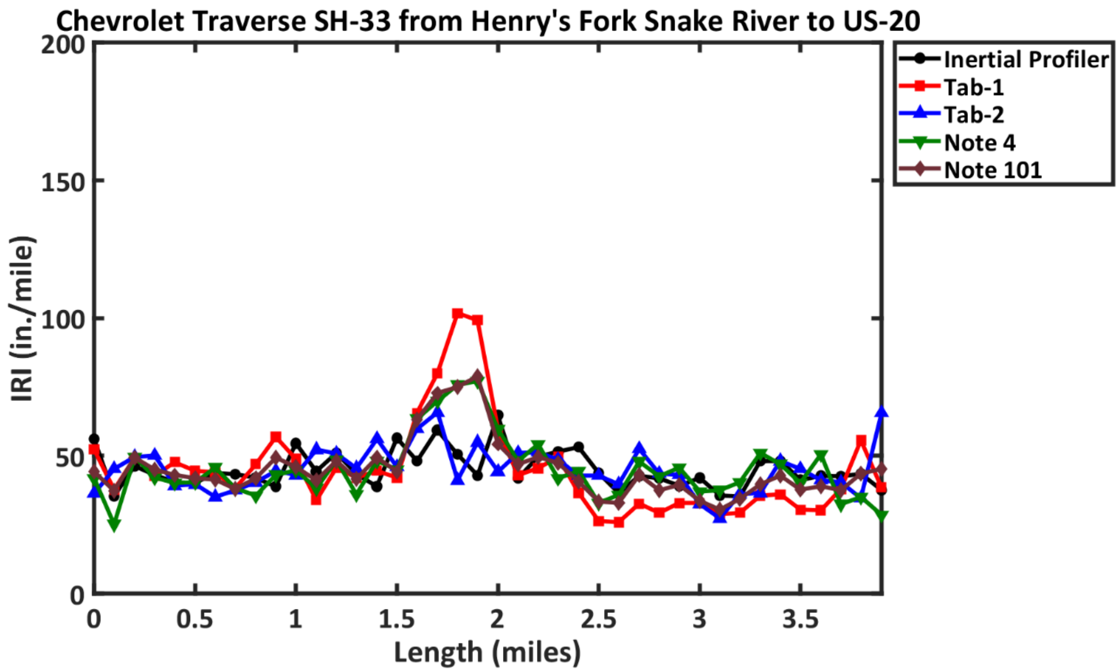


Figure 117. Modified IRI of US-33 Section from Henry's Fork Snake River to US-20 in D5 using Tab-1, Tab-2, Note 4, and Note 101 Placed in Chevrolet Traverse.

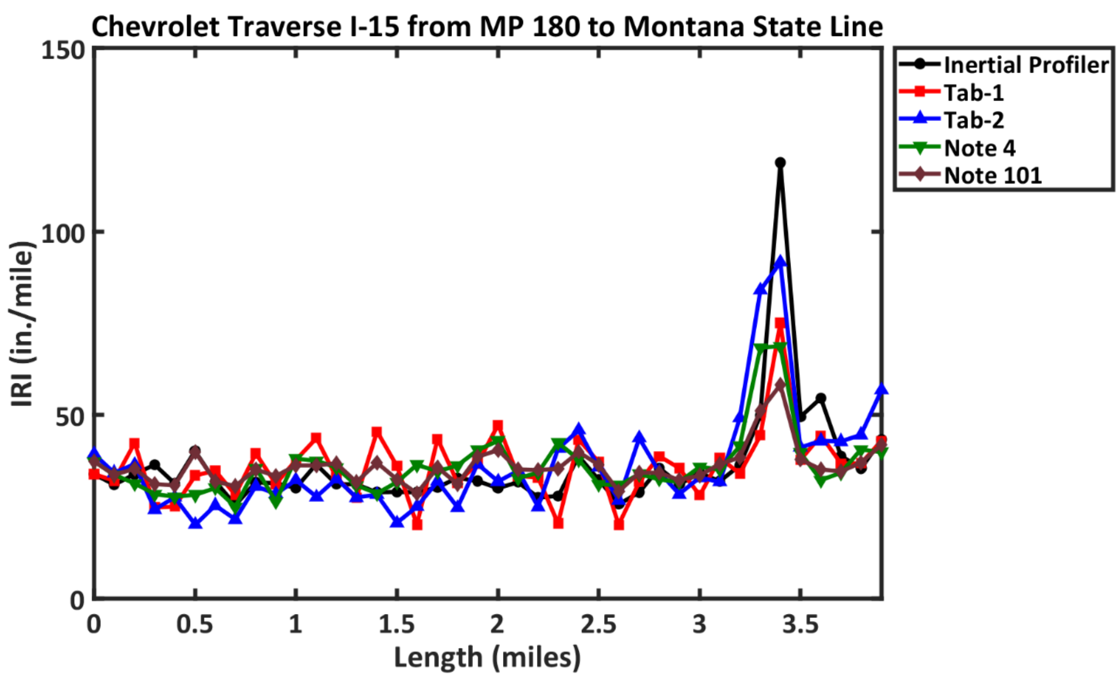


Figure 118. Modified IRI of I-15 Section from MP 180 to Montana State Line in D6 using Tab-1, Tab-2, Note 3, and Note 101 Placed in Chevrolet Traverse.

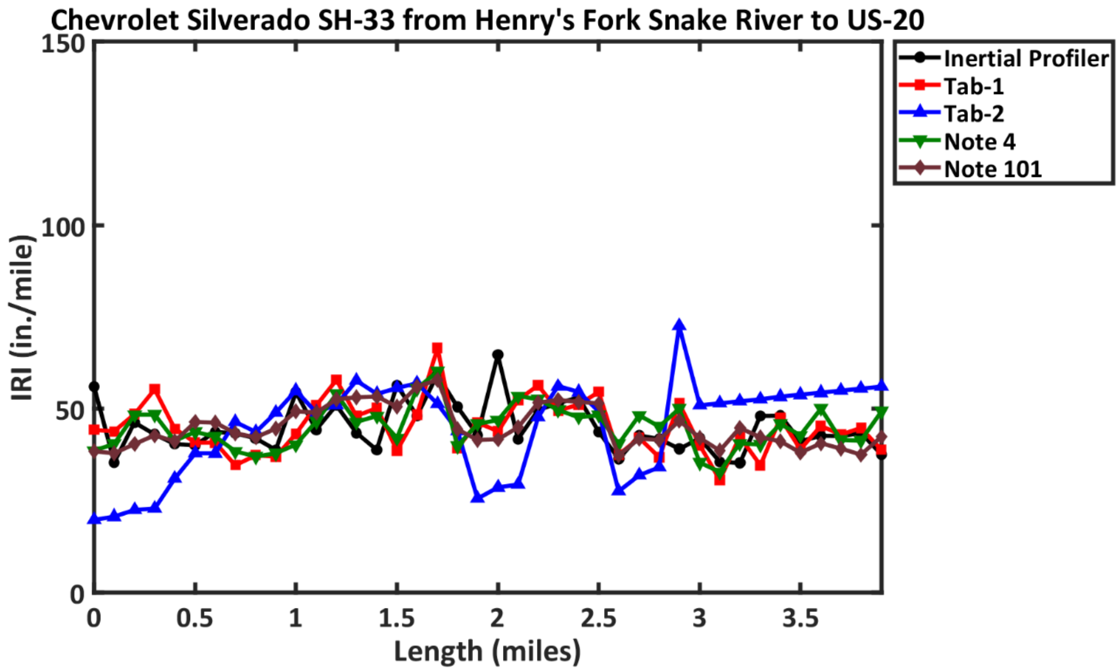


Figure 119. Modified IRI of SH-33 Section from Henry's Fork Snake River to US-20 in D6 using Tab-1, Tab-2, Note 4, and Note 101 Placed in Chevrolet Silverado.

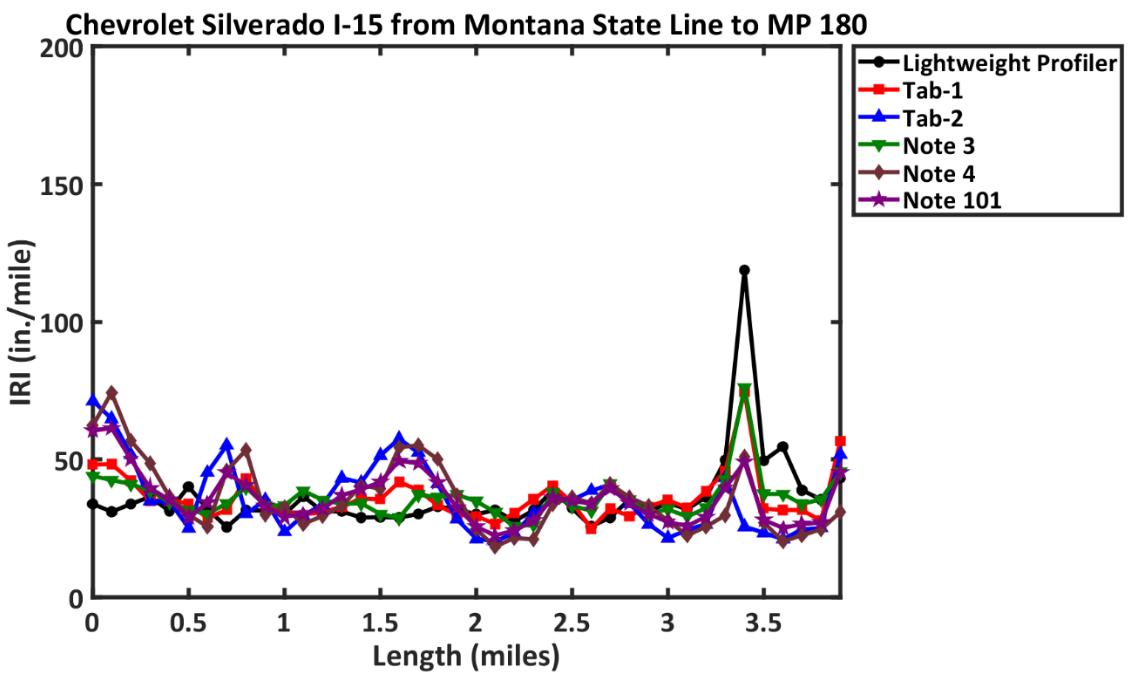


Figure 120. Modified IRI of I-15 Section from MP 180 to Montana State Line in D6 using Tab-1, Tab-2, Note 3, Note 4, and Note 101 Placed in Chevrolet Silverado.

Effect of Different Speeds using Chevrolet Colorado Tested in D4

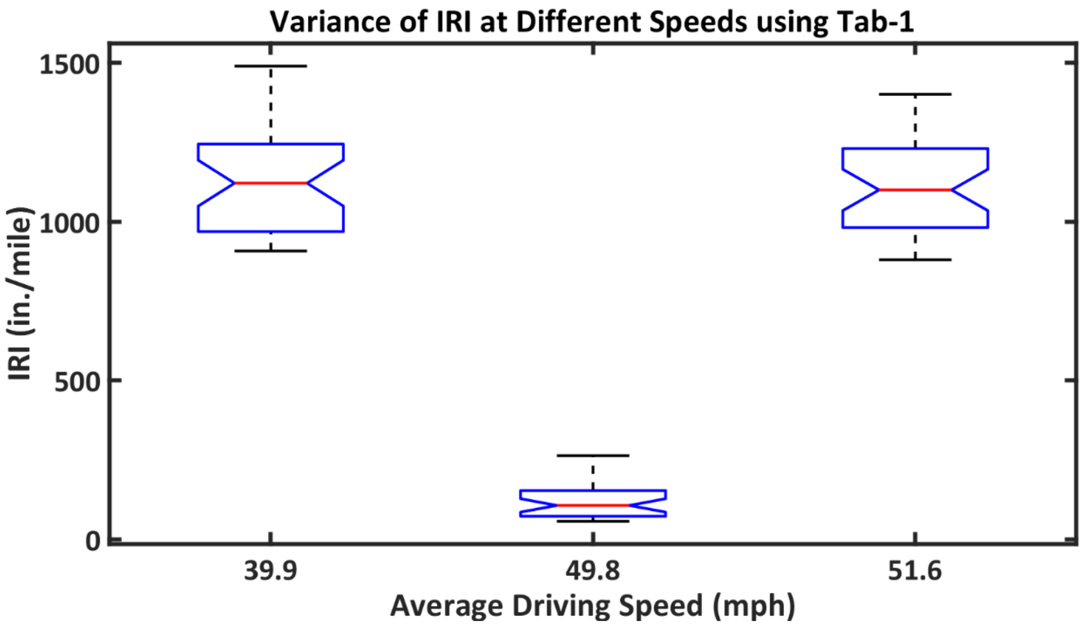


Figure 121. Variance of IRI at Different Speeds using Tab-1

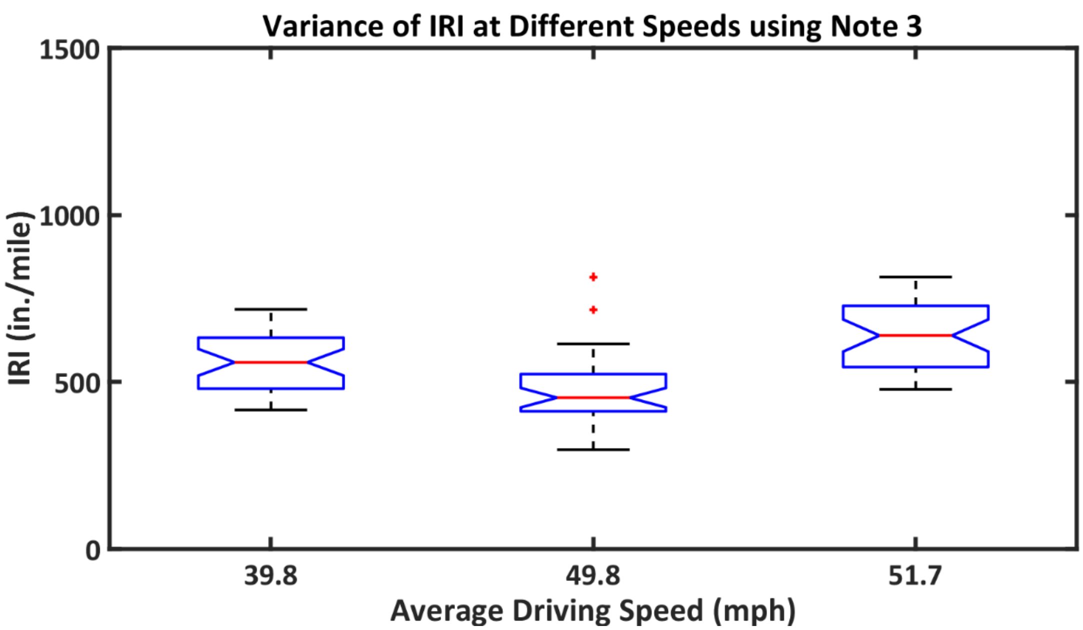


Figure 122. Variance of IRI at Different Speeds using Note 3

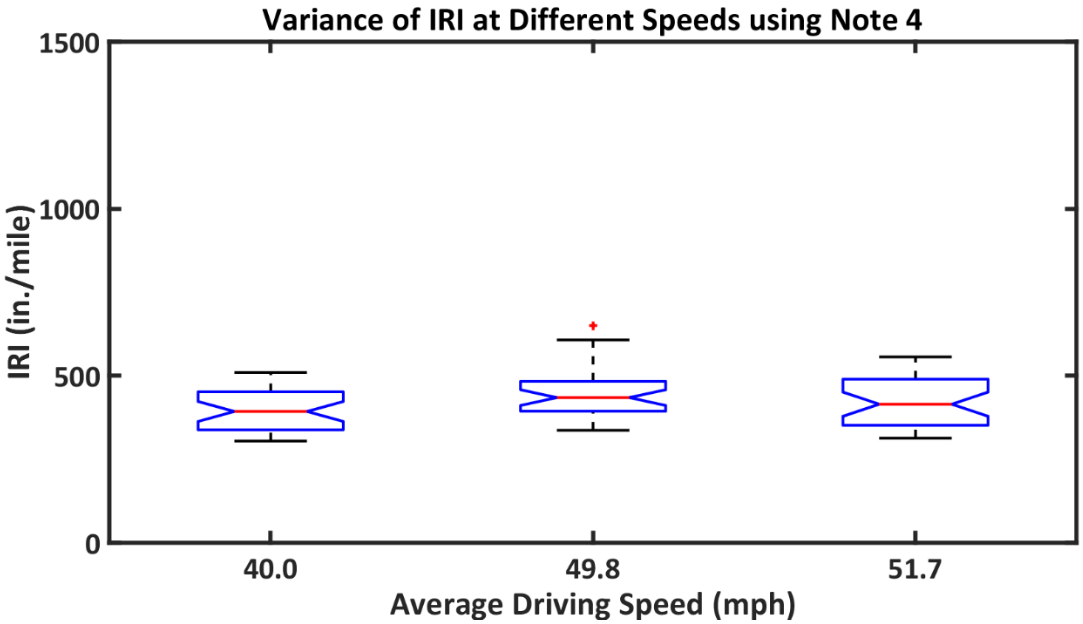


Figure 123. Variance of IRI at Different Speeds using Note 3

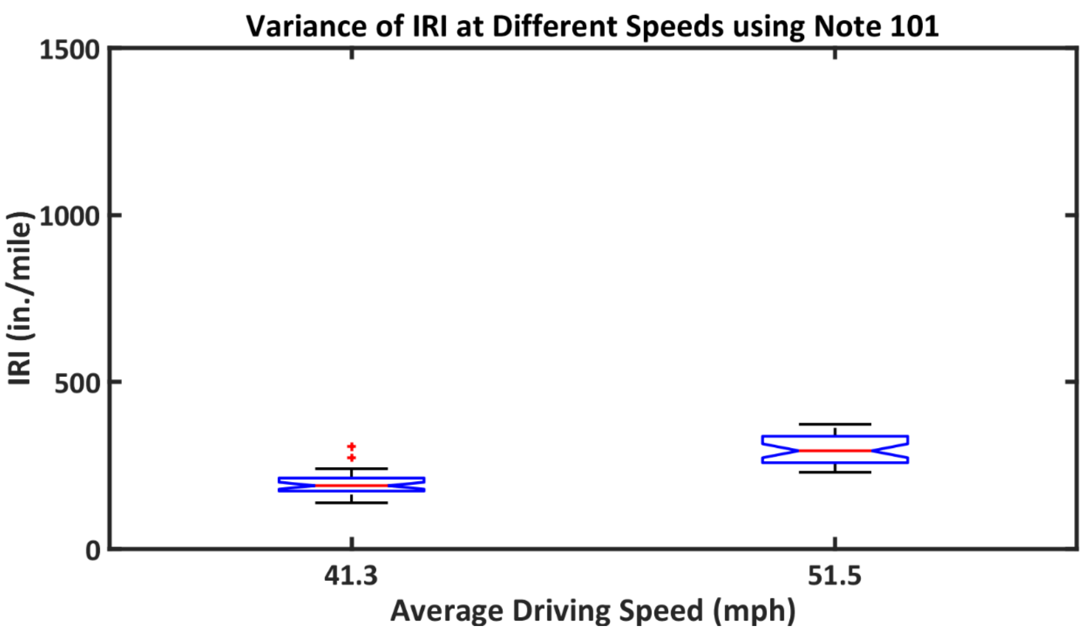


Figure 124. Variance of IRI at Different Speeds using Note 101

Table 20: Complete Roughness Dataset of Sh-67 located Mountain Home in D3 Collected by ITD's Inertial Profiler along with Tab-2 placed in GMC Canyon and Jeep Cherokee

From (mile)	To (mile)	Inertial Profiler	GMC Canyon	Jeep Cherokee
0	0.1	143	117	45
0.1	0.2	43	122	50
0.2	0.3	49	111	69
0.3	0.4	42	108	101
0.4	0.5	40	100	77
0.5	0.6	48	101	45
0.6	0.7	42	118	62
0.7	0.8	51	123	89
0.8	0.9	47	116	70
0.9	1	49	111	49
1	1.1	48	103	76
1.1	1.2	47	100	111
1.2	1.3	45	119	101
1.3	1.4	49	96	63
1.4	1.5	45	103	41
1.5	1.6	60	108	70
1.6	1.7	50	109	85
1.7	1.8	42	108	53
1.8	1.9	40	111	62
1.9	2	43	113	101
2	2.1	44	113	98
2.1	2.2	131	127	55
2.2	2.3	52	116	48
2.3	2.4	46	108	88
2.4	2.5	62	111	93
2.5	2.6	70	108	57
2.6	2.7	49	107	51
2.7	2.8	59	104	81
2.8	2.9	74	107	122
2.9	3	56	123	98
3	3.1	54	107	62
3.1	3.2	51	109	53
3.2	3.3	48	109	79
3.3	3.4	50	105	102

3.4	3.5	50	103	83
3.5	3.6	51	100	92
3.6	3.7	52	142	92
3.7	3.8	51	138	123
3.8	3.9	48	156	128
3.9	4	43	113	71
4	4.1	43	98	67
4.1	4.2	48	106	93
4.2	4.3	48	99	87
4.3	4.4	46	138	90
4.4	4.5	48	90	61
4.5	4.6	42	94	104
4.6	4.7	44	87	105
4.7	4.8	43	95	64
4.8	4.9	42	85	41
4.9	5	46	103	80
5	5.1	48	99	93
5.1	5.2	41	113	75
5.2	5.3	47	107	52
5.3	5.4	53	104	86
5.4	5.5	67	98	114
5.5	5.6	46	108	86
5.6	5.7	46	111	49
5.7	5.8	43	101	57
5.8	5.9	39	109	95
5.9	6	38	99	79
6	6.1	42	100	57
6.1	6.2	45	105	102
6.2	6.3	46	100	102
6.3	6.4	59	113	66
6.4	6.5	51	122	75
6.5	6.6	49	250	153
6.6	6.7	55	114	64
6.7	6.8	52	120	86
6.8	6.9	56	102	99
6.9	7	52	106	79
7	7.1	52	111	51
7.1	7.2	48	137	92

7.2	7.3	55	134	90
7.3	7.4	70	109	63
7.4	7.5	70	120	74
7.5	7.6	95	113	98
7.6	7.7	44	114	114
7.7	7.8	39	120	77
7.8	7.9	62	123	49
7.9	8	52	135	68
8	8.1	48	126	75
8.1	8.2	50	118	53
8.2	8.3	49	117	66
8.3	8.4	45	117	95
8.4	8.5	45	116	83

Table 21: Roughness data of I-84 section extended from Valley Road to MP191 collected by Lightweight profiler and five mobile devices placed in Chevrolet Traverse

From (mile)	To (mile)	Light Weight Profiler	Tab-1	Tab-2	Note 3	Note 4	Note 101
0	0.1	45	96	64	45	71	44
0.1	0.2	37	78	44	40	59	34
0.2	0.3	34	76	46	46	62	46
0.3	0.4	33	75	39	38	60	45
0.4	0.5	33	70	46	42	54	34
0.5	0.6	26	80	50	39	57	45
0.6	0.7	30	74	40	32	51	25
0.7	0.8	38	59	34	36	57	28
0.8	0.9	26	108	58	56	83	30
0.9	1	32	94	46	39	56	23
1	1.1	35	80	44	43	60	31
1.1	1.2	36	69	39	41	60	28
1.2	1.3	34	59	32	43	56	42
1.3	1.4	30	41	16	28	42	27
1.4	1.5	27	68	33	52	64	43
1.5	1.6	29	119	62	66	84	50
1.6	1.7	30	131	52	67	109	37
1.7	1.8	30	106	49	53	71	40
1.8	1.9	108	226	145	138	162	128

1.9	2	56	78	45	37	65	36
2	2.1	36	80	47	34	62	26
2.1	2.2	36	60	40	38	49	25
2.2	2.3	49	83	52	50	68	26
2.3	2.4	38	99	44	59	71	29
2.4	2.5	30	133	56	57	83	31
2.5	2.6	58	159	94	80	104	52
2.6	2.7	37	159	78	70	98	48
2.7	2.8	34	114	55	65	82	43
2.8	2.9	36	73	52	55	66	47
2.9	3	34	67	45	55	68	49
3	3.1	32	62	31	45	52	39
3.1	3.2	31	46	30	44	56	33
3.2	3.3	30	46	27	38	62	41
3.3	3.4	33	46	23	29	42	30
3.4	3.5	29	46	20	35	55	30
3.5	3.6	34	51	25	45	61	29
3.6	3.7	35	57	32	45	55	34
3.7	3.8	39	50	33	41	57	43
3.8	3.9	35	47	34	42	65	40
3.9	4	33	64	35	48	65	52
4	4.1	34	85	41	54	60	49
4.1	4.2	36	73	44	50	60	39
4.2	4.3	35	101	56	58	79	42
4.3	4.4	33	113	51	61	66	31
4.4	4.5	38	131	89	67	86	27
4.5	4.6	37	142	95	63	85	21
4.6	4.7	33	148	88	66	87	35
4.7	4.8	42	150	86	70	87	37
4.8	4.9	34	138	85	77	90	49
4.9	5	36	141	91	89	91	77
5	5.1	76	110	93	77	95	68
5.1	5.2	46	84	56	55	71	51
5.2	5.3	40	64	52	59	79	45

Appendix C
Operating Instructions for RoadBump Pro App

RoadBump Pro is an app that measures the roughness of pavement using the accelerometer data measured from the smartphone in which the app is installed. The smartphone needs to be placed firmly inside the vehicle to avoid vibrations other than that initiated from the vehicle suspension system. After recording the accelerometer data, the app can produce the roughness as International Roughness Index (IRI) or Pavement Serviceability Rating (PSR). Detailed operating instructions for measuring pavement roughness using this mobile application are presented in this appendix. Note that this appendix can be used as a stand-alone document by ITD engineers in the field attempting to measure pavement roughness using mobile devices.

Download and Installation Instructions

The RoadBump Pro app was developed for the Android platform, and therefore can only be installed on mobile devices (cellular phones or tablets) running the Android operating system. The application can be downloaded from the Google Play Store. Note that the RoadBump app is available for free download, whereas the RoadBump Pro version costs $99.99 per download (cost current as of March 2018). The primary difference between the regular version and the 'Pro' version is that the regular version only presents the user with an output graph, whereas the 'Pro' version presents the user with the ability to download the data for further calculations/manipulations. The current research study used the 'Pro' version of the app, and therefore, all instructions provided in the following sections are applicable to the 'Pro' version only.

Starting the App

Right after starting the app following screen will appear showing that it is waiting for GPS signal. This app uses GPS coordinates for producing a map marked with traversed road. After the device successfully establishes a link with the GPS a screen showing a start button will appear. Two screens are shown in **Figure 125**. As soon as the green start button appears on the screen the screen gets ready for collection roughness data.

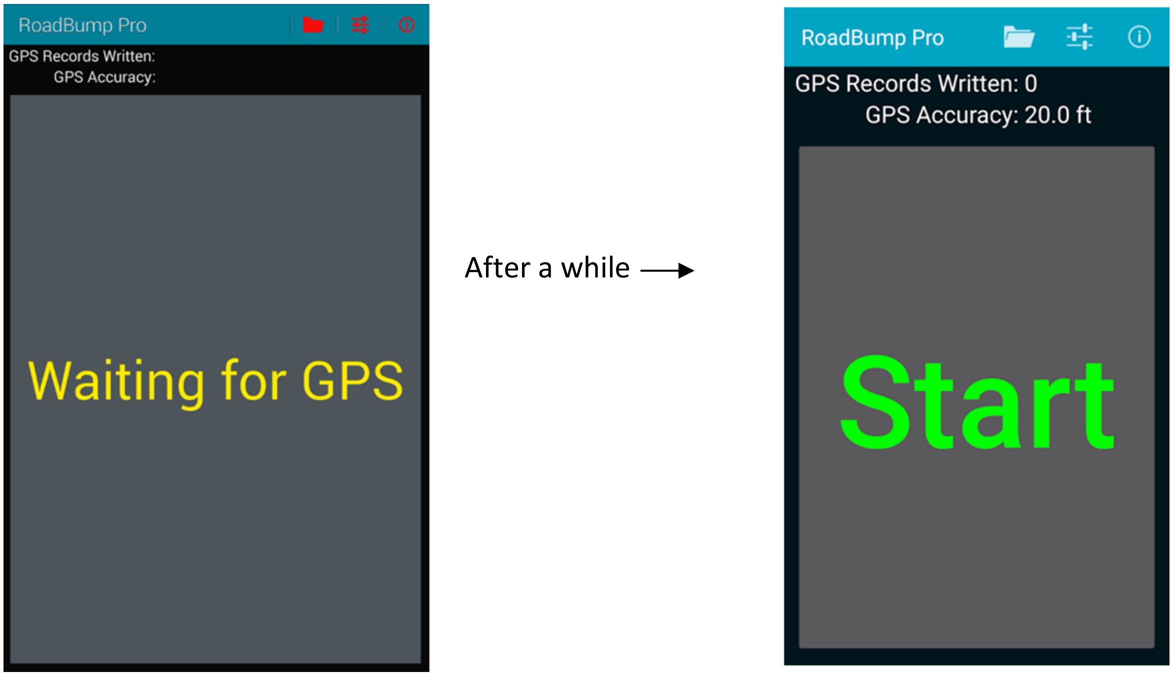


Figure 125. Initial Screens of the App

Operating the App

Operating this app can be divided into three different segments, including (1) data collection, (2) data extraction, and (3) data visualization. These segments are described below.

Data Collection

The mobile devices need to be placed firmly on the dashboard of the vehicle to ensure that the devices do not experience any vibration other than vehicle suspension system. As previously stated, the device gets ready for data collection when the green start button appears on the screen. Please note that, this app has a speed threshold, below which it does not record any data. Therefore, after the green start button appears, the driver should start driving the vehicle and pass the threshold speed. It was observed that the mobile devices are sensitive to the driving speed. Hence, before collecting IRI data, the driver should know the speed that was used to calibrate the mobile devices and drive the vehicle at that specified speed.

As soon as the vehicle reaches the beginning of the pavement section of interest at the specified speed, one should press the start button and following screen will appear meaning that it started collecting data.

Figure 126. Data Collection by the App

After covering the pavement section for collecting roughness data the red stop button needs to be pressed to terminate the data collection procedure by the app. The following screen with different options will appear.

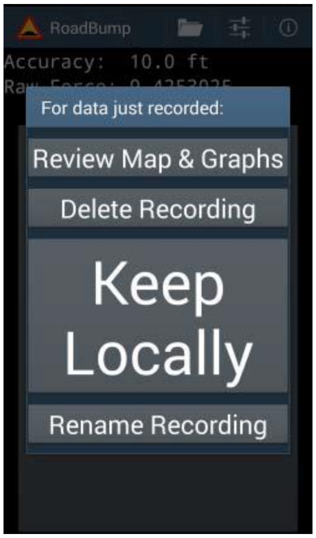


Figure 127. RoadBump Pro Screen after Data Collection

There are four different options on the screen. The first option is reviewing map and graph. This option will quickly show the IRI and the road marked on a map. Second option is for deleting the dataset from the device. The "Keep Locally" option will save the dataset for further analysis on this data. However, for being able to work with the data the user needs to extract the data from the device. Procedure for data extraction is covered later in this appendix. Please note that, by default the app saves the datasets with date and time. This makes it difficult to find the files when there are lots of IRI data collected by the same device. The final option “Rename recording” allows the user to rename the dataset to an understandable name. This helps while searching for the files in future.

This ends the discussion on data collection. In following sections, the procedure for data extraction and data visualization will be discussed. Please note that, this visualization is carried out on the files that are saved using the “Keep Locally” option. The user can retrieve the saved date files anytime. For example, the user can either visualize the active data right after data collection or later on visualize it from the saved data files.

Data Extraction

Data extraction provided by the RoadBump Pro app allows the user to access the datasets collected by the mobile device. These datasets include, the IRI, GPS, coordinates, and accelerometer data. After extracting data from the devices, one can carry out further data analysis. There is a vital procedure for calibrating and comparing mobile device data with standard data collection vehicle for pavement roughness, such as, inertial profiler. For extracting data from mobile devices, the users need to press the folder button located at top right corner of the screen shown in **Figure 128 (A)**. Please note that, there should be at least one dataset saved before following these procedures. After pressing the folder button another screen will appear with different options. This screen is shown in **Figure 128 (B)**. Other options are useless without the first option which is “Choose Recording”. The user needs to select the recording before extracting. After pressing this button another screen will appear with the available datasets. This screen is shown in **Figure 128 (C)**. The user needs to select the dataset that needs to be extracted. After selecting the dataset, the user will be redirected to screen shown in **Figure 128 (B).** Out of all the options “Generate CSV Files” should be selected for extracting the dataset from mobile device.

Figure 128. Data Extraction Procedure

After pressing the “Generate CSV button” the user will be presented with a screen shown in **Figure 129.**

Figure 129. Data Extraction Screen

In this screen, there are several different options for extracting different datasets. If the “Interpolated” option is selected then it will create CSV file with a lot of information, shown in **Figure 130**. Although, this file contains a lot of information, some of the information is not directly related to this project. Hence, this file will not be discussed in detail.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Time	Raw	MovingAvg	Speed (m/s)	t(s)	x(km)	x(miles)	delta t(s)	IRI (in/mile)	IRI (m/km)	PSR	Diff	Int Long	Int Lat	Int Speed (m/s)
2	1,424,966,680,629	9.2719965	9.441717	30.5	0.8059998	0.024683122	0.015337382	0.005	68.44481	1.0802526	3.7756488	0.16972065	-93.99048995	31.12945616	30.49899864
3	1,424,966,680,641	9.449669	9.463412	30.5	0.81799984	0.025049122	0.015564803	0.012	31.37556	0.4951951	4.3959656	0.013743401	-93.99049	31.1294595	30.49599266
4	1,424,966,680,650	9.127833	9.395327	30.5	0.82699984	0.025323622	0.01573537	0.009	95.11858	1.5012403	3.384193	0.26749325	-93.99049003	31.12946202	30.49373817

Figure 130. Interpolated.csv File Created by RoadBump Pro App

The second option on the screen shown in **Figure 128** will create a csv file that is most appropriate for this project. This file reports the IRI and PSR of a pavement section for every 0.1 mile. Note that the mobile device measurement validity is relied on the calibration data (reference data). In this project, the reference data is exclusively collected by ITD’s inertial profiler and lightweight profiler. Both two profilers also report IRI in every 0.1 mile, which is in consistent data format as the output data produced by the second output option.

	A	B	C	D
1	From Mile	To Mile	IRI Avg	PSR Avg
2	0.00	0.10	81.51	3.58
3	0.10	0.20	96.28	3.37
4	0.20	0.30	85.07	3.53
5	0.30	0.40	134.52	2.88
6	0.40	0.50	146.27	2.74
7	0.50	0.60	115.82	3.11

Figure 131. Segmented.csv File Created by RoadBump Pro App

Finally, the "Accelerometer and GPS" option reports the accelerometer data and GPS coordinates. These files should be accessed if advanced analysis is warranted, which is out of the scope of this project. Hence, these files will not be discussed in further detail.
Please note that there is an option for vehicle/device factor. This factor, defined as modification factor (MF), should be available before collecting pavement roughness data for inspection purposes. The MF needs to be calculated using the developed calibration process described in chapter 4 of this report. The textbox should be filled with a selected MF and after that a scaled IRI will be extracted from the device using a data cable. The datasets can also be shared with another person using the email option. After pressing the email option, the user will be presented with similar screen shown in **Figure 128** and the procedure is the same as extracting data using "Generate CSV Files" option. Other two options on this screen are self-explanatory. Selecting "Delete" will delete the dataset from the device and "Rename" allows the user to rename the name of the dataset.

Data Visualization

Data extraction described in the previous section allows the user to analyze the dataset outside of the mobile devices. However, the user can also visualize the datasets on the mobile device. Although this does not allow the user to work with the dataset, it gives an idea about the pavement condition. Please refer to **Figure 132** for visualizing pavement roughness data.

Figure 132. Data Visualization Procedure

The procedure is almost similar to extracting roughness data from the mobile device. In the beginning the user needs to press the red folder button on top-right corner of the home screen shown in **Figure 132-A**. After that, a dataset needs to be selected following the method for data extraction. Once the dataset has been selected, the user now needs to press the show button, marked on **Figure 132-B.** This will put forward a screen shown in **Figure 133**.

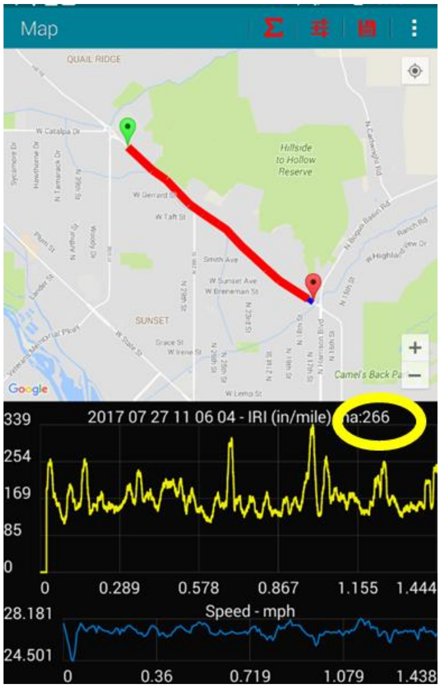


Figure 133. Data Visualization Screen

Data visualization is split into three horizontal sections. The first part of the screen shows the map with the traversed road, while second part of the screen shows the moving averaged IRI. Please note that, moving average is a filter that averages a certain number of steps and continues to do that until the dataset ends. A description on moving average is provided in Appendix D. Moving average step is marked on the figure. Please note that this step is not constant and changes from road to road. The moving average step that is used for generating this plot is shown in the spot marked on **Figure 133**. In this case a step of 266 is used for moving average. It was mentioned that this app can calculate different roughness indexes of pavement condition and visualize them on this screen. The procedure for visualizing other roughness index, e.g. PSR, is shown in **Figure 134**.

Figure 134. Different Pavement Condition Plots

The user can open a list of available pavement condition criteria by pressing the  button at the top-right corner on the screen. Pressing any option will visualize that corresponding pavement condition index on the screen. For demonstration purposes PSR was selected for visualization and shown in **Figure 134-B.**

Appendix D
Accelerometer, Signal and Signal Processing

Accelerometer

An accelerometer is an electronic device used to measure proper acceleration [36]. Proper acceleration is defined as the acceleration (or rate of change of velocity) of a body in its own instantaneous rest frame [37]. Acceleration found from the accelerometer is free from the coordinate axis, meaning it does not have any fixed coordinate system. For instance, an accelerometer at rest will measure an acceleration due to Earth's gravity pointing upwards (positive) of g $\approx$ 9.81 m/s^2. On the other hand, accelerometers in free fall (falling at a rate of about 9.81 m/s^2) will measure zero m/s^2. **Figure 135** shows a standalone accelerometer sensor circuit.

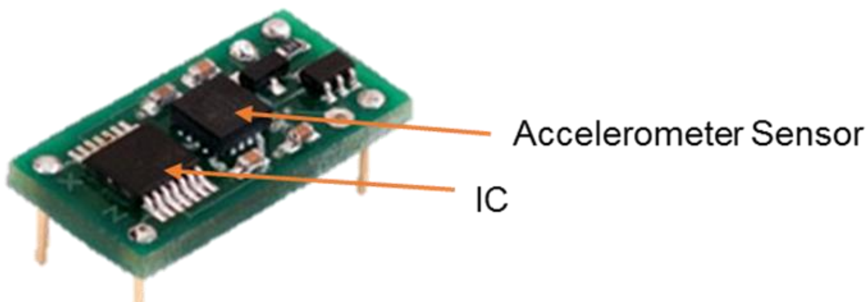


Figure 135. A Standalone Accelerometer Sensor [38]

Typical accelerometers have multiple axes. Two to determine most two-dimensional movement along a planar surface. When it has a third axis along with the two axes then it can offer 3D positioning, measure pitch, and roll. Most smartphones conventionally make use of three-axis models. However, cars use a two-axis accelerometer to determine the moment of impact. These devices are highly sensitive because they are intended to measure even very minute shifts in acceleration. Better accuracy is expected from an accelerometer with higher sensitivity. At the same time, it increases its capability to capture subtle movements. The basic principle of how accelerometer works are described in the following figure. To keep it simple, one-dimensional acceleration is considered in this case.

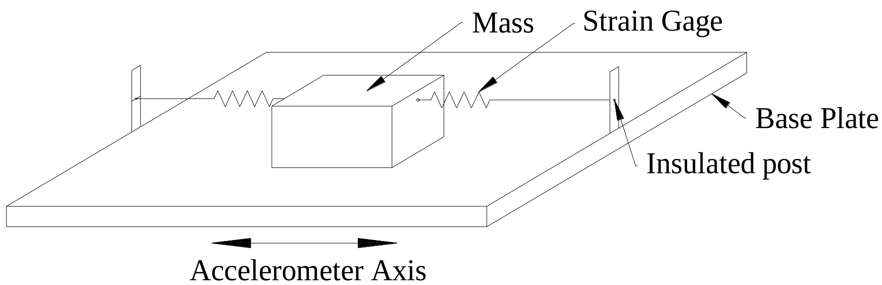


Figure 136. Schematic Diagram of a Simplified Accelerometer

The accelerometer in **Figure 136** has a base plate, an insulated post that reads the strain gage data, and a mass in the middle of the accelerometer base plate. The direction in which the strain gages are keeping the mass from moving is the accelerometer axis. This configuration has only one degree of freedom, which makes it a one-dimensional accelerometer. With the increase of the degree of freedom, the complexity of the setup escalates.

The working principle of accelerometer depends on the inertia of the mass inside of the accelerometer. When the body moves in some direction, the base plate moves with the body. Nevertheless, due to inertial resistance, the mass of the accelerometer intends to retain its initial status of motion. This causes the strain gage to "squeeze" which produces an electrical charge that is proportional to the force exerted upon it. As mass is a constant, charge and force are proportional to each other, so the charge is also proportional to the acceleration.

Accelerometers are usually mounted on the bottom of the inertial profiler. Thus, the accelerometer is not always perfectly vertical when the vehicle body undergoes pitch and roll as it travels over uneven roads. An error occurs if the vehicle pitches and accelerates longitudinally at the same time, or rolls and accelerates laterally at the same time. However, this error is small if the lateral and longitudinal acceleration is held under 0.1 g [30] It is noted that the gyroscopically stabilized accelerometers are available that will measure the true vertical acceleration accurately even if the vehicle body is tilted.

To properly capture the range of wavelength for measurement of roughness, an accelerometer must be valid up to 150 Hz. All accelerometers have a natural frequency at which their internal components respond excessively to input vibrations. They do not measure frequencies near that value very accurately. At a travel speed of 62 mph, a wavelength of 1 ft corresponds to a frequency of about 93 Hz. The natural frequency of an accelerometer should be at least 50 percent higher than that for safe operation.

Although accelerometer data is of importance to civil engineering applications, the data collection procedure and processing is beyond the scope of this research. Electrical Engineers developed the idea to work with these sensors. To understand how accelerometers work, a user needs to have some background information on the signal, signal processing, filter, and frequency response. The following is a review of data processing methods.

Signal and Signal Processing

A signal, in communication systems, is a function that "conveys information about the behavior or attributes of some phenomenon" [39]. In simple words, the signal is something that contains information. Like other electrical devices, the output from an accelerometer is voltage. A fluctuating voltage from the accelerometer contains the information of acceleration in two or three dimensions based on its available axes or dimensional capabilities. In this case, the sensor will provide a sequence of number, which is the signal.

A signal can be of two types: Analog signal and Digital signal. An analog signal is a continuous signal for which the quantity that varies with time resembles some other time varying feature. For example, in an analog light signal, the instantaneous voltage of the signal varies continuously with the intensity of the light beam. Unlike analog signals, the digital signal comprises a sequence of discrete values, which can only contain a finite number of values. A digital signal is constructed from a discrete set of waveforms of a physical quantity to represent a sequence of discrete values. **Figure 137** shows a plot containing both analog and digital signals. Please note that digital signals are step functions while analog functions are continuous.

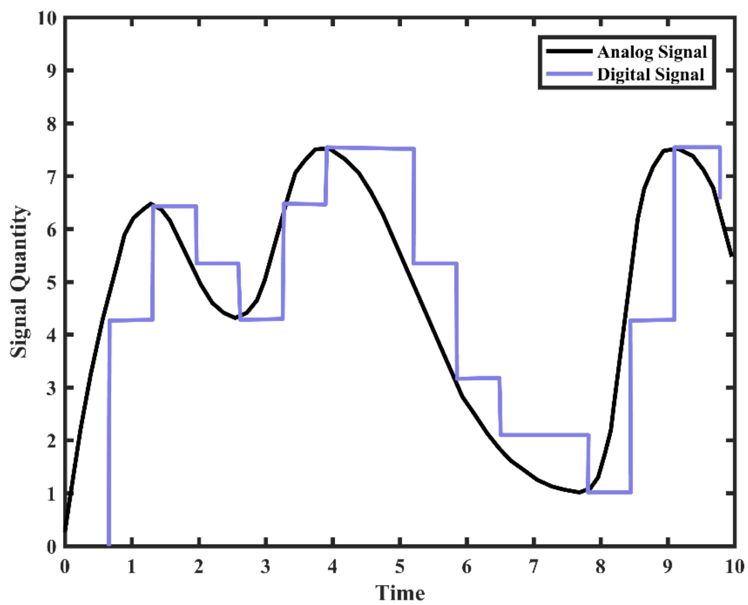


Figure 137. A Qualitative Graphical Representation of Digital and Analog Signal

Dipstick or rod and level profilers produce an elevation with each static setup. These sequences of numbers are inherently digital. This is because a continuous profile is impossible from these data. Similarly, the inertial profilers have computers connected to the transducer. At some intervals of time or distance, the computer takes the reading of the individual accelerometers and height sensors. Therefore, it is clear that the data collection interval has an impact on the viability of the collected data. To get a dataset of fine resolution the interval has to be small. It needs to be noted that, a dataset with small interval will have a huge amount of data, which needs a lot of storage space. For example, if sample interval Δx has the unit of yards, there are $\frac{1760}{\Delta x}$ samples per mile. A large dataset means the computation needs longer time because there are more numbers to process. To keep the process efficient the data set needs to be of a size that is not too small so that there is a lack of information. On the contrary, the size should not be too large so that it takes the inconsiderable amount of time.

Signal Processing

After gathering signal from the sensor, the information can be post-processed by a computer program to get the useful dataset. This step is called signal processing. In this step, signals are transformed into a more usable set of data. It can be defined as a signal modification, analysis, and synthesis. In other words, functions conveying "information about the behavior or attributes of some phenomenon" [39]. Signals are processed mainly for two reasons:

- For improving the quality of the measured data by reducing noise (unwanted data, a conjoined part of the data collected by electrical devices) from the data.
- To extract the useful information from the signal.

In this step signal from the accelerometer is gathered in one place and then they are fed into the aforementioned computer program to get the profile. The calculation of profile from accelerometer signal is a form of signal processing as well. It is almost impossible to find a signal that contains a wave of one frequency. So, a signal processor needs to disintegrate the complex signal into a set of simple waves by different signal processing techniques. Two of the commonly used techniques: (1) Frequency Response Analysis and (2) Power Spectral Density have been discussed in the following sub-sections.

Frequency Response Analysis

Filters, instruments, vehicles and other systems resemble a conceptual "Black Boxes" with an input and output. To understand the input/output behavior of these individual elements, the frequency response needs to be understood. Frequency response is the quantitative measurement of the output spectrum of a system in response to an input and is used to characterize the dynamics of the system. It is a measure of magnitude, phase and wavelength (see **Figure 138**) of the output as a function of frequency, compared to the input.

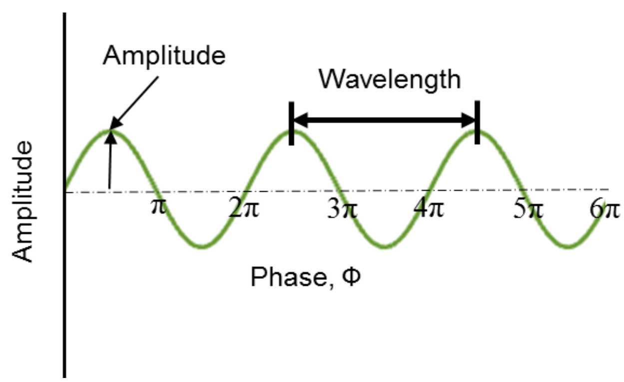


Figure 138. Phase, Wavelength, and Amplitude of a Sine Wave

In simplest terms, if a sine wave of a certain frequency is injected into a linear system, the response will be at that same frequency with a certain magnitude and phase angle relative to the input. For a linear system, input and output amplitudes have a linear relationship [40]. A nonlinear system, on the contrary, will yield an output of completely different magnitude and phase from the input. It is, therefore, significant to know how the pieces of the system are behaving in terms of frequency response.

Power Spectral Density

The power spectrum of a time series, x(t), describes the distribution of power into frequency components [41]. By Fourier analysis, a signal can be decomposed into a spectrum of frequencies or a number of discrete frequencies. The statistical average of a signal as analyzed in terms of its frequency content is called its spectrum. The reverse operation is possible as well. Which means an arbitrary shaped line can be constructed mathematically from a series of sinusoids with different wavelengths, amplitudes, and phases.

The Power Spectral Density (PSD) functions were originally developed from characterizing voltages. The same computation procedure is applied for road profiles to characterize them. However, the characterizations are not quite same. The differences between PSDs for road profile and voltage are:

- The variance has units of height squared rather than Volt squared
- The distribution is over wave number (cycle/unit length) rather than frequency

The power in the name PSD is titular in this case. This is because PSD has nothing to do with power, at least in the case of road profile computation. The power came in the name from its early application in electronics where it was applied in voltage analysis. Following figures are used to illustrate how PSD is applied in profile analysis. **Figure 139** shows two different road profiles.

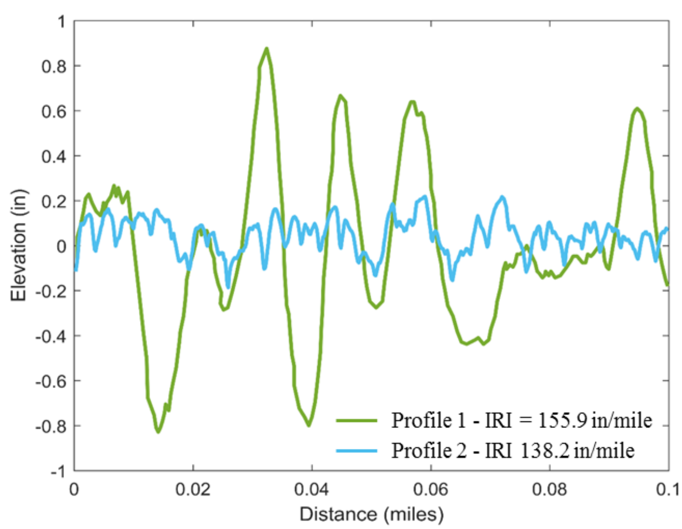


Figure 139. Road Profile of a 150m Section from Two Different Sites [18]

Although the shapes of the road profiles are quite different (Profile 1 is wavier than profile 2) their IRI is relatively close. This is one of the inherent problems with IRI. It does not have the profile information in it. To analyze the profile information, we need to seek help from PSD. **Figure 140** shows the PSD of those two profiles.

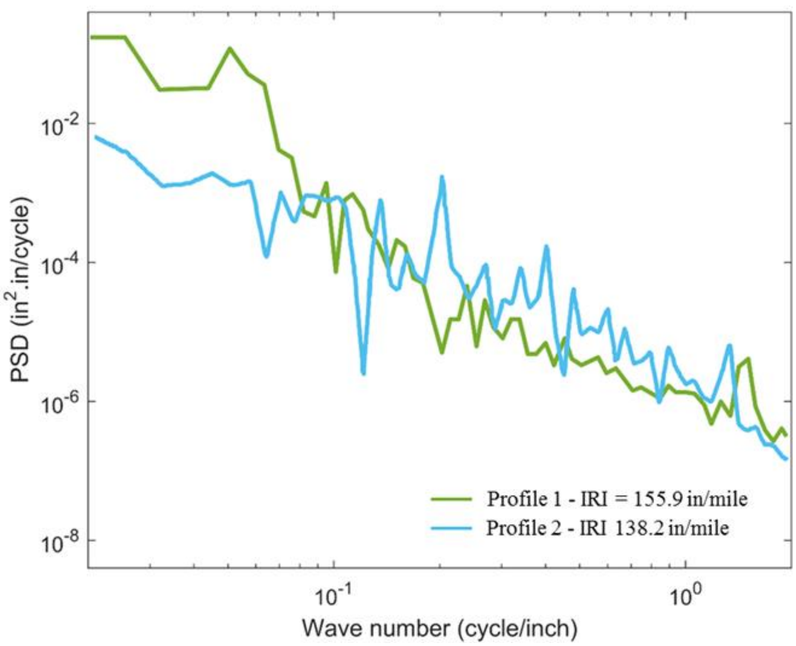


Figure 140. PSD of Road Profiles [18]

The wave number and left elevation PSDs were spread over a large range of value so a logarithmic scale was used for plotting. Amplitude is inversely related to wave number. The PSD plot reveals the characteristics of two profiles. The PSD for profile 1 has relatively higher amplitude for low wave numbers in the neighborhood of 0.03 cycle/ft (33 m cycle). It is correlated with the undulations visible in the previous plot. At the same time, profile 1 has lower amplitudes at higher wave numbers.

Signal Filtering

In electronics, components or circuits that modify voltage continuously are called filters. As mentioned earlier, the function of filters is to remove unwanted noise and to get information of interest. By definition "A digital filter is a calculation procedure that transforms a series of numbers (a signal) into a new series of numbers". Practically, the sequence of data has to be filtered before putting into use. Nowadays, all the profilers have filters built into the computer. Therefore, a profiler gets a filtered data based on the settings provided before starting data collection. It makes the system efficient by filtering out the junk data and saving disk space allowing more space to filtered data. In newer inertial profilers filtering is used to convert the data originating from the accelerometer and the height sensor into the same unit. Sometimes, an additional filter is added to prevent electronic noise from causing a large drift in the calculated profile. Sometimes the analyses involves multiple filters. In those cases, the output from one filter becomes input to the next. Conceptually, this is just like putting several screens to filter out the junk from the water. There is a myriad of filters available and many new filters can be programmed depending on the need of computation.

Moving Average: A Signal Filter

A good example of a filter is moving average, which is a simple filter commonly used in profile analysis. **Figure 142** is a graphical representation of moving average along with the original data. By definition, “a moving average filter replaces each profile point with the average of several adjacent points.” For a profile P that has been sampled at interval ΔX equation of moving average smoothing filter is shown in **Figure 141**,

$$P^{ma}(j) = \frac{1}{N} * \sum_{i=j-\frac{B}{2\Delta X}}^{i=j+\frac{B}{2\Delta X}} P(i)$$

Figure 141. Equation of Moving Average Filter

Here, P^{ma} is smoothed profile, B is the base length of the moving average, and N is Number of samples included in the summation.

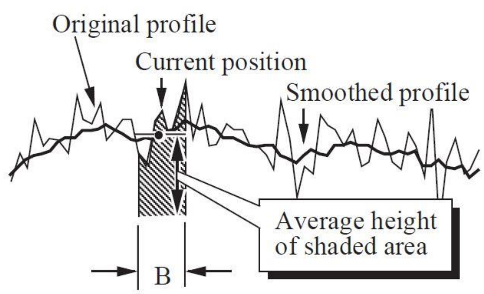


Figure 142. Moving Average Filter [18]

Moving average filter can be of two types. High pass and low pass filters. The low pass filter is applied to flatten the spikes. In other words, low pass filters are used to make the profile smoother. On the other hand, high pass filters are anti-smoothing filters that can keep the spikes and remove the low frequencies from the profile.

Appendix E Regression Equation Basics

This appendix discusses the basic theory behind regression analysis, and how the values of regression coefficients can be calculated. For demonstration purposes, a regression equation with two predictor variables has been derived. **Table 22** shows the predictor and criterion variables for multiple regression analysis.

Table 22. Example Predictor and Criterion Variables for Multiple Regression Analysis

Y	X1	X2
Y_1	$X1_1$	$X2_1$
Y_2	$X1_2$	$X2_2$
Y_3	$X1_3$	$X2_3$
...	...	...

Please note that increasing the number of independent variables increases the complexity of the formula for calculating the coefficients for final regression equation. After completing the regression analysis, the final regression equation is illustrated in **Figure 143**:

$$Y = I + n_1 \times X1 + n_2 \times X2$$

Figure 143. Regression Equation after Conducting Multiple Regression Analysis

The equation shown in **Figure 144** gives the formula for determining first coefficient (n_1) of equation in **Figure 143**.

$$n_1 = \left[\frac{R_{Y,X1} - R_{Y,X2} \times R_{X1,X2}}{1 - \left(R_{X1,X2}\right)^2}\right]\left(\frac{SD_Y}{SD_{X1}}\right)$$

Figure 144. Formula for Determining First Coefficient (n_1)

Here subscripts denote respective variables. For example, Y is the criterion variable, X_1 is the first predictor variable and X_2 is the second predictor variable. $R_{Y,X1}$ is the correlation coefficient between Y and $X1$. $R_{Y,X2}$ is the correlation coefficient between Y and $X2$. $R_{X1,X2}$ is the correlation coefficient between $X1$ and $X2$. SD_Y is the standard deviation for Y dataset. SD_{X1} is the standard deviation for $X1$ dataset. The procedure for calculating the correlation coefficient and standard deviation is explained later.

For determining the second coefficient (n_2) of the equation in **Figure 143**, a formula, similar to **Figure 144** is used as shown in
Figure 145.

$$\mathrm{n}_2 = \left[\frac{\mathrm{R}_{\mathrm{Y,X2}} - \mathrm{R}_{\mathrm{Y,X1}} \times \mathrm{R}_{\mathrm{X1,X2}}}{1 - \left(\mathrm{R}_{\mathrm{X1,X2}}\right)^2}\right]\left(\frac{\mathrm{SD}_{\mathrm{Y}}}{\mathrm{SD}_{\mathrm{X2}}}\right)$$

Figure 145. Formula for Determining Second Coefficient (n_2)

$R_{Y,X2}$ is the correlation coefficient between Y and $X2$. $R_{Y,X1}$is the correlation coefficient between Y and $X1$. $R_{X1,X2}$ is the correlation coefficient between $X1$ and $X2$. SD_Y is the standard deviation for Y dataset. SD_{X2} is the standard deviation for $X2$ dataset.

Please note that multiple regression takes into account the standard deviation and correlation among the datasets. Thus, the equation produced by multiple regression analysis is a combination of two broadly used statistical tools. Finally, the intercept, I, is calculated using the formula shown in **Figure 146**.

$$\mathrm{I} = \overline{\mathrm{Y}} - \mathrm{n}_1 \times \overline{\mathrm{X1}} - \mathrm{n}_2 \times \overline{\mathrm{X2}}$$

Figure 146. Formula for Determining the Intercept (I)

Here, $\overline{\mathrm{Y}}$ is Average of Y dataset (Criterion variable), $\overline{\mathrm{X1}}$ is the average of $\mathrm{X1}$ dataset, and $\overline{\mathrm{X2}}$ is the average of $\mathrm{X2}$ dataset. The procedure for calculating the correlation coefficient and standard deviation is explained below. Please note that the correlation coefficient, denoted by r or R explains the relation between two datasets. The closer the absolute value of r is to one, the better the data are described by a linear equation. If r =1 or r = -1, the datasets are perfectly aligned. Data sets with values of r close to zero show little to no straight relationship. For demonstration purposes, a correlation study is shown using two datasets. The formula for calculating correlation coefficient is shown in **Figure 147**.

$$r = \frac{\mathrm{n} \times \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{X_i Y_i} - \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{X_i} \times \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Y_i}}{\sqrt{[\mathrm{n} \times \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{X_i^2} - (\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{X})^2][\mathrm{n} \times \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Y_i^2} - (\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Y})^2]}}$$

Figure 147. Formula for Determining Correlation between Two Datasets

Here, n is the number of data points in the dataset, and the subscript i denotes the i^{th} component in that dataset.

Finally, the standard deviation shows how tightly the provided data is clustered around the mean. This function can be operated on one dataset only. This is why one dataset denoted by X is considered for the sake of this example. The formula for calculating the standard deviation is shown in **Figure 148**.

$$\mathrm{SD} = \sqrt{\frac{\sum_{\mathrm{i}}^{\mathrm{n}} (\mathrm{X_i} - \overline{\mathrm{X}})^2}{\mathrm{n} - 1}}$$

Figure 148. Formula for Calculating Standard Deviation

Here, n is the number of data points in the dataset, $\overline{\mathrm{X}}$ is the average of dataset X, and the subscript i denotes the i^{th} component in that dataset.