Measurement of Pavement Roughness Using Android-Based Smartphone Application

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Pavement roughness is an expression of the irregularities in a pavement surface that adversely affect the ride quality of a vehicle. Roughness also affects vehicle delay costs, fuel consumption, tires, and maintenance costs. Roughness is predominantly characterized by the international roughness index (IRI), which is often measured with inertial profilers. Inertial profilers are equipped with sensitive accelerometers, a height-measuring laser, and a distance-measuring instrument for measuring vehicle vertical acceleration data and the pavement profile. Modern smartphones are equipped with several sensors including a three-axis accelerometer, which was used in this project to collect vehicle acceleration data with an Android-based application. In the study, acceleration data were double integrated numerically to obtain a pavement profile, which was input into the software program ProVAL. The pavement roughness was then calculated. For the initial validation, pavement profile and acceleration data were collected with both an inertial profiler and the newly developed smartphone application from three test sites. The initial validation results suggest that the newly developed smartphone application can measure IRI with good correspondence to the inertial profiler and with good repeatability between measurement replications. However, calibration is needed for rougher pavement sections because the current analysis techniques do not directly account for acceleration damping resulting from vehicle suspension systems. With improvements in analysis that consider the vehicle suspension effects and additional validation, the approach could be used to reduce the cost of acquiring pavement roughness data for agencies and to reduce user costs for the traveling public by providing more robust feedback about route choice and its effect on estimated vehicle maintenance cost and fuel efficiency.

There are about 2.6 million mi of paved public roads in the U.S. roadway network, and many transportation agencies use a pavement management system to manage their pavement networks in an efficient and cost-effective manner (*1*). Pavement management systems require pavement roughness information along with other distress data. Pavement roughness is the deviation of pavement surface profile from planarity and affects overall ride quality. Pavement roughness also slightly increases fuel consumption and therefore emission levels. Fuel consumption can be increased as much as 4% to 5% by very rough pavements (*2*). Most transportation agencies use measures of the international roughness index (IRI) in planning maintenance and rehabilitation operations. Decades ago, roughness measurements were made with manual equipment, such as a sliding straightedge. Technological advances have led to highly automated pavement condition assessments that use sophisticated data collection vehicles equipped with sensitive inertial profilers.

According to NCHRP Report 334, most transportation agencies now collect pavement roughness data with 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 to $10.00 per mile with an average cost of $6.12 per mile (*3*). The 139,577 miles of roadways of the state of Illinois 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 for the Virginia Department of Transportation "a contractor is employed to gather roughness data at an annual cost of $1.8 million" (*4*), and data are collected once every 5 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 often performed with outdated roughness data. In addition, infrequent roughness measurements preclude identification of rapidly developing distress features on pavements, such as potholes that occur during spring thaw and dangerous blowups in portland cement concrete pavements, representing a missed opportunity for enhancing roadway safety and so increasing tort liability.

Modern smartphones have built-in three-axis accelerometers and GPS, 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 crowdsourcing system could save agencies millions of dollars while also providing the traveling public with useful feedback on route choice and its effect on user costs, sustainability, and perhaps safety (through real-time tracking of high-acceleration events caused by severe potholes, blowups, etc.).

The objectives of this study are as follows: (*a*) demonstrate a new cell phone application, Roughness Capture, for collecting vehicle

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vertical acceleration data by using smartphone accelerometer capabilities; (*b*) analyze acceleration data to obtain pavement profiles; (*c*) calculate pavement roughness from the estimated pavement profile with the ProVAL program; and (*d*) make a preliminary validation of the Roughness Capture application through a comparison with results obtained with an industry standard inertial profiler on three pavement sections in Illinois.

PAVEMENT ROUGHNESS

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." Rough pavements affect vehicle accelerations, which in turn adversely affect vehicle wear, ride quality, and safety (*5–8*). The IRI has gained general acceptance worldwide as a common scale for quantifying pavement roughness. The IRI was identified as the preferred roughness parameter considered in the international road roughness experiment, which was held in Brasilia, Brazil, in 1982 and supported by the World Bank (*9*). Now, the IRI is the standard scale used to quantify pavement roughness in the United States. The IRI is calculated from the profile of the pavement, which can be measured with manual or automated pavement profilers. According to Perera et al., three vehicle responses have relationship with IRI: road meter response, vehicle vertical acceleration, and tire load (*10*).

The IRI is a numerical scale used to quantify the deviation or roughness of a pavement surface on the basis of 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 1) that simulates the suspension motion response of a reference vehicle traveling at 50 mph (*11*).

Figure 1 shows the five components of the quarter car model: body mass supported by a single tire, axle mass, a vertical spring representing a tire, a suspension spring, and a damper (*10*). 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 inches per mile or meters per kilometer. Generally, a software program is used to determine the IRI from the measured pavement profile. A profile obtained from each wheelpath is used to determine IRI, and the average value is then reported.

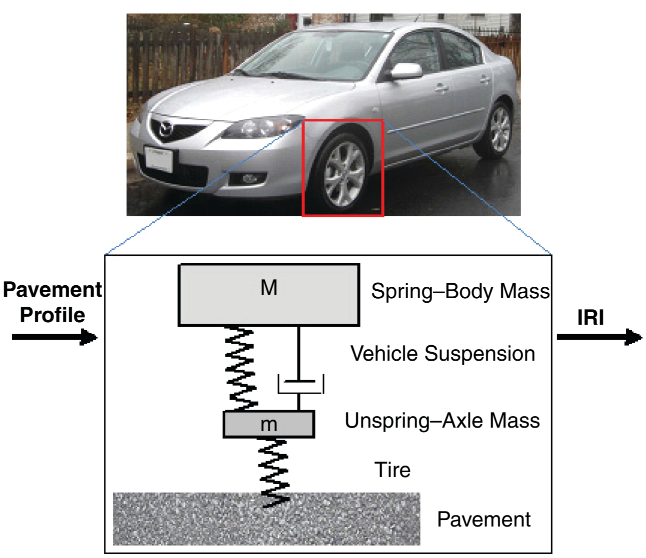


FIGURE 1 IRI calculation (*10*).

TABLE 1 Pavement Ride Quality Based on Roughness (*12*)

Category	IRI Rating (in./mi), by Highway Type: Interstate	Non-Interstate	Interstate and Non-Interstate Ride Quality
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	

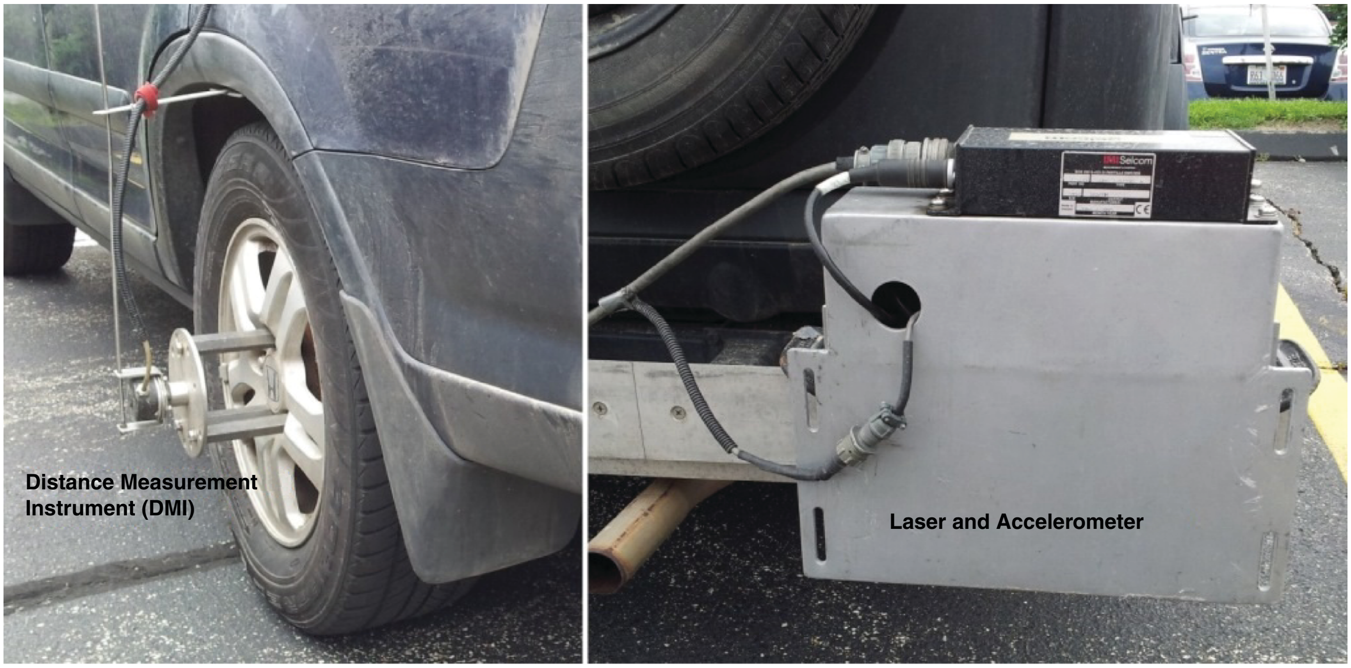
Pavement ride quality can be classified according to IRI. The U.S. Department of Transportation categorizes pavement ride into five groups, as shown in Table 1 (*12*).

EXISTING ROUGHNESS MEASUREMENT SYSTEMS

Although pavement profile measurements were of major interest to researchers decades ago, most agencies now conduct pavement roughness measurement routinely (*13*). Although many devices and methods are available for evaluating pavement ride quality, most are not in use because of low accuracy or measurement inefficiencies. The devices typically used in the United States can be divided into four categories: calibration and construction control, response-type systems, accelerometer-based systems, and noncontact profile measurement systems. Calibration and construction control devices are used to check the profile of the new constructed layer and include profilographs, dipsticks, and Ames profilographs. Response-type systems include Mays ride meters and B&K accelerometers. Accelerometer-based systems include portable universal roughness devices, Dynatest 5000 roughness distress meters, and self-calibrating roughness units. Noncontact profile-measuring systems include K.J. Law roughness surveyors, laser road surface testers, South Dakota profilometers, automatic road analyzers, and surface dynamic profilometers. The Australian Road Research Board, International Cybernetics SurPRO, and Surface Systems and Instruments reference profilers are the most widely used.

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 and 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 because of their inefficiency and inaccuracy (*13*). For instance, the California profilograph can evaluate only 1.9 to 3.1 mi of pavement per hour. It has been reported that profilographs tend to amplify or attenuate the true pavement profile (*10*).

Because of these shortcomings, efficient, automated, and highly repeatable inertial profilometers were developed. According to



(a) (b)

FIGURE 2 Automated pavement profiler and equipment on typical data collection van.

Woodstrom (*13*), modern inertial profilometers require four basic subsystems (Figure 2):

- Accelerometers for determining the height of the vehicle relative to an inertial frame of reference,
- Height sensors for measuring the instantaneous riding height of the vehicle relative to a location on the road below the sensor,
- Distance or a speed sensor for determining the position of the vehicle along the length of the road (now combined with GPS), and
- Computer hardware and software for computing the road profile.

The IRI is used to measure roughness in 47 states; however, at least 10 approaches have been used to collect IRI data (*14*). Not only do variations exist among the tools used to collect pavement profiles, but various analysis methods are also used (choice of wheelpath data, averaging techniques).

In addition to the shortcomings and expenses associated with current pavement roughness measurement systems, this study was motivated by the potential benefits of a smartphone-based roughness measurement system, such as crowdsourcing 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).

ROUGHNESS CAPTURE APPLICATION

Pavement surface irregularities (nonplanar 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 cell phone with a three-axis accelerometer can be used to collect vehicle vertical acceleration data, as demonstrated in studies such as those conducted at the Massachusetts Institute of Technology to identify localized pavement defects (*15*). An Android-based cell phone application is developed in the present study that can capture acceleration for characterizing pavement roughness and individual pavement distresses. Figure 3 shows vehicle vertical acceleration data collected with Roughness Capture, an Android-based smartphone application developed by Applied Research Associates in Champaign, Illinois, and validated by researchers at the University of Illinois through a project sponsored by the NexTrans University Transportation Center.

Modern smartphones are equipped with several sensors, including multiaxis accelerometers, temperature probes, gyroscopes, light intensity sensors, and magnetic field sensors (*16*). The Roughness Capture application collects acceleration in three orthogonal directions, a time stamp, and GPS coordinates and stores them in an ASCII text file. The data collection rate is specified by the user and generally is in the range of 10 to 100 samples per second, but higher sampling rates are possible depending on 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).

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 the determination of IRI with 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 used with the Roughness Capture application.

FIGURE 3 Smartphone-based Roughness Capture system: (*a*) cell phone application capturing vertical acceleration, (*b*) Roughness Capture interface, and (*c*) acceleration data capturing.

DATA COLLECTION

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

During this study, a data collection rate of 100 points per second was used. For the standard speed of 50 mph, the vehicle traveled 880 in./s. Hence, the spacing of acceleration data points was 8.8 in.

DATA ANALYSIS

Inertial profilers provided pavement roughness parsed out in 0.1-mi sections within the 2-mi test sites. Vehicle acceleration data collected by roughness capture were analyzed to estimate pavement roughness. First, acceleration data were 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

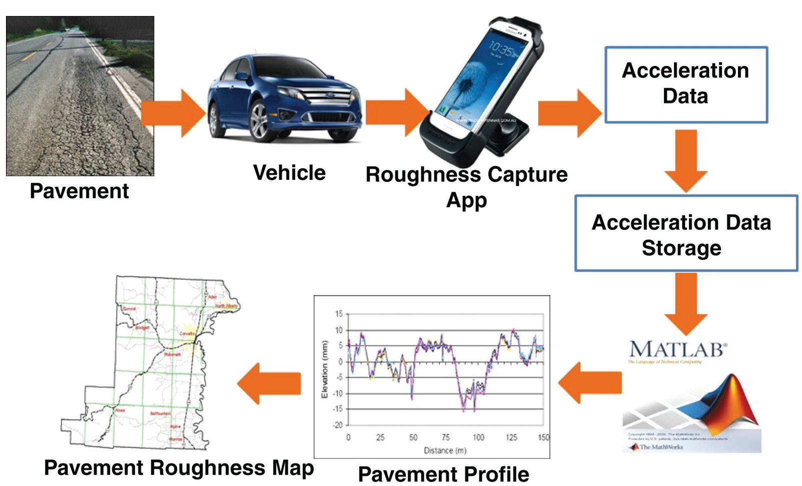


FIGURE 4 Project approach (app = application).

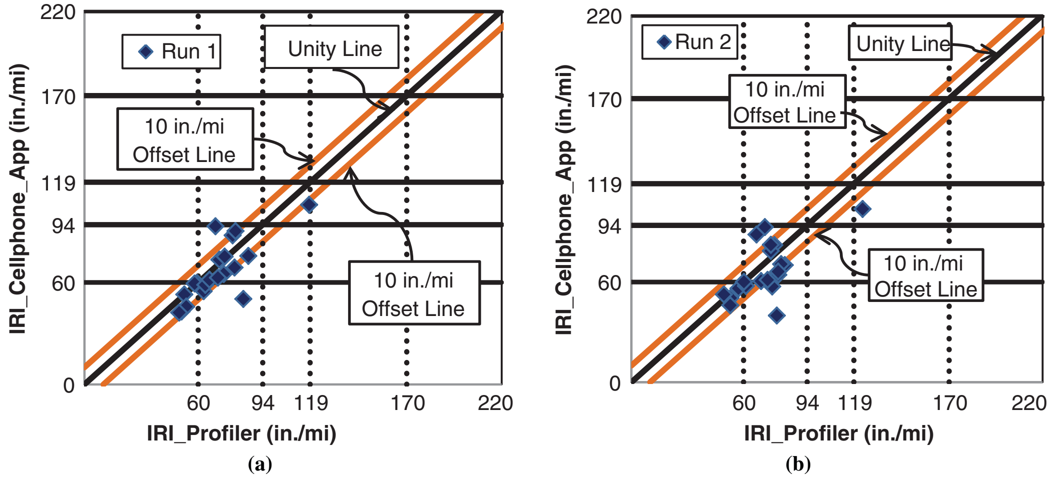


FIGURE 5 Comparison of pavement roughness data measured by cell phone application and profiler for County Route 32: (*a*) Run 1 and (*b*) Run 2.

with ProVAL (*17*) to estimate roughness according to the IRI. (A detailed mathematical proof and verification of the developed method is beyond the scope of this paper.) Pavement roughness of each 0.1-mi section was estimated with ProVAL across the 2-mi-long test sections. The approach does not produce a true profile of pavement surface but rather produces a perceived profile, a result of the dampening effect of the vehicle's suspension system. Efforts to incorporate vehicle suspension effects into the data analysis scheme used in Roughness Capture are under way and will be reported in a subsequent paper.

RESULTS

Comparison of IRI Estimated by the Application and the Data Collection Vehicle

Figure 5 shows pavement roughness values estimated by the smartphone-based application and an industry standard inertial profiler for two runs at Site 1. IRI values of every 0.1-mi section of the 2-mi 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 in./mi offsets from the unity line to aid visualization of the magnitude of deviation of the smartphone-measured IRI values from those of the inertial profiler. Most of the values (17 of 20 sections) were in the 10-in./mi offset band, indicating a very good correspondence between the two methods. In Figure 5*a*, only one 0.1-mi section shows distinctly different IRI values, which could change the pavement ride category assessment for that section. In Figure 5*b,* only three 0.1-mi sections were outside the in./mi offset lines. Although some differences exist, it appears that the same overall pavement management decision would be reached for the 2-mi section with the IRI values determined with each approach.

Figure 6 shows the pavement roughness measured by the roughness capture application and inertial profiler for two runs conducted at Site 2. Again, IRI values estimated by the Roughness Capture smartphone application corresponded closely to those measured by the inertial profiler system without the need for system calibration.

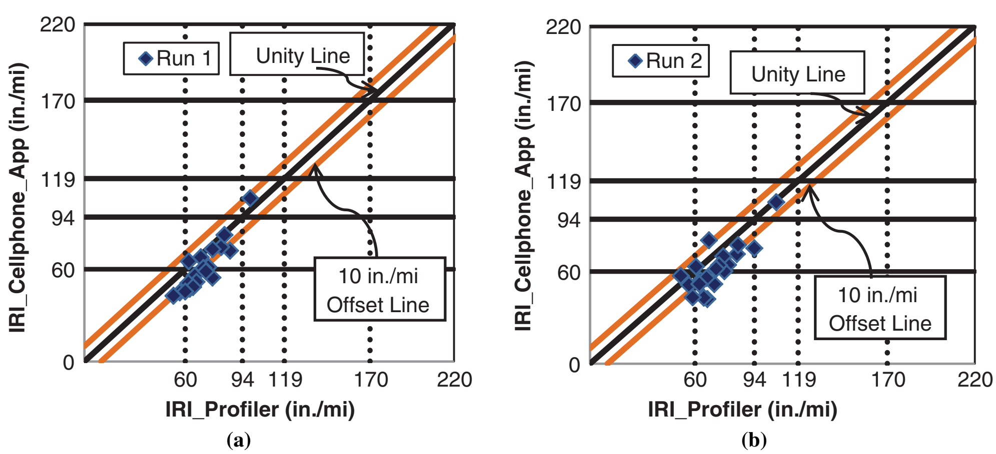


FIGURE 6 Comparison of pavement roughness data measured by cell phone application and profiler for County Route 9: (*a*) Run 1 and (*b*) Run 2.

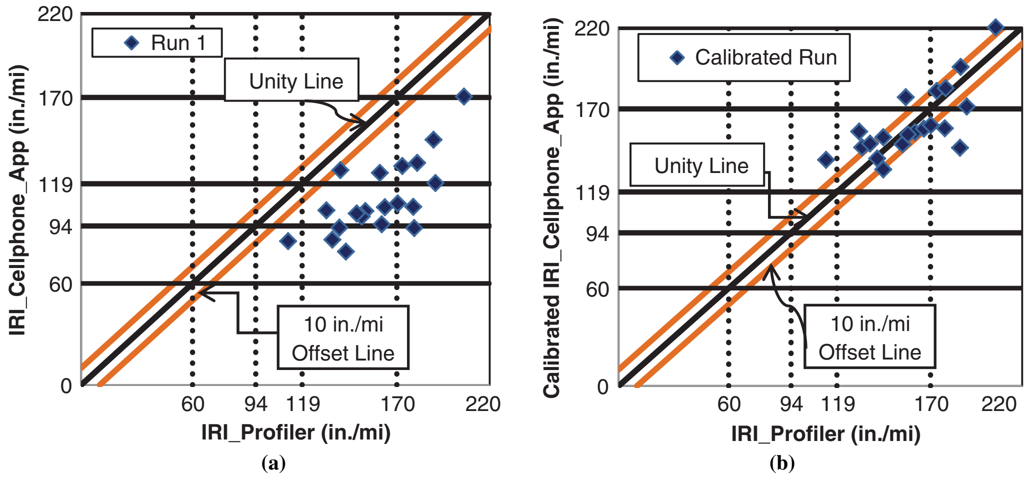


FIGURE 7 Comparison of pavement roughness data measured by cell phone application and profiler for County Route 23: (*a*) original run and (*b*) calibrated run.

Figure 7*a* shows the pavement roughness values measured at Site 3, which had much higher pavement roughness. On this section, it was observed that the uncalibrated smartphone-measured IRI values were below the unity line (IRI was underpredicted). As mentioned, acceleration data were sampled at a longitudinal distance of 8.8 in. in the smartphone-based system according to a 100-samples-per-second data collection rate. In contrast, the more sophisticated inertial profiler system collects data at intervals of less than 1 in. Because of the high pavement roughness and high number of significant vehicle acceleration events, the 100-samples-per-second data collection rate used could have contributed to the underprediction of pavement roughness in this section. Another explanation could be the heightened effect of damping that results from the vehicle suspension system, which is not accounted for in the analysis scheme. A regression equation (calibrated IRI = 0.95 * cell phone measured IRI + 58) was used to explore whether a simple linear correlation could be used to calibrate smartphone-determined IRI values. Figure 7*b* shows calibrated smartphone-measured IRI, which are dispersed around the unity line similarly as for Sections 1 and 2. Testing is under way to assess factors such as vehicle type (varying suspension characteristics), smartphone type, and vehicle wander on IRI measurement, which will be incorporated in an enhanced analysis model that will account for dampening by the vehicle suspension.

Repeatability of Smartphone-Based IRI Measurement System

Figures 8 through 10 show IRI data for every 0.1-mi section of Sites 1 through 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, and the *y*-axis values chart the IRI measured by the roughness capture application. Pavement ride categories as presented in Table 1 were used to form the *y*-axis scale. It appears that the effects of vehicle suspension on the 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 coefficient of variation (CV) is 11%, 9%, and 9% at Sites 1, 2, and 3, respectively. In comparison, the CV of measuring IRI with an inertial profiler may

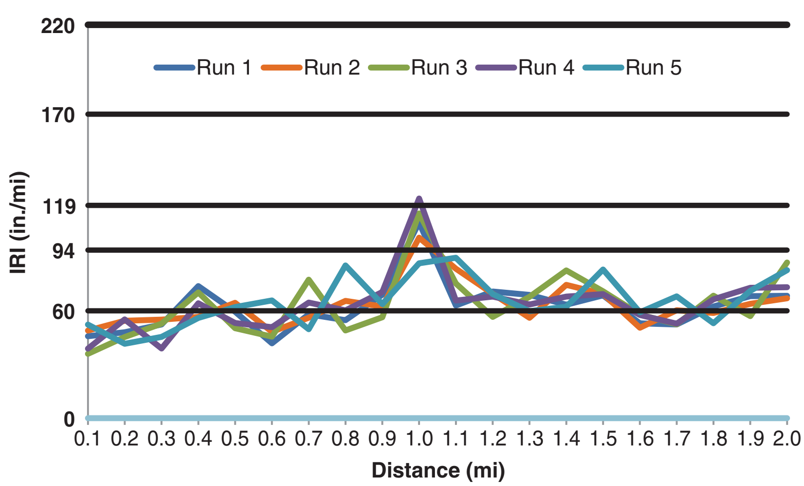


FIGURE 8 Estimation of IRI at County Route 32 for five runs.

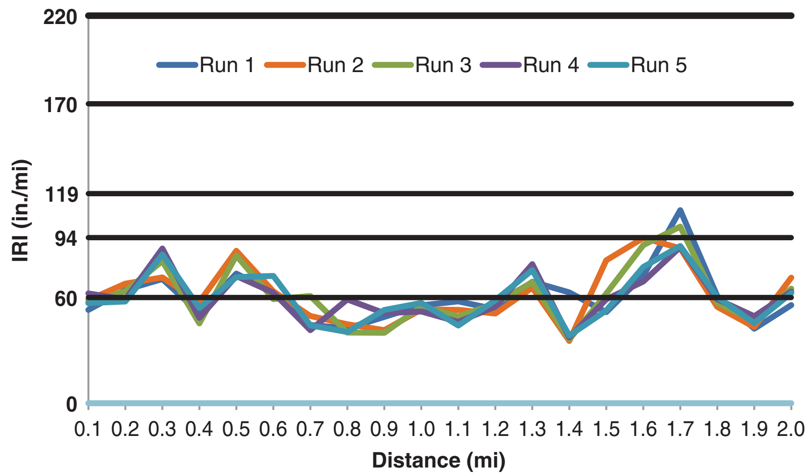


FIGURE 9 Estimation of IRI at County Route 9 for five runs.

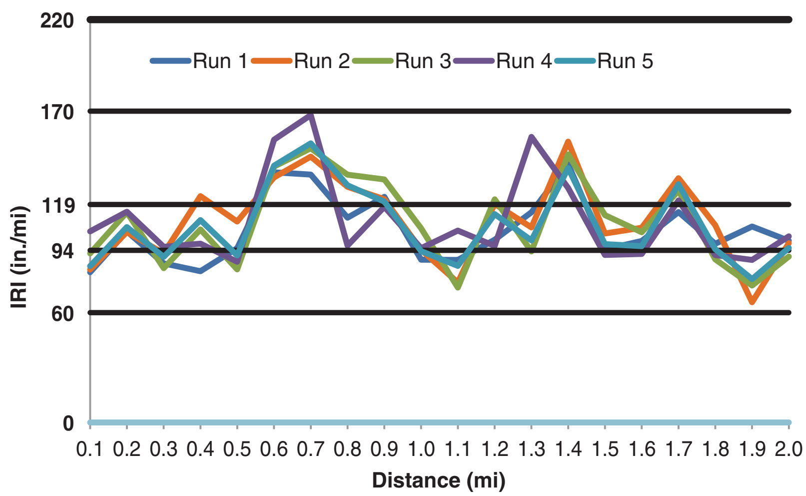


FIGURE 10 Estimation of IRI at County Route 23 for five runs.

be less than 5%; however, considering the cost of measuring IRI via an inertial profiler (*3*), a CV of 10% for the smartphone-based Roughness Capture application appears to be reasonable. It was also noticed that precisely matching the location of pavement segments used in comparing smartphone-based roughness with the reference data from a data collection van is important. As location matching improves, accuracy improves. The figures show that repeatability of the roughness capture application is quite good overall. Most of the repeated measurements for each 0.1-mi 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.

Table 2 shows average IRI, standard deviation, and CV of every 0.1-mi section of each testing site. CV is less than 15% except for a few sections. For one pavement section, CV was estimated as 22%. The highest CV measured was 28%, in Section 2. Because it was impossible to drive the test vehicle along exactly the same path because of vehicle wander, the repeatability of IRI measurements with the new roughness capture application appears to be acceptable for collecting useful pavement condition data rapidly and inexpensively. This conclusion is further justified because of the possibility of using crowdsourcing 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 crowdsourcing feasibility study will be the subject of another investigation.

SUMMARY AND CONCLUSIONS

Pavement roughness data are a critical input for maintenance and rehabilitation planning and overall pavement management, and data collection costs state agencies millions of dollars annually. A smartphone-based application, Roughness Capture, was developed and was shown to be able to measure IRI data in economically. The application was used in an experiment that compared estimated IRI values against those obtained with an industry-standard inertial profiler system. The conclusions drawn from this study are as follows:

1. IRI values measured with the smartphone application were similar to those collected with the inertial profiler at two test sites having low to medium roughness, and few outliers were observed.

TABLE 2 Repeatability of Roughness Capture Data

Average IRI (in./mi)	SD	CV	Average IRI (in./mi)	SD	CV	Average IRI (in./mi)	SD	CV
County Route 32			County Route 9			County Route 23		
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

NOTE: SD = standard deviation.

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.

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

3. The repeatability of the roughness capture application was found to be acceptable for the intended application. For Site 1, the CV was in the range of 7% to 22%; only one value exceeded 20%, and most values were less than 15%. At Sites 2 and 3, CV was as low as 4%. CV was higher than 20% for only three of the 40 test sections.

4. Because vehicle suspension systems vary widely, vertical acceleration data collected by smartphones mounted in various vehicles will be dampened to varying degrees. To address this phenomenon, vehicle mass and suspension system characteristics must be considered. In future work, these factors will be included as part of the IRI calculation to arrive at more accurate pavement profile and roughness estimation while simultaneously obtaining information about vehicle ride characteristics. This approach will require operation of a fleet of vehicles over pavements with known profiles so models can be calibrated and validated.

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 under way to assess effects of factors such as vehicle type (varying suspension characteristics), smartphone type, and vehicle wander on IRI measurement. A crowdsourcing feasibility study will be the subject of a later investigation. It is hoped that the approach can be used to significantly reduce agency costs for acquiring pavement roughness data and to reduce user costs for the traveling public by providing robust feedback about route choice and its effect on estimated vehicle maintenance cost and fuel efficiency and perhaps safety.

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The presented findings and opinions are those of the authors and do not necessarily reflect those of the sponsoring agency.

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