USDOT Region V Regional University Transportation Center Final Report

098IY04 Integration of Smart-Phone-Based Pavement Roughness Data Collection Tool with Asset Management System

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CHAPTER 1. INTRODUCTION

1.1   *Background and motivation*

With shrinking maintenance budgets and the need to 'do more with less,' the need for accurate, robust asset management tools are greatly needed for the transportation engineering community. There are about 2.6 million paved public roads in the United States roadway network, and many transportation agencies utilize a pavement management system (PMS) to manage their pavement network in an efficient and cost-effective manner (Flintsch and McGhee 2009). PMSs require pavement roughness information along with other distress data. Pavement roughness is the deviation of pavement surface profile from planarity, which affects overall ride quality. Pavement roughness also slightly increases fuel consumption and therefore emission levels. Fuel consumption can be increased as much as 4-5 percent for very rough pavements (Klaubert 2001). Most transportation agencies use measures of the International Roughness Index (IRI) in planning maintenance and rehabilitation operations. Decades ago, roughness measurements were generally performed using manual equipment, such as a sliding straightedge. Technological advances have led to highly automated pavement condition assessments using sophisticated data collection vehicles equipped with sensitive inertial profilers.

According to NCHRP Report 334, most transportation agencies now collect pavement roughness data using automated systems for at least part of their roadway network. Although very little has been reported in the literature on the cost of conducting IRI measurements, one study found reported pavement profile data collection and analysis involve agency costs in the range of $2.23 - $10.00/mile with an average cost of

$6.12/mile (McGhee 2004). Considering the 139,577 miles of roadways of the state of Illinois, this would involve an expenditure of approximately $1.4 million per pavement network system assessment. This is consistent with a report by the Mid-Atlantic universities transportation center which found that the Virginia Department of Transportation (VDOT), "a contractor is employed to gather roughness data at an annual cost of $1.8 million" (Sauerwein and Smith 2011), and data are collected once every five years for secondary roads. Many transportation agencies do not collect pavement condition data on an annual basis for large portions of their road network because of these high costs. Thus, maintenance and rehabilitation decisions are oftentimes performed using outdated roughness data. In addition, in-frequent roughness measurements preclude the identification of rapidly developing distress features on pavements such as potholes developing during spring thaw or dangerous blow ups in Portland cement concrete pavements, which is a missed opportunity for the enhancement of roadway safety and therefore increases tort liability.

Modern smartphones have built-in, 3-axis accelerometers and global positioning systems, which were investigated in this study as an efficient means for collecting and mapping vehicle vertical acceleration data and estimated pavement roughness (IRI). If successful, this crowd-sourcing based system has the potential to collectively save agencies millions of dollars.

Besides shortcomings and expenses associated with current pavement roughness measurement systems, this study was also motivated by other potential benefits of having a smart-phone based roughness measurement system, such as crowd sourcing for real-time pavement condition assessment (pothole or other pavement defect detection) and the ability to inform users about route choice in terms of user costs and sustainability (fuel use/emissions/carbon footprint).

1.2   *Study objectives*

The objectives of this study include:

(a) Segments of roadways in Illinois will be selected in order to evaluate the ability of the tool to assess roughness created by cracks of varying severity level (crack width, spalling, cupping, tenting, and potholing).

(b) Data collection at selected sites/segments will be conducted. First, a data collection van (DCV) will be operated over the selected segments, and the Android-based application will also be used to collect acceleration and GPS data. The collected data will be used to compare acceleration data as collected by the Android-device to the roughness data collected by the DCV, which will also be compared to distress information collected by other sensors on the DCV (video logs, laser-based profile measurements, and accelerometer data). Maintenance activities such as crack routing, sealing, and local milling (bump grinding) will be documented, as these activities affect the relationship between pavement distress severity level and pavement roughness. Repeatability trials and trials at different vehicle speeds will also be assessed.

(c) The robustness of the Android-based pavement roughness system will also be tested by running a selected fleet of other vehicles over selected pavement segments and collecting data with the Android-based application. This will help researchers to assess the degree of calibration required to use the Android-based application over a wide array of vehicle types.

(d) Using the data collected above, the Android-based application will be improved, calibrated, and validated (independent test sites will be used and results compared to DCV results) in order to be used for wide-spread data collection.

1.3 *Organization of the research*

The organization of the remainder of this report is now summarized. Chapter 2 provides the concepts underlying pavement roughness, measurement and evaluation procedures. Chapter 3 introduces a newly developed cellphone application to measure pavement roughness. Chapter 4 presents pavement site selection criteria, data collection, and analysis procedures. Chapter 5 provides results and a discussion of study findings.

Finally, Chapter 6 provides a summary, conclusions and recommendations for future work.

CHAPTER 2. PAVEMENT ROUGHNESS

This chapter introduces the concept of pavement roughness and outlines standard measurement principles using an inertial profiler and other currently available devices. The Digital Survey Vehicle (DSV) is commonly used for pavement roughness data collection. A short description of DSV systems is also provided.

2.1   *Introduction*

According to ASTM E867, pavement roughness can be defined as "the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality" (ASTM 2012). As rough pavements impart vehicle accelerations, this in turn adversely affects vehicle wear, ride quality, and safety (Van Deusen 1967; Brickman et al. 1972; Abaynayaka et al. 1976; Gillespie and Sayers 1981). In order to introduce a common scale worldwide to quantify pavement roughness, an International Roughness Index (IRI) has gained general acceptance. The IRI is so-named because it was identified as the preferred roughness parameter considered in the International Road Roughness Experiment (IRRE) which was held in Brasilia, Brazil in 1982 and supported by the World Bank (Sayers et al. 1986). Now, the IRI is the standard scale used to quantify pavement roughness in the United States. IRI is calculated from the profile of the pavement, which can be measured using manual or automated pavement profilers. According to Perera et al. (2005), three vehicle responses have relationship with IRI, including road meter response, vehicle vertical acceleration, and tire load.

The International Roughness Index (IRI) is a numerical scale used to quantify the deviation/roughness of a pavement surface based on a simulated vehicle response resulting from travel over a pavement with a given profile. Pavement profile (elevation versus position along route) is processed through a quarter car simulation model (Figure 2.1) that simulates the response of a reference vehicle traveling at 50 miles per hour in terms of vehicle suspension motion (MnDOT 2007).
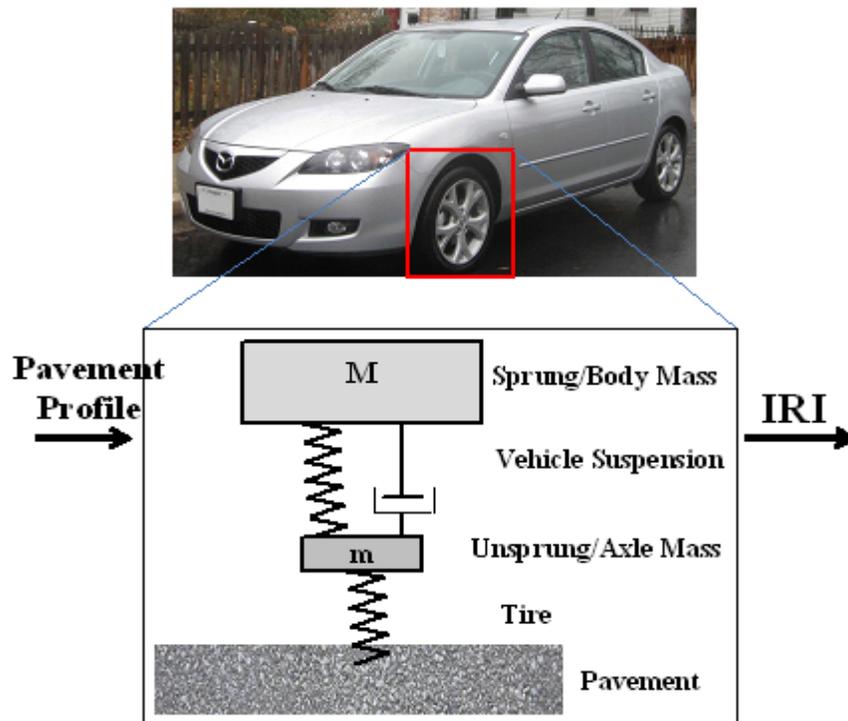
Figure 2.1 Schematic illustrating international roughness index calculation (after Perera et al. 2005)

From Figure 2.1, it can be seen the quarter car model has five components which include body mass supported by a single tire, axle mass, a vertical spring representing a tire, a suspension spring and a damper (Perera et al. 2005). The suspension deflection is determined by the simulation and normalized by the distance traveled by the vehicle in the simulation to obtain the average suspension motion over the simulated distance. The obtained value is expressed as IRI with a unit of inch/mile or m/km. Generally, a software program is used to determine the IRI from measured pavement profile. A profile

obtained from each wheel path is used to determine IRI, and the average value is then reported.

Pavement ride quality can be classified based on IRI. According to the U.S. Department of Transportation (1999), pavement ride can be categorized into five groups, as shown in Table 2.1.

Table 2.1 Pavement Ride Quality Based on Roughness (*13*)

Category	IRI Rating (inch/mile)		Interstate and NHS Ride Quality
	Interstate	Non-Interstate	
Very Good	< 60	< 60	Acceptable 0 - 170
Good	60 - 94	90 - 94	
Fair	95 - 119	95 - 170	
Poor	120 - 170	171 - 220	Less than acceptable > 170
Very Poor	> 170	> 220	

2.2   *Existing pavement roughness measurement systems*

Although pavement profile measurements were of major interest to researchers decades ago, most agencies now conduct pavement roughness measurement on a routine basis (Woodstrom 1990). While many devices and methods are available to evaluate pavement ride quality, most are not currently utilized because of low accuracy and/or measurement inefficiencies. The devices that are typically used in the US can be divided into four categories: calibration and construction control, response-type systems, accelerometer-based systems, and non-contact profile measurement systems. Calibration and construction control devices are generally used to check the profile of the new constructed layer which includes profilographs, dipsticks, and Ames profilographs. Response-type systems include Mays Ridemeters and B&K accelerometers. Accelerometer-based systems include Portable Universal Roughness Devices (PURD), Dynatest 5000 Roughness Distress Meters, Self-Calibrating Roughness Units, and. Noncontact profile-measuring systems include K.J. Law Roughness Surveyors, Laser Road Surface Testers, South Dakota Profilometers, Automatic Road Analyzers (ARAN),

and Surface Dynamic Profilometers. ARRAB (Australian Road Research Board), ICC SurPRO (International Cybernetics Corporation), and SSI (Surface Systems and Instruments) are the most widely used reference profilers.

Profilographs are generally used for construction inspection, quality control, and acceptance of smoothness of concrete pavement. A rolling straightedge consists of a rigid beam having a fixed wheel on each end and a third wheel capable of vertical movement located at the middle of the straightedge. An indicator is attached to the middle wheel which records the deviation of the pavement at the center wheel relative to the plane of the rolling straightedge. Rolling straightedges are quickly becoming obsolete and impractical for general use due to inefficiency and inaccuracy (Woodstrom 1990). For instance, the California profilograph can only evaluate 1.9 to 3.1 miles of pavement per hour. It has been reported that profilographs tend to amplify or attenuate true pavement profile (Perera et al. 2005).

With these shortcomings, efficient, automated, and highly repeatable inertial profilometers were developed. According to Woodstrom (1990), modern inertial profilometers 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 of 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

Figure 2.2 Automated pavement profiler and equipment on a typical data collection van

IRI is used to measure roughness in 47 states within the US; however, at least 10 different approaches have been used to collect IRI (Finn 1998). Not only do variations exist among the tools used to collect pavement profile, but different analysis methods are also used (choice of wheel path data, averaging techniques).

2.3 *Data collection vehicle*

The Digital Survey Vehicle (DSV), a.k.a., data collection vehicle, is a sophisticated and powerful device used in pavement and infrastructure management (a.k.a., 'million dollar van'). The DSV collects high-resolution images of the pavement surface and right-of-way (ROW) while traveling at posted speeds. Pavement surface conditions are captured with a very high-resolution downward facing camera, and three ROW cameras collect images of the surrounding area.

In addition to the digital images, the DSV measures longitudinal profile (roughness) and transverse profile (rutting and cross slope) of the pavement surface. The DSV has a global positioning system (GPS) receiver and an inertial navigation system, which together are capable of measuring the location of the vehicle with sub-meter accuracy while moving, even during short outages of the GPS signal. All data and images

are collected in a digital format and geo-referenced with GPS data. The DSV used in this study was equipped with the following integrated survey systems as shown in Figure 2.3:

a) ICC Road Profiler (ASTM E-950) with up to 5-laser sensors. It is currently configured with two 32 kHz lasers in the wheel paths and one 16 kHz laser in the center front bumper position.

b) Applanix POS/LV 420 Inertial Navigation System

c) OmniStar Differential GPS Receiver

d) Geo3D Kronos Asset Management Camera System with four 2448 x 2048 color digital area scan video cameras. These are typically configured three to the front in panoramic mode and one to the rear.

e) Distance Measuring Instrument accurate to 1 ft/mi

f) DSV Positioning Computer showing the real time vehicle location during data collection on a client provided GIS map.

Figure 2.3 Digital survey vehicle used in this study

CHAPTER 3. ROUGHNESS CAPTURE CELLPHONE APPLICATION

Chapter 3 describes smartphone's accelerometer utilization to collect pavement roughness data. Details regarding the Roughness Capture Application are also provided herein. Finally, details are provided regarding how the smartphone application can collect data from pavement sections, determine roughness, provide network level condition assessment information.

3.1   *Introduction*

Pavement surface irregularities (non-planar road profile) lead to vertical accelerations in moving vehicles. The magnitude of vertical acceleration depends on the severity and frequency of pavement distresses and other surface irregularities, vehicle suspension characteristics, and vehicle speed. A 3-axis accelerometer enabled cellphone can be used to collect vehicle vertical acceleration data, as demonstrated in previous studies, such as those conducted at the Massachusetts Institute of Technology (Data-Informed 2013) to identify localized pavement defects. An android-based cellphone application has been developed in the present study that can capture acceleration for the purpose of characterizing pavement roughness and individual pavement distresses. Figure 3.1 shows vehicle vertical acceleration data collected using Roughness Capture, an android-based smartphone application developed by Applied Research Associates, Inc. in Champaign, Illinois and validated by researchers at the University of Illinois under a project sponsored by the NexTrans University Transportation Center.

3.2   *Roughness capture application*

Modern smartphones are equipped with a number of sensors including multi-axis accelerometers, temperature probes, gyroscopes, light intensity sensors, magnetic field sensors, etc. (Sensors and Cellphones 2013). The Roughness Capture application collects acceleration in three orthogonal directions, a timestamp, and GPS coordinates and stores them in an ASCII text file. Data collection rate is specified by the user, generally in the range of 10 – 100 samples per second, but higher sampling rates are possible depending upon smartphone hardware. In general, the higher the data collection rate, the better the accuracy of the estimated pavement profile (with diminishing returns at very high sampling rates).

(a) Cellphone App Capturing Vertical Acceleration

(b) Roughness Capture Interface

(c) Acceleration Data Capturing

Figure 3.1 Illustration of smartphone based roughness capture system

3.3   *Project approach*

Data collection and analysis included the collection of vehicle vertical acceleration data, the storage and retrieval of data from a smartphone, the generation of a MATLAB script to double integrate the collected acceleration data into profile data, and finally, the determination of IRI using the ProVAL software program (Figure 4). Data collection was performed at a driving speed of 50±2 mph. An android-based cell phone (Samsung Galaxy with Android Operating System 2.4) was utilized in conjunction with the Roughness Capture application.
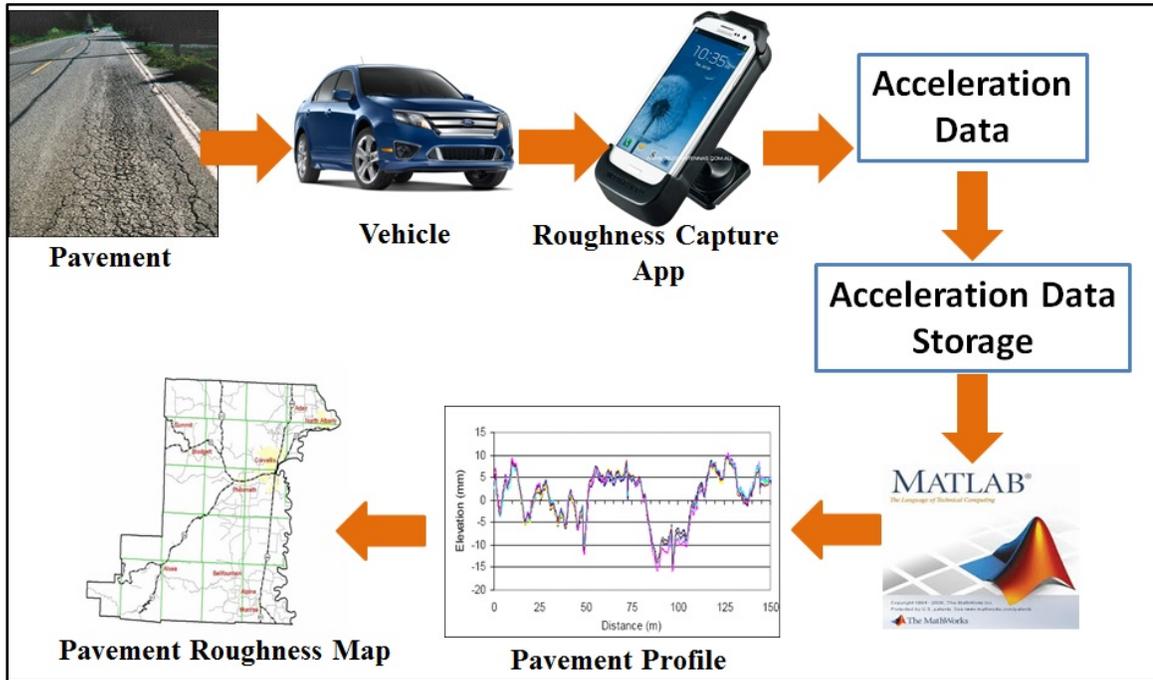
Figure 3.2 Project approach

CHAPTER 4. FIELD DATA COLLECTION AND ANALYSIS PROCESS

This chapter introduces selection criteria for pavement sections evaluated, and provide illustrative examples of the data acquisition procedure used. Data analysis techniques are also described in this chapter.

4.1   *Data collection*

For validation of the new Roughness Capture app, a Honda CRV equipped with an internal profiler was used to collect reference pavement profile data. The inertial profiler consisted of an accelerometer, a height sensor, distance measuring instrument (DMI), and a computer system for data acquisition and storage. Pavement profile data along with vehicle driving speed and traveled distance were collected. While collecting profile data using the inertial profiler, a smartphone was mounted on the dashboard using a standard car mount (Figure 3.1), and the Roughness Capture application was used to collect acceleration data, GPS location, and timestamp. Three test sites were selected from three different county highways within a 10 mile radius of Rantoul, IL, and having a wide range of pavement roughness (Figure 4.1). Test sites were 2-miles long, and the test vehicle was driven at steady speed of 50 mph in the rightmost driving lane. Site 1 was the northbound lane of County Highway 32 east of Rantoul, IL. Site 2 was the westbound lane of County Highway 9, and Site 3 was on the southbound lane of County Highway 23, both in close proximity to Rantoul, IL (Figure 4.2). A minimum of two data collection runs were conducted at each site, with five replications used in selected instances to assess Roughness Capture repeatability.

During this study, a data collection rate of 100 points/second was used. For the standard speed of 50 mph, the vehicle travels 880 inches/second. Thus, the spacing of acceleration data points was 8.8 inches.
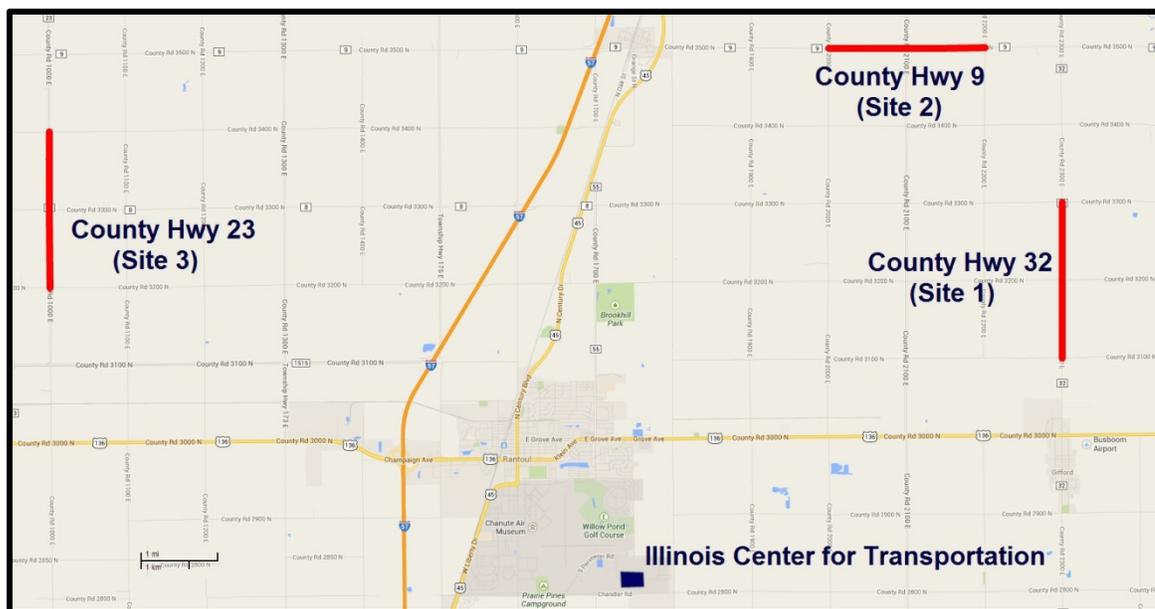
Figure 4.1 Location map of data collection sites

(a)   **(b)**

(c)

Figure 4.2 Pavements with distress level: (a) few or no visible distress, (b) few transverse cracking, and (c) very rough pavement with many types of distresses

4.2   Data analysis

Inertial profilers provided pavement roughness parsed out in 0.1-mile sections within the 2-mile test sites. Vehicle acceleration data collected by roughness capture was analyzed to estimate pavement roughness. First, acceleration data was processed by an in-house MATLAB code to obtain pavement profile data (double integration of acceleration data), and then the estimated pavement profile was analyzed using ProVAL (The Transtec Group, Inc. 2013) to estimate roughness in terms of IRI. A detailed mathematical proof and verification of the developed method is beyond the scope of this report, but will be provided in the PhD dissertation of Mr. Shahidul Islam. Pavement roughness of each 0.1-mile section was estimated using the ProVAL software across the 2-mile long test sections. It is acknowledged that our current approach does not produce a true profile of pavement surface, but rather a 'perceived profile.' This is due the effects of dampening provided by the vehicle suspension system. Efforts to incorporate vehicle suspension effects into the data analysis scheme used in Roughness Capture are underway, and will be reported in a subsequent paper.

CHAPTER 5. RESULTS AND DISCUSSION

This chapter describes comparison of cellphone measured roughness to profiler measured roughness, repeatability of roughness measurement using cellphones, summaries findings of this research, and finally, illustrates directions for future research.

5.1   *Comparison of IRI estimated by cellphone application and data collection vehicle*

Figure 5.1 shows pavement roughness values estimated by the smartphone based app and an industry standard inertial profiler for two different runs at site 1. IRI values of every 0.1-mile section of the 2-mile section were plotted (20 points). A good correlation between the two methods was observed, without the need for system calibration. For reference, two horizontal lines were drawn at 10 inch/mile offsets from the unity line to help visualize the magnitude of deviation of the smartphone measured IRI values from those of inertial profiler. It can be seen that most of the values (seventeen sections out of twenty) were in the 10 inch/mile offset band, indicating a very good correspondence between the two methods. In Figure 5.1(a), only one 0.1-mile section showed distinctly different IRI values, which might change the pavement ride category assessment for that particular section. In Figure 5.1(b), only three 0.1-mile sections were outside of the inch/mile offset lines. Although some differences exist, it appears that the same overall pavement management decision would be reached for the 2-mile section using the IRI values determined using each approach.
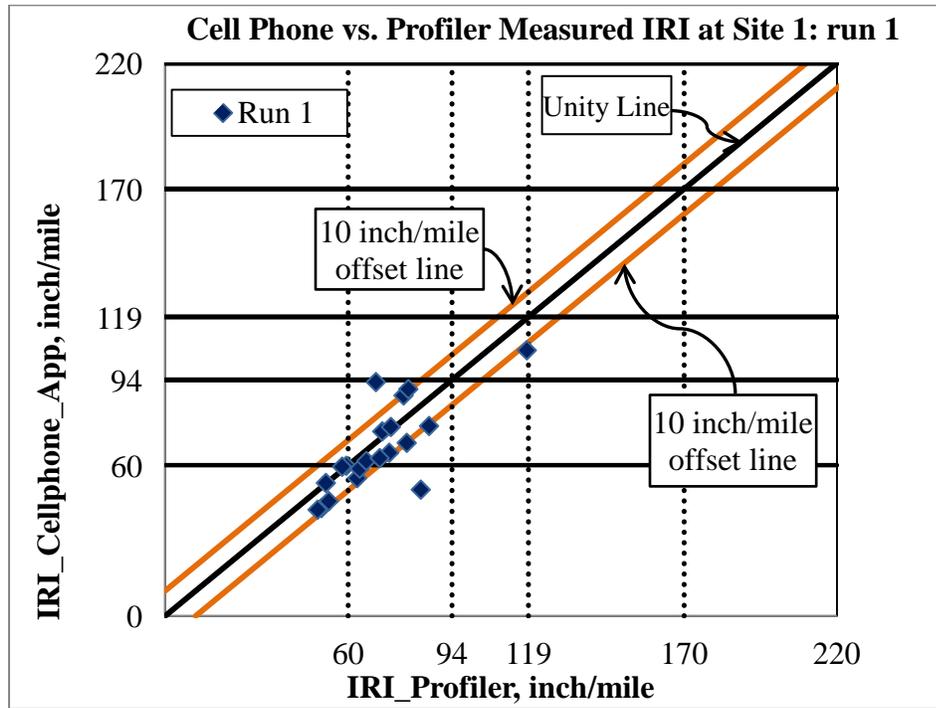
(a)
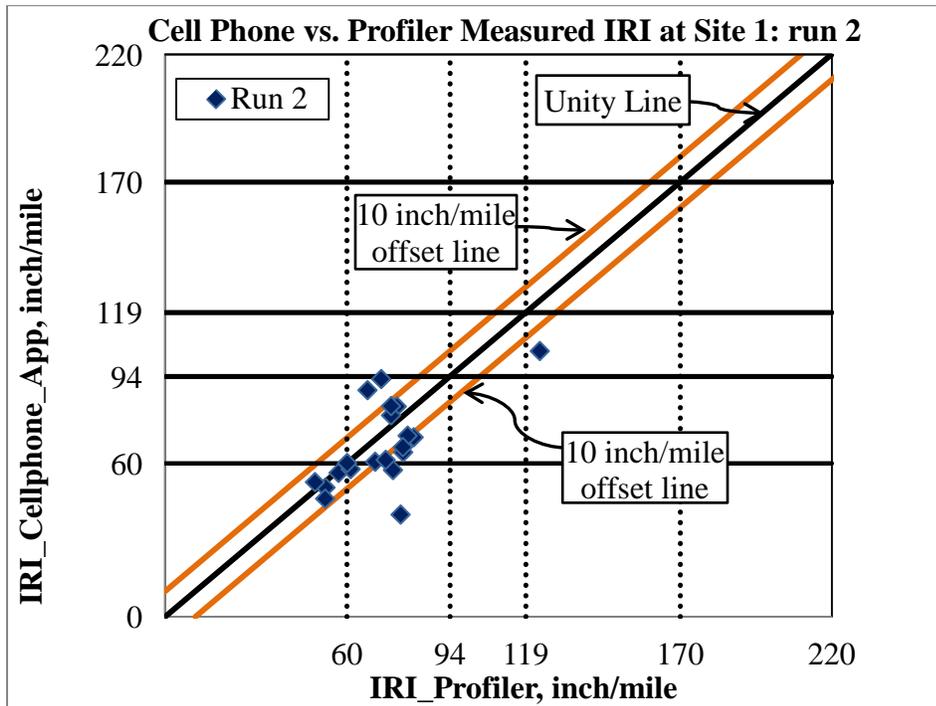
(b)

Figure 5.1 Comparison of pavement roughness data measured by cellphone application and profiler for County Highway 32: (a) Run 1 and (b) Run 2

Figure 5.2 shows the pavement roughness measured by the roughness capture application and inertial profiler for two different runs conducted at pavement site 2. Again, IRI values estimated by the Roughness Capture smartphone application corresponded closely to those measured by inertial profiler system without the need for system calibration.


(a)
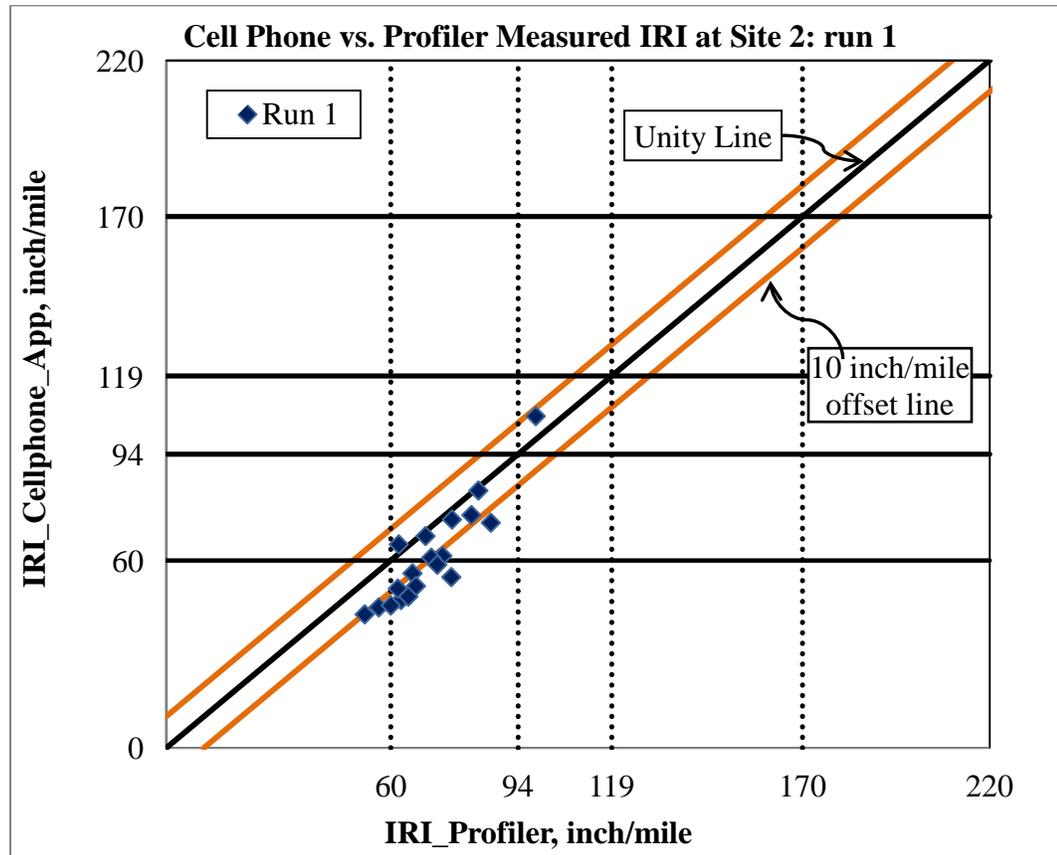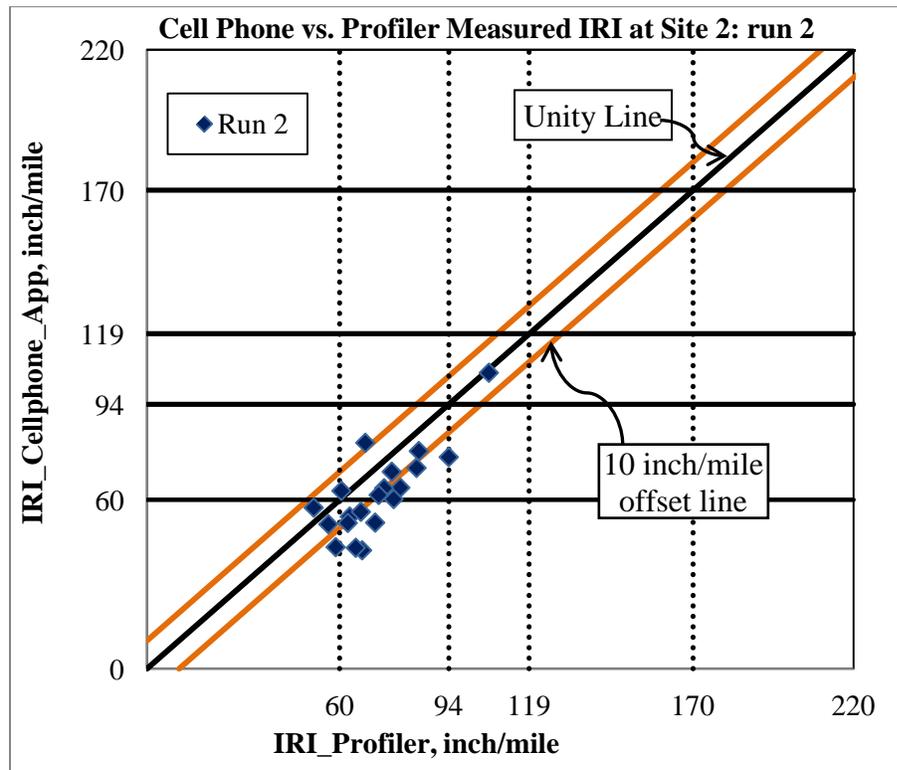
(b)

Figure 5.2 Comparison of pavement roughness data measured by cellphone application and profiler for County Highway 9: (a) Run 1, and (b) Run 2

Figure 5.3(a) shows the pavement roughness values measured at site 3, which had much higher pavement roughness. In this section, it was observed that the uncalibrated smartphone measured IRI values were below the unity line (IRI was underpredicted). As stated earlier, acceleration data was sampled at a longitudinal distance of 8.8 inches in the smartphone based system using a 100 sample/section data collection rate. In contrast, the more sophisticated inertial profiler system collects data at intervals of less than 1 inch. Due to the high pavement roughness and high number of significant vehicle acceleration events, it is speculated that the 100 samples/second data collection rate used might have contributed to the underprediction of pavement roughness in this section. Another explanation is the heightened effect of damping resulting from the vehicle suspension system, which is not currently accounted for in our analysis scheme. A regression

equation (calibrated IRI = 0.95*Cellphone measured IRI + 58) was used to explore if a simple linear correlation could be used to calibrate smartphone determined IRI values. Figure 5.3(b) shows calibrated smartphone measured IRI, which are dispersed around the unity line in a similar fashion as sections 1 and 2. Testing is underway to assess factors such as vehicle type (varying suspension characteristics), smartphone type, and vehicle wander on IRI measurement, which will be incorporated with an enhanced analysis model that will account for vehicle suspension dampening.


(a)

(b)
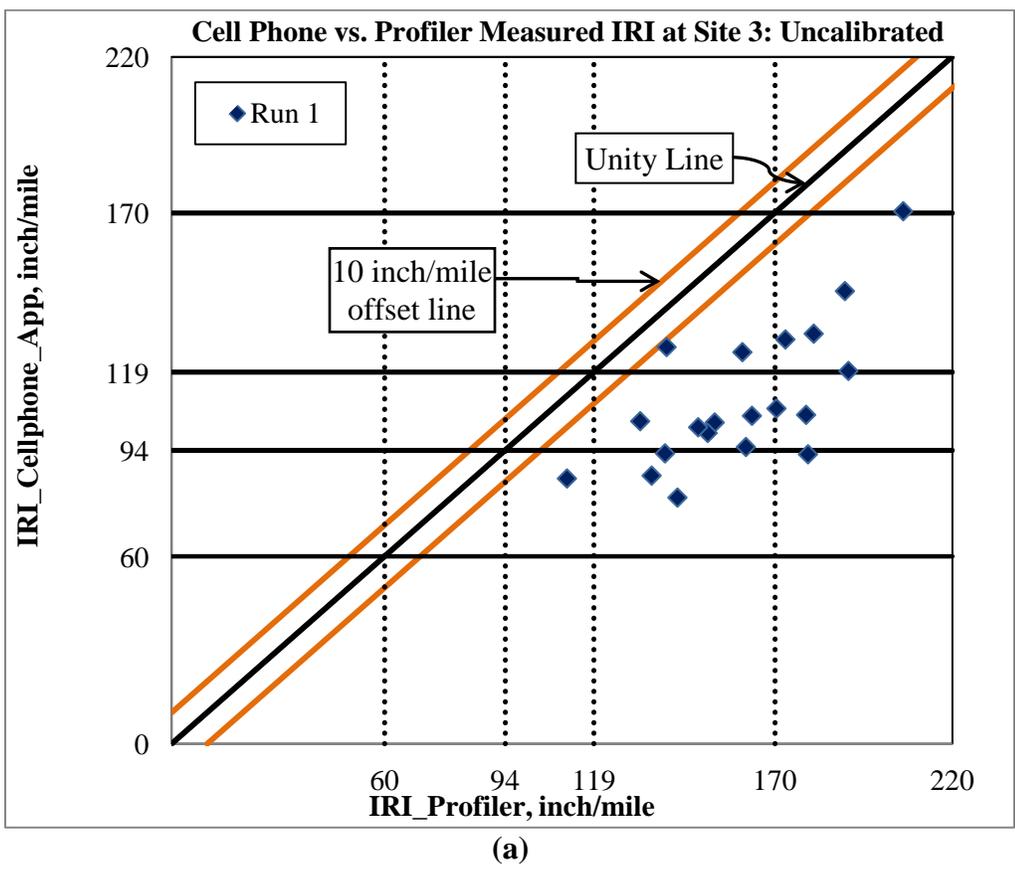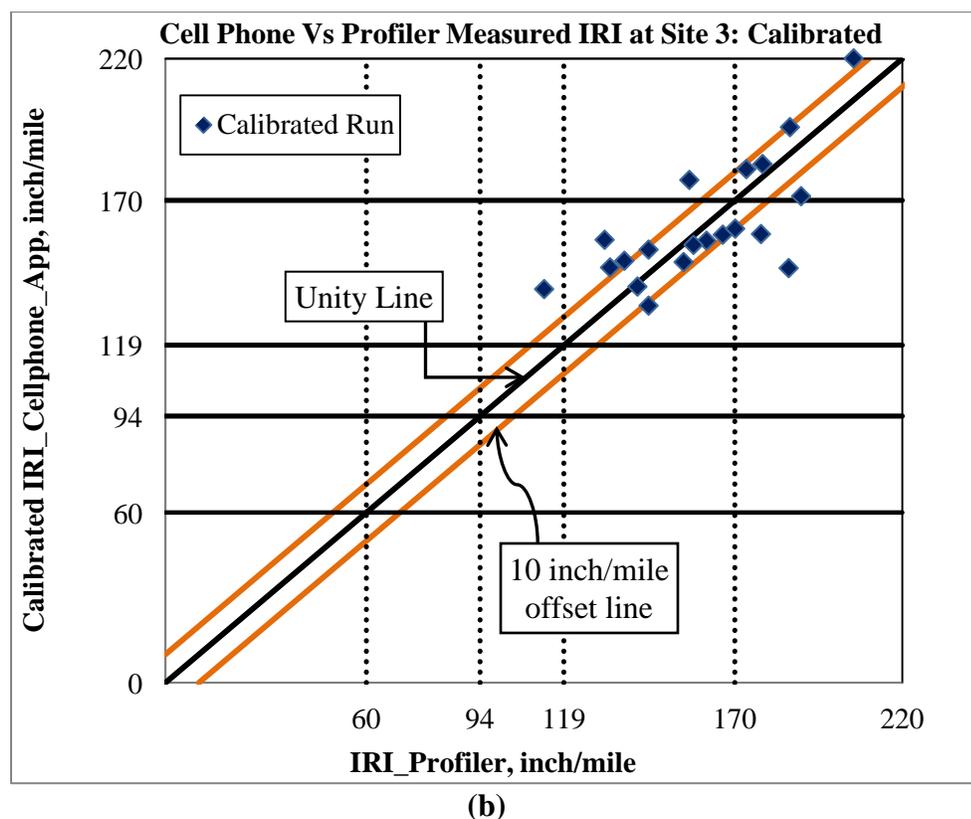
Figure 5.3 Comparison of pavement roughness data measured by cellphone application and profiler at County Highway 23: (a) Original Run and (b) Calibrated Run

5.2   *Repeatability of smartphone based IRI measurement system*

Figures 5.4 through 5.6 show IRI data for every 0.1-mile section of sites 1-3, respectively. IRI data were collected five times to assess the repeatability of the "roughness capture" android-based smartphone application. The x-axis values represent the distance along the driving lane whereas y-axis values chart the IRI measured by the roughness capture app. Pavement ride categories as presented earlier in Table 2.1 were used to form the y-axis scale. The results suggest that the effects of vehicle suspension on vertical acceleration value is higher on rougher roads, and measured IRI values at Site 3 are lower than reference values of IRI. Here, the average COV's are 11, 9, and 9 percent at Site 1, Site 2, and Site 3, respectively. In comparison, the COV of measuring IRI with an inertial profiler may be less than 5 percent, but considering the cost of measuring IRI

via an inertial profiler (McGhee 2004), a COV of 10 percent for the smartphone-based Roughness Capture application appears to be reasonable. We have also noticed the importance of precisely matching the location of pavement segments used when comparing smartphone based roughness to the reference data from a data collection van. As we continue to improve location matching, accuracy is found to improve. From these figures, it can be seen that repeatability of the roughness capture application is quite good overall. It can be seen that most of the repeated measurements for each 0.1-mile pavement section were within the same smoothness band, which indicates that the range of deviations did not change the smoothness classification of those pavement sections.
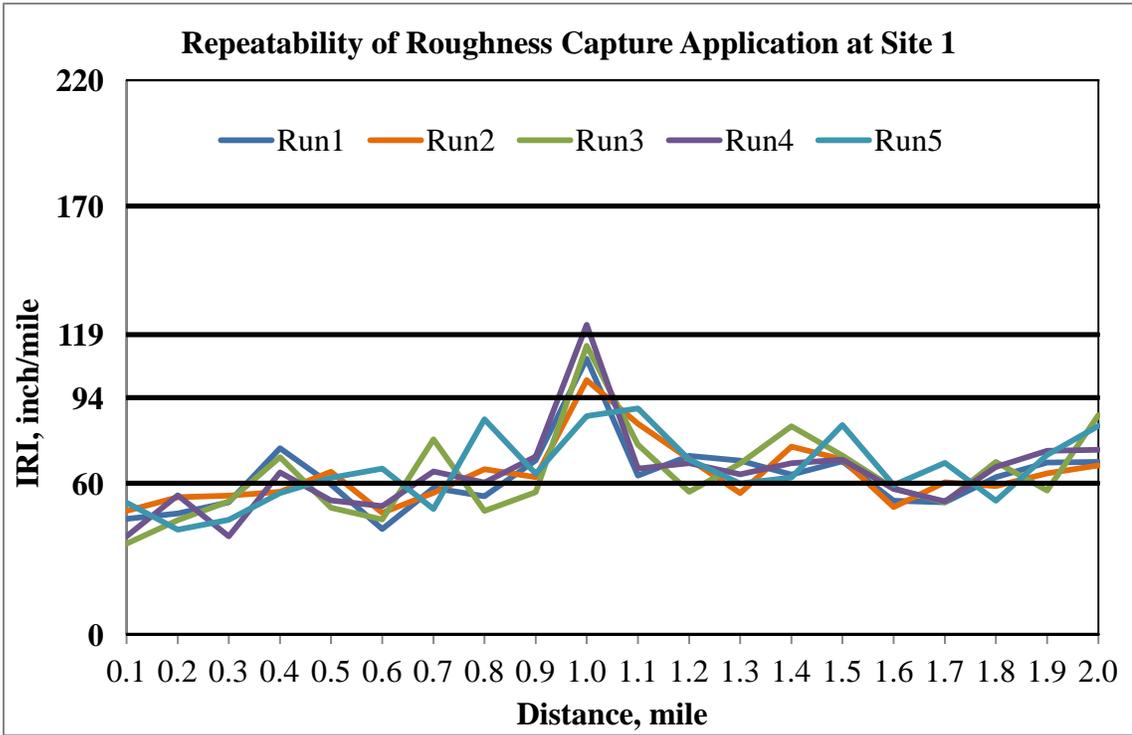

Figure 5.4 Estimation of IRI at County Highway 32 over five different runs
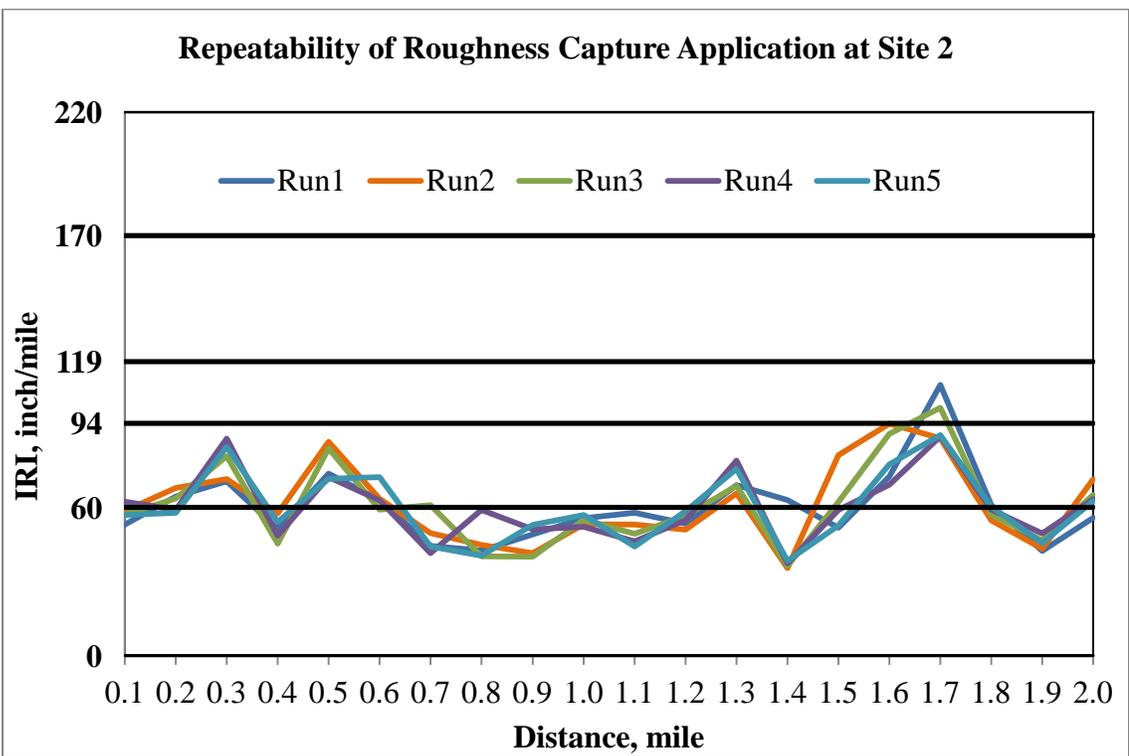
Figure 5.5 Estimation of IRI at County Highway 9 over five different runs
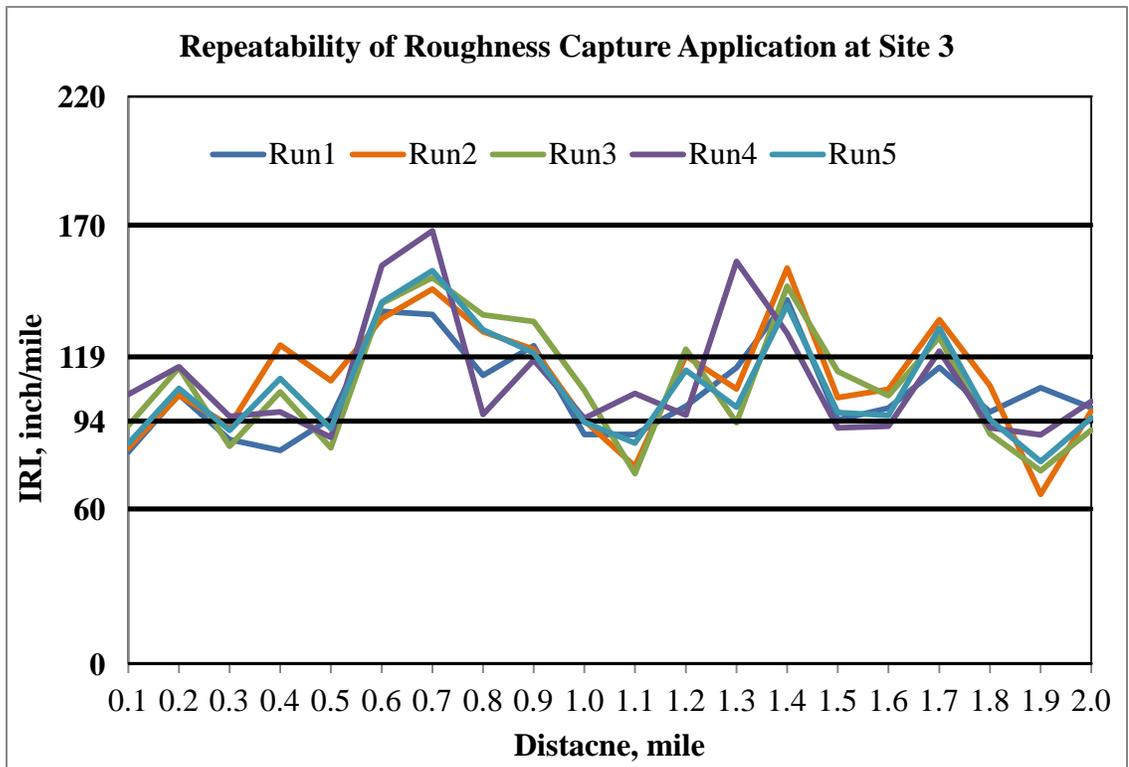
Figure 5.6 Estimation of IRI at County Highway 23 over four different runs

Table 5.1 shows average IRI, standard deviation, and coefficient of variance (COV) of every 0.1-mile section of each testing site. From the left portion of the table, it can be seen that most of the COV's are less than 15 percent except for a few sections. For one pavement section, the COV was estimated as 22 percent. The highest COV measured was 28 percent, within section 2. Given the fact that it was impossible to drive the test vehicle along the exact same path in terms of vehicle wander; the repeatability of IRI measurements with the new roughness capture app appears to be acceptable for the purpose of collecting useful pavement condition data in a rapid, inexpensive manner. This conclusion is further justified considering the possibility of using crowd sourcing to obtain a large number of measurement replications, which can then be used to arrive at a more accurate and possibly real-time pavement condition assessment. A crowd sourcing feasibility study will be the subject of a later investigation.

Table 5.1 Repeatability of Roughness Capture data

County Highway 32			County Highway 9			County Highway 23		
Average IRI, inch/mile	St. Dev.	COV	Average IRI, inch/mile	St. Dev.	COV	Average IRI, inch/mile	St. Dev.	COV
44.4	6.8	15	57.5	3.4	6	89.5	9.2	10
48.9	5.9	12	62.5	4.1	7	109.0	5.5	5
48.9	6.7	14	79.0	7.7	10	90.0	4.6	5
64.2	8.0	12	51.3	4.8	9	103.9	15.2	15
57.9	6.0	10	77.5	7.1	9	93.5	10.0	11
50.5	9.2	18	64.1	4.9	8	140.9	8.0	6
61.2	10.5	17	48.1	7.7	16	150.1	11.8	8
63.0	14.0	22	45.3	7.8	17	120.4	15.9	13
64.4	5.6	9	46.9	5.8	12	123.2	5.7	5
106.9	13.8	13	54.5	1.9	4	95.6	6.3	7
75.5	11.4	15	50.1	5.5	11	85.8	12.3	14
66.9	5.8	9	54.8	2.9	5	110.2	11.5	10
63.3	5.4	9	71.5	5.5	8	114.0	24.8	22
70.2	8.5	12	42.0	11.7	28	141.5	9.4	7
72.3	6.1	8	61.3	11.9	19	100.0	8.6	9
55.7	3.7	7	80.5	10.8	13	99.5	5.7	6
57.2	6.9	12	95.1	9.5	10	125.2	7.3	6
61.8	6.2	10	58.4	2.5	4	96.1	7.3	8
66.7	6.4	10	45.4	2.8	6	82.9	15.8	19
75.7	8.8	12	63.6	5.6	9	96.9	4.2	4

CHAPTER 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1   <u>*Summary*</u>

With an enormous roadway network, increasing traffic and loading, and shortfalls in transportation spending, the timing and prioritization of pavement evaluation and maintenance has never been more critical. Pavement roughness data is a critical input for maintenance and rehabilitation planning and overall pavement management, and has traditionally cost state agencies millions of dollars annually. A smartphone-based application will not only save millions of tax dollars but also provide ease in data collection and possibly real time International Roughness Index (IRI) assessment and localized roughness (i.e., pothole) identification in pavement sections.

In this project, an android-based cellphone application has been developed which is able to collect vehicle vertical acceleration data while driving. A MATLAB script has been created which filters collected acceleration data, performs integration to produce profile of pavement, and finally executes quarter car simulation to estimate pavement roughness in terms of IRI. Pavement roughness data have been collected using an inertial profiler, and simultaneously, vehicle vertical acceleration data also collected from different pavement sections with different roughness level. A smartphone based application was shown to be capable of measuring IRI data in a very economical manner, and was used in an experiment to compare estimated IRI values against those obtained with an industry standard inertial profiler system. It has been found that IRI values measured by smartphone application and inertial profiler are very close to each other for pavements with very good to fair condition in terms of roughness.

6.2   Conclusions

The conclusions drawn in this study were:

(a) IRI values measured by the smartphone application roughness capture were similar to those collected with the inertial profiler at two test sites having low to medium roughness, with very few outliers observed. Even the outliers were in the same ride category or within one ride category of the reference measurement. These results were obtained without the need for system calibration.

(b) At test site 3, which had relatively high roughness, the smartphone based system produced measured IRI values which were lower than those collected with the inertial profiler. It is speculated that a higher sampling rate and/or the inclusion of a vehicle suspension model may be needed to bring the values into closer correlation, which will be investigated in a subsequent study. However, a simple linear calibration was able to bring the results into close correlation, and can be easily accomplished in practice if deemed necessary.

(c) The repeatability of the roughness capture application was found to be acceptable for the intended application. For test site 1, the coefficient of variance (COV) was in the range of 7-22, where only one value exceeded 20 percent, and most values were less than 15 percent. At site 2 and site 3, COV's were as low as 4 percent. COVs were higher than 20 percent for only 3 of the 40 test sections.

(d) As vehicles suspension systems vary widely, vertical acceleration data collected by smartphones mounted in different vehicles will be dampened to differing degrees. To address this phenomenon, two factors including vehicle mass and suspension system characteristics need to be considered. In future work, these factors will be included as part of the IRI calculation to arrive at more accurate pavement profile/roughness estimation, while simultaneously obtaining information about vehicle ride characteristics. This will require operating a fleet of vehicles over pavements with known profiles in order to calibrate and validate models.

6.3   <u>*Recommendations*</u>

Further validation of roughness capture will be pursued in follow up studies, particularly for rough pavement sections, where a higher sampling rate will be investigated. Testing is also underway to assess factors such as vehicle type (varying suspension characteristics), smartphone type, and vehicle wander on IRI measurement. A crowd sourcing feasibility study will be the subject of a later investigation. In the long run, it is hoped that the approach can be used to significantly reduce the cost of acquiring pavement roughness data for agencies and to reduce user costs for the traveling public by providing more robust feedback regarding route choice and its effect on estimated vehicle maintenance cost and fuel efficiency, and eventually perhaps even a measure of safety.

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