Probe Vehicles Used to Measure Road Ride Quality

Pilot Demonstration

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New vehicle technology is leading to efficient methods for assessing the condition of the National Highway System. The use of simple sensors such as accelerometers, installed in vehicles, could provide a cost-effective way to assess ride quality for pavement management. A pilot study compared data gathered from accelerometers with the current state-of-the-art practices for measuring ride quality. After a review of relevant previous studies involving probe vehicles, this study assessed the use of probe vehicles' acceleration measurements to evaluate the pavement profile. The repeatability of acceleration measurements with cross-correlation and standard deviation was obtained. With visual methods and the coherence function, acceleration measurements were compared with profile measurements obtained from inertial profilers. The literature review reinforced the view that using probe vehicles for pavement condition data collection would be promising and that measuring pavement condition with typical onboard sensors could provide a cost-effective way to collect data for pavement management. Probe vehicles are most practically used in pavement management applications to describe ride quality by using vehicle accelerometers and the Global Positioning System. The pilot study confirmed that the acceleration runs were repeatable. Visual inspection of the acceleration and profile plots suggested that the acceleration profiles and smoothness measurements were similar. Analysis with the coherence function also confirmed this strong relationship. The tested methodology provides a practical way to evaluate smoothness while providing a wider base of coverage compared with that of inertial profilers.

Pavement and bridge condition assessments are key asset management business processes that allow Department of Transportation (DOT) personnel to make cost-effective decisions regarding the preservation and renewal of pavement and bridge assets. Effective asset management, as with any decision support tool, requires reliable and sufficient data, calibrated analysis models and procedures, and tools that help visualize and quantify the impact of the considered solutions. The 2001 AASHTO *Pavement Management Guide* discusses in detail the technologies and processes used for the selection, collection, reporting, management, and analysis of data used in pavement management at the state level. Although there is an extensive range of data needed in a pavement management system (PMS), emphasis is placed on the robust collection of pavement condition data. Pavement condition information, if collected efficiently and accurately, provides the best indication of road performance in relation to safety, ride comfort, and structural integrity (*1*).

At the national level, the Highway Performance Monitoring System, used by FHWA, requires states to submit pavement condition data periodically for a sample of roads on the National Highway System. These data are collected by state DOTs using automated, semiautomated, and, in some cases, visual methods. The pavement condition data are stored, along with road classification and travel vehicle by type (*2*). The current process is limited in its overall effectiveness. Since data collection and processing techniques differ from state to state, it is often difficult to compare and develop a uniform method of addressing infrastructure issues. The issue of uniformity of the data is particularly challenging at the national level because state, regional, and local agencies have often independently developed data collection practices and standards (*3*).

The actual task of collecting the data can be onerous and time-consuming. Agencies must utilize a small fleet of data collection vehicles to cover a large amount of road mileage. This requirement creates issues with prioritizing infrastructure projects and can lead to decision making that is not thorough. One positive development is the more frequent use of automated data collection methods. For example, NCHRP Synthesis 334 found that essentially all North American highway agencies are collecting pavement condition data through some automated means. Furthermore, the synthesis found that 33 agencies (out of 56) use service providers (also called vendors or contractors) to collect at least some of the automated data (*4*). Although processes to evaluate these data have presented new challenges (the data collected are different in nature from those in previous manual methods), the use of automated equipment increases the safety and speed of the data capture and may facilitate the development of more uniform data collection practices.

OBJECTIVES

The objective is to report on a study to test the feasibility of assessing ride quality of existing roads by using the relationship between acceleration measurements obtained from instrumented vehicles during naturalistic driving studies and road profile measurements obtained from inertial-based laser profilers. The goals of the study are to

- Review the most relevant preliminary studies involving probe vehicles and report the findings,

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• Assess the repeatability of acceleration measurements by using cross-correlation and standard deviation, and
• Compare acceleration and smoothness profile measurements by using visual methods and the coherence function.

BACKGROUND

Concept of Probe Vehicle

The way in which transportation agencies collect, store, and analyze data has evolved alongside advances in technology, such as mobile computing, advanced sensors, imaging technologies, distributed databases, and spatial technologies. These technologies have enabled the data collection and integration procedures necessary to support the comprehensive analyses required for asset management (*5*). These data collection procedures often require investment in application-specific vehicles whose cost entails larger pavement inspection intervals. For example, transportation agencies use high-speed laser profilers to collect smoothness data. Probe vehicles, however, use onboard technology installed in typical passenger cars and trucks. This technology includes, but is not limited to, the Global Positioning System (GPS), speedometers, accelerometers, and antilock braking systems. By measuring with built-in, inexpensive vehicle sensors and transmitting data via an available wireless connection, a large amount of data can be collected at a relatively low cost. In a fully integrated network, passenger cars would become the data collection devices.

The idea for probe vehicles as useful traffic and infrastructure tools has been explored for several years. The benefits of a successfully deployed probe system have been imagined by several organizations and researchers. Although a large-scale system may not exist for some time, the general consensus is that the data collection and asset management processes would be significantly improved. The main reason for this belief is that the integrated probe vehicle system takes advantage of a deployed sensor system greater in scale than any other data collection unit in the world: on-road vehicles (*6*). The data collected by probe vehicles would be dynamic and would cover a large scope of the networks in which the vehicles are deployed to provide a constantly updated condition database (*7*).

Some of the concept's major advancements have been performed under the umbrella of a nationwide initiative, formerly known as Vehicle Infrastructure Integration (VII). Sponsored by the U.S. DOT, the IntelliDrive initiative conducted multiple research projects aimed at creating a safer, more effective transportation system (*8*). In 2007, VII launched a proof-of-concept project to identify the feasibility of a vehicle-to-infrastructure collaboration process. Data collection was conducted by gathering the vehicle data and its position in order to create a snapshot of the current status of the vehicle. By saving a large amount of snapshots along the route of the vehicle, data and position information could be readily collected. The technology uses current items, some of which are already installed in vehicles, to collect data, to communicate with infrastructure and other vehicles, and to relay information to satellite locations. In most probe vehicle systems, these tasks are achieved by onboard sensors, GPS, and a wireless communication device (*9*). The majority of tests and research conducted in this area rely on these basic concepts. The use of probe vehicles provides a logical next step in the evolution of data collection technologies by developing a methodology that could provide wide coverage and uniformity across jurisdictions.

Evaluating Ride Quality

Probably the most practical and easily deployable probe vehicle application for pavement assessment is relating onboard sensors to ride quality. Ride quality, or smoothness, is one of the most vital condition indicators. When state agencies program maintenance, repair, and rehabilitation work on their road networks, they do so by measuring road smoothness, since it has a significant influence on the performance of the pavements and is directly linked to the costs assumed by roadway users. Although smoothness is only one of many condition indicators used by data collection agencies, it is the driving indicator in the public eye. Typical road users have a much keener perception of road smoothness than other aspects such as friction and structural capacity. Ride quality can have a great effect on vehicle performance. Fuel consumption, tire wear, and vehicle durability are all greatly influenced by the smoothness of the road. A road with more bumps will have a negative impact on the performance of the vehicle. Therefore, it is important for a road to have an acceptable level of smoothness (*3*).

Many smoothness measurement techniques have evolved since the 1960s, when the smoothness of a road was first computed by measuring the vertical deviations of the road surface along a longitudinal line of travel in a wheelpath (i.e., a longitudinal profile). Since then, many different profilers have been developed to capture those aspects of a longitudinal profile that affect ride quality, vehicle dynamic loading, and safety. Currently the most commonly used profilers are the laser-based inertial profilers for measuring longitudinal profiles at highway speeds and computing the international roughness index (IRI), which was developed by NCHRP and the World Bank (*10*).

The procedure for determining the IRI is described in ASTM E1926. The IRI is the accumulation, usually expressed in inches per mile, of all the vertical differences from an otherwise smooth vehicle path across a given length of road. If the sum of these differences is large, the surfaces are described as rough, creating an uncomfortable experience for roadway users. However, if the sum is small, the surfaces are usually very smooth and travel is not as disruptive to either the vehicle or its passengers. The IRI has become the standard for measuring ride quality on the nation's pavements (*3*).

Although the IRI is measured with standard test vehicles, useful road surface condition and performance information can be obtained from vehicles instrumented for naturalistic driving studies (passenger cars and large trucks). It can be argued from a physical perspective that the road profile (i.e., a measure in the pavement profile of vertical distance variations experienced by a vehicle) has a direct influence on the vertical acceleration of a vehicle traveling along the roadway. The vehicle travel speed (horizontal speed) influences the speed at which it traces this profile (vertical speed), and the changes in speed determine the acceleration. The collected acceleration can be used to provide ride quality data. Furthermore, acceleration data can be collected with instruments that are readily found in production vehicles. Most vehicles with a higher center of gravity, including small trucks and sport utility vehicles, are equipped with rollover stability control, which includes vertical accelerometers. Newer passenger cars are also outfitted with accelerometers for electronic stability control. When placed perpendicular to the traveled surface on the vehicle, and when combined with several transducers, an accelerometer establishes an inertial reference for the vehicle. This reference can then be translated into road roughness as a longitudinal profile is created. The setup of an accelerometer on a profiling vehicle is outlined in ASTM E950-98.

The methodology tailored toward probe vehicles is still being improved and studied. The ability to interpret the data that are collected depends on variables such as network size, fleet size, road type, and environmental conditions. This study explores the relationship between vehicle kinematic signatures (accelerations) and pavement profile data obtained by using an inertial profiler. Preliminary analysis of the data suggests that this approach is feasible and that useful information can be extracted from the specially instrumented vehicles.

Naturalistic Driving Studies and Testing Environment

The Virginia Tech Transportation Institute has instrumented a large fleet of vehicles to support naturalistic driving studies (*11*). Naturalistic data collection is the collection of driver behavior and performance data in a natural environment. Data regarding vehicle position, orientation, speed, acceleration, range, range rate, headway, time to collision, brake pedal input, and qualitative data such as preincident maneuvers can be used to describe driver behavior. Qualitative data such as the roadway type, number of lanes, traffic density, time of day, and weather can be used to describe the driving environment.

Relating these data provides an understanding of the conditions that exist during events, such as accidents, and attains baseline data during regular driving. This in situ process uses drivers who operate vehicles that have been equipped with specialized sensing, processing, and recording equipment. In effect, the vehicle becomes the data collection device. The drivers operate and interact with these instrumented vehicles during their normal driving routines while the data collection equipment continuously records events of interest during the entire driving period (*11*). The foundation of the probe vehicle approach being tested is that the data could be very valuable for assessing the condition of the infrastructure and the driver perception of infrastructure health and level of service. Focus is placed on the use of vehicle position, orientation, speed, and acceleration for the calculation of pavement smoothness and associated global positioning.

The Virginia Smart Road, located at Virginia Tech Transportation Institute, provides an opportunity to gather pavement condition data in a closed circuit where the characteristics of a public road are maintained. The sections of the Smart Road are composed of varying pavement types. That makeup enables the identification of different ride quality characteristics by using probe vehicles. The instrumented vehicles operated at the Smart Road efficiently collect and store data, including acceleration and GPS information. The unique setting is an ideal way to gather and assess pavement condition data without the need for testing on public roads.

FINDINGS FROM PREVIOUS STUDIES

Auburn University's Probe Vehicle Study

Auburn University was enlisted by the VII Pooled Funds Study to research the use of connected vehicles in pavement maintenance. The main focus of the study was to utilize onboard sensors to obtain the IRI of the road. In addition, it was proposed that measurement of the steer angle could be used to detect potholes (*12*).

Testing was performed at the National Center for Asphalt Technology test track. Vehicles instrumented with accelerometers, gyroscopes, and suspension deflection meters were used to estimate the IRI. Vehicles experienced vibrations while traveling along a road surface. These vibrations increased on rough roads and decreased on smooth roads. By taking the root mean square of a signal measurement, the amount of overall vibrations across a given segment was determined. Variables such as speed and vehicle suspension were also taken into account. The resulting data displayed the same trend as the known IRI values for the pavement sections, with only a few expected differences in magnitude. Roughness changes slowly over time; thus an estimation of the IRI will be much more robust and accurate with the use of the higher penetration of measurement vehicles (*12*).

The detection of potholes by using typical vehicle sensors was also explored during the Auburn study. The existence of large bumps in the road was identified by spikes in the measured vibration signal. The research team instituted two algorithms (i.e., a sigma threshold and wavelet transform) to correctly detect these spikes in the signal. The sigma threshold algorithm simply takes the standard deviation of the signal and searches for values greater than the desired threshold. Meanwhile, the wavelet transform algorithm requires more computation power. It involves using a Fourier transform to represent the signal as a superposition of the wavelet function. This transform was performed by using Matlab. A scaling factor in both methods was adjusted to identify more or fewer spikes in the signal (*12*).

The final report recommended that a pilot program be conducted with one or more state DOTs. The most feasible applications for improving pavement maintenance included implementing a root-mean-square algorithm on accelerometer measurements to estimate the IRI and using a sigma threshold algorithm on accelerometer measurements to detect potholes (*12*).

European Intelligent Roads Program

The European Intelligent Roads program is an effort designed to evaluate the use of probe vehicles in road condition data collection. This study tested several methods of data collection to determine the feasibility of a large-scale deployment of such methods. The theory is that inexpensive sensors, some of which are already deployed on production vehicles, can provide nearly constant updated information about road networks without the use of special measuring equipment. Databases already collected by profilometers, skid resistance devices, and user surveys were used for comparison. Tests were conducted in Sweden and the United Kingdom with a variety of probe vehicles and sensors. General findings from the European Intelligent Roads study are as follows: GPS data provide relatively accurate vehicle location for practical use, rural roads have much more potential for probe vehicle deployment than urban roads, and lateral acceleration correlations with steering angle and speed could potentially identify rough pavement sections with a higher level of filtering (*13*).

Bearing Information Through Vehicle Intelligence

In 2008 the Swedish Transportation Authority launched a project aimed at using normal vehicles to measure road stability. The dynamic system uses vehicle data, field measurements, and controller area network–bus data to accurately detect sections of pavement with reduced stability. The project is still under way, although several hours of testing have already been conducted. Several different types of vehicles are being used, ranging from small passenger cars to larger trucks.

The first test measurements were conducted in February, March, and April 2010. The road conditions ranged from standard to extremely icy. There was a total of 6 days of data acquisition. One distinct finding from the preliminary tests was that different types of road materials used different wavebands from the reference sensors. For roads that were half gravel and half asphalt, the acceleration measurements were inherently different (*14*).

Massachusetts Institute of Technology's Pothole Patrol

The Computer Science and Artificial Intelligence Laboratory at Massachusetts Institute of Technology presented the preliminary results of a new infrastructure assessment project at the MobiSys 2008 international conference. The system, referred to as the Pothole Patrol, is an experimental evaluation that attempts to address road condition issues. It assesses road condition by using a mobile sensor system with a fleet of probe vehicles, namely, a group of seven Toyota Prius taxis in the Boston area. The main goal of the project is to successfully detect potholes and other road anomalies along probe vehicle routes by using accelerometer data. This type of opportunistic mobility enables the collaboration of several vehicles without any additional cost to transportation agencies. Using probe vehicles for this type of pavement monitoring creates a dynamic measurement system that encompasses a large portion of the road network. An onboard computer implements several sensors, including a GPS device and the accelerometer, as the taxi drives its normal route throughout the day. The GPS coordinate was reported to be within 3.3 m of the actual geographic information system location on average, which is consistent with typical GPS measurements.

The research needed to implement several machine-learning and cluster-based filtering processes to reduce the number of false positive pothole detections. These filters addressed anomalies such as braking, door slams, turns, acceleration, speed humps, railroad crossings, sudden swerving, and high-speed anomalies. From the preliminary evaluation, it was determined that the Pothole Patrol process yielded only a 7.6% false positive detection rate. It was also concluded that the success rate for anomaly detection was higher on roads in good condition. Inadequately maintained roads present many more unknowns, so the process is more prone to false positive detection. In the controlled experiments, less than 0.2% of the detections were misidentified (*7*).

VERIFICATION RESULTS

Collection of Data on Smoothness and Acceleration

A smoothness profile was obtained by using an inertial-based laser profiler at the Virginia Smart Road in May 2010, and the acceleration profile was obtained during the Brake Assist Study by using instrumented vehicles from the Naturalistic Driving Study at the Virginia Smart Road. Although the study aimed to increase optimal braking performance during panic or emergency braking scenarios, a wide range of data, including vertical acceleration, was collected and documented by the vehicles (*15*).

For the acceleration profile, measurements were obtained at 2-m intervals (10-Hz data collection system with vehicle speed of 70 km/h). The total number of measurements presented in Figure 1 includes 1,051 individual measurements. For the smoothness profile, measurements are typically obtained at 25- to 150-mm (1- to 6-in.) intervals; however, only measurements taken at 2-m intervals were selected to match the acceleration profile. The profile measurements were taken along both wheelpaths; these two measurements were averaged to provide one value at each interval. Both sets of distance measurements were converted to feet before being analyzed. Since the acceleration measurements were taken consecutively with no break in data collection, GPS coordinates were used to identify the beginning and end of each test run.

Repeatability of Acceleration Measurements

Before the acceleration and smoothness profiles were compared, the repeatability of acceleration measurements was analyzed. Four test runs were used in the analysis. All of the measurements were taken by the same instrumented vehicle from the Naturalistic

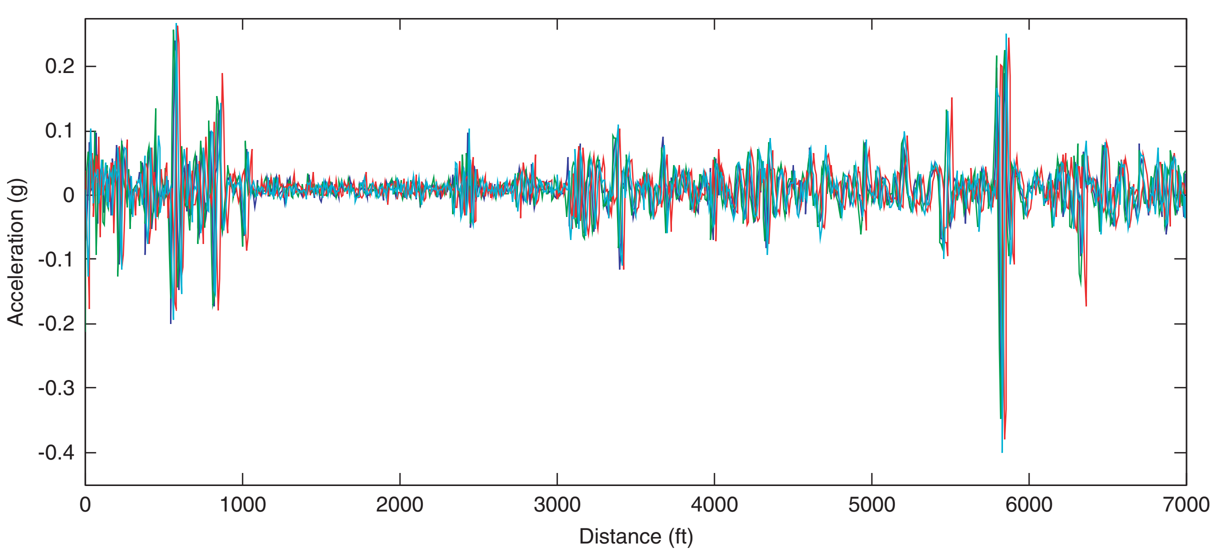

FIGURE 1 Acceleration measurements on Virginia Smart Road.

Driving Study, traveling uphill in the right lane of the Virginia Smart Road. A plot of all four test runs can be found in Figure 1. Since the outfitted accelerometer obtained measurements at slightly different locations and intervals, the measurements were interpolated, with one test run as the reference (Test Run 3, 1,051 measurements).

One of the signal processing methods that can be used to determine the accuracy of acceleration measurements is cross-correlation. This technique has been successfully implemented previously to determine the repeatability and reproducibility of the profiler measurements (*16*). Cross-correlation is a measure used to verify the similarity of two waveforms. It is defined as follows (*17*):

$$\varphi_{xy}(\tau) = E\left[x(t)\,y(t+\tau)\right] = \lim_{L\to\infty}\frac{1}{L}\int_0^L x(t)\,y(t+\tau)\,dt \qquad \tau \ge 0 \quad (1)$$

where

$E[\cdot]$ = expected value,
L = length of measurement set,
τ = shift factor, and
$x(t)$, $y(t)$ = two waveforms defined in range of $t = [0, \infty)$.

Since the friction measurements are discrete, the cross-correlation function can be estimated by

$$\varphi_{xy}(m) = E\left[x_n y_{n+m}\right] = \lim_{L\to\infty}\frac{1}{L}\sum_{n=0}^{L-1} x_n y_{n+m} \qquad m \ge 0 \quad (2)$$

where m is the shift between the measurements and n is the nth measurement of waveforms x and y.

Equation 2 can be normalized by dividing it by the standard deviation of the two waveforms (measurements). To make the computations more efficient, the waveform measurements can be shifted to have a mean of zero (*16*). Cross-correlation can then be used to find how much one waveform needs to be shifted to obtain the best match with another waveform. The amount of shifting that provides the highest cross-correlation is selected. After the signal is shifted, the integral of the product of both signals is calculated from Equation 1. The integral is maximized when the signals perfectly match. This procedure can be used to determine the optimum shift to synchronize the measurements.

Figure 2 illustrates the operation by using a subset of two different test runs of collected acceleration data. It is evident that one data set is shifted slightly to the left. Although a visual shift could be applied, the cross-correlation can find the optimum offset that maximizes the correlation between all measurements.

The cross-correlation between the two acceleration measurements is shown in Figure 3 and was calculated by using the MATLAB cross-correlation function. The peak cross-correlation occurs at a −4 measurement offset. This offset is used to synchronize the measurements. Figure 4 shows the aligned measurements after the reference run has been shifted four measurements to the left. This procedure was performed for each of the test runs. The maximum cross-correlation value was then used as a shift factor to match up the data more accurately. A four-measurement shift (approximately 25 ft) was applied to Test Runs 1 and 2, and a two-measurement shift (approximately 12.5 ft) was applied to Test Run 4.

After the measurement shift, the repeatability was assessed by using the standard deviation of the measurement differences. The process of shifting based on cross-correlation results yielded the smallest standard deviation differences in each of the test runs. To evaluate repeatability, the standard deviation of the differences, as suggested by Bland and Altman (*18*), between the reference run (third run) and the other runs was evaluated. These results, along with the variance for each test run, are shown in Table 1. The square root of the average variance describes the total average standard deviation. This value was determined to be 0.0225. These values were significantly reduced after shifting and can be considered relatively low (ideal repeatability) across the acceleration measurements.

To compare the repeatability of acceleration measurements and road profile measurements (current practice), a signal-to-noise ratio for each measurement type was computed. The signal-to-noise ratio can accurately compare the repeatability of two measurement sets that use different units. The signal-to-noise ratio was found by dividing the average standard deviation of all measurement sets by the total average

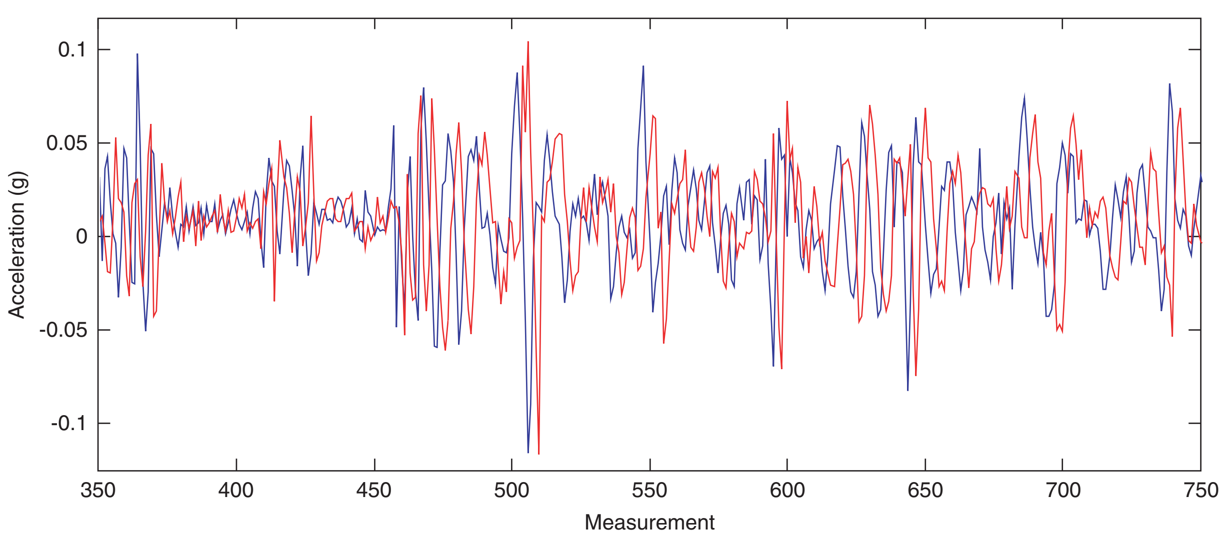

FIGURE 2 Acceleration measurements before cross-correlation shift.

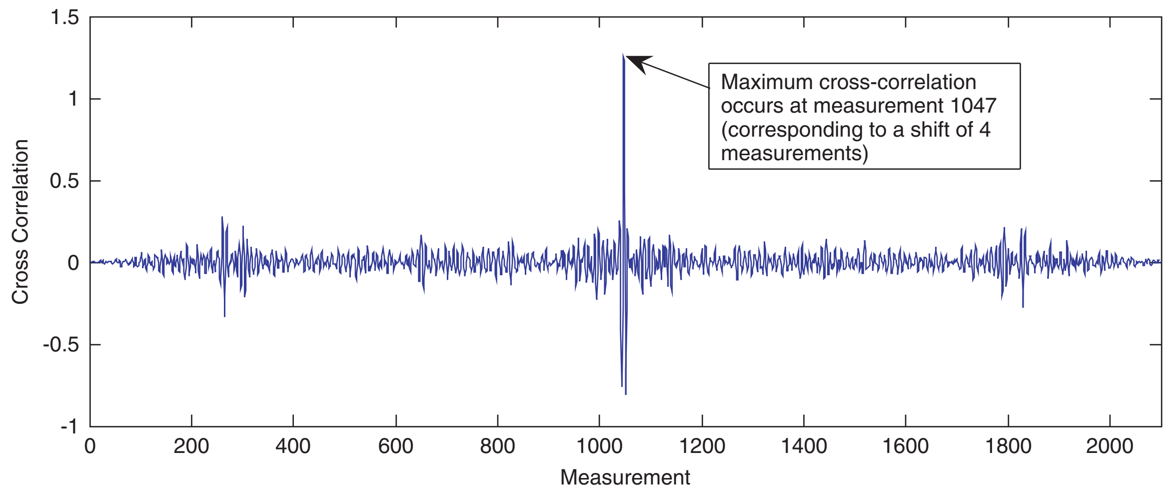

FIGURE 3 Cross-correlation between acceleration Test Runs 1 and 3.

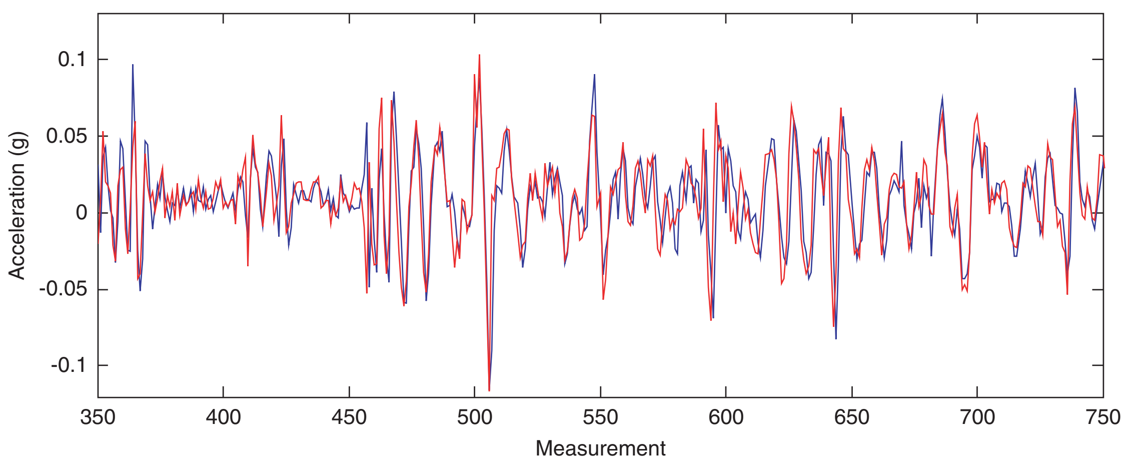

FIGURE 4 Acceleration measurements after cross-correlation shift.

standard deviation of measurement differences (shown earlier as 0.0225 for acceleration measurements). The calculated signal-to-noise ratio for the acceleration measurements was 1.21. The calculated signal-to-noise ratio for the profile measurements was 1.16. The higher the signal-to-noise ratio, the more repeatable the measurements are. The accelerometer measurements are shown to be at least as repeatable as, if not more repeatable than, the road profile measurements collected by high-speed laser profilers.

TABLE 1 Acceleration Standard Deviation and Variance of Differences

Measurement Type	Test Runs Compared	Value (g)
Standard deviation of differences	1 and 3	0.0244
	2 and 3	0.0206
	4 and 3	0.0224
Variance of differences	1 and 3	0.00053984
	2 and 3	0.00042248
	4 and 3	0.00050327

Validation of Acceleration and Smoothness Relationship

A comparison of smoothness profile and acceleration profile measurements performed at the Virginia Smart Road is presented in Figure 5. Similarities between the two profiles can be observed. Both profiles include three major sections, with Section 1 extending roughly from 0 to 1,000 ft, Section 2 from 1,000 to 3,050 ft, and Section 3 from 3,050 ft to the end of the measured sections. Sections 1 and 3 comprise an asphalt pavement and Section 2 features a continuously reinforced concrete pavement. In Section 2, two subsections of roughly 100 ft each are made up of an epoxy-coated high-friction surface starting at roughly 2,400 ft. These section divisions are denoted in Figure 5 by vertical green lines. Red circles indicate prominent acceleration and profile peaks, which can be observed at the same location in both profiles.

The coherence function between the acceleration and profile signals is shown in Figure 6. This function measures how much one signal is linearly related to the other signal at each frequency or wavelength (*19*). It is a real function that varies between 0 and 1 and can be viewed as similar to an R^2 measure between the two signals

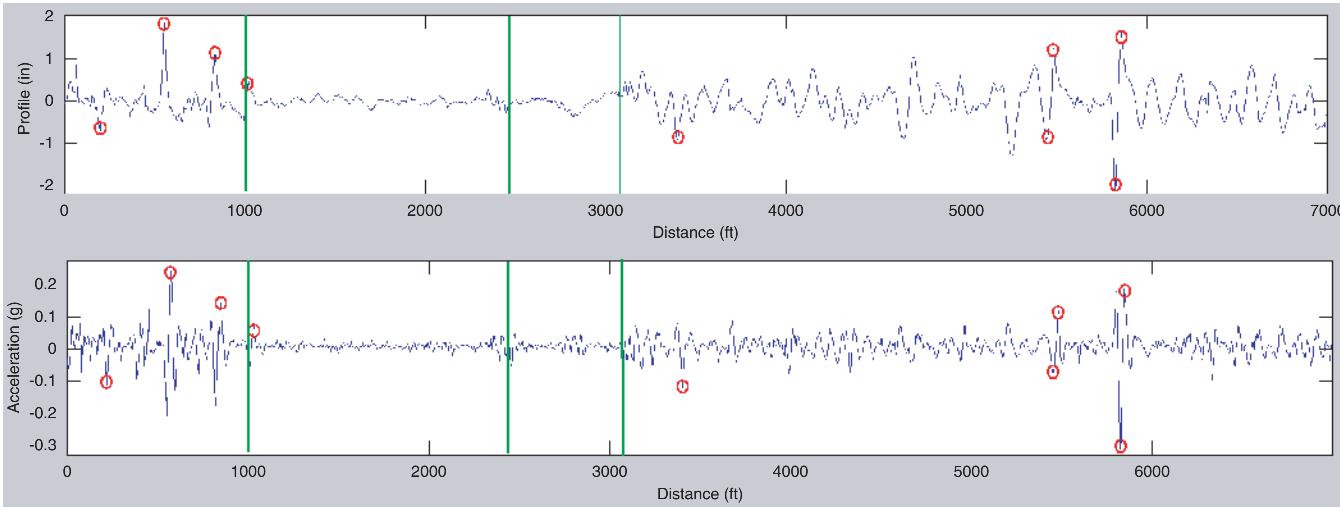

FIGURE 5 Reference profile smoothness data and acceleration data from Virginia Smart Road.

at each frequency. It can be seen that between wavelengths of 50 to 300 m, the coherence function is generally higher than 0.50 with relatively strong coherence (mostly above 0.80) for wavelengths between 70 and 200 m. At short wavelengths (high frequency) the coherence is generally relatively low; this finding may be attributable to the presence of noise at high frequencies. Furthermore, it is possible (though further investigation is needed) that the vehicle suspension works as a low-pass filter that diminishes accelerations at wavelengths shorter than 50 m. To obtain a better understanding of the effect of noise and the low-pass filtering characteristics of the vehicle suspension, data would need to be collected at higher frequency rates.

A relatively simple and quick measure of agreement between the two measurements is Pearson's correlation coefficient. Pearson's correlation between the two signals presented was calculated as 0.50. This value, although not very high, warrants further investigation of the relationship between the two signals.

FINDINGS AND CONCLUSIONS

This study compared acceleration measurements obtained from instrumented vehicles used during naturalistic driving studies with road profile measurements. The most relevant previous studies involving probe vehicles were reviewed and their findings reported. The repeatability of acceleration measurements obtained from instrumented vehicles used during naturalistic driving studies at the Virginia Smart Road was analyzed by using cross-correlation and standard deviation. Finally, the acceleration measurements were compared with the profile obtained from inertial profilers by using visual methods and the coherence function.

The following summarizes the primary findings and conclusions of the study:

- The literature review suggests that use of probe vehicles for pavement condition data collection is very promising. Measuring

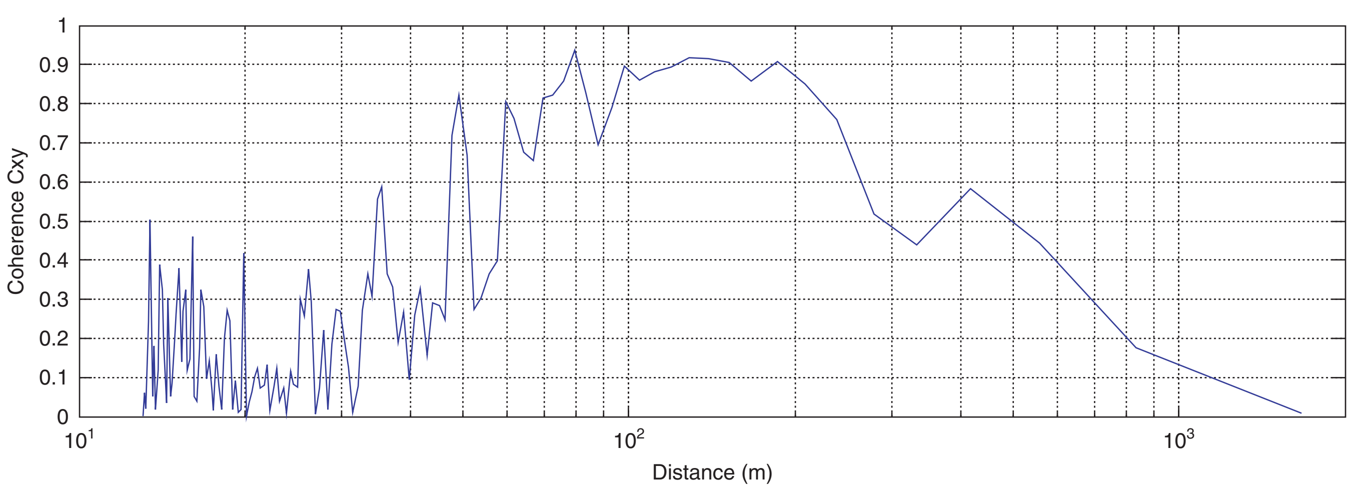

FIGURE 6 Coherence between acceleration and profile data.

pavement condition with typical onboard sensors can provide a cost-effective way to build a robust data set for a range of roads. The most practical of these applications is the use of vehicle accelerometers and GPS to describe ride quality.

- On the basis of the standard deviation of measurement differences, it is confirmed that the acceleration runs are very repeatable (average standard deviation of 0.0225). The repeatability was confirmed by showing that the acceleration measurements yielded a higher signal-to-noise ratio than the profile measurements. It is suggested that this finding be further validated with the collection of more vertical acceleration data.
- Visual inspection suggests that the acceleration profiles and smoothness measurements are very similar. The measurements follow the same trends through the various pavement sections of the Virginia Smart Road. Most of the large peaks in each waveband can be seen in the same locations. This finding confirms the theory that the vehicle experiences larger vertical accelerations when traveling across rough pavement and allows for further assessment of acceleration as a proper tool for describing ride quality.
- To describe further the relationship between acceleration and smoothness, the coherence function can be used. The data show that between wavelengths of 50 and 300 m, the coherence function is generally higher than 0.50 with relatively strong coherence (mostly greater than 0.80) for wavelengths between 70 and 200 m. The coherence is low at shorter wavelengths, most likely because of the presence of noise at high frequencies. It is possible that the vehicle suspension works as a low-pass filter that diminishes accelerations at wavelengths shorter than 50 m.

This preliminary study provides the background for future condition data analysis. The tested methodology provides a simpler way to evaluate smoothness and to establish a wider base of coverage. This method is believed to be a practical application since accelerometers are readily available in most production vehicles, and the information collected by the devices is directly related to ride quality. Because of the broad introduction of rollover stability control systems in high center-of-gravity vehicles and since electronic stability control is available in many passenger cars, vertical accelerometers and gyroscopes can now be found in millions of today's cars. Specifically, vertical accelerometers and roll-rate gyroscopes are elements of rollover stability control systems. In addition, suspension deflection sensors can be found in some vehicles equipped with active or semi-active suspensions (*12*).

The proposed methodology can support the management of road infrastructure systems by providing objective, wide-ranging and frequent pavement (and possibly bridge deck) condition data at the national, regional, and local levels. It provides a very cost-effective tool with which state highway agencies, local governments, and regional planning organizations can collect the road surface condition information necessary for supporting network-level asset management business processes. With this approach, the amount of data collected on a given network would exponentially increase since an integrated vehicle fleet would collect information at every instant of travel. Given the right penetration percentage, data collection could be an ongoing process and would result in a very robust data set and, in turn, a more accurate depiction of the quality of the road infrastructure.

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