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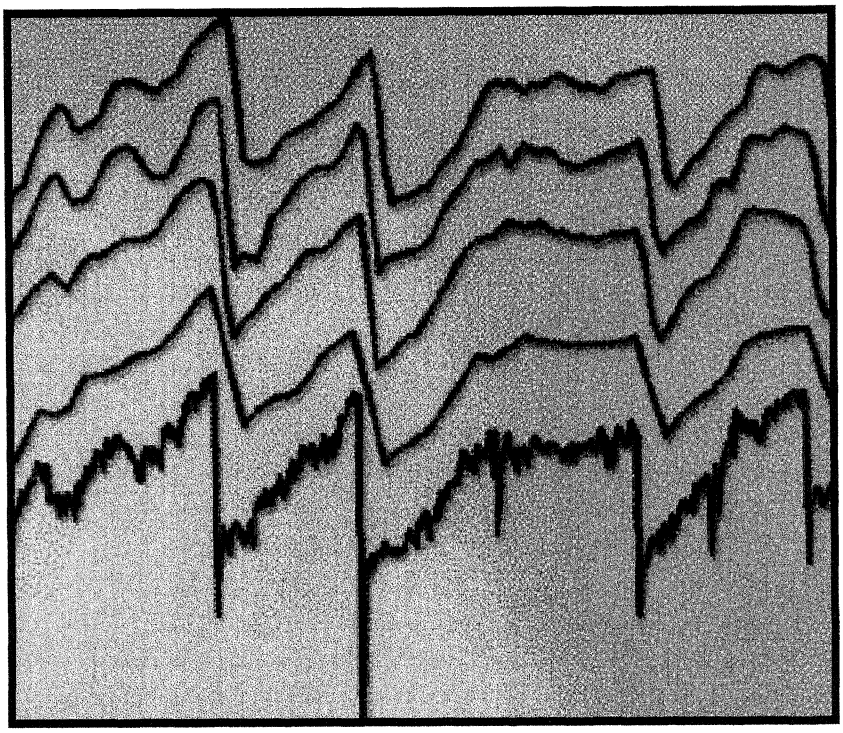

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GUIDELINES FOR LONGITUDINAL PAVEMENT PROFILE MEASUREMENT

FINAL REPORT

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
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ABSTRACT

Monitoring pavement roughness with profile measurements involves several interdependent variables that fall into five categories: the equipment design, the pavement shape, the measurement environment, the manner in which the equipment is operated, and the driver and operator proficiency. Current standards appear to address the equipment design, but not the other variables. As a result, these standards need to be reconsidered.

In this research, thirty-four factors that fall into the five categories listed above were studied. The goal of each study was to develop guidelines for profile measurement that would improve their accuracy and repeatability, as well as agreement between measurements made with various equipment configurations and measurement procedures. Results were cast in terms of the impact of each factor on measurement of profile, and the resulting International Roughness Index and Ride Number.

Overall, several aspects of the profile measurement process that require better standardization were identified. This document presents the technical background for the project, and findings from all of the studies used as a basis for new profile measurement guidelines. The guidelines themselves appear in concise form in a companion document entitled Operational Guidelines for Longitudinal Profile Measurement.

SUMMARY

An essential element of a pavement management system is a means to monitor pavement surface roughness, distress, and other properties. Most pavement management activities include the use of devices that measure longitudinal profile for assessment of surface roughness. When longitudinal road profile measurements are used for assessment of road condition, they are always summarized by an index that reduces the thousands of elevation values into a single value. The International Roughness Index (IRI) is the most broadly used index. However, no matter what index is calculated from a longitudinal profile, the quality of the information is only as good as the profile measurement.

Although technology has been available for measuring longitudinal profile for decades, it has still not fully matured. A prevailing sense exists in the highway community that if every agency measured the same road with their device, they would obtain a variety of different results. Errors in profile and discrepancies between measurements arise from variations in equipment, inappropriate operating procedures, and aspects of the pavement surface and the surrounding environment. In many cases, these factors interact to reduce their repeatability and accuracy. For example, drivers of vehicles used for profiling may not all track in the same position within a lane, which affects the measured profile even if they are using excellent equipment. In addition, the actual shape of the road changes with time in response to the environment.

This project sought to improve the accuracy and consistency of roughness measurement through the development of guidelines for network-level and project-level measurement of longitudinal pavement profile. The technical work focused on the measurement IRI and Ride Number (RN), but the findings are relevant to other indices. The goal was to identify factors that affect roughness measurements, quantify their effect on repeatability and accuracy, determine how and when they can be controlled, and communicate the findings to practitioners by providing guidelines. The guidelines appear in concise form in a companion document entitled *Operational Guidelines for Longitudinal Pavement Profile Measurement*. These guidelines should be used by profiler operators, analysts of profile data, pavement managers who use roughness data, and engineers who design and build profiling equipment.

Thirty-four individual factors that affect longitudinal profile measurement were studied in this research. These factors fall into five broad categories: (1) profiler design, (2) surface shape, (3) measurement environment, (4) profiler operation, and (5) driver and operator proficiency.

PROFILER DESIGN

Several aspects of the design of a profiler were identified that could improve their performance and the agreement between profilers from different manufacturers. Perhaps the most important is the manner in which the data are sampled and the sensor signals are processed to compute profile. Accurate measurement of IRI requires a sample interval of 167 mm or shorter, and accurate measurement of RN requires a sample interval of 50 mm

or shorter. No matter what the sample interval, proper anti-aliasing filters must be applied to the height sensor and accelerometer signals. All of the sensor signals should be scanned for errors such as signal loss and large spikes.

The height sensor was found to be the component of profiling systems most critical to their accuracy. Laser, optical, and infrared height sensors are all sufficient for measurement of IRI and RN, but they differ in footprint size. Thus, consistency in the way they judge short road features relies on over-sampling and applying anti-alias filtering. Ultrasonic height sensors are not sufficient and should be replaced.

To promote standardization, it is suggested that all profilers collect at least two profiles, spaced 170 to 180 cm apart laterally.

SURFACE SHAPE

There are several ways that aspects of the pavement surface shape confound profile measurement. Transverse, daily, and seasonal variations in profile all combine to make an individual measurement a mere sample of the road shape. The lateral position of the measurement has a strong influence on the profile, because the pavement surface shape changes across the lane. On some sections, a shift in lateral tracking position of 30 cm changes the IRI in repeat runs by as much as 40 percent, and changes of 5 to 10 percent are common. A 30 cm shift on rutted pavement changed the RN by a full point on a five point scale. In PCC pavement, roughness variations of 10 percent are common over a 24-hour cycle. Thin asphalt pavements over a granular base are subject to large temporary increases in roughness in winter caused by frost heave.

Other aspects of the pavement shape affect profile measurement by interfering with the operation of the sensors within a profiler. The most well known example of this is the fact that certain kinds of coarse macrotexture cause an extreme bias in roughness measured using ultrasonic height sensors. Distresses with characteristic dimensions on the same order as the footprint size of typical height sensors also cause variations in the way each type of sensor measures rough roads, because the differ in footprint size. Proper use of common signal processing techniques eliminates most of these errors.

MEASUREMENT ENVIRONMENT

Each type of height sensor in common use in profilers is prone to bad readings caused by some aspect of the measurement environment. Some aspects of the measurement environment, such as excessive surface moisture in rainy conditions, render profile measurement completely useless. Profiler operators should know how to recognize these conditions and stop collecting data. Other aspects of the measurement environment may cause a single erroneous reading in an otherwise accurate profile. For example, the height sensor may pass over a surface contaminant such as a piece of tire tread. If the operator encounters the bad reading, the measurement can be marked as suspect. The equipment itself should aid the operator in this regard by scanning sensor signals for probable errors.

PROFILER OPERATION

The aspect of profiler operation that influences the repeatability of roughness measurement most is lateral positioning. As described above, the path a profiler takes over a section has a strong influence on the roughness it measures because of transverse variations in profile. Two measurements that follow a different path can produce equally valid but different results. The starting point of a section also determines what features are included in a measurement. Some steps can be taken to eliminate the variations caused by these factors, and alerting drivers and operators to the fact that this is important is likely to help.

Other aspects of profiler operation that are under the driver's control can lead to errors. Driving at speeds outside of the recommended range for a profiler can cause invalid measurements. Longitudinal acceleration and deceleration of a profiler greater than 0.15 g interferes with the operation of the accelerometers, and should be avoided. (This level of acceleration is approximately equivalent to changing speed at a rate of 5 kph per second, or 3 mph per second.)

Operators should verify their equipment periodically on designated sections so that failures in the system are identified as soon as possible.

PROFILER OPERATOR

The driver and operator of a profiler have a tremendous influence on the quality of profile data. It is also up to them to control the speed of the profiler, control the lateral position of the host vehicle, stay in the correct lane, and devote adequate attention to safety. The operator must prepare the profiler at the start of a day to make sure it is working properly, find data collection landmarks and trigger the system, conduct quality control during measurements, and often do on-the-spot maintenance. It is suggested that agencies engaged in profiling activities try to maintain an experienced profiling crew.

CHAPTER ONE
INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

State highway departments and transportation agencies in the United States oversee a highway network with a value roughly equivalent to the nation's annual gross national product. Responsible management of the road network is achieved by pavement management systems that function at the state level. An essential element of a pavement management system is a means to monitor pavement surface roughness, distress, and other properties. Most states use devices that measure longitudinal profile for assessment of surface roughness. The output of these devices are broadly used to decide how much funding to allocate to highway departments, to set priorities in the planning of road maintenance and repair, and to decide how the deterioration of specific road should be corrected. Given the important application of longitudinal road profile measurements, they should be as accurate and reliable as possible. This study seeks to improve the process of measuring longitudinal road profile.

When longitudinal road profile measurements are used for assessment of road condition, they are always summarized by an index that reduces the thousands of elevation values into a single value. The International Roughness Index (IRI), which was developed in research sponsored by the National Cooperative Highway Research Program (NCHRP) and the World Bank, is the most broadly used index (*1, 2*). It is used as a general pavement condition indicator. The Ride Number (RN), originally developed by the NCHRP to judge the ride quality of roads, is just beginning to gain interest in state highway agencies (*3, 4*). Some state highway agencies have created their own roughness index such as the Michigan Ride Quality Index (*5*) and the Texas Serviceability Index (*6*) for the purpose of judging the ride quality of roads or their general condition. Many of the alternative indices used within individual states are simply the IRI transformed to a 0 to 5 Present Serviceability Index (PSI) scale with a conversion equation. No matter what index is calculated from a longitudinal profile, the quality of the information is only as good as the profile measurement.

Although technology has been available for measuring longitudinal profile for decades, it has still not fully matured. A prevailing sense exists in the highway community that if every agency measured the same road with their device, they would obtain a variety of different results. Errors in profile and discrepancies between measurements arise from variations in equipment, inappropriate operating procedures, and aspects of the pavement surface and the surrounding environment. In many cases, these factors do not directly affect profile measurement, but interact to reduce their repeatability and accuracy. For example, macrotexture and surface distress cause transducers that are used to measure profile to work properly on one type of pavement surface, but not on another. Drivers of vehicles used for profiling may not all track in the same position within a lane, which affects the measured profile even if they are using excellent equipment. In addition, the actual shape of the road changes with time in response to the environment.

Current standards for profile measurement address requirements for many aspects of equipment performance, but leave out others. They also rarely cover operational procedures and techniques for diagnosing measurement errors. In order to achieve more accurate and reliable measurements throughout the profiling community more guidance is needed. This document presents the results of an investigation of most of the factors relevant to obtaining accurate and repeatable measurement of longitudinal profile with commonly used technology in North America. The results are translated into a set of guidelines for profile measurement that should improve the quality of such measurements and serve as a basis for further standardization.

RESEARCH OBJECTIVE

The objective of this research was to develop and recommend guidelines for measurement of longitudinal pavement profile for computation of IRI and RN. More specifically, the goal was to identify factors that affect roughness measurements, quantify their effect on repeatability and accuracy, determine how and when they can be controlled, and communicate the findings to practitioners by providing guidelines. The research also sought to explain the underlying cause of common measurement problems so that agencies that measure longitudinal profile can maximize the quality of the roughness estimates within their pavement management system and plan for future enhancements.

SCOPE

A number of methods are currently in use for measuring the roughness of roads. All of them produce a roughness index, but not all devices do this by direct measurement of the longitudinal elevation profile. Response-type road roughness measuring systems and profilographs are examples of devices that measure some response to the profile, but not the profile itself. This study was limited to devices that measure and record genuine elevation profiles from which the various roughness indices can be calculated. The study also focuses on devices that make measurements at ordinary traffic speeds. These are of the class known as "inertial profilers."

Inertial profilers consist of a vehicle with three essential transducers: accelerometer(s), road sensing transducer(s), and a distance measuring system. (See figure 1.) The accelerometer measures the vertical motion of the vehicle body. Data processing algorithms convert the acceleration signal to the elevation path followed by the body of the host vehicle as it travels along the road. The distance of the road surface below the elevation path of the host vehicle is measured with a noncontacting sensor such as a laser, optical, or infrared transducer. When this is subtracted from the elevation of the vehicle body, the road profile is obtained. The distance measuring system determines the position along the road, and is usually picked up from the vehicle speedometer or from direct measurements of rotation of one of the vehicle wheels.

Once a longitudinal profile is measured any profile-based roughness index can be calculated. Although a dozen or more types of roughness indexes exist, the IRI is the most broadly used as a general pavement condition indicator (*7, 8*). Several other alternatives are available that seek to judge ride quality. These usually emphasize different types of road features than the IRI and are usually cast onto a different type of scale. Consequently, they are not always affected by the factors studied in this research in the same way as the IRI. Thus, one of them, the RN, is discussed in this report to provide a broader coverage of possible uses for longitudinal profile than just the IRI. RN is based on an NCHRP study by Janoff (*3, 4*). It has undergone some modifications since its conception (*9*), and the final version is described in a Federal Highway Administration (FHWA) report (*10*).

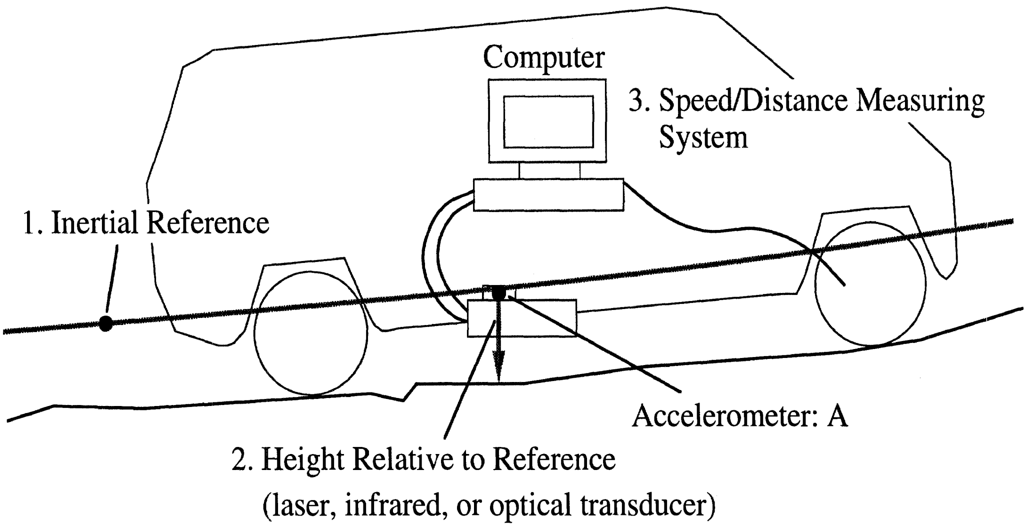

Figure 1. The inertial profiler.

The appropriate guidelines for profile measurement practice depend heavily on the final use of the data. Two major applications of profilers that are addressed in this report are network-level and project-level roughness surveys.

Profile data collection at the network level involves coverage of a large portion of the entire highway network. Nearly all states collect roughness data on their interstate and primary highway network either annually or biennially. The information that is collected at the network level is used to assess the current condition of the highway network, and to forecast the future condition. This information is generally used by the management in the highway agency to set policy and to justify budget requests. It can also be used to establish programs and set priorities for pavement rehabilitation. Network-level roughness surveys can tolerate some random error in the measurements, but no systematic errors. In other words, the roughness must be measured within a reasonable percentage, but without bias. The requirement that so much distance must be covered in a limited amount of time also means that repeat measurements cannot be made, and excessively time-consuming operating procedures and manual quality-control checks are impractical.

Project-level profile data are collected on specific pavement sections to obtain more detailed information about their roughness characteristics. The information is often used to formulate specific rehabilitation strategies, and for closer diagnosis of the problems that are associated with the project. In project-level data collection, it is usually feasible to make repeat measurements and to process the profiles beyond the calculation of a roughness index. An analyst may even study longitudinal profile plots. The accuracy requirements are much greater for project-level data collection for two reasons:

1. Often, project-level data collection is performed on relatively smooth sections, where most sources of profiling error are more significant.
2. The measurements are utilized for more detailed analyses, such as identification of specific locations along the road that need attention and planning of appropriate corrective measures.

Many of the error sources covered in this report pertain to both network-level and project-level profile measurement. However, several instances are discussed where operating procedures and equipment capabilities are recommended for project-level profile measurement that are not practical or necessary at the network level.

The Importance of Measuring True Profile

Measurement of true profile is an elusive goal. Several calibration studies have been conducted throughout the years without the benefit of a reference measurement that is considered the true profile of the road. This is because no such measurement exists. The real shape of the road can only be defined using an infinite number of points that include the topography, the road surface as seen by an automotive tire, macrotexture, microtexture, and so on. Fortunately, most applications of road profile measurements have a range of wavelengths associated with them. Thus, we endeavor to define that range of wavelengths needed for a given application, and try to measure profile accurately in that range. In the case of the IRI, that range is 1.3 to 30 m. Thus, an accuracy study that focuses on the measurement of IRI must include a reference measurement that is valid in that range (such as a Dipstick or Rod and Level). Without such a measurement, only the repeatability of a profiler or the agreement between multiple profilers can be assessed.

For measurement activities that include only one device, it is essential that the device correctly measure the portion of the true profile that is required. In the past, analysts have attempted to correct inaccurate IRI measurements by correlating to some reference device and devising a calibration factor to adjust future values. This is not valid. Using correlation to "correct" inaccurate measurement of IRI is not an improvement over using a response-type system. In fact, this procedure simply reduces a profiler to an expensive, high-maintenance response-type system. The profiler may still register a high number on rough roads and a low number on smooth roads, but the results no longer have meaning when compared to other devices or to historical roughness data. The only way to fix a device that produces inaccurate roughness values is to diagnose the error in the measurement of the profile and correct it.

RESEARCH APPROACH

Guidelines for longitudinal pavement profile measurement were developed by studying factors that affect the quality of a road profile measurement individually. The study attempted to understand the effect of each of thirty-two factors on profile and, ultimately, on measured roughness. Many of the factors were studied using specialized experiments conducted under this research project. The rest were covered using data that were available from past research, theoretical analysis, or information provided in the literature. Usually, the factors that influence profile measurement most were studied with new experiments.

The list of factors covered in this research includes most of the things that are known to affect profile measurement. The NCHRP Panel that supervised this project provided a list of factors they thought the study should address as a guide. Augmenting the list was the prior experience of the research team in studies such as the Ann Arbor Road Profilometer Meeting in 1985; the 1993 and 1994 Road Profiler Users' Group (RPUG) studies; a survey conducted in the FHWA study "Interpretation of Road Roughness Profile Data;" discussions with attendees at RPUG meetings; and phone conversations and e-mail correspondence with several profiler manufacturers (*10-13*). Some factors were also added to the study after the researchers encountered them during experimental work, or when operators of profilers that participated in experiments expressed concern about them.

The factors addressed in this research fall into five broad categories: the profiler design (hardware, data processing methods, etc.), the pavement surface shape (geometrics, surface distress, texture), the measurement environment (surface conditions and weather), the profiler operating procedures, and driver and operator proficiency. Most past studies have focused on the effect of profiler design on measurement accuracy. This study differs from them in that it sought to cover all five of the categories above. This study also treated individual factors systematically rather then covering them in a single, large experiment. (This approach was considered a more valuable expenditure of testing resources than a typical profiler roundup, because it had already been done recently by the RPUG.) For example, rather than attempting to study the performance of every make and model of profiler available in the U.S., profilers were selected for study to cover a broad range of design options, such as the type of sensing technology and sampling frequency. In addition, pavement test sections were selected with properties that were likely to challenge various profiler designs and to include special cases known to cause problems, rather than selecting a matrix of pavements for statistical comparison of roughness values.

Many of the factors covered in this study affect the accuracy of profile measurement directly. That is, they cause errors that result in a bias in the measured roughness value. These are given particular attention because this research seeks to eliminate errors in profile measurement. However, other factors confound the measurement process without causing errors, per se. For example, some measurement factors compromise a profiler's repeatability by causing random error in replicate measurements. Even if the average of the measurements is accurate, if the scatter is too high, the profiler is not useful when only one measurement is made.

Some measurement factors also affect the agreement between profilers without causing measurement errors. These differences arise because the roughness of a road varies with time, and with the track over which it is measured. For example, three perfectly accurate profilers may disagree on the roughness of a section if the first profiler tracks over one lateral position, the second profiler tracks over another, and the third measures the section one month later, or at a different time of day, when the profile has changed. These factors must be understood so that roughness values from different profiling systems, operators, and times can be interpreted properly and have the same meaning. This research studied measurement factors in the context of their effect on accuracy, repeatability, and agreement.

All of the experimental and analytical studies in this research sought to understand the underlying effect of measurement factors on profile. However, the purpose of most profile measurements is to determine the roughness of a section. Thus, many of the studies in this report quantify the results using two summary profile indices: the IRI and RN. The IRI was selected because it is in widespread use in the U.S. Currently, the FHWA requires states to report IRI of a portion of their network for the national Highway Performance Monitoring System (HPMS) (*14*). The IRI was originally developed to provide a stable means of quantifying roughness that could be compared by different agencies and did not change with time. If the IRI is to serve highway agencies in this capacity, it must be measured accurately *and* have the same meaning from state to state. The RN was selected because some pavement features that affect the IRI do not affect RN, and some features that affect RN do not affect the IRI. In particular, RN is sensitive to shorter wavelengths. Although RN is only beginning to gain acceptance in state highway departments and transportation agencies, the results provided for it are relevant to any index that covers a similarly short wavelength range.

A series of field experiments and analyses was conducted to quantify the effect of each factor. Targeted studies were made of each of the factors and the way they interact, in order to better understand the underlying reasons for the effect on roughness measurement. Many of the experiments were designed around the use of the ProRut system obtained on loan from the FHWA. The ProRut uses laser road sensors and allows data collection at intervals as small as 10 mm, thus providing a high resolution measurement capability as the basis for the experiments. Profilers from other organizations were also invited to participate in the experimental program. The other participants were two Ohio Department of Transportation (DOT) profilers (infrared and laser sensors), two profilers from Pennsylvania DOT (ultrasonic and laser sensors), and a laser profiler from the Minnesota DOT. Each profiler completed a three-day program of measurements. Testing was performed on a selection of local road sites in the Ann Arbor area chosen for particular forms of distress and on test sites at the General Motors Proving Grounds (GMPG) in Milford, Michigan. These sites included a range of surface textures, and provided a traffic-free environment for specialized testing and reference measurements by a Dipstick.

In addition to the physical experiments, analytical studies were designed to utilize existing data from other experimental studies. A large amount of data was already on hand from the RPUG studies, from an FHWA project that had just been completed by the research team, and from the Long-Term Pavement Performance (LTPP) study. These sources provided several thousand profile measurements from different profiling devices operated on the same test sections, repeated measurements on test sections, and repeated measurements over time. Finally, some theoretical predictions were used to augment experiments in the study of sampling and filtering techniques. All of the data sources used in this research are described in Appendix A.

Chapter 2 describes the effect of the factors studied on measurement of IRI and RN. To translate these findings into guidelines for measuring longitudinal profile the observations were summarized into a list of rules that could be readily communicated and assimilated by profiler users. The collective set of guidelines is published in a separate document entitled *Operational Guidelines for Longitudinal Pavement Profile Measurement.*

CHAPTER TWO
FINDINGS

High-speed road profiling technology was introduced in the 1960s at the General Motors Research Laboratory by Spangler and Kelly (*15*). Profiling technology found broad application beyond research in the U.S. in the late 1970s when many state and federal agencies in charge of monitoring pavement condition began using them to judge the serviceability of roads in place of response-type road roughness measuring systems. A major advantage of profilers over response-type systems is that they are capable of providing a stable and transportable way of measuring roughness. In other words, roughness values produced by a valid profiler can be compared to values from prior years and values measured by other valid profilers. In principle, this means that state agencies can compare their roughness values with confidence that they have the same meaning. Unfortunately, insufficiencies in profiler design, data processing techniques, and operational practices have compromised the accuracy of profile measurement.

The capabilities of many of the profilers in use around the world in the mid-1980s were studied in the Ann Arbor Profilometer Meeting (*13*). Many of the profilers that participated in the meeting were deemed adequate for use in network-level roughness surveys. The study identified several aspects of profiler design that significantly affected their performance. However, the manner in which the profilers were operated was identified as the most significant source of difference between measurements.

In 1993 and 1994 the RPUG conducted two major experiments that compared the performance of more than forty profilers in use in North America (*11, 12*). The overall accuracy of the profilers was not as good as the profilers in the Ann Arbor Profilometer Meeting. The decline in performance was partly caused by the proliferation of inexpensive equipment that was lacking in adequate sensor technology and proper data processing techniques. The study was designed to remove some of the sources of variation in operational practices, but many operational factors did affect the results.

The RPUG studies and the Ann Arbor Profilometer Meeting identified several individual factors that affect the accuracy and repeatability of profile measurements, but the effect of many of them were not quantified directly. Other factors of concern in profile measurement have been identified in past RPUG meetings, other studies, and in communications with the NCHRP Panel overseeing this research.

Thirty-one individual factors in the measurement and analysis of road profile were studied in this project. This chapter presents technical discussions of each of these factors, broken up into five broad categories as follows:

1. Profiler Design: aspects of profiler configuration, data collection method, and signal processing techniques that affect the measured profile.
2. Surface Shape: geometrical properties of the pavement surface, distress, and texture.

3. Measurement Environment: aspects of the environment in which a profiler must function that are not a property of the pavement shape.

4. Profiler Operation: the manner in which a profiler is driven and operated.

5. Profiler Operator: proficiency of the drivers and operators themselves.

The effects of the individual factors are expressed in the context of their influence on measurement of IRI and RN. Often, a factor affects each of them differently. For example, the IRI value (which is a measure of slope expressed in units of m/km) increases with roughness. A value of 0 m/km implies that the road is perfectly smooth, and a value of 3 m/km is a typical cutoff value for judging a road in need of repair. In contrast, the RN is expressed on a 0 to 5 scale, where a higher value indicates a smoother road. Most sources of error make a road appear rougher. In this report, the phrase "increases the apparent roughness" refers to an increase in IRI and a decrease in RN.

RN is derived from a Profile Index (PI) computed directly from the profile. Its value is obtained using the nonlinear transformation:

$$RN = 5e^{-160(PI)} \qquad (1)$$

In some cases, it is more convenient to discuss the effect of an error source on PI rather than RN. It is important to recognize that a change in PI of a given percentage does not cause a change in RN of equal percentage, and an upward bias in PI causes a downward bias in RN.

The IRI and RN are also sensitive to a different range of wavelengths: The IRI is most sensitive to wavelengths from 1.3 to 30 m; and the RN is most sensitive to wavelengths from 0.38 to 11.4 m. Appendix B describes the IRI and RN in more detail.

SUMMARY OF SIGNIFICANT FACTORS

Each of the profile measurement factors affects profiler performance in one or more of four ways.

1. Accuracy: The majority of factors covered in this chapter affect the accuracy of profile measurement. The consequence is a bias in the roughness value.

2. Agreement: Some factors affect the agreement between profilers. This differs from accuracy in that no standard is set for what is correct. For example, two profilers that differ in lateral sensor spacing may both measure profiles accurately, but yield different values of roughness because they do not measure in the same two paths. Since no standard exists for sensor spacing, neither profiler is considered more correct than the other.

3. Repeatability: Several of the factors, particularly aspects of pavement shape and profiler operation, affect the repeatability of a profiler. That is, they cause scatter in the roughness values that are measured in repeat tests.

4. Interpretation: A few of the factors relate to the interpretation of roughness measurements. These factors do not affect agreement between profilers or repeat

measurements by the same profiler, but they do affect the meaning of the measurement.

Table 1 provides a listing of the measurement factors covered in this chapter, and a listing of which aspect of profiler performance is affected by each factor.

Table 1. Profile measurement factors.

Factor	Accuracy	Agreement	Repeatability	Interpretation	Factor	Accuracy	Agreement	Repeatability	Interpretation
Profiler Design	×	×		×	Measurement Environment	×			
Sample Interval	×				Wind	×			
Computation Algorithm	×				Temperature	×			
Automated Error Checking	×				Humidity	×			
Height Sensors	×	×			Surface Moisture	×			
Accelerometers	×				Surface Contaminants	×			
Longitudinal Dist. Meas.	×				Pavement Markings	×			
Number of Sensors				×	Pavement Color	×			
Lateral Sensor Spacing		×			Ambient Light	×			
Surface Shape	×		×		Profiler Operation	×		×	×
Transverse Variations			×		Operating Speed	×			
Daily Variations			×		Speed Changes	×			
Seasonal Variations			×		Lateral Positioning			×	
Surface Texture	×				Triggering			×	
Pavement Distress	×		×		Longitudinal Positioning			×	
Curves	×				Segment Length				×
Hills and Grades	×				Freq. of Data Collection				×
					Profiler Sanity Checks	×			
					Profiler Driver and Operator	×		×	

Accuracy

Several aspects of *profiler design* affect their accuracy, including the sensors within a profiler and the way signals are collected and processed. The *sample interval* of a profiler is critical to the accuracy of the roughness it measures, with different requirements for accurate measurement of IRI and RN. Proper anti-alias filtering of the accelerometer and height sensor signals, selected in accordance with the sample interval is also critical.

A *profile computation algorithm* that runs concurrently with data collection can determine a roughness index correctly on a continuing basis. However, this method introduces a phase shift in the profile that displaces the long wavelength features slightly. This should be taken into account when identifying pavement locations in need of corrective action. The computation algorithm should include *automated error checking* that scans the transducer signals for improper speed or signal level errors to help avoid collection of invalid profile data.

All high-speed profilers use one of four types of noncontacting *height sensors*: laser, infrared, optical (visible light), and ultrasonic. Laser, infrared, and optical height sensors can sample at a high enough rate and with resolution adequate for the measurement of IRI and RN. Ultrasonic height sensors do not. The *accelerometers* commonly used in profilers all have to meet the resolution requirement for roughness measurement.

Accurate *longitudinal distance measurement* in a profiler is important primarily from an operational standpoint. Most profilers measure longitudinal distance with an accuracy of better than 0.5 percent. The resulting errors in IRI and RN are of the same order, and thus inconsequential. Only in network monitoring applications where roughness is measured over very long distances is distance error important, and these errors can be overcome by resetting the location reference at landmarks every few kilometers.

The factors listed under the category *surface shape* affect profile measurement accuracy by interfering with the operation of the height sensors and accelerometers. The most well known example of this is coarse *surface texture* that can introduce aliasing errors. Profilers with ultrasonic height sensors are particularly prone to this error, measuring IRI values 50 to 100 percent high on chip sealed asphalt. Profilers with laser and infrared height sensors are not sensitive to surface texture if their signals are processed properly with anti-aliasing filters.

Distress with characteristic dimensions on the same order as the footprint size of typical height sensors (e.g., narrow transverse cracks the size of a laser spot) may also compromise the accuracy of profilers that do not apply anti-aliasing filters.

Roadway geometrics have the potential to cause measurement errors by changing the orientation of the accelerometer from perfectly vertical. Operating on *curves* causes the accelerometer to tilt sideways and erroneously measure a component of the lateral acceleration. On typical curves this affects the appearance of the profile, but not the IRI and RN as long as the lateral acceleration does not exceed 0.15 g. Measuring profiles on *hills* that conform to the *AASHTO Policy on Geometric Design of Highways and Streets* does not cause errors in roughness measurement.

The *measurement environment* affects profile accuracy primarily by interfering with the operation of the height sensors in two ways. First, some factors may cause a bias in measurements by a height sensor (akin to an error in calibration). Operators should learn to recognize conditions within the environment that adversely affect height sensor readings and suspend data collection until conditions change. Second, some cause height sensor measurement errors that appear as spikes in the profile. In project-level profiling, erroneous spikes should prompt the operator to repeat the measurement. In network-level profiling, the software in the profiler should warn the operator and provide a means of marking the bad readings as suspect. Each type of height sensor is affected by the measurement environment differently.

Severe *winds* that generate sound under a profiler cause invalid readings in ultrasonic height sensors. Winds also cause measurement errors in any type of noncontacting height sensor if a significant amount of sand, snow, or other surface contaminants pass under the profiler. Ultrasonic height sensors are sensitive to *temperature* to the degree that it renders them inadequate for measurement of roughness. Laser, optical, and infrared sensors all operate properly over a broad range of temperatures. Sensor manufacturers usually provide temperature limits. *Humidity* below 90 percent (and noncondensing) does not affect the accuracy of height sensors. Of course, water condensation on the surface of emitters, pick-ups, lenses, or mirrors disrupts height sensor function.

No height sensor is accurate on roads with excessive *surface moisture* such as standing water, ice, or snow. Profiling should not be done if enough moisture is present to submerge the surface texture or to cause splash and spray behind vehicle tires. *Surface contaminants* potentially increase the apparent roughness of a section.

The change in surface reflectivity at *pavement markings* does not affect laser, infrared, or ultrasonic height sensor performance. Optical height sensors may read a spike on white pavement markings. The spikes have little effect on IRI, but are more significant to RN. Changes in *pavement color*, such as the change at a transition from Portland cement concrete (PCC) to asphalt concrete (AC), is not a problem for laser, infrared, or ultrasonic height sensors. Optical height sensors were not tested on a color transition.

The laser, ultrasonic, and infrared height sensors in common use are not affected by changes in *ambient light*. Optical sensors are affected by ambient light, necessitating use of a shroud to shade the surface under the sensors. Proper maintenance of the shroud is essential to avoid errors from ambient lighting.

The aspect of *profiler operation* that is most crucial to measurement accuracy is the speed. Driving at speeds outside the recommended range for a profiler or aggressive braking can cause invalid measurements.

Most profilers are valid over a broad range of *operating speed*. The range depends on the design of the profiler and the range of wavelengths to be measured. The manufacturer usually specifies the range of speed in which valid profile data can be collected. Maximum speed is limited by a profiler's data collection rate and the roughness of the road. The sampling rate of ultrasonic height sensors severely limits their performance, often necessitating operation at speeds below normal posted limits. High speed on rough roads can excite vehicle motions that cause height sensor readings to go out of range. Usually, the road is so rough in these cases that the error is insignificant relative to the total roughness. The minimum speed at which a profiler should operate is dictated by the longest wavelength it needs to measure. Most profilers can measure the wavelength range of interest for the IRI and RN at speeds as low as 25 kph.

Speed changes (braking and acceleration) can cause errors in profile data because the accelerometer does not stay vertical, but erroneously measures a component of the longitudinal acceleration. Moderate accelerations of 0.15 g or less can be tolerated in network-level measurement, but the operating speed should be held reasonably constant in project-level applications and measurement of new construction.

Profiling from a dead stop or a rolling start influences accuracy because the profiler must operate below its lower cutoff speed at the start of the run. To avoid these errors, short sections before and after a stop should be ignored.

The *profiler driver and operator* have a tremendous influence on the accuracy of profile data. Drivers control the speed of the profiler, and must avoid operating speeds and severe braking that cause errors. The operator must constantly conduct quality control checks during profiling activities. The operator must also make constant judgment calls in adverse conditions as to whether valid profile can be measured.

Agreement

Some aspects of *profiler design* affect the agreement between profilers, but the discrepancies are not considered errors. A profiler's *lateral sensor spacing*, in conjunction with its *lateral position*, determines where the profiles are measured and consequently the roughness. The size of the *height sensor* footprint also determines the way surface features with small dimensions such as narrow cracks contribute to measured roughness.

Repeatability

Several aspects of the pavement *surface shape* affect the repeatability of profile measurements. Perfectly accurate profile measurements of the same road section at different times may not agree because the roughness of roads changes with time.

Changes in temperature over a twenty-four-hour cycle cause *daily variations* in the shape of PCC slabs. Subsurface movements caused by cyclic changes in temperature and moisture over a yearly cycle cause *seasonal variations* in the roughness of PCC pavements that are at least as large as the daily changes.

Seasonal variations in asphalt concrete pavement profile occur mainly because of changes in volume of the subsurface layers. In freeze-thaw environments, AC pavements on granular base material are subjected to frost heave that will increase roughness, even on pavements that are very smooth the rest of the year. Often, the bumps caused by frost heave disappear in the spring and the roughness returns to the level of the previous fall.

Pavement sections may exhibit significant *transverse variations* in roughness. The nature of the variation depends strongly on the surface type. *Pavement distress* such as alligator cracking, longitudinal cracking, and rutting cause the largest transverse roughness variations.

Transverse variations interact with *profiler operation* to affect repeatability. The particular *lateral positioning* that a profiler maintains as it passes over a pavement section influences the measured roughness. Typical variations in the lateral position taken by different drivers can cause a significant change in roughness values.

The *longitudinal positioning* of the start of a profile affects the roughness. With automated *triggering*, errors in starting location are negligible. However, with manual triggering the starting location of a section varies enough to cause significant changes in the roughness values on short sections. Longitudinal positioning affects repeatability even more on sections with major distress that is sparsely distributed.

The *profiler driver and operator* influence the repeatability of profile data. Drivers control the lateral positioning of the profiler, and the operator must trigger data collection and make sure the longitudinal positioning of the measurement is correct.

Interpretation

The *segment length* used for reporting roughness has a strong impact on the interpretation of the values. The roughness of a very long segment provides a single number that functions as a summary value, but has the disadvantage that it fails to identify locations along the road in need of corrective action. Relatively extreme values of roughness are not unusual on short segments. Segments 160 m long or longer are recommended for judging the overall condition of a road network, and segments 25 m long are recommended for judging the roughness of bridge approaches, railroad tracks, and other rough events.

Since roughness varies significantly over time, the *frequency of data collection* on a road network affects the interpretation of the data. Annual surveys must be viewed as a statistical sampling of the road condition, and individual roughness values should be considered estimates of the roughness.

The *number of sensors* in a profiler determines the utility of the data. Measurement in one wheeltrack only is not sufficient to characterize the roughness of a road because a combined roughness value from two wheeltracks is significantly different in most cases. A minimum of two sets of sensors, one each on the right and left, is recommended for all profiling applications.

PROFILER DESIGN

This section discusses the effect of profiler design on profile measurement. Rather than comparing one brand of profiler to another, the studies reported here seek to address each aspect of profiler design separately. The information provided in this section should be useful both at the level of designing a system, and enhancing the performance of existing systems with improvements targeted at specific aspects of the design. The factors covered include the physical configuration of the systems, the capabilities of the sensors, and the manner in which the sensor signals are processed. The guidelines that resulted from the study of these factors are minimum performance specifications for components of the profiling system, suggested standards for equipment design, procedures for making sure that components are functioning properly, and suggested software improvements for error detection and diagnosis.

One of the most important topics in this section is sample interval. For each application, profiles must be collected with the appropriate sample interval. However, this is not enough. The profiler must also apply anti-aliasing filters that adhere to established signal processing rules, no matter what the sample interval. As is the case in the study of sample interval, the results in each section usually suggest design specifications that are clearly best for acquiring quality roughness data. The exception was the discussion of height sensor performance. Ultrasonic sensors were found to be insufficient for measurement of IRI and RN. In contrast, optical, infrared, and laser sensors are all capable of measuring accurate profile if their signals are processed properly and screened for errors, but they do not all perform the same way in every case, and they each have advantages and disadvantages.

Generally, profiler users should strive to understand all of the issues raised in this section. It is essential, however, that profiler manufacturers thoroughly understand them.

Sample Interval

The study of the impact of sample interval on profile measurement uncovered several important issues pertinent to obtaining accurate profile measurements. Most of these issues relate to well established sampling theory, but are intimately tied with the selection of a minimum sample interval necessary for a given application. In particular the use of filters to avoid aliasing errors and the consequences of failing to do so are discussed in this section. A basic description is given of the manner in which measurements are sampled throughout the profile measurement process. This is followed by detailed discussion of the aspects of the process found to be most crucial to accuracy.

A road profile represents the elevation of the road along a continuous imaginary line on the surface. Since profilers are based on digital equipment, the measurement cannot be continuous. It is instead a discrete collection of sampled points. In this process it is very important to accurately measure the components (that is, the wavelength range) of the profile of interest. It is also important, for economic and logistical reasons, not to measure unnecessary information.

Profile is computed from a combination of longitudinal distance, height, and acceleration measurements. The height and acceleration measurements require special conditioning, because they are random signals. The accelerometers in a profiler are analog sensors. They output a voltage that is continuous and proportional to the acceleration. Height sensors, on the other hand, are usually digital transducers, so they can only make a measurement a finite number of times in a second. For example, most of the Selcom laser sensors used in profilers measure 16,000 times per second. This is a *sampling rate* of 16 kHz for that sensor. It is impractical to record and use all of the data that is transduced by the sensors in a profiler. Thus, data are digitized and recorded into computer memory at discrete intervals. The longitudinal distance between points that are digitized and fed into the profile computation algorithm is the *sample interval* of the profiler. In common practice, profilers range in sample interval from 25 to 360 mm.

A crucial step that must be performed on the height sensor and accelerometer signals before the data are recorded is anti-aliasing. Aliasing is a problem inherent in all digital sampling. As a consequence of digitizing at a given sample interval, some high frequency components of the quantity being measured will contaminate the lower frequency components (*16*). This problem is solved by filtering the sensor signals prior to analog-to-digital conversion. If the height sensors are digital, the signal must either be converted to analog before filtering, or a digital filter is used. In either case, avoiding aliasing errors in the measurement of road profile is complex and involves a strong interaction between height sensor footprint, road surface properties, sample interval, and the use to be made of the profile. Thus, considerable effort is dedicated here to explaining the aliasing problem and how to eliminate it.

After anti-aliasing, digitizing, and profile computation one other step is often performed. This is the application of a moving average filter and further decimation of the profile before it is recorded. For example, K.J. Law profilers usually operate with a sample interval of 25 mm. A moving average filter with a baselength of 300 mm is then applied and the profile point is saved every 150 mm. The longitudinal distance between points in the profile when it is saved is the *recording interval.* In most profilers the sample interval is the same as the recording interval.

As described, the flow of data from the road to a final profile measurement includes sensing with transducers, anti-alias filtering, decimation, conversion to digital format, combination of sensor signals into profile, a second (optional) anti-aliasing filter, and saving to disk at the recording interval. The remainder of this section discusses some key aspects of this process.

1. First, a description of the aliasing problem and the manner in which it affects profiling are provided. Recommendations for avoiding aliasing errors based on sampling theory are given.
2. Next, the theoretical effect of sample interval on accuracy of IRI and RN is discussed. The theoretical calculations are made under the assumption that anti-aliasing was performed and that the sample interval and recording interval are the same.
3. Next, the theoretical results are verified using experimental data. Data collected with various methods of avoiding aliasing errors are used to demonstrate the importance of anti-aliasing.
4. Last, the effect on IRI and RN of applying a moving average to a profile and decimating it to a recording interval larger than the sample interval is illustrated.

Aliasing

This discussion is intended to illustrate that **anti-aliasing is essential to the quality of profile measurement**.

The actual sensitivity of the IRI and RN to sample interval depends heavily on the quality of the measurement. In particular, it depends on how well aliasing errors have been eliminated. Aliasing occurs when, as a consequence of sampling at a finite interval, the short-wavelength content of the true road profile contaminates the measurement of the longer-wavelength content. A simple example to illustrate this phenomenon is pictured below. (See figure 2.) A sine wave is sampled at an interval slightly longer than its period of oscillation. The only information that is available to the measurement is the set of sampled values. When connected, the sampled points appear to define a sine wave of a much longer wavelength. It is in this manner that the short road features that the IRI and RN should ignore are aliased into the longer wavelength range of the measurement and artificially increase the roughness.

From a more practical standpoint, imagine a height sensor with a very small footprint that measures a few centimeters deep into a narrow crack. This is a feature in the road that is likely to be ignored by a tire passing over it, and should be ignored by the IRI and RN calculation. (See figure 3.) If the profiler is operating with a very short sample interval, the crack will be insignificant because its depth will be attenuated in the moving average. However, if the sample interval is longer than 167 mm, the crack will appear to be a dip a few centimeters deep and more than 333 mm long. It will erroneously increase the roughness of the section because, after sampling, there was not enough information available to recognize it as a narrow crack. (It looks instead like a longer dip in the road.)

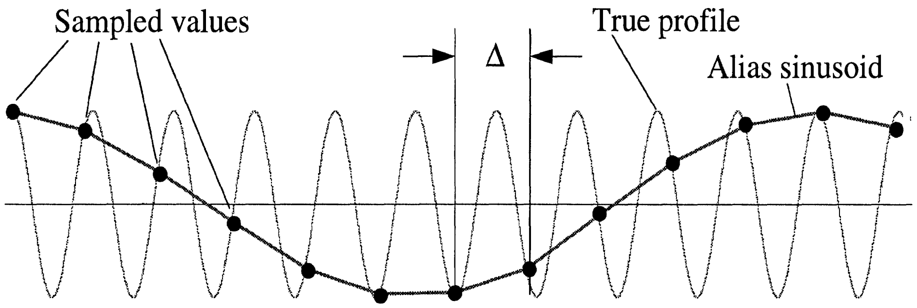

Figure 2. Simple example of aliasing.

The potential for this type of error in the measurement of road profile is enormous. In particular, cracks and opened PCC joints can easily lead to this type of aliasing error. Many features that can cause aliasing errors are intentionally built right into pavement. Keep in mind that coarse surface macrotexture is desirable from the standpoint of safety. Tining, large aggregate, and many types of coarse seal coat are all features that have caused aliasing errors in common profiling equipment.

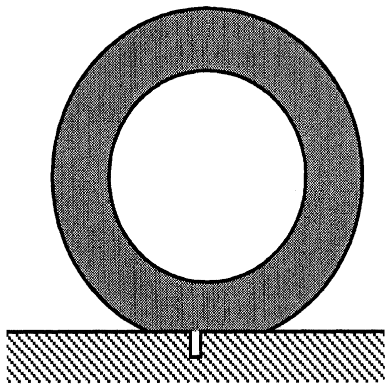

Figure 3. A tire over a narrow crack.

Fortunately, aliasing can be avoided. Refer once again to the example pictured in figure 2. Assume that the original sine wave has a wavelength that is outside the range of interest, but the aliased sine wave does not. In the example, a single point was measured every Δ. As an alternative, consider a case in which a sampling rate was used that allowed ten measurements to be made over the distance Δ. Then, before the sensor readings were digitized, each set of ten measurements were averaged to a single value. (Note that the average over a distance Δ of the original sine wave is close to zero.) These averaged values could then be digitized at a sample interval of Δ. This procedure leads to a much higher level of quality in the measurement. The original sine wave still does not appear in the final measurement, but the (artificial) longer, aliased sine wave is also virtually eliminated.

The procedure just described is a simplified explanation of how anti-aliasing should work in a profiler. In reality, anti-aliasing is a bit more complicated. The signals from height sensors and accelerometers should pass through an analog filter to eliminate the short-wavelength content before they are digitized. It is also important to use the same filter on the height sensor and accelerometer signals. If anti-aliasing is performed on only one of the sensors or differently on each, aliasing errors will still result. They will just be more complicated aliasing errors.

The recommended anti-aliasing filter and sample interval are highly interrelated for a given application. Although this is a complicated issue it has been studied exhaustively, and many good references are available on the subject (e.g., (*16*)). The most important rule of sampling is the Nyquist Sampling Theorem. This rule states that the sample interval Δ should be:

$$\Delta = \frac{\lambda}{2} \qquad (2)$$

where λ is the shortest wavelength of interest in the profile. So, if the shortest wavelength of interest is 0.3 m, the sample interval must be 0.15 m or shorter.

Of course, it is not sufficient to simply set up the sensors to sample the height and acceleration every 0.15 m and use the signals to compute profile. This would lead to serious aliasing errors. Instead, the sensor signals must pass through an anti-aliasing filter (before analog to digital conversion) to eliminate short wavelength roughness that is not of interest. For a sample interval of Δ the cutoff wavelength (λ_c) in the anti-aliasing filter should be:

$$\lambda_c = 2 \bullet \Delta \qquad (3)$$

Since most profiler sensors are time-based instruments (K.J. Law uses distance-based sensors), the filter will have a cutoff frequency, not a cutoff wavelength. The cutoff frequency f_c and the cutoff wavelength λ_c are related through the travel speed V:

$$f_c = \frac{V}{\lambda_c} \qquad (4)$$

To achieve a cutoff wavelength of 0.3 m in a profiler that is traveling at 24 m/s (86.4 kph), a cutoff frequency of 80 Hz must be used. Unfortunately, the travel speed of the profiler is not always predictable. Most profilers operate over a broad range of speeds and, for practical reasons, must even tolerate modest speed changes. Thus, the filter cutoff must be set somewhat conservatively. A simple strategy is to set the cutoff for the highest speed that is permitted by the profiler. Another is to force the operator to enter the expected speed and set the cutoff accordingly, but this creates a new opportunity for error. Some profiler manufacturers use filters that adjust to the vehicle speed on the fly, but the details of the algorithms for doing this are not available.

For an analog sensor, like an accelerometer, the recommendations just presented work well. Height sensors, on the other hand, are rarely analog sensors. Instead of providing a continuous signal proportional to height, they provide a discrete number of readings at a given rate. For example, ultrasonic height sensors can only take a valid reading every 0.01 s (*17*). At a speed of 108 kph, this is one reading every 0.3 m. Thus, they can only measure wavelengths of 0.6 m and longer. Since it is not possible to take readings more often and apply an anti-aliasing filter, measurements by ultrasonic height sensors are likely to be invalid over a much broader range of wavelengths. In contrast, Selcom laser height sensors sample at a rate of 16,000 Hz or faster. If the cutoff frequency of the anti-aliasing filter is 80 Hz, this rate is more than sufficient.

Theoretical Study

The theoretical sensitivity of the IRI and RN to sample interval was derived in the spatial frequency domain. (Spatial frequency is expressed in terms of distance, rather than time, so typical units for spatial frequency are cycles per meter, rather than cycles per second.) This was done to determine the bias that should be expected in the IRI and RN at common values of sample interval. The methodology employed is described in a recent FHWA report (*10*). The calculations were extended to include the 250-mm moving average in the IRI and RN algorithm and the presence of anti-aliasing filters. Overall, sample interval influences the accuracy of IRI and RN in four ways.

1. Sample interval determines the effective baselength of the moving average in the IRI and RN algorithm. (See Appendix B.)
2. Sample interval influences the wavelength response of the quarter-car filter. If the sample interval is shorter than 1 m, this effect is negligible.
3. Sample interval dictates the minimum wavelength that can be measured. If sample interval is too large, important components of the road roughness are left out.
4. The cutoff frequency of anti-aliasing filters is usually based on sample interval.

The anti-aliasing filter is represented in the calculations using a two-pole Butterworth low-pass filter. Since the theoretical treatment used here does not include consideration of individual sensor signals, the filter is applied directly to the profile. This is the equivalent of assuming that the filters operate perfectly and the same filter was applied to accelerometer and height sensor signals. The cutoff wavelength is always set to twice the sample interval.

The first step in calculating the IRI and RN is the application of a moving average. The algorithm is set up to use a baselength as close to 250 mm as possible. However, if the sample interval is of the same order of magnitude as the intended baselength a slightly different effective baselength is achieved. This is because the number of points in the average must be an integer, so the effective baselength is always an integer multiple of the sample interval. For example, the number of points in the average is computed as follows:

$$I_B = \mathrm{NINT}(B/\Delta) \tag{5}$$

Where I_B is the number of points used in the moving average, NINT stands for "nearest integer", B is the baselength (250 mm), and Δ is the sample interval. (The value of I_B must be at least one.) Of course, the fraction in the brackets will rarely produce an integer exactly, so the effective baselength, which is $I_B \bullet \Delta$, is rarely 250 mm. Table 2 lists some examples of this calculation. The effective baselength ranges from 175 mm to 300 mm. These fluctuations cause the wavelength content of the moving average to shift, and introduce a small bias in the result.

Figure 4 shows the sensitivity of the IRI to sample interval on a road of white noise slope. (White noise slope is a common theoretical approximation of a typical road. On any real road, the results in figure 4 would be slightly different.) At each value of sample interval, the error (in percent) relative to the case of an infinitely small sample interval is given. A positive error represents an upward bias in IRI, and a negative error is a downward bias.

Table 2. Effective moving-average baselength.

Sample Interval Δ (mm)	B/Δ	I_B	Effective Base-length (mm)
25	10.00	10	250
50	5.00	5	250
75	3.33	3	225
100	2.50	3	200
125	2.00	2	250
150	1.67	2	300
175	1.43	1	175
200	1.25	1	200
225	1.11	1	225
250	1.00	1	250
275	0.91	1	275
300	0.83	1	300

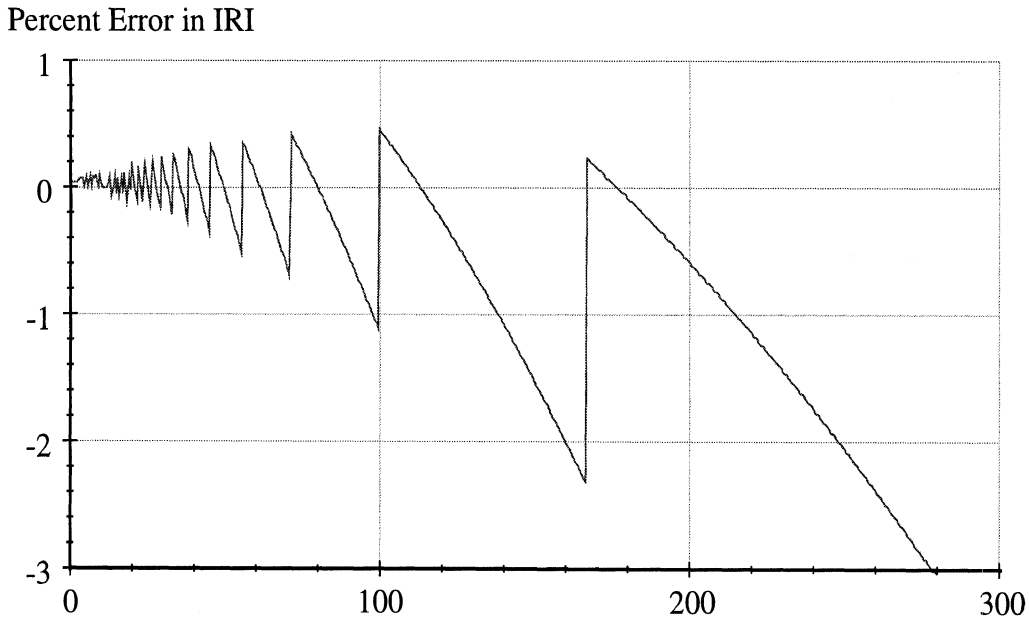

Figure 4. Expected error in IRI versus sample interval.

The error changes smoothly as the effective baselength of the moving average changes until the number of points in the average transitions from one integer to another. This causes an abrupt change in the effective baselength and, in turn, an abrupt change in the expected error. The largest jump occurs at a sample interval of 167 mm. This is the transition from two points in the moving average (for a baselength of 334 mm) to one (for a baselength of 167 mm). In this case, the downward bias of 2.3 percent changes sharply to an upward bias of 0.2 percent. As sample interval increases beyond this point, the IRI gets steadily smaller as more and more of the wavelength content in the IRI is not measured.

The expected error level holds under 2 percent until the sample interval reaches 160 mm. Although these errors are small, it is not wise to build any error into the measurement process. (Enough external factors are available for this.) These errors can be eliminated by sampling at a very short interval. A convenient way to do this is to sample at an interval of 55 mm or less (which holds the bias under 0.5 percent), perform the moving average, then decimate the profile to a larger interval before it is saved. This is discussed under "Recording Interval."

Figure 5 shows the sensitivity to sample interval of the PI that is used to compute RN on a road of white noise slope. PI is a root-mean-square (RMS) value that is transformed to RN. (See Appendix B.) At each value of sample interval, the error (in percent) from the case of an infinitely small sample interval is given. A positive value of percent error means an upward bias in PI, or higher roughness, and a downward bias in RN.

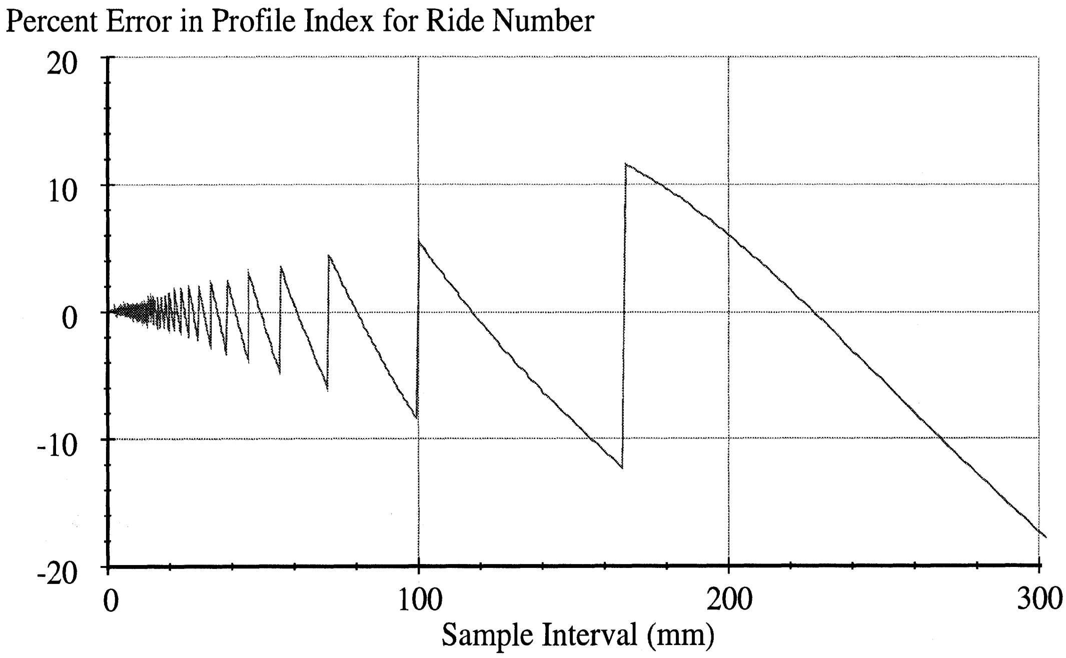

Figure 5. Expected error in Profile Index versus sample interval.

Again, the error changes smoothly when the effective baselength of the moving average changes smoothly. The abrupt changes occur as the number of points in the moving average transitions from one integer to another. For example, the transition at a sample interval of 167 mm (from one point in the average to two) causes a change from a downward bias in PI of 12.3 percent to an upward bias of 11.5 percent. For the same range of sample interval, the error level in the PI is much higher than that of the IRI. This is because the RN is heavily dependent on short wavelength roughness that is not as important to the IRI. To prevent the error level from increasing beyond 2 percent, a sample interval of 25 mm or shorter must be used.

Analytical Treatment

The effect of sample interval on roughness measurement was studied by decimating profiles of relatively short sample intervals to longer intervals and observing the change in roughness value. For this purpose, profile measurements with a sample interval of about

250 mm from the ProRut and the K.J. Law infrared profiler were available. These two devices differ significantly in their treatment of aliasing, so the results from each are discussed.

K.J. Law infrared profilers perform anti-aliasing at two stages of the measurement process before the profile is computed. First, the sensor footprint is 6 mm long (along the direction of travel) and 37 mm wide. This footprint averages out features that are much shorter than 6 mm such as coarse microtexture, and features that are much less than 37 mm wide such as longitudinal cracks. Second, a low-pass filter with a cutoff of about 50 mm is applied to the height sensor and accelerometer signals before they are digitized. These two steps together eliminate most aliasing errors.

Two profiles measured by a K.J. Law infrared profiler with a sample interval of 25 mm were decimated (without averaging) to various other values of sample interval. The IRI and RN of the decimated profiles were then compared to that of the original profile. Figure 6 shows the results for the IRI of a smooth asphalt section of relatively smooth macrotexture and a section of severely faulted PCC. The analysis can only include values of sample interval that are multiples of 25 mm. Each point in the figure represents the average of the available possibilities for a given sample interval. For example, decimation from a sample interval 25 mm to an interval of 250 mm gives rise to ten possible profiles, each with a different starting point. The IRI used in the figure for this case is the average of the IRI of all ten profiles.

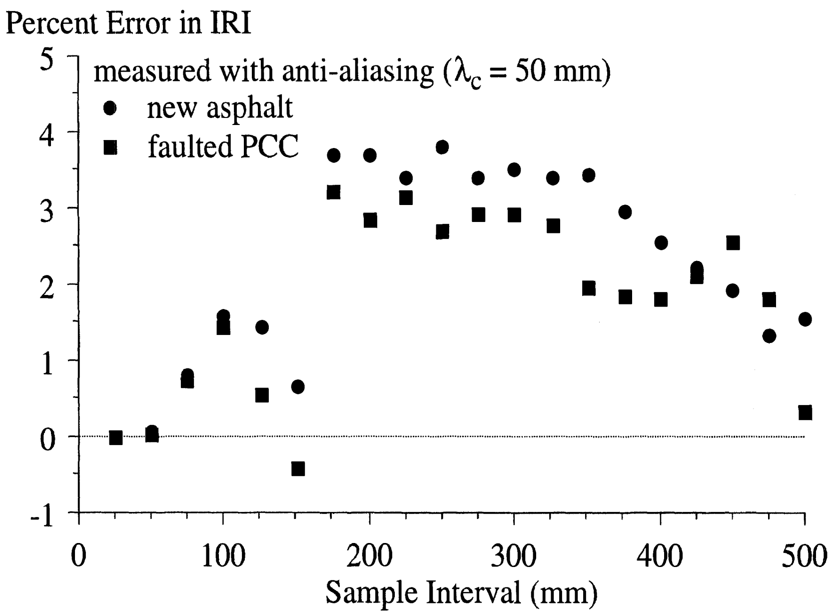

Figure 6. Effect of sample interval on IRI with anti-aliasing.

Although less detail is available in figure 6, some of the basic characteristics of the theoretical predictions given in figure 4 are duplicated. For example, the error reaches a local peak at a sample interval of 100 mm and steadily decreases until a large jump at 175 mm. The error then steadily decreases as sample interval grows beyond 175 mm. In general, the results showed an upward bias in roughness not predicted by the theory. This is because the decimation in the experiment changes the sample interval, but the anti-aliasing filter did not change. At a new, longer, sample interval the original anti-aliasing filter is insufficient. In a typical measurement by the K.J. Law profiler the profiles are decimated, but they are averaged first. The averaging protects against the aliasing errors introduced by the decimation. The benefits of this type of procedure are discussed in the next section.

Figure 7 shows the results of the same exercise performed on a profile measured with the ProRut. The ProRut performs anti-aliasing, but much less aggressively than the K.J. Law profiler. First, the height sensor footprint is 2 mm long in the direction of travel and 5 mm wide. Very little averaging is done by this small sensor footprint. This is an advantage when trying to detect very short features like cracks, but a greater potential for aliasing errors in the measurement of IRI and RN also exists. Second, the cutoff wavelength of the anti-aliasing filter performed on the sensor signals is much shorter than 50 mm (so short it was not detected by spectral analysis). The result of the lack of aggressive anti-aliasing is that the error level in IRI grows rapidly beyond the acceptable range as sample interval increases. The figure demonstrates that in a profiler with a small sensor footprint, anti-aliasing that does not eliminate wavelengths shorter than 50 mm, and a sample interval greater than 167 mm is doomed to measure IRI with a large upward bias.

The results presented in figure 7 provide one explanation of the systematically high measurements of IRI endemic to all of the ultrasonic profilers and many of the other profilers in the 1993 and 1994 RPUG experiments (*11, 12*). Ultrasonic profilers are not able to achieve the sampling rate necessary to properly apply anti-aliasing filters. They are therefore prone to error, particularly on roads of coarse macrotexture. This effect may also have been present among laser profilers with a small sensor footprint if a recording interval of 100 mm or longer was used without application of anti-aliasing filters. Height sensors with a small footprint are particularly prone to aliasing errors caused by coarse macrotexture from large aggregate in asphalt, chip seals, or tining of concrete. Of course, if the proper filters are applied to the sensor signal, these errors can be avoided.

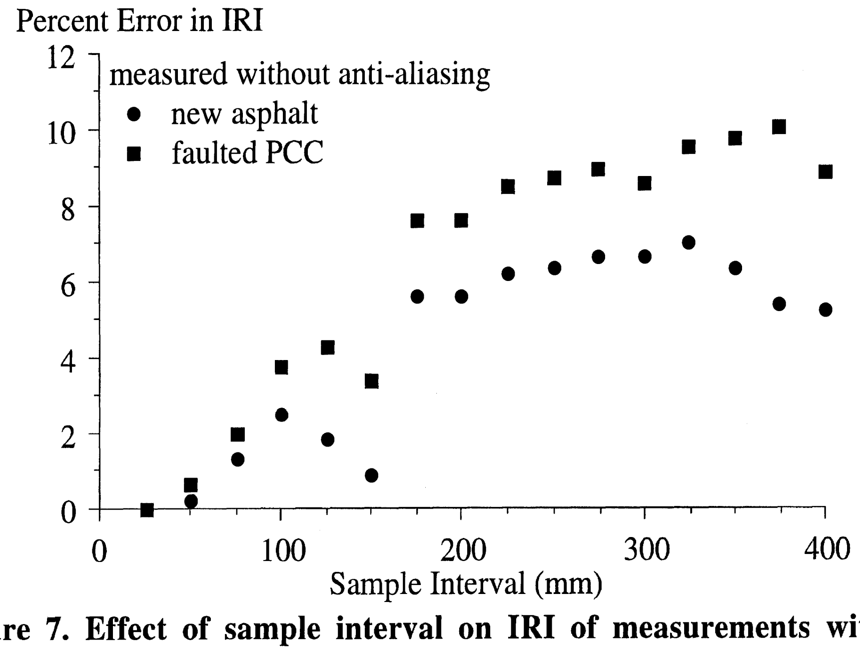

Figure 7. Effect of sample interval on IRI of measurements without aggressive anti-aliasing.

The same analysis described here for the IRI was performed with the RN. Figure 8 shows the results. Even with aggressive anti-aliasing, decimation of the profiles to a sample interval as short as 75 mm resulted in an upward bias in roughness of over 5 percent. Increasing sample interval beyond 75 mm led to a severe bias in RN. Aliasing errors affect short wavelengths most. Since RN depends on shorter wavelengths (primarily from 0.38 to 11.4 m) more than the IRI, it is much more prone to aliasing errors. This is because the decimation in the experiment changes the sample interval, but the anti-aliasing filter did not change. The error would be much lower (more like the theoretical prediction) if the cutoff wavelength of the anti-aliasing filter was always twice the sample interval. RN should be measured with anti-aliasing and with a sample interval of 50 mm or less.

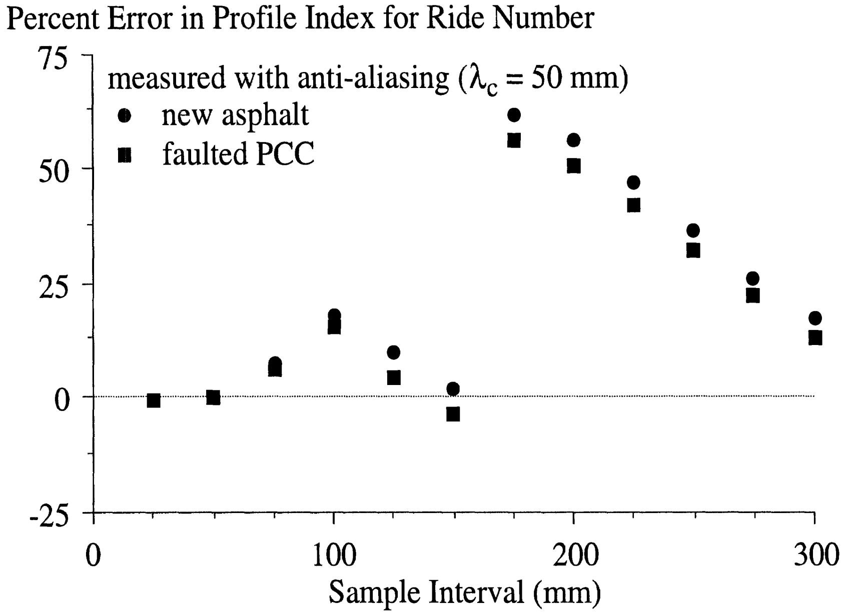

Figure 8. Effect of sample interval on PI for RN of measurements with anti-aliasing.

Record Interval

Thus far, the analysis has assumed that the sample interval and the recording interval are the same. The recommended upper limit for sample interval (in both measurement of IRI and RN) is shorter than that of many devices in common practice. This section examines the benefits of using a short sample interval then applying the 250-mm moving average and recording profile at a longer interval.

Often, a short sample interval of 25 mm is used for analyses other then the IRI and RN. For example, it is easier to quantify faulting or identify specific types of distress if the sample interval is very short. After these analyses have been performed, the profile can be decimated to a longer recording interval to save data storage space. To avoid introducing new aliasing errors into the profile, it must be filtered again. If the decimated profile is going to be used to calculate IRI or RN, the filter should be a 250-mm moving average, since it is the first step in the calculation procedure anyway. It is important, however, not to apply the moving average a second time in the roughness calculation.

Figure 9 shows the error in IRI that results if a profile with a sample interval of 25 mm is decimated to a larger recording interval after a 250-mm moving average is applied. (The moving average is not applied a second time in the IRI calculation.) The same profiles that were studied in figure 6 were used in this calculation. The error caused by the decimation is much lower here because the moving average was applied first. In this case, a very low bias exists if the sample interval is 125 mm or less. The bias holds near or below 1 percent until the recording interval increases to 250 mm. Thus, a recording interval of 125 mm or less is preferred and as large as 250 mm is reasonable for measurement of IRI, as long as a sufficiently short sample interval is used.

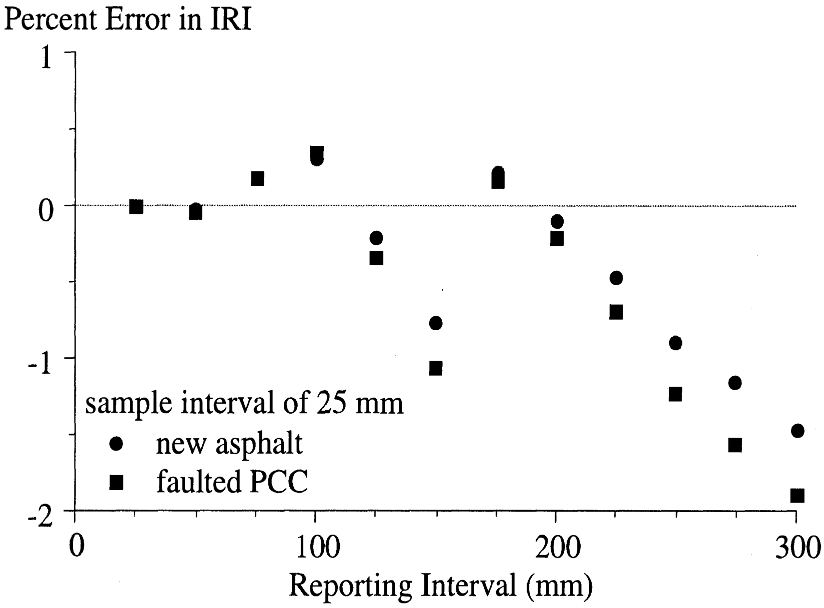

Figure 9. Effect of recording interval on IRI of measurements with a sample interval of 25 mm.

The same analysis suggests that accurate measurement of RN requires a recording interval of 75 mm or less and a sample interval of 50 mm or less. These are somewhat conservative estimates, but it is the opinion of the authors that the cost of computer storage and speed no longer prohibit the use of a short sample interval and recording interval.

Profile Computation Algorithm

Inertial profilers compute profile from a combination of the output of three sensors: a height sensor, an accelerometer, and a longitudinal distance sensor. Vertical acceleration measured at a point fixed on the vehicle body is integrated twice to construct a floating reference height. The height sensor, mounted in the same position as the accelerometer, measures the distance from the floating reference to the road surface. The height sensor signal is subtracted from the height of the floating reference to compute the profile elevation. The longitudinal distance measurement is needed to associate a position with each profile elevation. This method of measuring profile was invented by Elson Spangler and William Kelly (*15, 18*). It is described mathematically by the following:

$$Z(x) = H(x) + \iint_x A_t(s)/V^2 ds ds \qquad (6)$$

where x is longitudinal distance, Z(x) is the computed profile, H(x) is the height sensor measurement, and the term with the integral is the floating reference derived from (temporal) vertical acceleration $A_t(s)$ and forward speed V. The acceleration is divided by forward speed squared to convert it into spatial acceleration in units of 1/length. The height sensor measurement is the distance from the vehicle to the ground and should always be negative.

All inertial profilers use a discrete adaptation of eq. 6 to compute profile. For example, the ProRut computes profile using the following procedure:

Step 1: Calculate the bias in the accelerometer signal and remove it. This step helps minimize error in the integration that follows.

Step 2: Convert temporal acceleration (A_t) to spatial acceleration (A_s):

$$A_s(i) = A_t(i)/V^2 \tag{7}$$

Step 3: Integrate the spatial acceleration once to obtain slope. This is done with a recursive finite difference equation:

$$S_a(i) = C \bullet S_a(i-1) + \Delta \bullet A_s(i) \tag{8}$$

where Δ is the sample interval and S_a is the component of the slope profile measured by the accelerometer. The first term includes a drift-removal coefficient:

$$C = \frac{\Delta}{L} \tag{9}$$

where L is usually set to three times the longest wavelength of interest.

Step 4: Differentiate the height sensor signal (H) once to obtain slope:

$$S_h(i) = \frac{C \bullet H(i+1) - H(i)}{\Delta} \tag{10}$$

where S_h is the component of slope profile measured by the height sensor.

Step 5: Combine the slope from the height sensor and accelerometer signals to get the slope of the road profile (S):

$$S(i) = S_a(i) + S_h(i) \tag{11}$$

If the final goal of the profile measurement is to get IRI or RN, this result can go directly into the calculation. (Remember to skip the conversion to slope in the IRI and RN calculation procedure.)

Step 6: Integrate the slope profile to obtain elevation. The integration is performed backwards in this step to cancel the phase lag introduced in the computation of the slope profile. In this equation, "i" should step from the last value to the first.

$$Z(i) = C \bullet Z(i+1) + \Delta \bullet S(i) \tag{12}$$

This method of profile computation cancels the phase shift associated with integration by moving forward through the profile in steps 1 through 5, then backward in step 6.

Unfortunately, this method cannot be used in a running profile computation that takes place as a profiler passes over a section. It must instead be applied after the measurement is complete. Therefore, it is not practical for use in network-level profiling applications, where long stretches of road must be covered and roughness is computed in real time.

Devices that compute profile during the measurement cannot avoid the phase shift. Pong (*19*) demonstrated that some common profile computation algorithms do introduce a phase shift in the profile that grows with wavelength. In the synchronization of the 1993 RPUG data (described in Appendix C), lining up the short wavelength features in the profiles meant that plots of the long wavelength content (8 to 40 m) from many of the profilers were shifted up to 0.5 m from the ProRut and Dipstick. This is not always noticeable in the plots, and has a very small effect on the IRI and RN.

Most profilers apply a high-pass filter to profiles as a final step in the computation. This is not a necessary step, but it improves the appearance of the plots. Inertial profilers do not measure extremely long wavelengths validly anyhow, so the high-pass filter should remove incorrect information and pass the valid part of the profile through. Without the filter, a plot of the raw profile usually drifts vertically several meters. The drift in the plot obscures the short deviations that are of interest in a profile. Figure 10 shows a set of measurements by the ProRut, a Dipstick, and a K.J. Law profiler. The ProRut and Dipstick drift significantly. (The Dipstick does not use a filter, and the ProRut used a value of 305 m for L in eq. 9.) The K.J. Law profiler applied a high-pass filter with a cutoff of 91 m. All of these profiles may be valid, but they do not compare easily in figure 10 because they all show a different range of wavelengths.

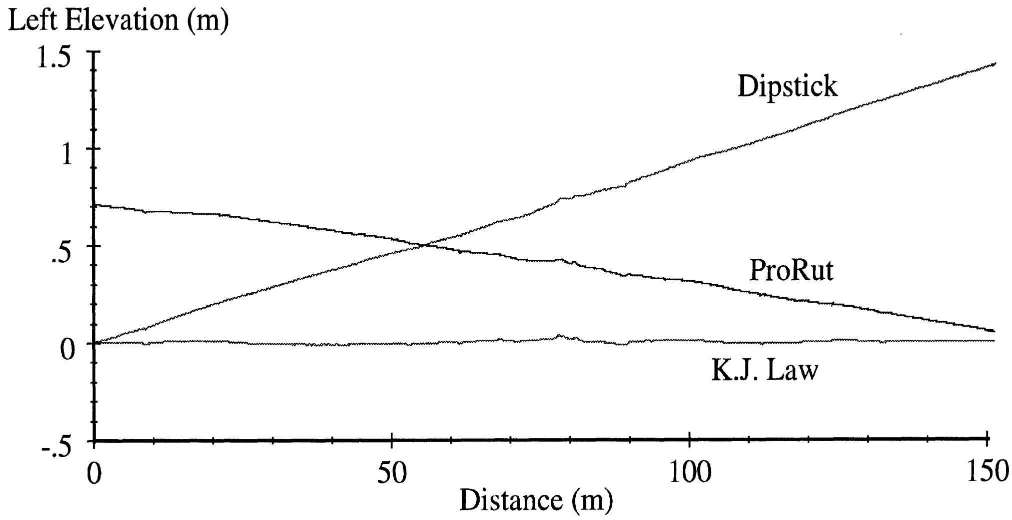

Figure 10. Unfiltered profiles.

Figure 11 shows the same profiles after they were all high-pass filtered with a cutoff of 91 m. This plot has two advantages over figure 10. First, the profiles show the same range of wavelengths, so they can be compared. Second, features in the road that affect roughness are visible, so display of profiles with a high-pass filter helps the operator and analyst recognize features of interest in the road and diagnose potential measurement errors.

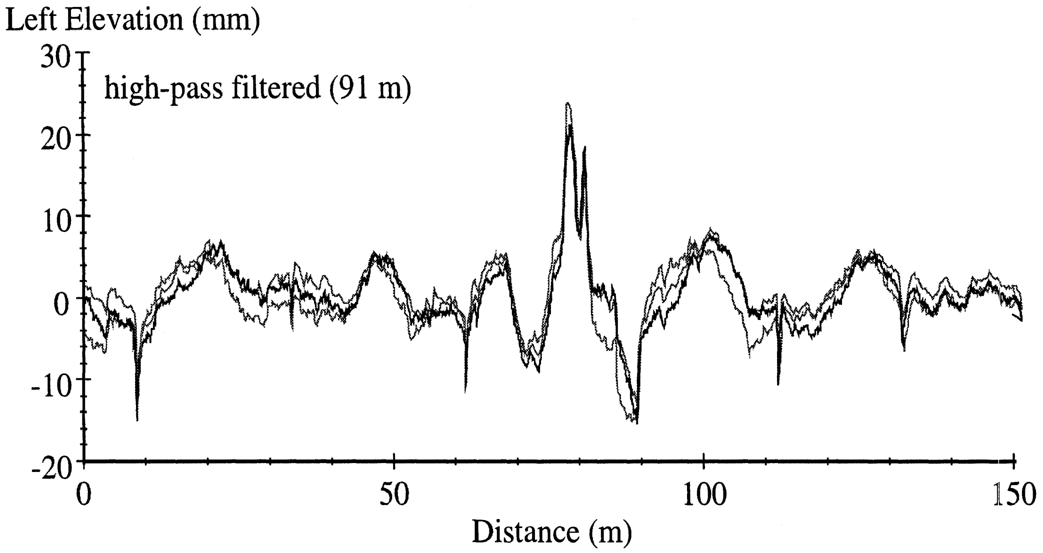

Figure 11. Profiles filtered with a 91-m high-pass.

The high-pass filter is a useful plotting tool, but it is not a necessary step in obtaining a roughness value. In fact, if the cutoff wavelength is set too short, it may eliminate some of the range of interest. Figure 12 shows the percent error in IRI and RN caused by a two-pole Butterworth high-pass filter as a function of wavelength. This plot was derived theoretically for a moderately rough road of white noise slope. The error is always negative, because the high-pass filter always eliminates roughness. The most common high-pass filter cutoff in use for profiling in North America is 91 m. This causes an error in IRI of –0.01 percent and an even smaller error in RN. Standardizing the cutoff would promote agreement between profile plots output by profilers. The 91-m cutoff is also short enough to display road features of interest.

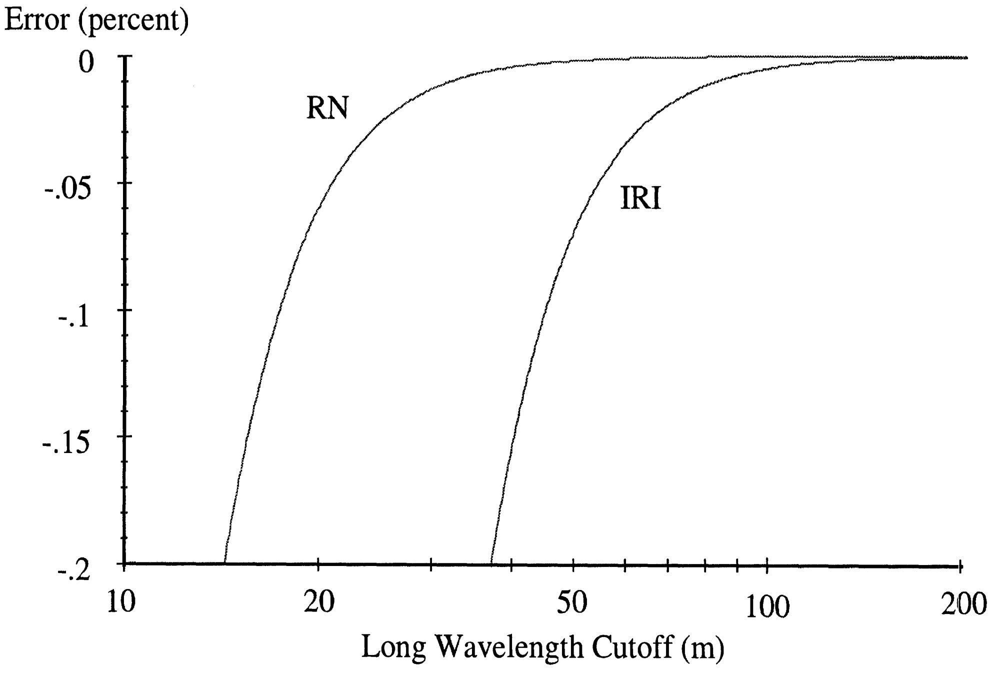

Figure 12. Impact of high-pass filter cutoff on roughness.

Automated Error Checking

In the course of this study, the researchers heard several anecdotes that they would classify as "data collection horror stories." These are instances where a switch in the wrong position, a loose wire, or some aspect of the profiler condition or its operation caused the operator to spend hours or days measuring erroneous data without finding out about it until afterward. (Which always raises the question: What errors went undetected?)

Most of the measurement problems that contaminate profile data are obvious, but only if the operator looks for them. Profilers usually have some real-time display that includes the roughness of each segment, individual sensor readings, or even plots of profile and sensor signals that help the operator monitor the profiler as it collects data. These display options are a great help in ensuring the quality of profile data. The operator can use these features to make sure a profiler is working properly, but this is a difficult thing to do constantly. Usually, if a profiler operates well for a while, even the most watchful user will relax their error-checking routine. Therefore, if any of the error checking can be automated, many data collection errors may be avoided.

In particular, the software in a profiler should monitor the sensor signals and look for patterns that can only exist if something is wrong. Three types of error are discussed in this section that are easy to recognize: (1) improper speed, (2) excessive signal levels, and (3) signal loss. A strategy for detecting each of the errors is suggested. If an error is detected, the profiler should either warn the operator with a beep to get their attention or stop data collection completely.

Improper Speed

Inertial profilers are subject to errors when they are operated at improper speeds or with large accelerations. All inertial profilers have upper and lower speed limits beyond which they do not collect valid profile. Most profilers operate properly over a broad range of speed, but it is inevitable that traffic, stop signals (on secondary roads), or other obstacles will cause a driver to violate the speed limits of a profiler. When this occurs, data collection should be suspended. Since profilers already monitor their speed continuously they can automatically check profiler speed. The software in a profiler can constantly watch for the following undesirable conditions: (1) operation outside the valid speed range, (2) acceleration or deceleration above 0.2 g, or (3) excessive tire skid or wheel lockup. Detection of any of these circumstances should prompt temporary suspension of data collection and an audio warning signal. Testing for the latter two conditions requires differentiation of the speed signal. This operation is imprecise because speed is usually digitized coarsely and differentiation amplifies noise. Thus, acceleration and deceleration limits in the software should not be too restrictive.

Excessive Signal Levels

Spikes in accelerometer and height sensor readings are an unavoidable aspect of profiling. Many of the extremely high roughness values observed in recent RPUG experiments were caused solely by a single erroneous spike within the profile (*10*). Several features in the measurement environment may cause the height sensors in a profiler to temporarily read out of their range. (See the "Measurement Environment" section of this chapter.) Spikes caused by a surge in the power supplied to the sensors and electronics in a profiler may also cause excessive readings. A profiler should include some protection against sensor readings that are out of range. Often, the signal conditioning circuits within a profiler include protection against excessive values of sensor output. If this is not the case, the software in a profiler should check every reading that is digitized to make sure it is within the proper range.

Accelerometer readings that are out of range for a single sample and very different from two surrounding readings should be replaced by the average of those two readings. If the accelerometer goes out of range for several consecutive readings, an audio warning should be issued to the operator and that portion of the profile should be marked as suspect. Some profilers already use this type of strategy on the accelerometer and height sensor signals. A single height sensor reading that is out of range should not be removed because extreme changes in height sensor output are not always errors. If a height sensor has a narrow footprint, it may read a large change in height that is legitimate over a crack or an opened PCC joint. Several consecutive height sensor readings out of range should also prompt an audio warning.

Signal Loss

Occasionally, one of the sensors in a profiler may completely cease to operate and read a constant value. This can happen if a wire comes loose, a switch is in the wrong position, or some other failure occurs in the electronics. Unfortunately, the error is not always easy to detect. A profiler can still compute (an incorrect) profile if the height sensor or accelerometer is not functioning. When this occurs, the roughness value may not be very different from the correct value, so the operator may not know there is a problem.

Table 3 lists the IRI values from the right wheeltrack of fifteen sections (described in Appendix A) computed with the complete profile and two cases of signal loss: (1) with the height sensor signal only and a constant zero value for the accelerometer signal, and (2) with the accelerometer only and a constant value for the height sensor signal. These two cases of signal loss rarely produce an IRI value that is close to the truth, so operating without one of the sensors produces bad data. The problem is that the roughness values are not so different that the operator would know right away if signal loss occurred.

One way to detect signal loss is to view the profile. However, recognizing a problem in a profile takes experience. Figure 13 shows a complete profile, a profile computed from the accelerometer only, and a profile computed from the height sensor only. The profile was measured on a rough asphalt pavement (section 5) with severe transverse cracking and some bumps. The profile computed from the accelerometer only is wavy and it does not contain any of the short wavelength deviations caused by the cracking. An experienced analyst could pick this profile out as suspect, but only if a view of the actual pavement is available. The plot looks like a profile of a new overlay, so a look back at the profile without information about what the pavement surface was would not expose the problem. The profile computed from the height sensor only contains all of the short wavelength deviations of the correct profile, but less waviness.

Table 3. IRI computed with signal loss.

Section	IRI (m/km)			Range	
	Complete Profile	Ht. Sensor Only	Accel. Only	Ht. Sensor (mm)	Accel. (g)
12	0.77	1.03	0.51	13.6	0.47
1	0.99	1.44	1.31	19.3	0.49
10	1.07	1.51	1.46	20.9	0.36
13	1.23	1.29	0.55	12.9	0.42
14	1.34	1.53	1.13	19.8	0.38
15	1.68	1.92	0.78	21.9	0.63
3	2.07	2.43	1.38	42.9	0.84
6	2.10	2.27	1.46	32.9	0.54
5	2.76	3.56	2.39	34.1	1.52
11	3.04	4.10	2.57	71.6	1.93
4	3.12	3.92	2.06	60.5	1.31
9	3.23	3.37	1.67	80.4	0.39
2	3.72	4.42	2.28	58.4	1.13
8	3.79	4.36	2.99	61.0	1.38
7	4.53	6.08	5.25	83.4	1.36

Plotting profile and checking roughness values would help reveal signal loss in some cases, but this is a very taxing activity for an operator who must cover long stretches of road every day. Some profilers show the individual sensor signals on a computer screen as the profile is measured. With this feature, signal loss could be recognized right away at a glance. If a profiler does not have this feature, it can at least make sure that the sensors are active.

Table 3 lists the total range of height sensor and accelerometer readings covered during the measurement of each section. The measurements listed in the table were done using the ProRut at the posted speed limit. The ProRut has all of its sensors mounted on the vehicle body just behind the driver door. This means that they will generally fluctuate over a much smaller range than the sensor readings on a bumper-mounted profiler. On the two smoothest sections in the table, new asphalt (section 1) and three-year-old PCC (section 12), the accelerometer only covers a range of about 0.5 g and the height sensor covers a range of less than 20 mm. Certainly, a range much smaller than this is not possible on any road, particularly in a profiler with sensors mounted on the bumper. If a profiler travels more than 150 m at moderate speed without fluctuations in the accelerometer covering at least 0.1 g and without fluctuations in height sensor covering at least 5 mm, it should warn the operator.

Some profilers use a "bounce test" to make sure the sensors are operating properly at the start of a day of data collection. In the bounce test, the profiler is parked on level pavement. With the instruments on, the profiler is shaken, usually in pitch and in roll. The height sensor and accelerometer signals fluctuate, but the profile will be flat if the profiler is working properly. (The profile will not be completely flat because of noise and drift, but it should not show any signs that it had bounced.) All profilers should have this feature, and profile measurement must not start until a bounce test is used to make sure the sensors are on and warmed up.

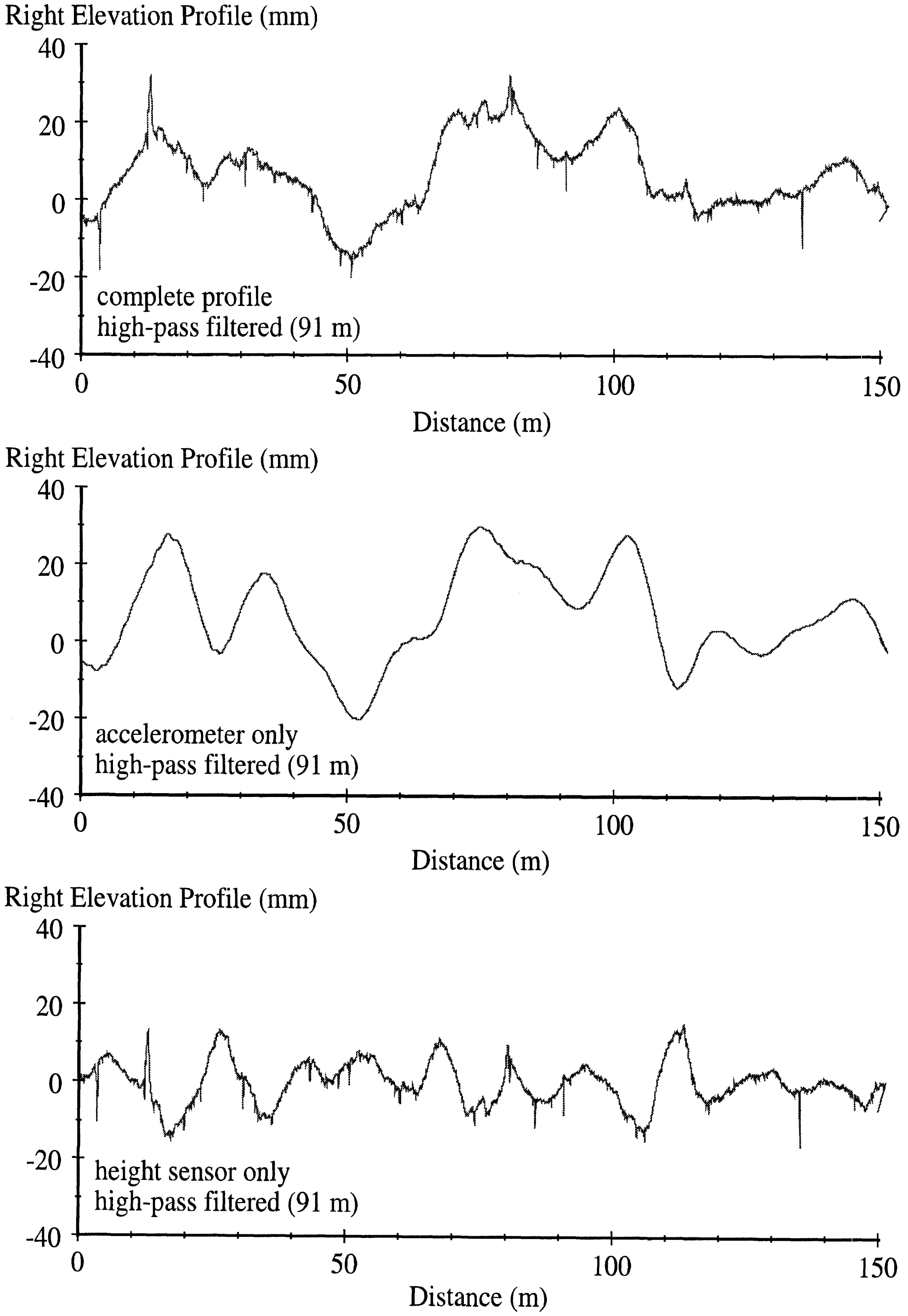

Figure 13. Profile computed with and without signal loss.

Height Sensors

The height sensor in a profiler measures the vertical distance from the vehicle body to the road. This value is subtracted from a floating reference height, measured by the accelerometer, to get road elevation. All profilers now in use in North America measure height with one of four types of noncontacting transducer.

1. Laser—Laser sensors measure distance by means of triangulation. A spot of invisible light is projected on to the road surface. It is reflected through a lens mounted at an angle on to a light-sensitive displacement sensor. The size of the laser light spot is the sensor footprint. Selcom supplies laser sensors to several profiler manufacturers. Their sensors commonly use a footprint that is 1 to 5 mm in diameter.

2. Infrared—Infrared sensors operate on the same principle as laser sensors, but they use infrared light instead of laser light. K.J. Law, Inc. makes an infrared sensor with a footprint 6 mm long (in the direction of travel) and 37 mm wide (in the transverse direction).

3. Optical—Optical sensors are exclusive to K.J. Law profilers. They also detect the position of a projected image using triangulation, but the image is a slit of light in the visible infrared spectrum that is 6 mm long and 150 mm wide.

4. Ultrasonic—Ultrasonic sensors measure distance by emitting a short burst of sound waves. The sound travels down to the pavement surface and reflects back upward and the elapsed time is used to compute the distance. The footprint of ultrasonic sensors is 50 to 100 mm in diameter.

Several studies of profiler performance have been done that distinguish them primarily by the height sensor. Often, a pair of profilers with different types of height sensor are compared, or a single profiler is tested against a reference measurement (*20-27*). The Ann Arbor Road Profilometer Meeting (*13*) and the 1993 and 1994 RPUG studies (*11, 12*) included most of the profiler designs in use in North America at the time. In all of these studies, the repeatability and accuracy of the profilers involved were heavily linked to their height sensor.

In the RPUG studies, optical profilers exhibited the best repeatability and the best agreement with reference measurements. Most of the laser profilers showed sufficient performance for use in network-level profiling. Ultrasonic profilers showed so much scatter and bias that they did not appear sufficient for roughness measurement. (A summary of the performance of most of the profilers in the 1993 RPUG study is provided in Appendix C.) The poor repeatability of ultrasonic sensors has been recorded in other studies as well (*20, 24, 26*).

Overall, the four types of height sensor listed above differ in their sampling rate, resolution, footprint size, and sensitivity to the environment. Ultrasonic sensors cannot sense the road often enough or with enough resolution to measure roughness reliably. Optical, laser, and infrared profilers have all demonstrated that they can be repeatable and accurate over a range of conditions.

Sampling Rate

In the measurement of IRI and RN, the shortest wavelength of interest is about 0.3 m. At a speed of 100 kph, a profiler must sample the road every 0.005 s to measure wavelengths this short. However, this is not enough. An accurate profiler must sample the road more often than that and apply filters to remove aliasing errors. Laser, optical, and infrared height sensors all operate with a sufficient sampling rate to measure wavelengths of 0.3 m and longer without aliasing errors.

The sound wave used in a reading by ultrasonic sensors only takes about 0.002 s to travel from the vehicle to the road and back. However, multiple echoes of the sound wave do not die out for up to 0.01 s (*17*). This severely limits the sampling rate of ultrasonic sensors at high speed. Ultrasonic sensors should not be used to measure wavelengths shorter than 3 m (*10*).

Resolution

The resolution of a height sensor is the smallest unit of distance it can measure accurately. When the IRI was first proposed, Sayers recorded that the resolution required of the final profile for accurate measurement of IRI is a function of roughness (*2*). His study recorded that on roads with IRI less than 3.0 m/km a resolution of 1 mm and a sample interval of 500 mm or less was required. On roads rougher than 5 m/km, resolution of 2.5 mm was permissible. The resolution required of the height sensor is probably about the same magnitude. In their advertisements, K.J. Law reports dynamic resolution of 0.25 mm in their infrared height sensors, and Selcom reports a value of about 0.06 mm. These values represent the resolution of each reading. Since both of these sensors take readings fast enough to allow anti-aliasing filters to be applied, the resolution of the height sensor signal after it is processed is actually much better because random errors and quantization errors are smoothed out. Laser, infrared, and optical height sensors all have sufficient resolution for measurement of IRI and RN if their signals are processed properly, even on roads as smooth as 1 m/km.

Advertisements for ultrasonic profilers cite values of resolution of 1.5 to 3 mm. This level of resolution is not sufficient for measuring roughness on smooth roads, but may be good enough on rough roads. This is demonstrated in figure 14. The figure shows the error in IRI in profile measurement that results when the height sensor signals are quantized to various levels of resolution. The profiles were originally measured with the ProRut on two roads: new asphalt and severely faulted PCC. On the severely faulted PCC, the error level does not grow beyond 5 percent until the resolution is larger than 3 mm. Thus, a profiler with ultrasonic height sensors may operate properly on a road this rough. On the new asphalt, which is very smooth, the error reaches 5 percent when the resolution is still under 1 mm.

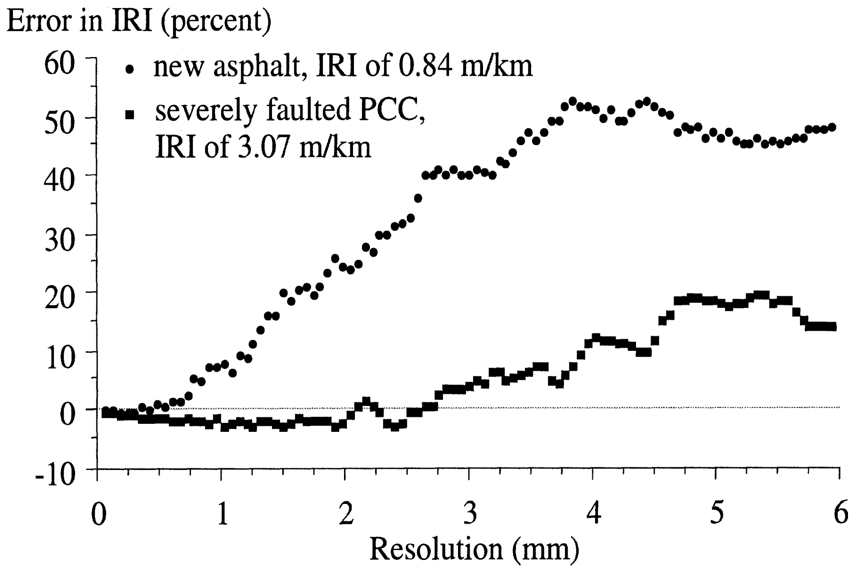

Figure 14. Sensitivity of IRI to height sensor resolution.

Figure 15 shows the sensitivity of RN to height sensor resolution on the same two roads that were featured in figure 14. In this case, a bias toward higher roughness is negative, because the RN decreases. Both figures demonstrate that a better height sensor resolution is required on smooth roads, because the resolution limit is a greater percentage of the total height sensor signal. On the smooth road, the error in both IRI and RN grows quickly after the resolution is increased beyond about 0.75 mm. Figures 14 and 15 only estimate the effect of height sensor resolution on roughness. To truly study resolution, the sensor signals from a profiler would have to be obtained at an extremely close interval. Then the resolution limits could be simulated before filtering. Data for this analysis was not available, but the issue should be investigated for extremely smooth roads if high-speed profilers are going to be used for measurement of new construction. Particularly if the roughness values are used to determine construction quality incentive payments.

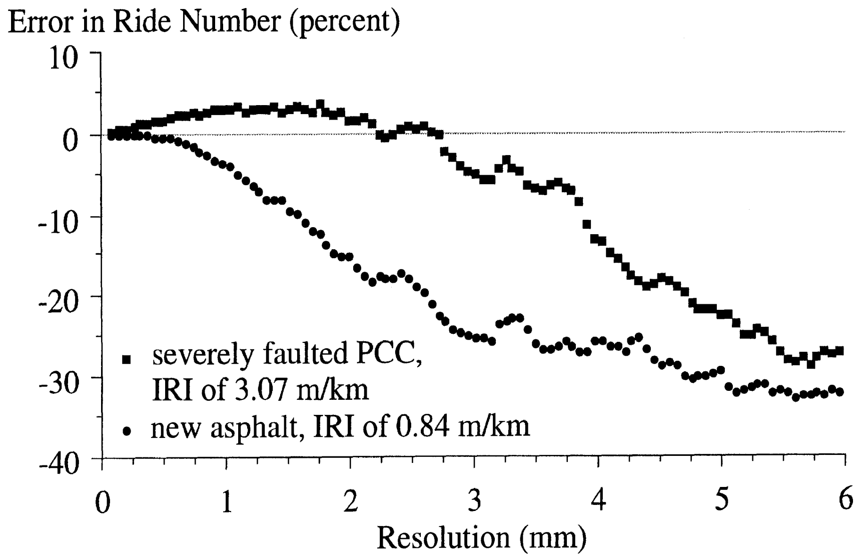

Figure 15. Sensitivity of RN to height sensor resolution.

Footprint

Height sensor footprint strongly affects the way a profiler measures small features in the road, particularly surface texture, and narrow cracks and joints. Infrared height sensors, which have a footprint 37 mm wide and 6 mm in the direction of travel, are likely to measure a much smaller dip over a narrow PCC joint or crack than a laser sensor with a footprint that is 1 to 2 mm in diameter. Even if both sensor signals are filtered to remove wavelengths shorter than 0.3 m, the profiler with the laser sensor will probably measure a higher roughness because it includes spikes that the profiler with the infrared sensor did not. No standard exists yet for which is the better sensing strategy. Narrow cracks do not affect vehicles much, because they are enveloped by the tires. Thus, if the final use of a profile is to judge the effect of roughness on vehicle response, it might be desirable to weed out narrow downward spikes. This could either be done by a height sensor with a large footprint, or in post processing of a signal from a narrow height sensor. On the other hand, narrow cracks are a legitimate aspect of the current condition of many roads, and have some influence on the amount of time left in their service life. The "Pavement Distress" section of this chapter compares the way profilers measure narrow road features in detail. No standards exist for removing narrow downward spikes from profiles. This is a topic that should be addressed in the future by the profiling community.

Height sensor footprint also interacts with pavement macrotexture to affect profile measurement. Height sensors with a large footprint are more likely to average out short deviations in the surface caused by coarse macrotexture. Ultrasonic height sensors have a very large footprint, but they detect the highest feature within their footprint, rather than the average of the deviations within their footprint. Thus, they are extremely prone to aliasing errors on roads with coarse macrotexture. Optical and infrared height sensors both have a wide footprint, so they are likely to be less affected by macrotexture. Profiles measured with laser sensors are affected by macrotexture because of their small footprint, but proper use of anti-aliasing filters on the height sensor signals prevent errors in the final roughness value. A past study reported that coarse texture may scatter the light beam from laser sensors and cause sensor dropout (*28*). However, the ProRut used in these experiments, which has laser sensors, was exposed to some roads of extremely coarse macrotexture and did not experience sensor dropout. A more detailed discussion of the effect of macrotexture on profiler performance is provided in the "Surface Texture" section of this chapter.

Environmental Factors

Since the waves emitted by height sensors must travel through the air to function, they are sometimes prone to errors caused by the environment. Road surface moisture from rain and snow, and surface contaminants such as sand and leaves affect all noncontacting height sensors. The performance of a profiler with ultrasonic height sensors was so sensitive to air temperature in one study that the profiler appeared to need a temperature-dependent calibration (*26*). The change in reflectivity that occurs at white pavement markings have caused spikes in optical profilers used in the LTPP study. Optical profilers are also sensitive to ambient light, so the height sensors are shrouded. As long as the shrouds are kept in good condition and sunlight does not penetrate the shrouded area, the sensors are not affected. These effects are discussed in detail in the "Measurement Environment" section of this chapter.

Range

Height sensors used for measuring roughness on primary road networks and the interstate should have a total range of at least 250 mm. On twelve sections selected in the Ann Arbor, Michigan area to represent a range of surface properties, the total range measured by the height sensors in the ProRut was less than 100 mm. Some of these sections were very rough and they were all covered at the speed limit. However, the sensors in the ProRut are mounted in the vehicle body between the front and rear axle. Height sensors in a bumper-mounted profiler travel over a much larger range. Table 4 lists the total range measured by the height sensors in the ProRut and a profiler with sensors mounted on the front bumper. In the bumper-mounted profiler, a sensor range of 250 mm is sufficient on all of the sections except the roughest, which is so rough it does not require accurate measurement.

Table 4. Height sensor range in a center-mounted and a bumper-mounted profiler.

Section	IRI (m/km)	Height Sensor Range (mm)			
		Bumper-Mounted		Center-Mounted	
		Left	Right	Left	Right
12	0.77	29.3	27.6	13.4	13.6
1	0.99	57.1	63.7	20.3	19.3
10	1.07	102.9	87.9	21.5	20.9
3	2.07	123.0	118.5	44.7	42.9
6	2.10	101.7	117.2	45.0	32.9
5	2.76	129.1	137.7	50.1	34.1
11	3.04	188.8	240.6	76.6	71.6
4	3.12	152.3	208.6	65.9	60.5
9	3.23	160.1	146.2	42.0	80.4
2	3.72	191.5	168.2	76.5	58.4
8	3.79	174.6	207.9	62.6	61.0
7	4.53	425.5	491.8	79.9	83.4

Accelerometers

The accelerometer is used in a high-speed profiler to establish an inertial reference from which relative height measurements are made. The vertical acceleration of the host vehicle body is integrated twice to establish its vertical position. This is used as a floating reference height, and the height sensor measurement is subtracted from it to get the road elevation.

The accelerometer should be oriented vertically. Accelerometers are usually mounted just above each height sensor. Thus, the accelerometer is not always perfectly vertical when the vehicle body undergoes pitch and roll as it travels over uneven roads. An error occurs if the vehicle pitches and accelerates longitudinally at the same time, or rolls and accelerates laterally at the same time. Fortunately, this error is small if the lateral and longitudinal acceleration are held under 0.1 g. (See the "Speed Changes" and "Curves" sections of this chapter.) Gyroscopically stabilized accelerometers are available that will measure the true vertical acceleration accurately even if the vehicle body is tilted. These are not necessary for profilers used to measure road roughness unless the grade changes are much more severe than those found in the U.S. highway system, or if it is desirable to allow for more extreme vehicle movements.

The accelerometer in a profiler used on primary road networks and the interstate should have a total range of at least ±5 g. On fifteen sections selected in the Ann Arbor, Michigan area to represent a range of surface properties, the total range measured by the accelerometers in the ProRut was less than ±2 g. (See table 3.) Some of these sections were very rough and they were all covered at the speed limit. However, the sensors in the ProRut are mounted in the vehicle body between the front and rear axle. Accelerometers in a bumper-mounted profiler may read a range that is twice as large on some roads.

On a road with an IRI of about 7.5 m/km, a bumper-mounted profiler traveling 80 kph read accelerations as high as 8 g. This is an extreme case: At this speed a profiler is likely to be damaged on a road that rough. If a profiler is going to be used routinely on extremely rough roads, it should be able to read ±10 g. If not, the operator must be aware that very rough roads should be covered at a moderate speed.

To properly capture the wavelength range of interest for measurement of roughness, an accelerometer must be valid up to 150 Hz. All accelerometers have a natural frequency at which their internal components respond excessively to input vibrations. They do not measure frequencies near that value very accurately. At a travel speed of 100 kph, a wavelength of 0.3 m corresponds to a frequency of about 93 Hz. The natural frequency of an accelerometer should be at least 50 percent higher than that.

Longitudinal Distance Measurement

The distance measuring instrument is one of the three major types of transducer that make up a profiler. Distance must be measured properly to obtain accurate roughness statistics, but it must also be correct from an operational standpoint. In network monitoring, applications roughness is often measured over very long distances, such that even a small bias in longitudinal distance measurement can build up to a large net error. The error throws off distance "accounting" and the longitudinal positioning of each segment. In project-level applications, or measurement of new construction corrective action (such as grinding) is often recommended at specific locations. Thus, accurate measurement of longitudinal distance relative to fixed landmarks is very important.

In high-speed profilers distance traveled is usually measured by a pulser on one of the front wheels (*29*). A common configuration is to install an exciter ring with equally spaced notches on the back side of the disc brake rotor of one of the wheels. Rotation of the wheel is measured by detection of pulses as the wheel rotates and the notches pass (*30*). During normal operation, each pulse is associated directly with a fixed travel distance through the rolling radius of the tire. (The rolling radius is the effective radius of the tire when the vehicle is moving. It is generally smaller than the unloaded radius of a tire, but larger than the radius of a loaded, but stationary tire.) Since the rolling radius cannot be measured statically the distance pulser must be calibrated. This is commonly done by traveling a known distance and counting the pulses.

In the 1993 RPUG experiment, all of the test sections were laid out with artificial bumps spaced 206.7 m apart (*11*). Data that included the bumps were submitted from 33 high-speed profilers. All but three of these profilers consistently placed these bumps at the correct distance apart within 0.5 percent. (See Appendix C.) The majority of them were correct within a length equal to twice the sample interval, which means that the longitudinal distance measurement was essentially correct.

In measurements made for this study, five test sections were laid out along about 14.3 km of highway. Each of the four profilers covered these sections by measuring the entire 14.3-km stretch. Table 5 provides a summary of the distance between the start of the first and fifth section for five measurements made by each device. The level of variation in distance measurement within the five runs from each profiler was always less than 0.1 percent. This level of variation can be attributed to wander in the path the driver takes within the lane from run to run.

Table 5. Variation in distance measurement among profilers.

Device	Average (m)	Maximum (m)	Minimum (m)	Range (%)
Ohio laser	14288.0	14293.0	14283.5	0.07
Ohio infrared	14311.3	14315.6	14309.6	0.04
Penn laser	14261.4	14266.9	14257.3	0.07
Penn ultrasonic	14255.1	14259.1	14253.0	0.04

Tires

Each profiler listed in table 5 measured the total distance between sections with reasonable repeatability, but they did not agree with each other. The variation among the profilers covered about 0.4 percent of the total distance. This is most likely caused by calibration error. Although the distance pulser was probably calibrated correctly in each profiler, there are several factors that can make the effective rolling radius of a tire different than it was during calibration. The result is a bias in longitudinal distance measurement. The rolling radii of radial-ply tires are affected by the following:

- Tread wear: Typically, the tread depth of an automobile tire accounts for about 2 percent of its radius.
- Change of tires: A change of tires is likely to result in a change in effective rolling radius, even for the same make and model of tire. (Remember, you are probably replacing a worn tire with a new tire, so tread wear is again an issue.)
- Inflation pressure: Underinflating typical radial-belted tires to half of their rated pressure will decrease the static radius about 6 percent, overinflating to 1.5 times the rated pressure increases the static radius about 3 percent (*31*). However, the rolling radius is not affected nearly as much.
- Tire warm-up: The inflation pressure of an automobile tire rises as the tire heats up and stabilizes after about 30 minutes of driving (*31, 32*). At highway speeds the inflation pressure of a typical radial-ply tire can increase 28 kPa (4 psi) over cold inflation levels during warm-up.

Bias-ply tires are constructed in a manner that is much less resistant to circumferential stretching than radial-ply tires. As a result, they are sensitive to all of the factors listed above and some others:

- Inflation pressure: The rolling radius of a bias-ply tire can change more than 0.5 percent for a change in inflation of 35 kPa (5 psi) (*33*).
- Tire warm-up: At highway speeds the inflation pressure of a typical bias-ply tire can increase 56 kPa (8 psi) over cold inflation levels during warm-up (*34*).
- Operating speed: The effective rolling radius of typical bias ply tires changes about 3 percent over a range of speeds from 40 to 120 kph (*35*).

The effect of tire inflation pressure on distance measurement was investigated on a new asphalt section and a severely faulted PCC section using the ProRut. The ProRut was mounted on a 1991 Dodge Grand Caravan with BFGoodrich Touring TA 205/70R15 (radial-ply) tires. The inflation pressure of all four tires was varied from about 170 kPa (25 psi) to about 345 kPa (50 psi). The recommended pressure is 240 kPa (35 psi).

In each run the measured separation between a reference feature at the start and end of the section was identified. In the case of the severely faulted PCC, this was a relatively simple plotting exercise: The 25-mm sample interval made the location of faults and opened cracks obvious within one profile sample. Since the new asphalt section contained very little short-wavelength roughness, the peak of longer road bumps at the start and end of the section could only be located within two or three samples, or 75 mm. Tables 6 and 7 list the results. Note that the percent error in distance measurement represents the change in effective rolling radius of the tires.

A modest change in inflation pressure of 35 kPa (5 psi) caused an error in distance measurement of about 0.1 percent. In network profiling, long stretches of road are often covered in one measurement. With an error of 0.1 percent in distance measurement it would take about 100 km of travel to build up an error of 100 m. This is not of great concern, particularly for a profiling system that allows the operator to insert event markers in the measurement at reference locations as a means of resetting the longitudinal distance. However, an error in distance measurement also leads to errors in roughness index values.

Table 6. Measured separation between reference features on faulted PCC at various tire inflation pressures.

Tire Inflation Pressure		Separation	Error in Distance Measurement	
(kPa)	(psi)	(m)	(m)	(Percent)
344.7	50	293.525	-0.650	-0.22
310.2	45	293.475	-0.700	-0.24
275.8	40	293.938	-0.238	-0.08
241.3	35	294.175	—	—
206.8	30	294.450	0.275	0.09
172.4	25	294.825	0.650	0.22

— Reference measurement.

Table 7. Measured separation between reference features on new asphalt at various tire inflation pressures.

Tire Inflation Pressure (kPa)	Tire Inflation Pressure (psi)	Separation (m)	Error in Distance Measurement (m)	Error in Distance Measurement (Percent)
344.7	50	276.700	-0.825	-0.30
310.2	45	276.850	-0.675	-0.24
275.8	40	277.125	-0.400	-0.14
241.3	35	277.525	—	—
206.8	30	277.825	0.300	0.11
172.4	25	278.300	0.775	0.28

— Reference measurement.

Roughness Measurement

Longitudinal distance measurement affects roughness indices in two ways. First, errors in distance measurements cause a small shift in the wavelength content of a profile. Some components of roughness that were outside the range of influence of a roughness index will erroneously shift in and others that should have counted will shift out. Other parts of the wavelength content will get an incorrect frequency weighting by shifting within the range of influence. This condition causes a bias in measurement of both IRI and RN.

Underestimating distance makes a section of road appear rougher. The extent of the error in IRI and RN depends on the wavelength content of the road. In the case of RN, the resulting change also depends on the overall roughness of the road because it is computed using a nonlinear transform to a five-point scale. (See Appendix B for details.) RN values nearest to the low end of the scale are affected most.

Figure 16 shows the error in RN that results from bias in distance measurement. The error level was estimated by varying the sample interval of a profile from its correct value and recomputing the roughness. The figure shows the results for two sections of dissimilar wavelength content. The primary source of roughness in the new asphalt section is in the long wavelength range. The severely faulted PCC has a strong short wavelength content because of faults and cracks. Both sections have a higher RN (and appear smoother) if distance is overestimated. Although the level of the error in RN is different for the two sections, it is on the same order of magnitude.

The second effect of longitudinal distance measurement on roughness indices is simply that the roughness appears to occur over a different distance. The IRI accumulates (or "counts") roughness using the average rectified value of a profile filtered by a quarter-car model. The average rectified value has units of slope (or length/length), so shrinking the total distance is the same as increasing all of the slope values. IRI is therefore directly affected by a distance measurement bias. (This effect is analogous to the general trend of a road feeling rougher at a high travel speed.)

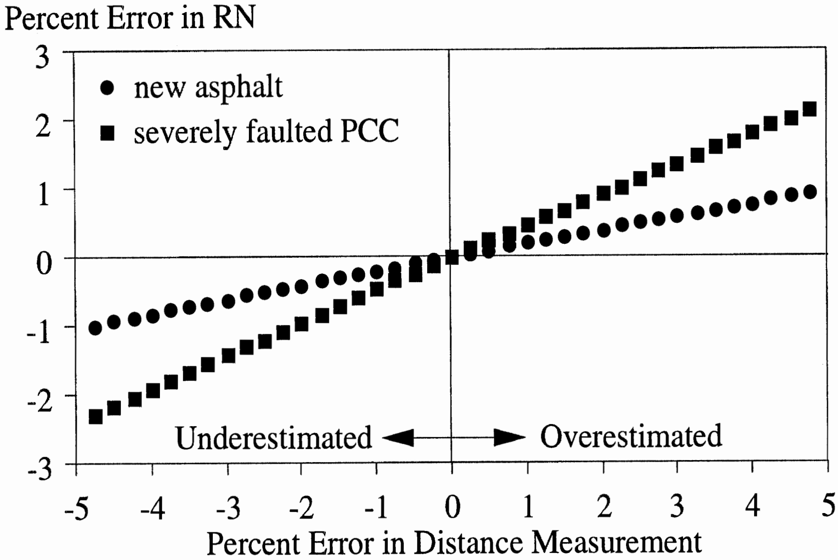

Figure 16. Error in RN caused by an error in distance measurement.

The RN, which accumulates the roughness of a road by computing the RMS of a filtered profile, is immune to this aspect of distance measurement error. The RMS of a varying signal is computed without regard to the time or distance over which the variations occur, so the signal can be stretched or squashed longitudinally without changing the results.

Figure 17 shows the error in IRI that results from bias in distance measurement on a smooth asphalt section and a section of severely faulted PCC. The error level was estimated by varying the sample interval of a profile from its correct value and recomputing the roughness. As expected, the roughness increases when the distance is underestimated. The level of error on both sections is about equal to the error in distance measurement.

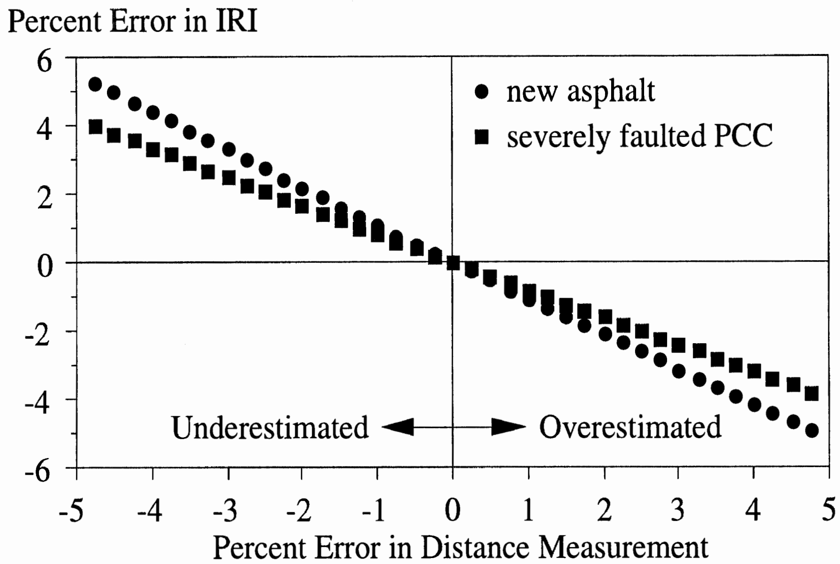

Figure 17. Error in IRI caused by an error in distance measurement.

In figures 16 and 17 the error in roughness is approximately linear over the range of error in distance measurement shown. (It would certainly not be linear over a larger range.) For example, the error in IRI on the new asphalt section is about 1.07 times the error in distance measurement. Table 8 provides the ratio of error in IRI and RN to the error in distance measurement for 15 sections (described in Appendix A) of diverse surface properties. The negative sign in the IRI column indicates that underestimating distance leads to overestimation of IRI, and vice versa. The table indicates that a small bias in distance measurement will result in an error in IRI that is 0.4 to 1.1 times as large as the distance error, and an error in RN 0.1 to 1.2 times as large, depending on the surface type.

Table 8. Error in IRI and RN that results from a bias in longitudinal distance measurement.

Section	Ride Number	$\frac{\%\ \text{error in RN}}{\%\ \text{error in distance}}$	$\frac{\%\ \text{error in IRI}}{\%\ \text{error in distance}}$
12	4.23	0.13	-0.76
1	4.14	0.20	-1.07
13	4.02	0.16	-0.80
10	3.97	0.23	-1.09
14	3.80	0.15	-0.82
15	3.65	0.22	-0.68
3	3.21	0.31	-0.78
6	3.17	0.38	-0.92
9	2.59	0.41	-0.99
5	2.53	0.42	-0.83
4	2.47	0.37	-0.73
11	2.32	0.47	-0.82
2	2.16	0.46	-0.82
8	2.02	0.30	-0.40
7	1.35	1.21	-0.85

Calibration

The type of distance measuring instrument described above is sufficient for use in measurement of longitudinal profile and roughness statistics. However, the instrument will only operate properly if it is calibrated each time a change in effective rolling radius is expected. That requires that the personnel in charge of profiler maintenance are aware of the influence of tires on distance measurement.

Certainly, the calibration should be performed each time the pulser wheel tire is changed and twice throughout the tread life. Calibration should be done using tires that started out at the recommended cold inflation pressure and are warmed up. The warm-up is done by driving the profilers for about 30 minutes before the calibration measurements are made. The calibration should be done over a distance of 300 m or more, and done under similar conditions as a typical profile measurement. That is, at a common operating speed for the profiler and with no greater care to avoid lane wander than is used in day-to-day operation. At the beginning of each day of regular profiler operation, the tires should be checked for proper cold pressure. This must be done before the host vehicle has traveled more than a km or so.

Number of Sensors

The majority of profilers in service in North America measure profile in two tracks: one under the left side of the host vehicle and one under the right. A recent survey reported that of fifty-six states and provinces that responded forty report roughness from both sides, eleven report the roughness of the left side only, and five report the roughness of the right side only (*7*). Of the forty agencies that report roughness from both sides, thirty-four only retain the average of the two sides and the other six retain the individual roughness values for the left and right. The FHWA requires states to report IRI of HPMS sections for the right side only (*14*). The motivation to collect roughness in only one track is cost. Each set of sensors implies higher cost for equipment, maintenance, and data storage, and extra effort for calibration and data handling. However, collecting data in an extra wheeltrack does not increase the distance that must be covered, and each extra set of sensors improves the quality of a measurement by providing a clearer picture of the condition of the road.

On some pavements, the IRI of a single track on one side of the lane is a good estimate of the roughness, but this is usually not the case. The IRI and RN of most pavements varies significantly across a lane, such that measurements from two tracks provide a much better representation of the roughness than one. Indeed, our study of transverse variation in roughness (reported later in this chapter) suggests that IRI and RN values in two tracks does not completely define the roughness. This is likely to be the case no matter what index is measured. Further, a single profile is usually insufficient for identification of specific distress types or features that require attention. Two profiles are not usually enough for distress identification either, but do supply a much better set of clues, particularly if the analyst suspects that an anomalous feature is the result of measurement error.

Figure 18 illustrates the inaccuracy of using the IRI from the right side only as an estimate of the Mean Roughness Index (MRI). (MRI is the average of an IRI value from the left and an IRI value from the right.) The figure shows the bias (in percent) in using IRI on the right in place of the MRI of 799 sections from the General Pavement Studies (GPS) experiment of the LTPP study. A positive bias means the IRI is higher on the right, so only using a sensor on the right side overestimates the MRI. This is the case in 60 percent of these sections, so the distribution is skewed toward positive values.

The IRI from the right side is within 5 percent of the MRI in less than half of the measurements and is within 2 percent in only 153 of the 799 measurements. These statistics demonstrate that measuring the roughness on one side of a lane only provides very general information about the roughness on the other side. This is particularly true of roads with an AC surface. Table 9 provides a summary of the data presented in figure 18 by surface type. Pavements with both AC and PCC surfaces were rougher on the right side the majority of the time. Pavements with an AC surface layer had an IRI on the right side within 2 percent of the MRI only one-sixth of the time and within 10 percent only two-thirds of the time. All of the individual GPS surface types with asphalt on the top layer exhibited similar statistics. On PCC surfaces, the IRI on one side is a better estimate of the MRI, but is still insufficient for general use.

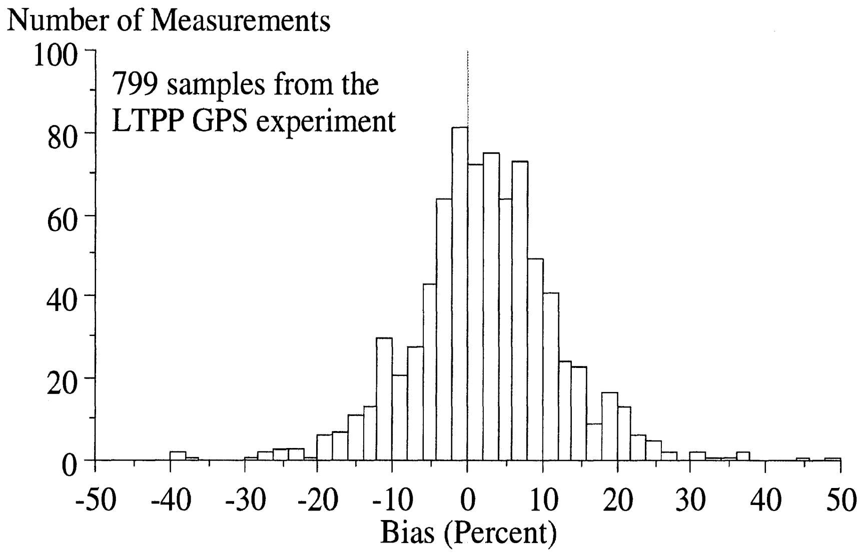

Figure 18. Bias in estimation of MRI using IRI from the right side.

Table 9. Estimation of MRI using IRI from the right by surface type.

	All		AC Surfaces[1]		PCC Surfaces[2]	
	Count	%	Count	%	Count	%
Number of Sections	799	100	506	100	293	100
IRI on the right above MRI	482	60	302	60	180	61
IRI on the right below MRI	317	40	204	40	113	39
IRI within 10% of MRI	570	71	332	66	238	81
IRI within 5% of MRI	355	44	198	39	157	54
IRI within 2% of MRI	153	19	79	16	74	25

1. Includes GPS experiments 1, 2, 6, and 7
2. Includes GPS experiments 3, 4, 5, and 9

The calculations for figure 18 and table 9 were made without any effort to weed out the profiles with major measurement errors. In fact, several of the sections with a large bias are cases in which a profile on one side contains spikes that are definitely not genuine road features. These were included to demonstrate that a major error in roughness on one side is moderated by the value on the other. The error is also much more likely to stand out if the second value is available for comparison.

Overall, measuring profile in one track does not do a sufficient job of characterizing the roughness of a lane. Although profile measurements from several tracks would provide useful information for distress identification, measuring profile in two tracks is a major improvement over just one. A minimum of two sets of sensors, one set on the right and one on the left, is recommended for all profiling applications.

Lateral Sensor Spacing

The majority of profilers in service in North America collect profile in two tracks; one of the left side of the host vehicle and one on the right. The separation between the footprints placed by the height sensors is their lateral spacing. The lateral sensor spacing in most profilers is determined by the need to collect rut depth concurrently with profile. Protocols for rut depth measurement developed for the FHWA recommend a three-sensor system with a lateral spacing of 172.7 cm (*36*). Naturally, the outer two sensors are also used for profile. A recent survey of seventeen states that collect profile found that a vast majority of them used a lateral sensor spacing of 175.3 cm (*10*). Most of these systems were commercially built and also measured rut depth. A handful of the states owned home-built systems that ranged in lateral sensor spacing from 149.9 to 162.3 cm. Some of these have been updated since the survey to a wider spacing.

The profiles of seven pavement sections were measured in several lateral tracking positions using the ProRut. The lateral sensor spacing in the ProRut is 182 cm, but the experiment covered so many lateral positions across the lane that the roughness in any position can be estimated within reasonable tolerance. Details about the experiment and all of the roughness values measured on these seven sections are shown graphically in Appendix D.

Table 10 shows the range of IRI values that would be measured by the ProRut if it tracked in the same location in every run but the sensors were spaced differently. All of the values assume that the center of the vehicle is placed 167 cm from the center of the right edge stripe. (In general, this places the center of the vehicle 175 to 180 cm from the right lane edge.) An estimate of the MRI that would be measured with this central placement is listed for several values of lateral spacing. MRI is the average of the IRI from the left and right side.

On most of the sections listed in table 10, the MRI is fairly insensitive to lateral sensor spacing. The new asphalt, severely faulted PCC, three-year-old PCC and AC with thermal cracks all have IRI values that do not change much over the range covered in the table. On the six-year-old PCC and the one-year-old PCC, an increase in sensor spacing causes the IRI on the right to increase and the IRI on the left to decrease. On the six-year-old PCC, these changes in IRI with lateral sensor spacing cancel each other out and the MRI holds steady. The one-year-old PCC section exhibits a sharp increase in roughness near the right edge of the lane, so the MRI is higher with a wider sensor spacing.

The old asphalt is the most sensitive to lateral sensor spacing. It has medium severity rutting with some longitudinal cracking in the ruts, so the IRI is highest in the ruts. (The section also has several sealed transverse cracks, but these contribute uniformly to roughness across the lane.) The 180 cm lateral sensor spacing places the two profiles in the center of the ruts, so it produces the highest MRI. As the sensors are drawn in, some of the rough features are missed, and the IRI on both sides decreases.

The lateral sensor spacing is not expected to change the measured roughness significantly on the majority of pavement sections, but it is likely to do so on any section with rutting or significant distress in the wheeltracks caused by heavy truck loading. A sensor spacing of 180 to 185 cm would correspond best to a typical track width of heavy trucks. However, automobiles have a narrower track than this and would not encounter two profiles that are this far apart simultaneously. Thus, a sensor spacing this large may measure roughness that does not represent their ride experience. To measure a set of two profiles that are more representative of a typical automotive ride experience, and place the sensors inside the ruts on rutted sections, a lateral sensor spacing of 170 to 180 cm is recommended. Most commercial profilers with two sensors for profile already space their sensors in this range, as does the protocol for rut measurement.

Note that the roughness values presented in this section assume that the profiler runs in a central tracking position, and only covers a lateral movement of the sensors of 30 cm. Variations in lateral tracking position during typical driving cover a broader range, and many drivers do not habitually travel in the center of a lane. Thus, variations in lateral positioning of a profiler are expected to cause much greater changes in measured roughness than variations in lateral sensor spacing.

Table 10. Variation in MRI with lateral sensor spacing.

	Mean Roughness Index (m/km)		
Lateral Sensor Spacing (cm)	new asphalt	AC with thermal cracks	old asphalt
150	0.87	1.20	2.05
155	0.87	1.20	2.08
160	0.88	1.21	2.12
165	0.89	1.21	2.15
170	0.89	1.21	2.19
175	0.90	1.20	2.23
180	0.91	1.21	2.24

Table 10. (cont.) Variation in MRI with lateral sensor spacing.

	Mean Roughness Index (m/km)			
Lateral Sensor Spacing (cm)	one-year-old PCC	three-year-old PCC	six-year-old PCC	severely faulted PCC
150	1.04	0.59	1.58	3.69
155	1.05	0.59	1.58	3.69
160	1.07	0.59	1.58	3.71
165	1.08	0.59	1.58	3.72
170	1.08	0.59	1.58	3.73
175	1.09	0.58	1.58	3.74
180	1.11	0.58	1.58	3.75

SURFACE SHAPE

This category of profile measurement factors includes any geometrical property of the pavement surface including curvature, the grade, roughness, distress, and texture. There are several ways that aspects of the pavement surface shape confound profile measurement. Longitudinal profile measurement usually involves measuring two paths along the pavement surface in a given lane. The lateral position of the measurement has a strong influence on the profile, because the pavement surface shape changes across the lane. The time and date of the measurement also influence the results in many cases, because of cyclic changes in roughness. Transverse, daily, and seasonal variations in profile all combine to make an individual measurement a mere sample of the road shape. Since the roughness of a road is really a function of lateral position and time, a single roughness value is actually a sampling of a statistical road property. The challenge is to optimize the profile measurement procedure to provide the most relevant information about the road surface with the resources available.

Other aspects of the pavement shape affect profile measurement by interfering with the operation of the sensors within a profiler. The most well known example of this is the fact that certain kinds of coarse macrotexture cause aliasing errors in measurements by ultrasonic height sensors. Roadway geometrics (i.e., curves, grades, etc.) may also cause measurement errors by changing the orientation of the accelerometer from perfectly vertical. Distresses with characteristic dimensions on the same order as the footprint size of typical height sensors also cause variations in the way each type of sensor measures rough roads.

Transverse Variations

This section examines variations in roughness that occur across a pavement lane. Road profile is usually measured in only two tracks per pass. Indeed, an automobile only experiences the road along two distinct tracks at a time. Thus, roughness is often thought of as a two-dimensional property of each side of the pavement lane (one profile on the left and one on the right), with little thought given to the path taken by the sensors. Roads are actually three-dimensional surfaces. A unique value of roughness exists for every path that can be taken on a given lane. The two values that a profiler produces per pass over a section only provide samples of the overall roughness. The difference between those two values is evidence that other values of roughness would be measured if the sensors moved along a different path.

The manner in which roughness varies across a lane is sometimes obvious. For example, many pavements develop visible distress in the wheeltracks most common to passing vehicles. Some fail along an edge first. In other cases, the variation in roughness across a lane cannot be recognized without profile measurements. This is usually true if the roughness stems from features that are not linked directly to visible distress. In still other cases roughness does not vary across a lane.

The transverse variation in roughness of seven sections was investigated experimentally. A camera, aimed at the edge stripe in the pavement, was mounted on the ProRut to monitor its lateral position. The position of the ProRut was displayed for the driver on a monitor graduated to show the lateral separation between the right height sensor footprint and the center of the right edge stripe. This served as a guide for the driver. To further aid the driver, all of the sections were straight and had very visible markings along the right edge. The video was also recorded and used after each run to judge the lateral position of the sensors at one-second intervals. In each run, the driver attempted to hold a target lateral position within a range of less than 20 cm, but a total range of 30 cm was considered acceptable.

Each section was visited twice. On the first visit the section was measured in seven to fourteen vehicle positions spread out over the entire lane. These measurements reveal the variation in roughness that exists across each section. On the second visit the section was measured six to eleven times in a position that the driver considered to be in the center of the lane. Often, the position was slightly to the right of the center of the lane, but seemed to be in the most common path taken by the prevailing traffic. These "central repeats" are used to determine the level of agreement that is possible with control over the lateral placement of a profiler. They also ensure that the trends observed on the first visit are caused by transverse variations in profile, rather than other sources of variation.

The seven sections investigated in this experiment are described in table 11. Further details about them are provided in Appendix A. A statistical summary of the transverse variations in roughness of each section is presented below. This is intended to demonstrate the level of variation that exists across the lane of some typical pavements. It is also provided to illustrate that the common practice of measuring profile in only two tracks does not define the roughness of a pavement, it only provides a snapshot of a complicated roughness picture. Following the summary the results, each road section is discussed. Appendix D also provides plots of the IRI and RN versus lateral position in the lane on all seven sections.

Table 11. Sections measured in the transverse variation experiment.

Section Number	Designation	Description
1	new asphalt	overlay of PCC, less than six months old
2	severely faulted PCC	21.3 m long slabs broken into several pieces with severe tilting and faulting
9	old asphalt	heavy truck traffic, sealed transverse and longitudinal cracks, mild rutting
12	three-year-old PCC	extremely smooth, 8.2 m long slabs
13	one-year-old PCC	12.5 m long slabs
14	AC with thermal cracks	transverse cracking, most severe along right edge
15	six-year-old PCC	no visible distress, but does not feel smooth

Summary of Roughness Variations

Table 12 summarizes the variations in IRI on each section. The table lists the total range of IRI values for all of the lateral tracking positions covered. It also provides the approximate value of IRI on tracks that are 76 cm and 258 cm from the right edge stripe.

These offsets represent the wheeltracks that would be traversed by a vehicle driving just to the right of the center of the lane. The table also lists the range of IRI that was measured on tracks that are within 30 cm of the central locations on either side. These values represent the range of roughness that could be measured by a driver with typical tracking behavior, but no special effort to drive in the center of the lane. Table 13 provides the same statistics for the RN. Although most of the values listed in these tables are the result of direct measurements, some of them are interpolated from two surrounding values.

All of these sections exhibit transverse variations in roughness. Beyond that, very few trends are common to all seven sections. The one-year-old PCC, three-year-old PCC, six-year-old PCC, and AC with thermal cracks are all roughest on the far right edge of the lane. Only a modest shift to the right of the central tracking positions causes these sections to appear significantly rougher.

Table 12. Summary of transverse variations in IRI.

Section	IRI (m/km)				
	Total Range	Edge Dist. 76 cm	Edge Dist. 46-106 cm	Edge Dist. 258 cm	Edge Dist. 228-288 cm
1	0.81-1.17	0.98	0.91-1.04	0.85	0.81-0.86
2	3.61-4.40	3.83	3.75-3.88	3.67	3.61-3.97
9	1.32-2.69	2.63	2.04-2.69	1.85	1.53-1.90
12	0.56-0.91	0.58	0.58-0.66	0.59	0.56-0.73
13	0.76-1.64	1.41	1.12-1.59	0.84	0.80-0.85
14	1.15-2.30	1.22	1.20-1.64	1.20	1.16-1.29
15	1.31-2.41	1.75	1.67-1.98	1.41	1.35-1.46

Table 13. Summary of transverse variations in RN.

Section	Ride Number				
	Total Range	Edge Dist. 76 cm	Edge Dist. 46-106 cm	Edge Dist. 258 cm	Edge Dist. 228-288 cm
1	3.71-4.16	3.75	3.71-4.10	4.14	4.10-4.16
2	0.99-1.69	1.44	1.38-1.50	1.57	0.99-1.69
9	1.66-3.35	1.66	1.66-2.59	2.27	2.19-2.99
12	3.64-4.15	4.04	3.86-4.07	4.05	4.02-4.13
13	3.33-3.99	3.66	3.47-3.78	3.92	3.91-3.95
14	2.13-3.69	3.14	2.77-3.38	3.67	3.60-3.69
15	2.30-3.39	3.21	2.92-3.28	3.33	3.33-3.39

Six-Year-Old PCC (Section 14)

Figure 19 shows the variation in IRI across a lane of the six-year-old PCC. The day of each measurement is indicated by point color. Overall, the IRI of this section covers a huge range. The IRI is lowest near the left edge and increases as the tracking position shifts from left to right. The increase is fairly linear (about 0.002 m/km per cm of lateral shift) until the tracking position shifts to 65 cm from the right edge, then the IRI increases sharply.

This section is still in good condition and has very little localized distress at the surface. Most of the roughness stems from slab effects, so the smooth trend across the lane is no surprise. The slabs are an average of 12.5 m long, and they are all cracked transversely in the middle. The half-slabs are curled upward. (The edges were higher than the center.) This section is located on the outside lane and has a bituminous shoulder. The higher roughness at the pavement edge is due to curling effects along the unrestrained right edge of the pavement.

The measurements made on November 9, 1997, are grouped around a relatively central tracking position. In four of the runs made on November 9, 1997, the right height sensor passed very close to 68 cm from the right edge stripe. (This placed the left height sensor 250 cm from the stripe.) In these runs, the IRI of the right side averaged 1.78 m/km and the IRI of the left averaged 1.40 m/km. Small variations from this "central" location do not change the IRI much on the left, but cause significant variation on the right.

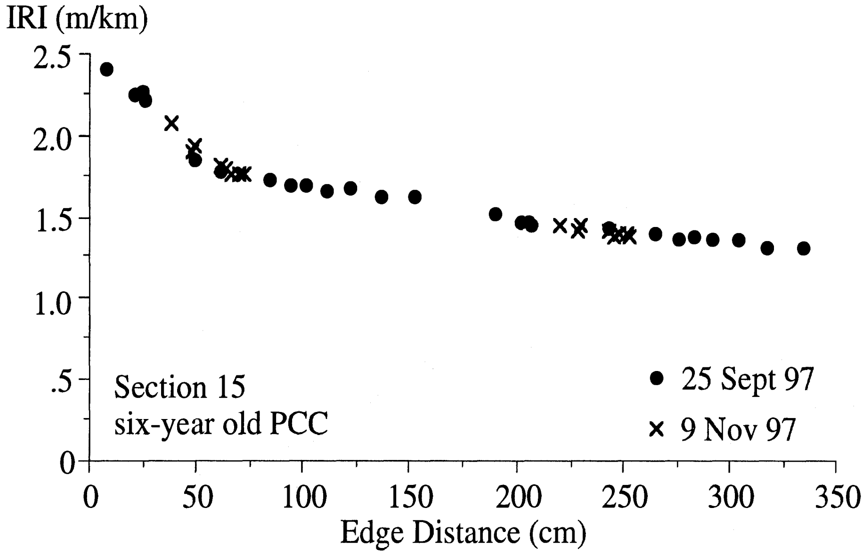

Figure 19. Transverse variation in IRI of six-year-old PCC.

The variation in RN across this section was less dramatic. The total range of RN values for tracking positions greater than 60 cm from the right edge was 3.19 to 3.39. The RN drops sharply for tracking positions near the right edge because of short-wavelength roughness at the joints.

One-Year-Old PCC (Section 13)

The transverse variations in IRI and RN on the one-year-old PCC were very similar to the those exhibited by the six-year-old PCC. This section was smoothest on the left, grew rougher as the track moved to the right and grew much rougher near the right edge. One pass over this section covered a track that was exclusively to the right of the right edge stripe, and tracked directly over the joint between the lane and the shoulder over one-sixth of the section. This track was much rougher than the others and was not included in the statistics.

Although the trend in roughness was the same in this section as in the six-year-old PCC, the underlying cause was quite different. On this section, most of the roughness was caused by spikes at the joints. The slabs on this section were separated by more than 15 mm. The joints were sealed, but the sealant was not flush with the surface of the slabs. (The depth was greater than 10 mm between most of the slabs.) At nearly every joint the ProRut measured a downward spike ranging from 5 to 15 mm deep. These spikes grew in depth with movement to the right, except in a track just inside the right lane edge.

Since this section is not faulted, the gaps at the joints just described are enveloped by vehicle tires, and do not degrade the ride quality of the road. Thus, the trends observed on this section are somewhat dubious. In reality, this section felt like new PCC no matter where the vehicle tracked. (More detail about the interpretation of spikes at joints is provided in the "Pavement Distress" section of this chapter.)

Three-Year-Old PCC (Section 12)

This was an exceptionally smooth section. The only major transverse variation occurred near the right edge, where the roughness was highest. The most interesting observation to be made about this section was the change in roughness over time, rather than the transverse variations. The central repeats were collected more than six weeks after the original data. Both sets of measurements showed that the slabs in this section were curled downward. (The center was higher than the edges.) However, the curling was more severe during the central repeats. Figure 20 shows the effect on the IRI. The original runs and the central repeats are distinguished by point type. The central repeats were collected on a cold, clear day with constant sunlight. The original data were collected on a hot, but cloudy day.

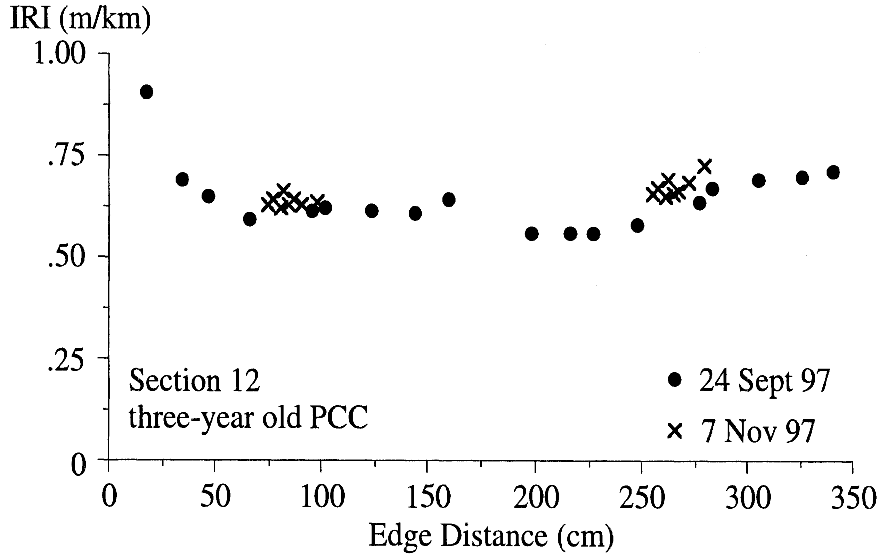

Figure 20. Variation in IRI of three-year-old PCC.

Severely Faulted PCC (Section 2)

The severely faulted PCC was by far the roughest section included in this experiment. The section was in service beyond its intended design life. The joints were spaced 21.3 m apart, but each slab was broken into as many as seven pieces. Each of the pieces of the slab was tilted with faults between them, but no faults appeared at the original joints. This section was so rough at the time of the experiment that traversing it at the speed limit was uncomfortable. In the summer that followed the experiment, it was reconstructed.

Most of the roughness was caused by tilting of the pieces of the original slabs and the faulting between them. Thus, the IRI did not vary much across the majority of the lane. For tracks between 19 and 290 cm from the right edge, the IRI only ranged from 3.61 to 3.94 m/km. A range of 0.33 m/km would be significant for a smooth section, but in this case it is not. This section would probably be selected for repair or reconstruction no matter where the IRI was measured.

The severity of the faulting and the openness and depth of the cracks and faults did not vary systematically with lateral position. Thus, the short wavelength roughness did not vary systematically across the lane. As a result, the transverse variations in RN were erratic.

New Asphalt (Section 1)

This section was overlaid less then six months before the experiment. It was very smooth, and most of the roughness occurred in the wavelength range greater than 20 m. This is no surprise: The roughness in the short wavelength range is usually eliminated in the process of installing an overlay. Since most of the roughness is caused by long wavelength features, which do not vary much transversely, the IRI and RN were consistent across much of the lane. For example, the IRI of all positions more than 124 cm from the right edge only ranged from 0.81 to 0.87 m/km. The consistency in this part of the lane is a result of the lack of short wavelength roughness. Long wavelength features are more likely to span an entire lane. (The entire width of a lane generally goes up and down hills together.) Short wavelength roughness, on the other hand, often causes variations in profile across a lane.

In contrast, the roughness in the portion of the lane less than 124 cm from the right edge was not consistent. Two phenomenon contributed to the variation. First, the short-wavelength roughness near the shoulder caused the IRI to increase steadily from 0.87 to 1.17 m/km as the tracking position moved toward the right edge. Second, two closely spaced core samples were taken on the right side of the lane about 800 m into the section. The area around these core samples was a depression about 13 cm wide, more than 15 cm long, and about 10 mm deep. This did not affect the IRI. However, profiling in a path that included this dip degraded the RN by about 0.25 units. (See figure 21.) Hitting or missing this narrow bump with a profiler completely changes the way this section is judged by the RN, just as it would change a typical driver's perception of this otherwise pleasantly smooth road.

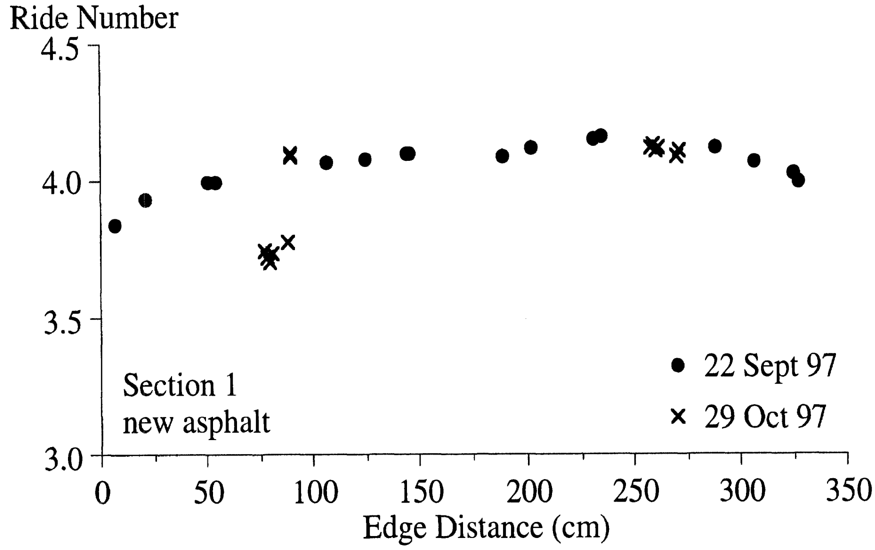

Figure 21. Transverse variation in RN of new asphalt.

AC with Thermal Cracks (Section 15)

The only distress in this section was transverse cracking. All of the cracks spanned the entire width of the lane. Across most of the lane, the cracks were not very severe. Within a half-meter of the right edge, however, they nearly always degenerated into a dip up to 40 cm long and 5 mm deep. A typical example is presented in figure 22. On the left side of the lane, the crack is narrow and does not contribute much to the roughness. As the profile is measured closer and closer to the right edge, the cracks grow deeper and the surrounding dip grows longer. It is a very rough feature near the right edge. The IRI and RN of this section were relatively consistent over most of the lane, but indicated much higher roughness within 70 cm from the edge.

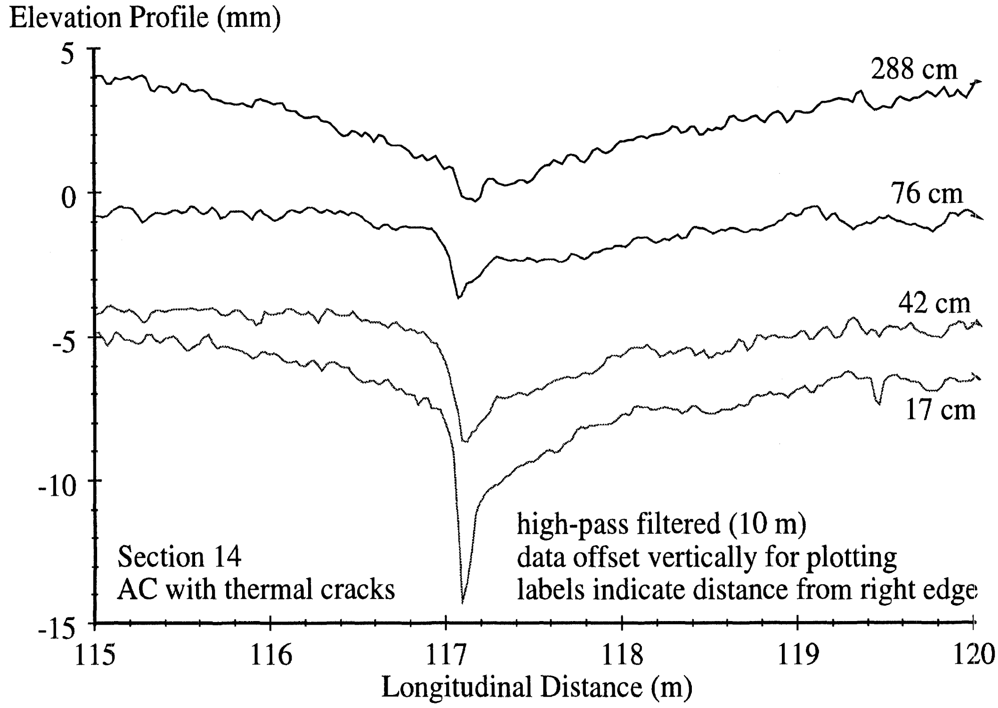

Figure 22. Transverse variations in a thermal crack on AC.

Old Asphalt (Section 9)

This section is on a two-lane undivided road that provides access to a large waste dump. The section is on the side leading to the dump, so it is subjected to traffic by loaded trucks. The personnel that conducted this experiment observed that many of the trucks passing over this section were most likely overloaded. The section is only mildly rutted but it has several longitudinal cracks within the developing ruts. It is also cracked transversely in several places. All of the major longitudinal and transverse cracks were sealed when this test was performed.

Figure 23 shows the transverse variation in IRI. The IRI is highest in the ruts. These ruts are centered 190 cm apart and are 70 cm wide. This corresponds almost directly to the footprint laid out by a typical truck axle with dual tires. (In Michigan, the total width of most trucks is 2.43 m and a typical track width is about 1.8 m.) The elevated roughness in the ruts is not directly caused by the rutted shape. It is instead a result of the longitudinal cracks and other forms of distress that appear within the ruts.

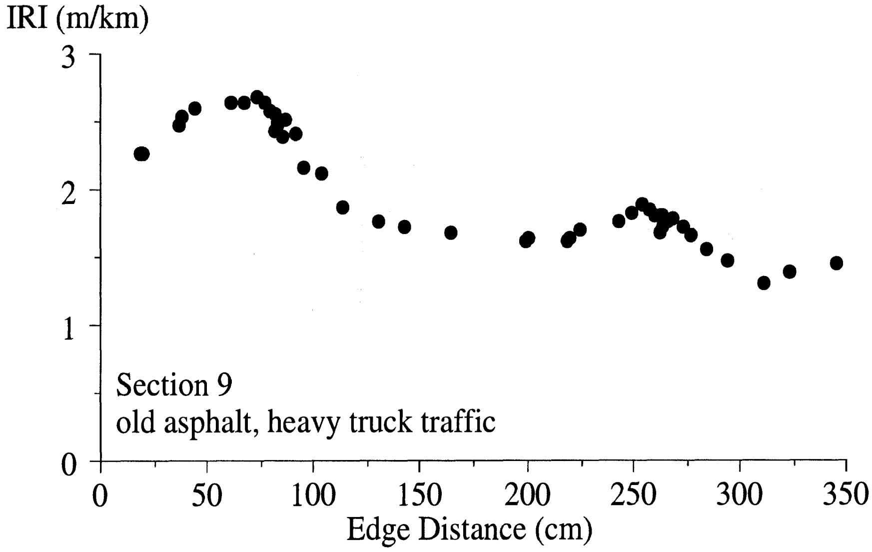

Figure 23. Transverse variation in IRI of old asphalt.

The RN showed a similar trend, but much more dramatic as shown in figure 24. The RN at some locations within the ruts was more than a full unit lower than the surrounding tracks. This is largely caused by longitudinal cracks. Although most of the longitudinal cracking on the right side of the lane was 110 to 120 cm from the edge, two very severe longitudinal cracks appeared about 70 cm from the edge. This accounts for the extremely low RN values in the band from 67 to 77 cm.

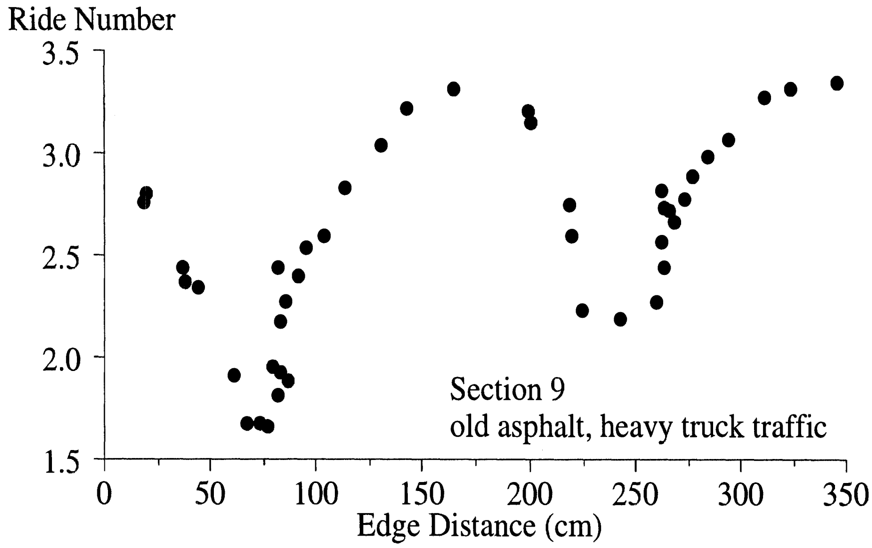

Figure 24. Transverse variation in RN of old asphalt.

Daily Variations

The roughness of all jointed PCC pavements includes some contribution, often significant, from the prevailing shape of the slabs. The nominal curvature built into slabs depends on several factors, including mix properties, base support, slab length, layer thickness, reinforcement, joint type, and temperature and moisture of the concrete material during curing. To further complicate matters, the actual shapes of PCC slabs fluctuates with time. Changes in temperature over a twenty-four-hour cycle interact with design and construction factors to cause variations in slab shape throughout the day. For example, if a cool night is followed by a hot, sunny day, it causes variation in temperature throughout the depth of the pavement (called a temperature gradient). The surface of the pavement slabs, heated by the sun and air, expands relative to the bottom and the edges curl downward. In the night and early morning hours when the temperature at the pavement surface is lower than the temperature under each slab, the surface contracts and the edges tend to curl upward. These changes are superimposed on the original shape of each slab. Usually, a pavement is always curled in one direction or another, and the temperature gradient influences the severity of the curvature.

Under the ongoing seasonal monitoring program of the LTPP study, several pavement sections in North America are being profiled during different seasons. The LTPP database was reviewed to select test sections that had two such measurements. At the time, data from eleven PCC test sections were available. The experimental design in the seasonal monitoring program called for measurements of the jointed concrete pavements in the morning and again in the afternoon. Of these sections, four were jointed reinforced concrete (JRC) and seven were jointed plain concrete (JPC). Up to five profile measurements at each time on each date are available. These measurements are not comprehensive enough to provide a systematic understanding of daily variations in roughness of jointed concrete, but they do provide an estimate of the level of variation in roughness and slab curvature that is possible.

Table 14 lists the four JRC sections and their MRI at various times and dates. (MRI is the average of the IRI from the right and left wheeltrack.) The roughness values were computed directly from the profiles after they were screened for potential measurement errors, rather than extracted from the LTPP database. All four of them were curled downward at all of the times and dates listed. Temperature gradient simply determines the severity of slab curvature, it never flattens the slabs or curls them upward. The two sections with slabs shorter than 10 m show a regular pattern that corresponds to the slab length. Figure 25 shows one of the profile measurements of section 4054 in Kansas that is filtered to show wavelengths shorter than 20 m. The shape of the profile shows a clear slab curl that repeats every 9 m or so. The other two sections do not show a pattern as regular as the one shown in figure 25. The mid panel cracks of these sections give rise to curled slabs of various lengths, so the shape is more erratic.

Table 14. Daily variation in MRI on four JRC pavements.

GPS Num (State)	Slab Len. (m)	Date	Season	Time		MRI (m/km)		
				Morning	Afternoon	Morning	Afternoon	Change
1606 (Penn.)	14.2	1/11/96	Winter	6:33	11:40	1.46	1.49	0.03
		4/10/96	Spring	8:40	15:08	1.51	1.55	0.04
		8/29/96	Summer	7:45	13:37	1.59	1.61	0.02
4018 (New York)	19.4	4/18/95	Spring	5:18	15:18	1.63	1.69	0.06
		4/10/97	Spring	9:21	14:35	1.91	1.97	0.06
4040 (Minnesota)	8.2	4/22/95	Spring	9:12	15:49	2.03	2.17	0.14
		6/27/95	Summer	8:15	16:10	1.94	1.99	0.05
4054 (Kansas)	9.1	1/17/96	Winter	9:35	13:04	1.80	1.81	0.01
		4/21/96	Spring	7:53	16:38	1.78	1.90	0.12
		9/17/96	Summer	5:26	12:29	1.59	1.78	0.19

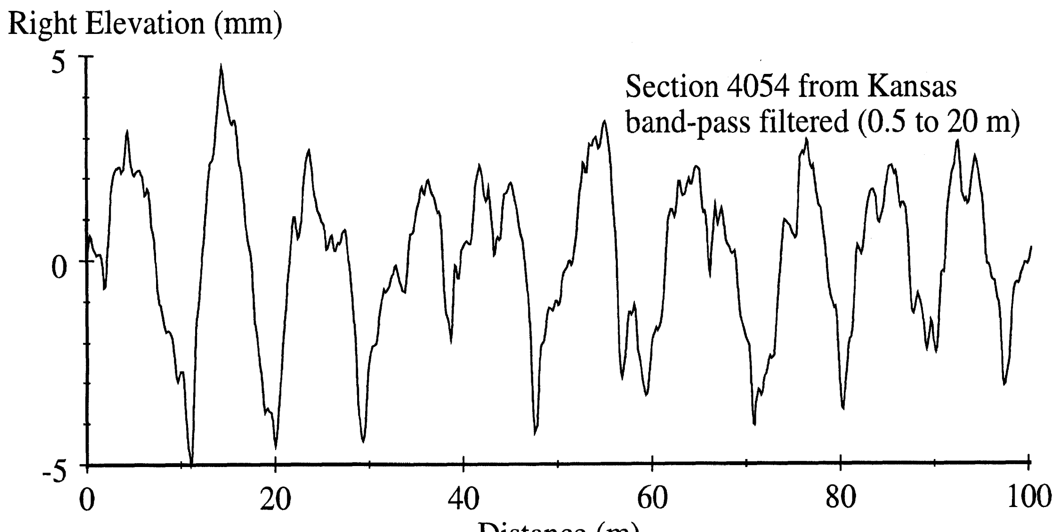

Figure 25. Curled shape of a JRC pavement.

All of the sections featured in table 14 are rougher in the afternoon than in the morning. This is because heating of the pavement surface as the sun rises exaggerates the downward curl. The effect on MRI is small in the sections with long slabs and a less regular curling pattern, but is significant on the two sections with shorter slabs. In the summer, the MRI of these sections elevates up to 0.19 m/km (10 percent) between sunrise and late afternoon. The RN of section 4054 from Kansas dropped 0.31 units from morning to late afternoon on the date listed for spring. In the winter, when the temperature does not change as much throughout the day and the sun provides little radiation to the pavement surface, cyclic changes are not likely to be significant. Indeed, this was the case in two examples listed in table 14.

The MRI values on the seven JPC sections at various times and dates are listed in table 15. Section 3019 from Georgia, which is curled downward, is the only section that is rougher in the afternoon than in the morning. The rest of these sections are curled upward. Rather than an inverted "bowl" shape similar to the downward curling shown in figure 25, these profiles show slabs that are flatter in the middle and lifted near the joints. All of the sections with slabs that are curled upward decrease in roughness from morning to afternoon, because the surface heats up and causes the lift at the joints to decrease. The most significant change is in section 3011 (from Utah). The change is more than 10 percent throughout the day on the spring and summer dates, but only about 3 percent on the winter date. The largest change in RN observed among these sections was 0.10 units. Often, the change in RN from morning to afternoon was no larger than the variation between repeats at each time of day.

Table 15. Daily variation in MRI on seven JPC pavements.

GPS Num (State)	Slab Len. (m)	Date	Season	Time		MRI (m/km)		
				Morning	Afternoon	Morning	Afternoon	Change
3019 (Georgia)	6.1	1/26/96	Winter	6:44	12:12	1.69	1.73	0.05
		4/5/96	Spring	7:15	13:02	1.55	1.61	0.06
		10/17/96	Fall	7:48	16:11	1.52	1.54	0.02
3002 (Indiana)	4.7	10/24/95	Fall	7:48	16:01	2.09	2.00	-0.09
		4/3/96	Spring	7:23	11:36	1.89	1.80	-0.09
3011 (Utah)	4.6	5/18/95	Spring	7:05	14:55	1.97	1.78	-0.19
		3/2/97	Winter	10:11	14:35	2.14	2.07	-0.07
		4/25/97	Spring	7:40	12:34	2.18	1.97	-0.21
3802 (Manitoba)	4.6	4/28/95	Spring	8:13	15:56	3.27	3.23	-0.04
		6/26/95	Summer	8:44	16:46	3.32	3.27	-0.05
3018 (Nebraska)	4.7	1/14/96	Winter	7:34	18:27	1.90	1.77	-0.13
3023 (Idaho)	4.1	9/9/94	Fall	11:47	15:01	1.51	1.48	-0.03
3042 (California)	4.7	11/30/95	Fall	9:43	17:45	1.03	0.98	-0.05
		5/8/96	Spring	9:26	15:17	1.02	0.96	-0.06
		8/14/96	Summer	10:39	13:51	1.05	1.02	-0.03

The most remarkable example of a daily change in roughness observed in this study was found in the data from the 1994 RPUG experiment. A section in Nevada was profiled with a Dipstick twice: once in the morning and once in the afternoon. Portions of these measurements are shown in figure 26. Heating of the pavement surface throughout the morning and early afternoon significantly reduced lift at the joints. The IRI of the left wheeltrack of this section reduced from 1.78 m/km to 1.45 m/km between measurements. This is a change of nearly 20 percent, and may affect the way this section is judged by a pavement management engineer.

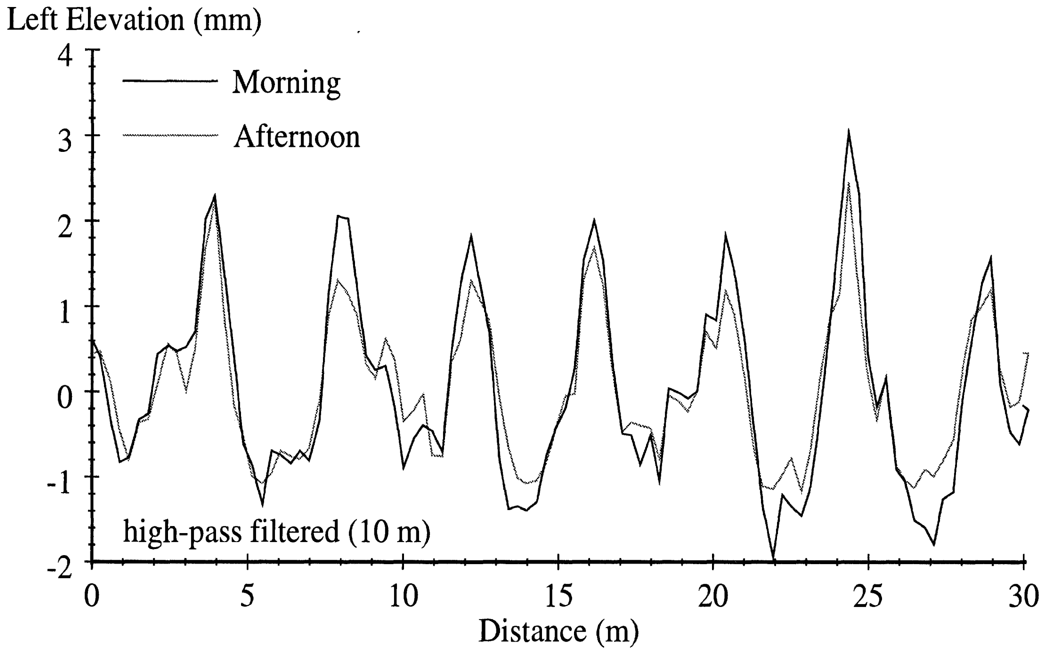

Figure 26. Change in slab shape from morning to afternoon.

In network-level profiling the roughness of most sections is rarely measured more often than once per year. The exact time of day and weather conditions associated with each measurement is not likely to be repeated each time a section is monitored. The time and date of measurements should accompany any roughness value that is entered into a database. This leaves the analyst free to consider possible daily variations as a cause of anomalous changes in roughness throughout the life of jointed concrete pavements. Roughness values on these pavements must be viewed as a sampling of the actual roughness, which fluctuates. The limited data discussed here showed that the roughness changes very little throughout the day in some cases, up to 0.2 m/km in others, and even more in extreme instances. If a specific design is prevalent among jointed concrete pavement in a given road network, it may be of interest to measure a few sections several times throughout a sunny day that follows a cool night to quantify the variation that is possible on that design.

Planning of profiling for project-level monitoring of jointed concrete pavements must account for possible daily variations in slab shape. On days where the temperature changes by 10 degrees C or more between dawn and late afternoon, the pavement should be profiled once in the morning and once in the afternoon. If this is not practical, one segment of each design within the project should be profiled two or three times throughout the day to help place limits on the possible variations.

Seasonal Variations

Environmental effects on pavement condition can cause cyclic changes in roughness. These changes are difficult to predict, because they are so heavily linked to temperature and moisture. Some of the asphalt concrete pavements over granular base material in the LTPP seasonal monitoring program exhibited elevated roughness in the winter. In the Northeast, the MRI of some sections was up to 0.71 m/km higher in the winter than in other seasons, but not every year. Novak and Defrain reported even larger changes in IRI of composite pavements in Michigan. Only limited data were available for PCC pavements. However, seasonal changes in their roughness seem to be most significant on pavements that also exhibit daily changes, and the seasonal changes are at least as large.

Composite Pavements

Novak and Defrain (*37*) reported changes in profile of composite pavements in Michigan that took place between the summer of 1990 and February of 1991. Nine examples that included three different seasonal effects on composite pavement were:

1. PCC pavements with joints that have deteriorated due to D-cracking and then were overlaid with asphalt concrete. During winter frost, tenting action in the deteriorated PCC material at the joint caused a localized frost heave. During the thaw period, fines that formed as a result of D-cracking pumped. The loss of fines, because of pumping, caused a depression at the joint during summer.

2. Pavements with a frost susceptible base layer tilt or fault because of frost action. When the slabs tilted the back slabs rose at deteriorated joints and the fore slabs depressed (typical of faulting caused by pumping). Frost action in the base layer can also cause the fore slabs to rise above the back slab at joints and cracks.

3. PCC pavement with D-cracking at the joints that was replaced by removing deteriorated material and replacing it with a bituminous patch, then placing an overlay. In winter, the PCC slabs contracted and some lateral movement of the bituminous joint repair material caused a depression in the repair area. In summer, expansion of the PCC slab compressed the bituminous repair material, causing a bump to occur.

A pavement section that exhibited a combination of the first two effects increased in IRI from 1.96 m/km in summer to 2.88 m/km in the winter. Another section increased in roughness from 1.61 m/km to 4.23 m/km. In a pavement described by the third effect, the bumps at the joints shrank as the bituminous patches settled and the IRI decreased from 1.77 m/km to 1.22 m/km.

Asphalt Concrete Pavements

Seasonal changes in asphalt concrete pavement profile occur mainly because of changes in volume of the subsurface layers. Typically, most of the movement is in the subgrade, but some movement may occur in the base. Seasonal changes in moisture conditions in the subgrade can occur, which results in volume changes in the subgrade. In freezing environments, subgrade that is susceptible to frost may change in volume severely and induce bumps on the pavement surface. This is called frost heave. Often, the bumps shrink or disappear after the freezing weather is over. These effects depend on annual precipitation, subsurface layer properties, and the depth of frost penetration.

The Connecticut DOT studied changes in roughness caused by these effects in 1989 and 1990 (*38*). They measured the roughness of 14 highway sections in a search for frost-prone highway beds. Some significant seasonal changes in roughness were observed in the study, but much less than the author expected from prior experience. Precipitation was lower than usual in both years of the study and the average temperature was unusually high. This study demonstrated that seasonal changes in roughness are not likely to be systematic, because they are heavily linked to the weather.

The LTPP study designated a small subset of the sites of the general pavement studies to be profiled every season in some years. Profile data from these "seasonal monitoring sites" were used to estimate the level of seasonal variation in IRI that is possible on asphalt concrete pavement. The profiles were screened rigorously for signs of potential measurement errors to prevent anomalous roughness values from contaminating the analysis. Thus, some of the sections that were selected by LTPP for seasonal monitoring are not discussed here.

Two sections (4165 in Oklahoma and 1802 in Mississippi) of asphalt concrete over a bound base were measured in four consecutive seasons. Neither of them showed any significant seasonal changes in IRI or RN. This is because they are in southern states that do not have cold winters.

Since seasonal effects in profile are heavily linked to temperature and moisture, asphalt concrete sections over granular base material from four broad climatic regions were selected by LTPP for seasonal monitoring: wet freeze, dry freeze, wet no freeze and dry no freeze. Of seven sections in the wet and dry no freeze zones, only one showed any seasonal change in roughness. This was section 1005 from Georgia. It was measured in five consecutive seasons starting in the fall of 1995. The profile of this section included several dips in the right wheeltrack in the winter and spring of 1996 that were not present in the fall of 1995. In the fall of 1996, the dips were no longer present. Over the yearly cycle, the IRI rose from 1.00 m/km to 1.15 m/km, then returned to 1.03 m/km. (A change in roughness of this magnitude and character could have been caused by tracking near the right lane edge.)

Five sections from the dry freeze region were profiled in up to seven consecutive seasons. Table 16 lists the MRI of these sections in each season. The values listed are the average of five repeat runs. The MRI of two of these sections held steady. Two other sections grew steadily rougher, but not because of seasonal effects. Only one of the sections showed elevated roughness in the winter. This section was 0.26 m/km rougher in the winter than in surrounding seasons.

Four sections from Northeast were profiled in up to eight consecutive seasons in 1993 through 1995, then some of them were profiled three more times in 1997. All of these sections are in the wet freeze region. In some cases, they were measured twice in the winter, once during regular rounds, and again during dates when the depth of frost penetration into the ground was at a maximum. Table 17 lists the progression in MRI of these sections over time. The values listed are the average of five repeat runs. All four of these sections exhibit a seasonal change in MRI in at least one of the three years. In many cases, these sections were rougher in the winter than in other seasons, and roughest in February during maximum frost penetration. For example, section 1803 in Connecticut increased in MRI by 0.18 m/km between July 1993 and winter 1994, then another 0.09 m/km by February. In the spring, the roughness decreased to the level of the previous fall.

Table 16. Seasonal values of MRI of five sections in the dry freeze region.

State	Colorado	Idaho	Montana	Utah	Wyoming
GPS Number	1053	1010	8129	1001	1007
MRI (m/km)					
Fall 93	1.24	—	1.05	1.10	0.92
Winter 93-94	1.22	1.49	0.97	1.12	0.92
Spring 94	1.23	1.53	1.03	1.13	0.94
Summer 94	1.25	1.57	1.06	—	0.95
Fall 94	1.20	1.58	1.02	1.09	0.94
Winter 94-95	1.24	1.57	1.11	1.10	**1.26**
Spring 95	1.27	1.70	1.19	1.12	1.00
Range	0.07	0.21	0.22	0.03	0.34
Seasonal Effect?					×
Minor Changes Only?	×			×	
Steady Progression?		×	×		

— No data available.

Table 17. Seasonal values of MRI of four sections in the wet freeze region.

State	Connecticut	Maine	New Hampshire	Vermont
GPS Number	1803	1026	1001	1002
MRI (m/km)				
Fall 93 (July-Sept)	1.55	1.48	0.66	—
Winter 94 (Jan)	1.73	—	—	—
Winter 94 (Feb)	1.84	1.52	1.07	—
Spring 94 (Apr)	1.60	1.41	0.73	1.15
Summer 94 (July-Sept)	1.57	1.41	0.74	1.32
Fall 94 (Oct)	1.57	1.37	0.68	1.20
Winter 95 (Jan)	1.57	1.54	0.87	1.25
Winter 95 (Feb)	1.62	1.60	0.72	—
Spring 95 (May)	1.60	1.38	0.68	1.18
Summer 95 (June-July)	1.58	1.37	0.74	1.22
Winter 97 (Jan)	1.64	1.12[a]	1.35	1.29
Winter 97 (Feb)	1.63	1.18	1.56	1.54
Spring 97 (Apr)	1.67	0.96	0.85	1.19
Seasonal Affect in Winter 1994?	Yes	Yes	Yes	—
Seasonal Affect in Winter 1995?	No	Yes	Yes	No
Seasonal Affect in Winter 1997?	No	—	Yes	Yes

— No data available. a. Resurfaced.

Section 1001 from New Hampshire exhibits the highest level of seasonal variation. If the MRI values from the winter are ignored, the roughness progresses steadily from 0.66 m/km to 0.85 m/km in three years. In every winter, the MRI is higher than the prevailing trend. In the winter of 1997, the MRI is double the value of the following spring. Figure 27 shows the profile from six different dates. The figure shows two cycles in which the profile is much rougher in February, but looks very similar in the preceding and following measurements.

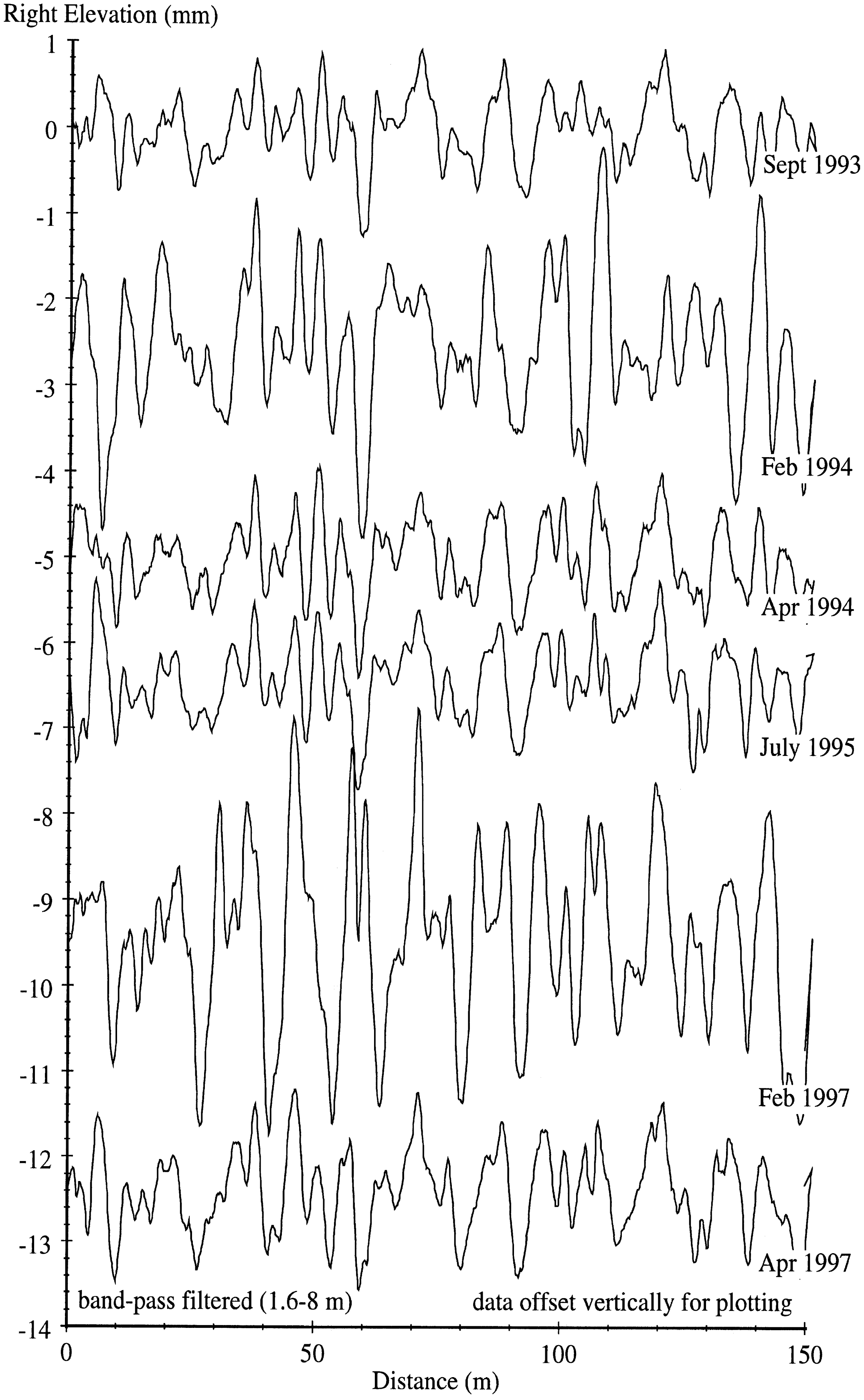

Figure 27. Seasonal changes in profile of LTPP section 1001 from New Hampshire.

The examples provided by the LTPP study show that very large seasonal changes in roughness are possible in asphalt pavement on granular base material. These changes do not occur every year because of variations in climate, but they do seem to be limited to winter. Profiler users should avoid measuring the roughness of their road networks in the winter. If this cannot be avoided, pavement management engineers should recognize that roughness values measured in winter may be elevated significantly because of seasonal variation.

Portland Cement Concrete Pavements

Subsurface movements caused by cyclic changes in temperature and moisture like those described for asphalt concrete pavement may also contribute to variations in the roughness of PCC. PCC is also sensitive to cyclic changes in temperature that occur throughout the day. Thus, seasonal changes that are observed in the roughness of PCC may be obscured by daily changes. For example, LTPP section 4054 from Kansas changed in MRI by 0.19 m/km between morning and afternoon in the fall of 1996. (See table 14.) The average values of MRI in the morning also varied by 0.21 m/km between January and September. On the other hand, section 1606 from Pennsylvania varied only 0.04 m/km between morning and afternoon on three different dates, but ranged 0.13 m/km between winter and the following fall. The limited data available suggest that seasonal changes in roughness of PCC pavements can be at least as significant as daily changes.

Surface Texture

Surface macrotexture is the portion of the road profile in the range of wavelengths from 0.5 to 50 mm (*39, 40*). Coarse macrotexture elevates noise at the tire-road interface and increases the rolling resistance of vehicles. The desirable level of macrotexture is the result of a trade-off between safety and a quiet ride and slightly improved fuel economy. Macrotexture is not in the range of wavelengths of interest in the measurement of roughness indices such as the IRI and RN.

Unfortunately, the presence of coarse macrotexture greatly increases the potential for aliasing errors in roughness measurement. For example, if a device with a very small sensor footprint measures a section with a coarse aggregate seal coat without anti-aliasing filters, it will mistake the texture for longer-wavelength roughness. In such a case, one reading may sample the elevation at the top of a piece of aggregate. If the next reading is 0.15 m along the road and samples the elevation in a low point within the texture, then the next is at a high point in the texture again, the profile will show a dip about the same depth as the aggregate size, but 0.3 m long. This false dip would increase the apparent roughness of the section. The way to avoid this source of error is to sample the pavement much more often than the shortest wavelength of interest and apply filters to remove the influence of short deviations. This is the basic concept of anti-alias filtering. It is described in more detail in the "Sample Interval" section of this chapter. Proper application of anti-aliasing filters virtually eliminates errors caused by coarse surface texture.

Three cases of coarse texture are discussed in this section: (1) chip-sealed asphalt, (2) concrete with exposed aggregate, and (3) tined concrete.

Chip-Sealed Asphalt

The coarse macrotexture present on pavement surfaces with a chip seal has the potential to cause roughness measurement errors. In particular, profilers with ultrasonic sensors measure sections with coarse chip seals with a large upward bias in roughness. Early problems with ultrasonic sensors on coarse-textured asphalt were reported in the development of the South Dakota profiler (*17*). Huft reported that coarse surface texture increased the IRI on some sections up to 0.2 m/km. Most of the error in roughness was caused by aliasing, but Huft also reported that increasing the operating speed exacerbated the effect, because the echo of the acoustic ping became scattered and harder to detect. This occurred mostly on sections of very large open-graded aggregate.

The effect of coarse chip seals on roughness measurement was well-documented in the 1993 RPUG study (*11*). Some of the relevant results are summarized in Appendix C of this report. In the study, profilers with ultrasonic sensors measured IRI up to 20 percent high on most sections, but 50 to 100 percent high on sections with a chip seal. The reason for the upward bias in roughness was threefold:

1. Ultrasonic sensors detect the highest feature within their footprint, rather than the average of the deviations within their footprint. On a coarse section, ultrasonic sensors read the height of protruding aggregate.
2. The acoustic ping of ultrasonic sensors is scattered and weakened by coarse texture, which leads to sensor dropout.
3. At highway speed, ultrasonic sensors can only sample about once every 0.3 m, which prohibits the application of proper anti-aliasing filters.

After the RPUG study, the profiling community in North America widely recognized that ultrasonic height sensors were not sufficient for measurement of IRI. The profiling community have been slowly replacing them. Profilers with laser and optical sensors also measured IRI that was high relative to the Dipstick on some sections, but the bias was much smaller and was not caused by coarse macrotexture. Instead, it was the result of narrow cracks and opened joints measured by these profilers that were not sensed by the Dipstick. (The Dipstick senses road features very differently than inertial profilers. Each reading is made by a precision inclinometer that measures the difference in height between the two supports that actually contact the road, normally spaced 305 mm apart. These supports make circular contact with the ground that is at least 25 mm in diameter and often much larger. As such, it will not sense a narrow crack.)

In this study, five profilers measured three sections at the GMPG interior noise loop to test their sensitivity to macrotexture. One of the sections had an extremely coarse chip seal. This section was covered by a chip seal of protruding stones 3 to 6 mm in diameter. The coarse macrotexture was built in intentionally to help study road-induced noise. A portion of this section 150 m long was also measured by a Dipstick. Table 18 compares the IRI and RN measured by the five profilers on the 150 m long segment to the values obtained with the Dipstick. The infrared and laser profilers agreed reasonably well with the Dipstick, but the ultrasonic profiler was 30 percent high. All of these profilers except the ProRut use anti-aliasing filters with a cutoff wavelength equal to twice their sample interval. That is why they are not affected by the extremely coarse texture of this section. Even the ultrasonic profiler averages two consecutive height sensor readings to help eliminate the effect of texture. That is why the bias on this section was not as high as that exhibited on chip sealed sections in the RPUG study.

Table 18. Measurement of a very coarse chip seal by five profilers.

Profiler	Number of Runs	IRI (m/km)	Bias (%)
Dipstick	1	2.87	—
Infrared	3	3.09	7.9
Laser 1	3	3.01	5.0
Laser 2	3	2.97	3.5
ProRut	3	2.97	3.5
Ultrasonic	3	3.92	29.7

— Reference measurement.

Concrete with Exposed Aggregate

The GMPG interior noise loop also included a segment of PCC with large exposed aggregate. This section had protruding pieces aggregate up to 40 mm in diameter. Although this type of surface does not exist on U.S. highway, it provided a good test of profiler performance of extremely coarse macrotexture caused by aggregate larger than that typical of a chip seal. Five profilers measured this section. Four of them applied anti-aliasing filters with a cutoff wavelength of twice their sample interval: an infrared profiler, two laser profilers, and an ultrasonic profiler. The infrared profiler had a sample interval of 25 mm, used anti-aliasing with a cutoff wavelength of 50 mm, and decimated the final profile to a reporting interval of 150 mm after a 300-mm moving average. The two laser profilers sampled approximately every 160 mm with anti-aliasing filters that remove wavelengths shorter than about 330 mm. The ultrasonic profiler, which could only sample once every 340 mm, could not apply anti-aliasing filters properly to the height sensor signal, but reported the average of two consecutive readings as a means of removing some of the aliasing error. The fifth profiler was the ProRut. It sampled every 10 mm, but the anti-aliasing filter on the height sensor signal cutoff at about 5 mm. Thus, the ProRut measurement contains significant chatter not present in the other measurements.

Figure 28 shows a short segment of the measurements filtered to show wavelengths shorter than 8 m. None of the four profilers with aggressive anti-aliasing showed any chatter caused by the coarse macrotexture. All of the chatter is eliminated by the anti-aliasing filters. The ProRut measurement includes significant chatter, but the IRI value agreed with the others. (All of the IRI values for a 150 m long segment agree within 9 percent.) This is because it passed through a 250-mm moving average as part of the IRI computation. Figure 28 shows the ProRut measurement after the moving average. It looks much more like the others. The 250-mm moving average prevented aliasing errors from affecting the IRI of the ProRut measurement, but this would not have worked on a profile that was sampled less frequently than once every 50 mm without anti-aliasing filtering.

Tined Concrete

Each of the five profilers listed in table 18 and figure 28 measured four sections near Ann Arbor that had tining. (These are sections 2, 3, 4 and 12, described in Appendix A.) Since all of the profilers made proper use of anti-aliasing filters, the coarse surface macrotexture caused by tining did not affect the roughness. In fact, the effect of tining was obscured by the difficulty caused by spikes at opened joints and cracks.

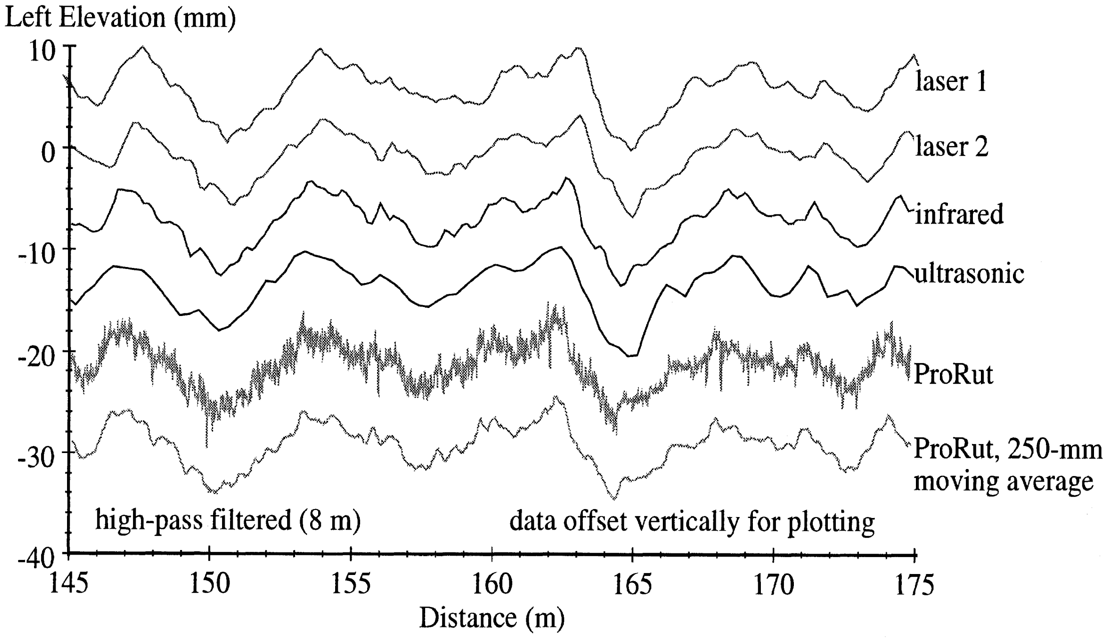

Figure 28. Measurements of concrete with exposed aggregate.

Pavement Distress

Pavement distress has a significant impact on the roughness of a road section. Several forms of pavement distress cause the roughness to vary across the lane. This was demonstrated in the "Transverse Variations" section of this chapter on pavements with rutting, faulting, spalling, transverse cracking, and longitudinal cracking.

Measurement of distress with a small characteristic length is affected by the sample interval and height sensor footprint of a profiler. For example, transverse cracks that are opened only a few millimeters may introduce much more roughness into a profile measured with a 1 mm height sensor footprint diameter than a 50 mm footprint diameter. Even if anti-aliasing filters are used by both profilers, the averaging done by the filter may not be the same as the averaging done within the sensor footprint. In addition, a narrow crack may be detected by a narrow footprint in one pass, but not in another if the longitudinal placement of the height sensor readings is shifted.

This section demonstrates the measurement of some common distress types by profilers with Selcom laser height sensors, K.J. Law infrared height sensors, and ultrasonic height sensors. Profilers with each of these types of height sensor measured a group of pavement sections in Michigan that cover a broad range of distress types. This section looks closely at the measurement of a transverse crack, some opened joints, a joint with spalling, a faulted joint, a bump caused by frost heave, and a section of alligator cracking.

The distinction between the profilers is mostly due to the size of the height sensor footprint. Particularly, measurements of the "narrow" distresses differ mostly because of the height sensor footprint. The Selcom laser sensors have a footprint that is 1 to 2 mm in diameter. The K.J. Law infrared sensors use five small spots spread out over an area that is 6 mm long (in the direction of travel) and 37 mm wide. Both of these sensor types take readings at a very short interval, then apply anti-aliasing filters to the height sensor signals. The ultrasonic sensor has a footprint that is 50 to 100 mm in diameter, but reads the highest feature within the footprint. The ultrasonic profiler averages two consecutive samples in the final profile as a means of reducing aliasing errors. The ProRut uses a Selcom laser height sensor with a footprint that is 2 mm long (in the direction of travel) and 5 mm wide. Measurements by the ProRut with a 25 mm sample interval but no anti-aliasing filters are provided to illustrate the presence of spikes in a profile without anti-aliasing.

Overall, the height sensor types differ mostly in the measurement of very narrow opened cracks and joints. In particular, some profilers register higher roughness on them even if they would be enveloped by vehicle tires (and do not increase vibration at the vehicle body). In some cases, the downward spikes that are registered on these features add little roughness from the point of view of a vehicle passenger, but would be very annoying if they were upward spikes of the same magnitude. In the case of cracks, this may be appropriate: At least they indicate pavement wear. However, the roughness should not be added at opened joints, because they are intentionally built in. Current standards for interpretation of longitudinal profile do not address the treatment of downward spikes sufficiently.

Transverse Cracks

Figure 29 shows a transverse crack in a jointed PCC pavement. The right side of the lane is pictured, but the crack spans the lane. It is narrowly opened with spalling in isolated locations, but there is no faulting across the crack. Not all profilers will measure this crack the same way, because it is opened by an amount that is larger than the footprint of some height sensors, and smaller than the footprint of others.

This crack is opened wider than the longitudinal dimension of the footprint of most Selcom laser height sensors. Thus, the crack will be detected as long as the sensor is operated at a very high sampling rate. In eleven measurements of this section by the ProRut, the crack caused a downward spike in the profile of the right side that ranged in magnitude from 2 to 13 mm. It was also operated without anti-aliasing filters at a sample interval of 25 mm. In all eleven measurements, the spike lasted only one sample. One of these measurements is shown in figure 30. The crack appears 19.9 m from the start of the section.

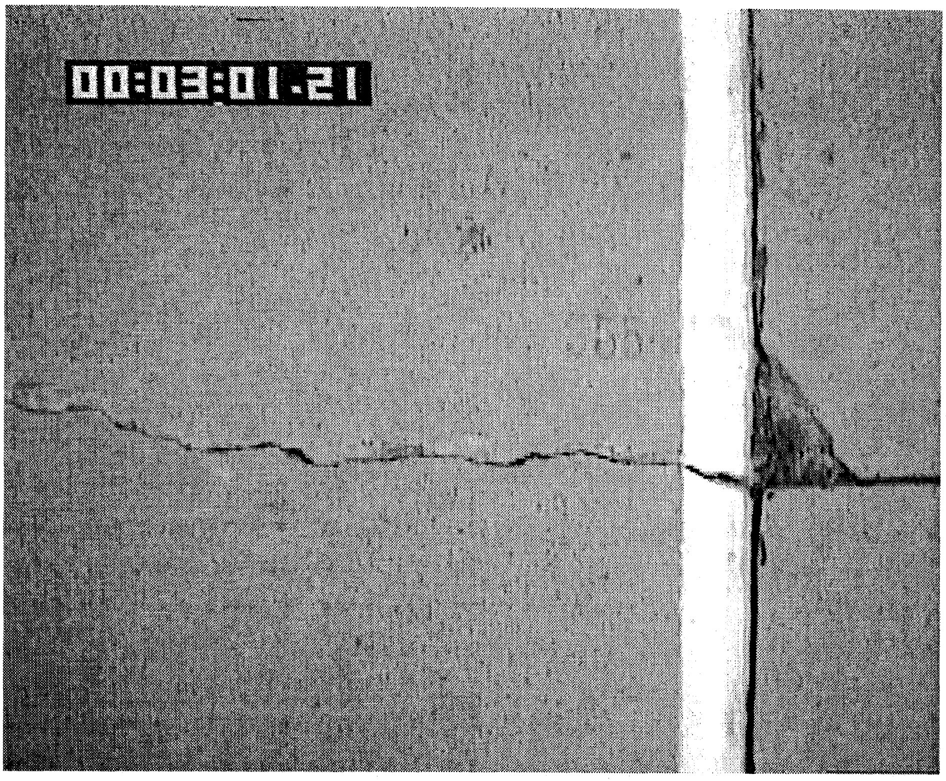

Figure 29. Transverse crack in PCC.

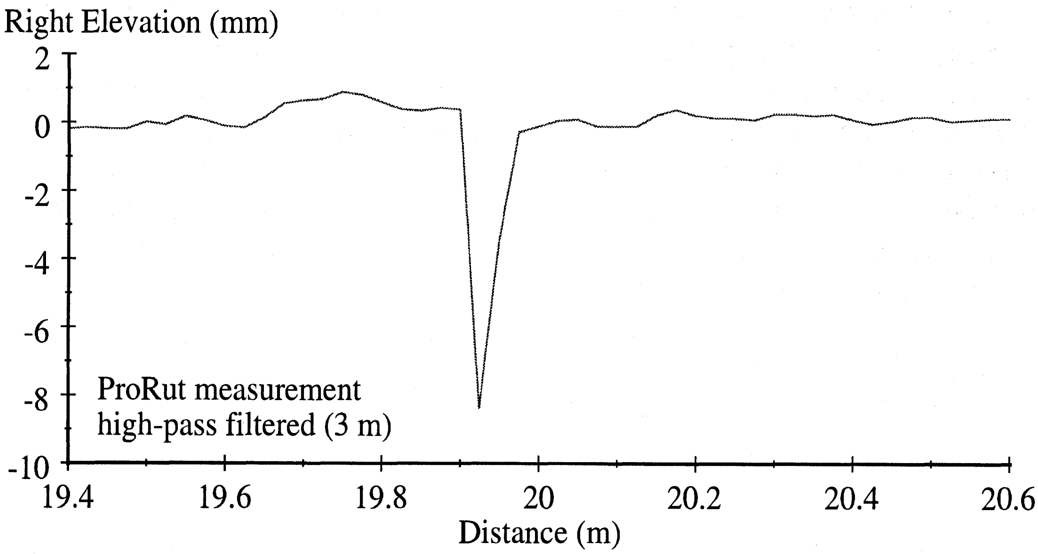

Figure 30. Measurement of a transverse crack in PCC by the ProRut.

In ideal operation, the height sensor of a profiler will have a sampling rate fast enough to detect the crack in every pass. Then the anti-aliasing filters should modify it before the profile is saved. For example, two profilers with laser height sensors measured this section using a recording interval of about 160 mm. They sampled the road at a much shorter interval (of about 2 mm), then applied anti-aliasing filters to the height sensor signals before recording the profile. They both detected the crack, but did not report them as a spike. Instead, they appear in the profile as a broader dip. This is pictured in figure 31. The two profilers are denoted as "laser 1" and "laser 2".

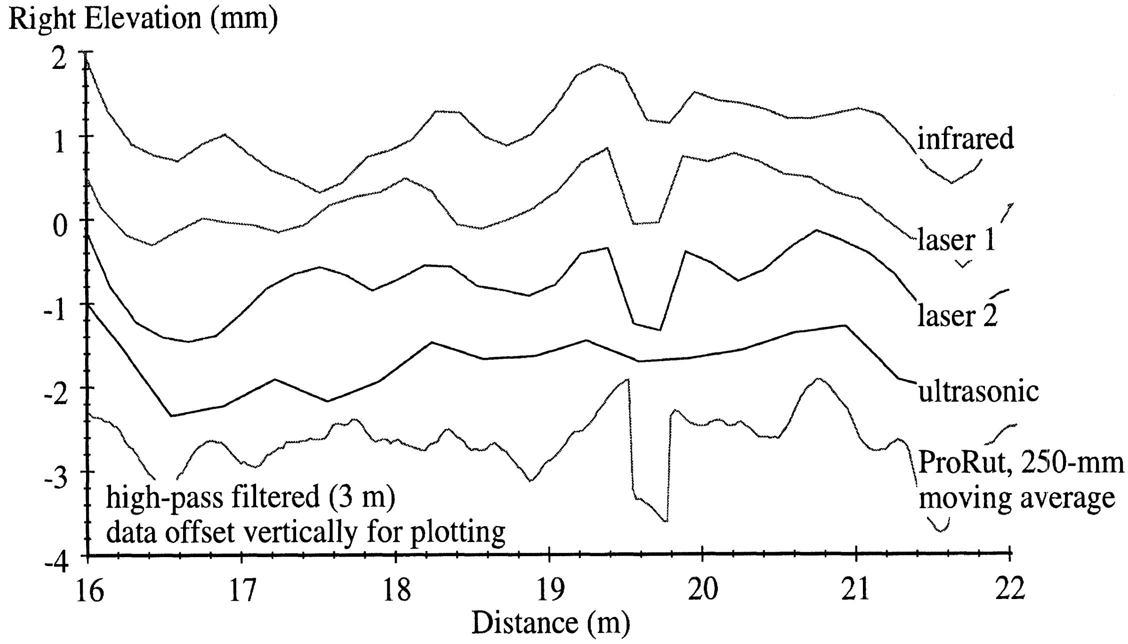

Figure 31. Measurement of a transverse crack by several profilers.

Figure 31 also shows a measurement of this section by a profiler with an infrared height sensor. This sensor uses a larger footprint than the laser sensors. This sensor also registers a dip in the location of the crack, but not as deep. That is because the larger footprint does not completely submerge into the crack, and the depth is averaged with some of the surrounding pavement. The measurement by the profiler with the ultrasonic height sensors barely shows any evidence of the crack at all, because its footprint is much larger than the opening of the crack.

Figure 31 demonstrates the difference in the way each type of height sensor measures a narrow crack. In the figure, the ProRut measurement is shown after the application of a 250-mm moving average. The moving average is the first step in the calculation of IRI and RN. After the moving average is applied, the profile is more like the others measured with laser height sensors. The figure suggests that each type of height sensor may produce a different roughness value on a section with transverse cracking.

Each profiler measured a 300 m long section (that includes the crack in figure 29) with moderate severity transverse cracking and mild spalling at least five times. Table 19 lists the average IRI and RN measured by each profiler in the right wheeltrack. The ultrasonic sensor, which ignores most of the cracks, measured the lowest roughness. (That is, the lowest IRI and highest RN values.) The infrared profiler and the two laser profilers measured roughness values that are about equal. Although the infrared height sensor does more averaging of narrow cracks in each height sensor reading, all three of the profilers apply anti-aliasing filters. Thus, they agree fairly closely in the wavelength range of interest for measurement of IRI and RN. (Keep in mind that some variation is expected because lateral positioning and timing of the measurements were not strictly controlled.) The ProRut produced the lowest RN. This is because it did not use anti-aliasing filters to minimize the influence of the cracks on measurement of short wavelengths (in the range from 0.3 to 2 m).

Table 19. IRI and RN on a PCC section with transverse cracks.

Profiler	Average Value, Right Wheeltrack	
	IRI (m/km)	Ride Number
ultrasonic	1.94	3.51
infrared	2.11	2.89
laser 1	2.17	2.75
laser 2	2.15	2.91
ProRut	2.09	2.64

Opened Joint

The same five profilers that covered the section discussed above also measured a PCC section with 15-mm wide gaps at the joints. The joints are sealed, but the seal is not flush with the surface. Instead, a dip about 10 mm deep exists at each joint. (The joints are not filled with debris, so the dip is the distance to the top of the sealant.) Figure 32 shows measurement of this section by five profilers. All of the profilers measured the downward curl of the slabs, so the plots show a concave downward shape every 8.2 m. The profilers with laser sensors and the profiler with infrared sensors probably detected the dip at some of the joints, but not at others. However, the anti-aliasing filters that were applied to the height sensor signals prevented the appearance of spikes in the profile. The ultrasonic profiler simply did not detect the dip at the opened joints because of its large footprint size.

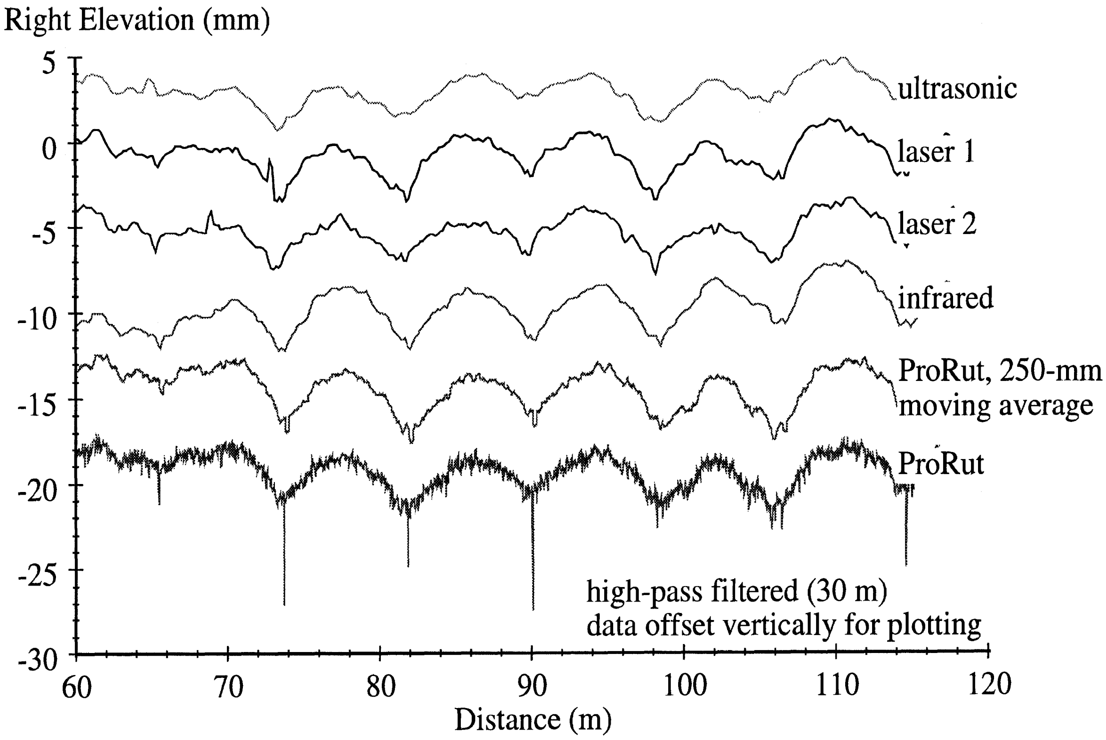

Figure 32. Measurement of opened joints by the several profilers.

The ProRut, which measured the section at a sample interval of 25 mm, registered a large spike at four of the seven joints shown in figure 32. The footprint is small enough to detect the dip at every joint, but the sample interval is larger than the gap. Thus, the ProRut does not always sense the dip. The figure also shows the ProRut measurement after a 250-mm moving average. This plot looks much more like the others, but shorter, wider dips still appear in the profile between some of the slabs. The averaged plot of the ProRut measurement shows that the moving average in the IRI and RN algorithm helps minimize aliasing errors and undue influence of narrow spikes on roughness. However, the anti-aliasing used by the other laser profilers and the infrared profiler is the recommended way to remove these errors. These three profilers produced an average RN of 4.12 to 4.14 on this section. When the ProRut was used without anti-aliasing, it produced an average value of 4.01. The difference is caused mostly by the residual effect of the downward spikes at the joints after the moving average. The ultrasonic profiler, which did not register any roughness at the joints, measured an average RN of 4.41.

Faulting

Height sensors with dissimilar footprint sizes are able to measure faulting equally. Figure 33 shows profiles from five devices measured on a severely faulted PCC section. The profilers are distinguished in the figure by their height sensor type. The figure includes three faults. Four of the profilers measured a similar shape at each fault.

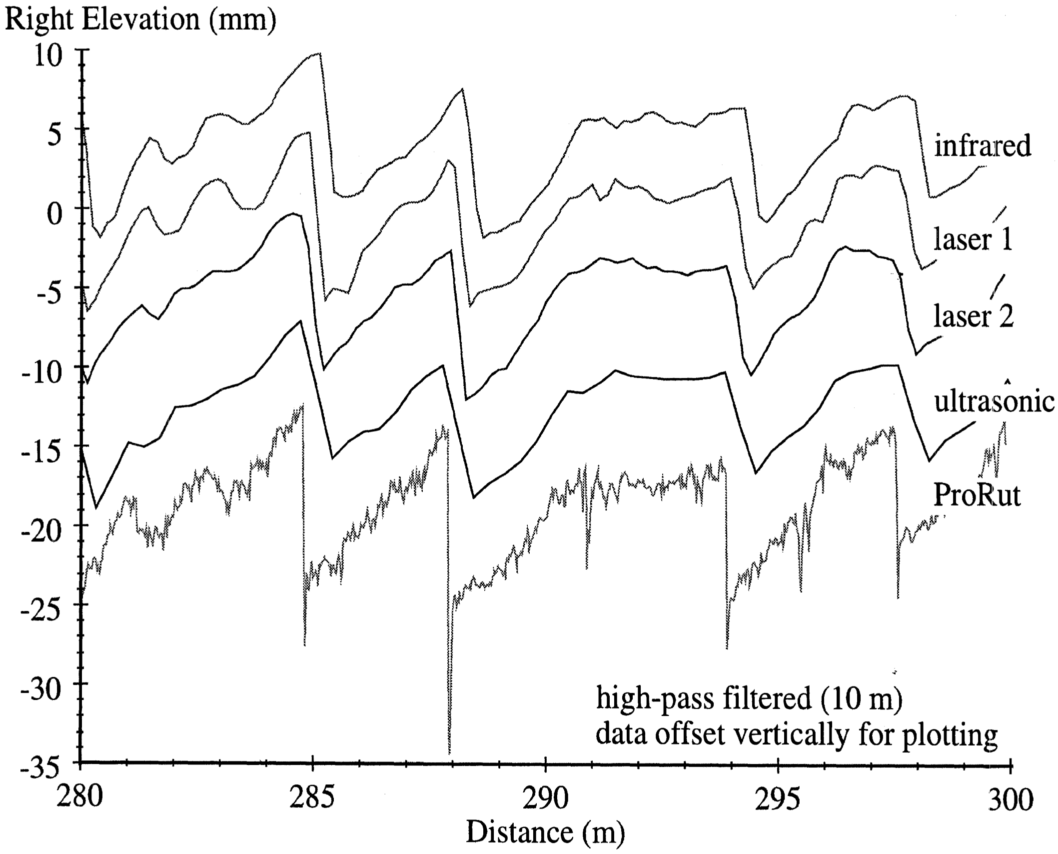

Figure 33. Measurement of faulting by the several profilers.

Since the change in elevation across a fault is not a "narrow" feature, the height sensor footprint size has little influence on its measurement. When the ProRut was operated without anti-aliasing, it measured spikes at the gaps in the faulted joints. The anti-aliasing filters in the other profilers with laser sensors and the profiler with infrared sensors prevented the appearance of spikes at the joints.

Spalling

Height sensor footprint does not affect profile of spalled cracks and joints as much as profile at opened cracks and joints. Figure 34 shows a transverse crack in PCC with spalling. The spalling ranges in its longitudinal dimension from 0 to 100 mm. At most locations along the crack, the spalling has a larger longitudinal dimension than the footprint of laser and infrared height sensors.

Figure 35 shows a measurement from five profilers, identified by height sensor type. The crack pictured in figure 34 is 117.3 m from the start of a section measured by five profilers for this study. The profiler with the ultrasonic sensors measured the smallest dip. This is because its footprint is as long or longer than the spalls. The laser and infrared profilers all measure a dip, but not of the same depth. None of the profilers measured the depth and longitudinal dimension of the spalling at this crack very consistently. This is because the longitudinal span of the spalls varies significantly with lateral position, and the profilers were operated without special effort to track in the same location. In the transverse variations experiment the RN of a section with spalling and severe faulting fluctuated erratically across the lane. (See the results for section 2 in Appendix D.) This was due in part to variations in the longitudinal dimension of the spalls.

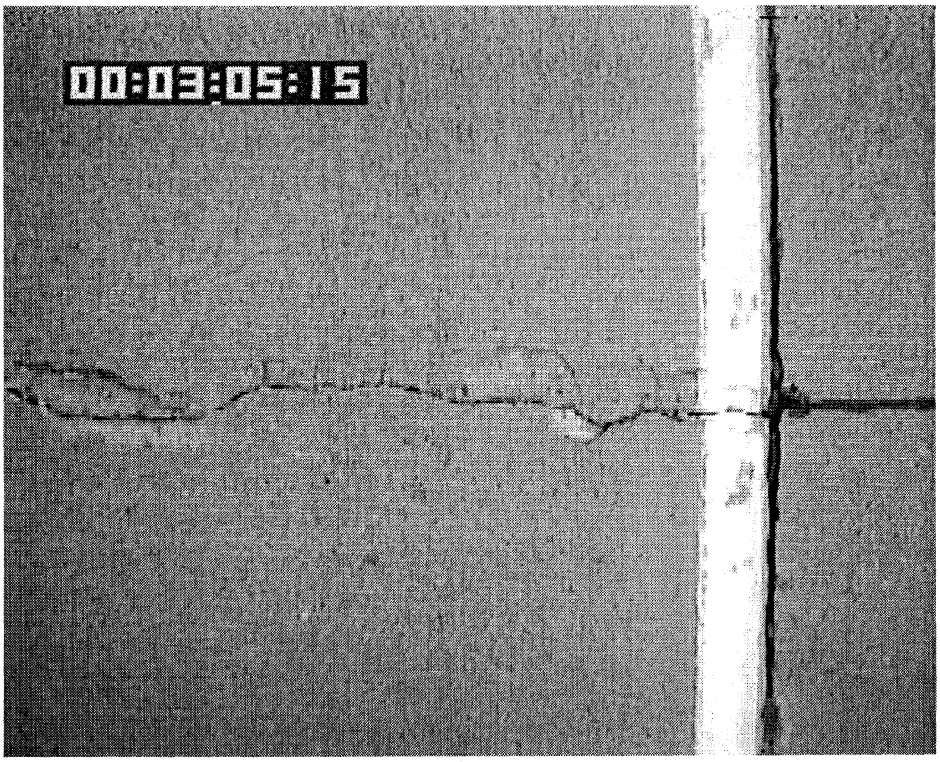

Figure 34. Transverse crack with spalling.

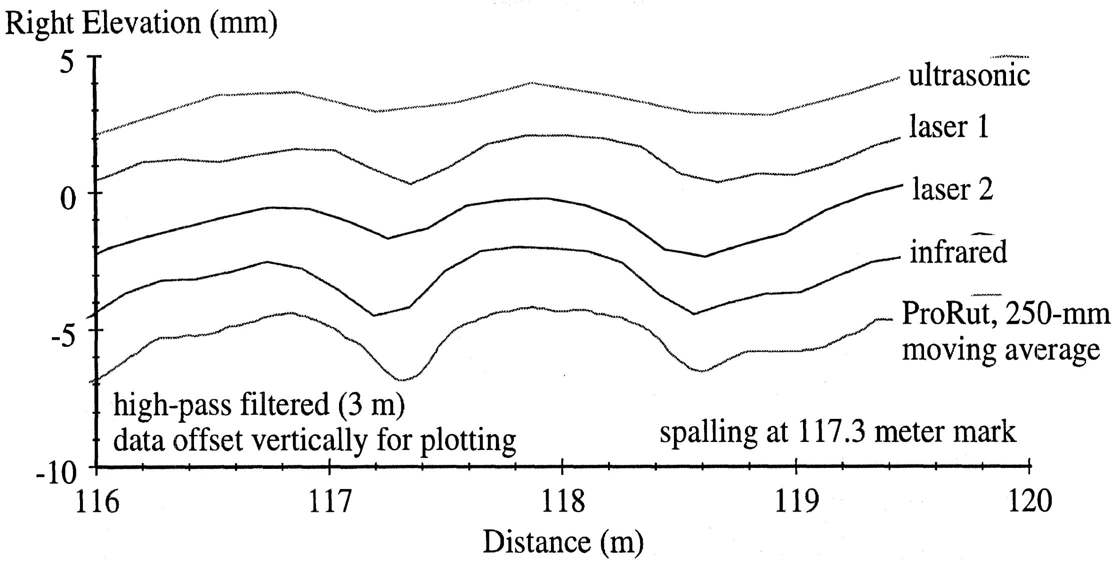

Figure 35. Measurement of spalling by the several profilers.

Alligator Cracking

Pavements with alligator cracking are difficult to measure consistently because they are covered with narrow cracks, and their shape varies transversely. Profilers with different height sensor types measure the narrow cracks differently, and the same profiler may measure a very different profile each time because of its lateral position. Figure 36 shows some alligator cracking in a section measured by five profilers for this study. This section is not very rough, but the alligator cracking is expected to cause profilers with different sensor footprints to disagree on the roughness, and exhibit less repeatability than they would on other sections. The profilers measured twelve sections near Ann Arbor, Michigan, five times each. These sections were selected to cover a range of surface types and distresses. (See Appendix A.) The profilers that participated in the study measured the section pictured in figure 36 with less repeatability than any of the others. Table 20 lists the IRI from the right side of the lane measured by each profiler. None of the profilers measured the IRI of the right wheeltrack of this section with a coefficient of variation of less than 4.5 percent. Two of them measured the IRI with a coefficient of variation of over 9 percent. Some of the variation level is caused by the narrow cracking, but most of it is due to lateral variations in profile positioning.

Table 20. Measurements of IRI of a section with alligator cracking.

Profiler	IRI (m/km)						Coeff. of
	1	2	3	4	5	Ave.	Variation (%)
infrared	2.10	2.21	2.37	2.59	2.57	2.37	9.2
laser 1	2.76	2.67	2.84	2.44	2.80	2.70	5.9
laser 2	2.04	2.19	2.07	2.28	2.14	2.14	4.5
ultrasonic	2.11	2.16	2.45	2.27	2.26	2.25	5.8
ProRut	1.91	2.10	2.06	1.86	2.04	2.39	9.9

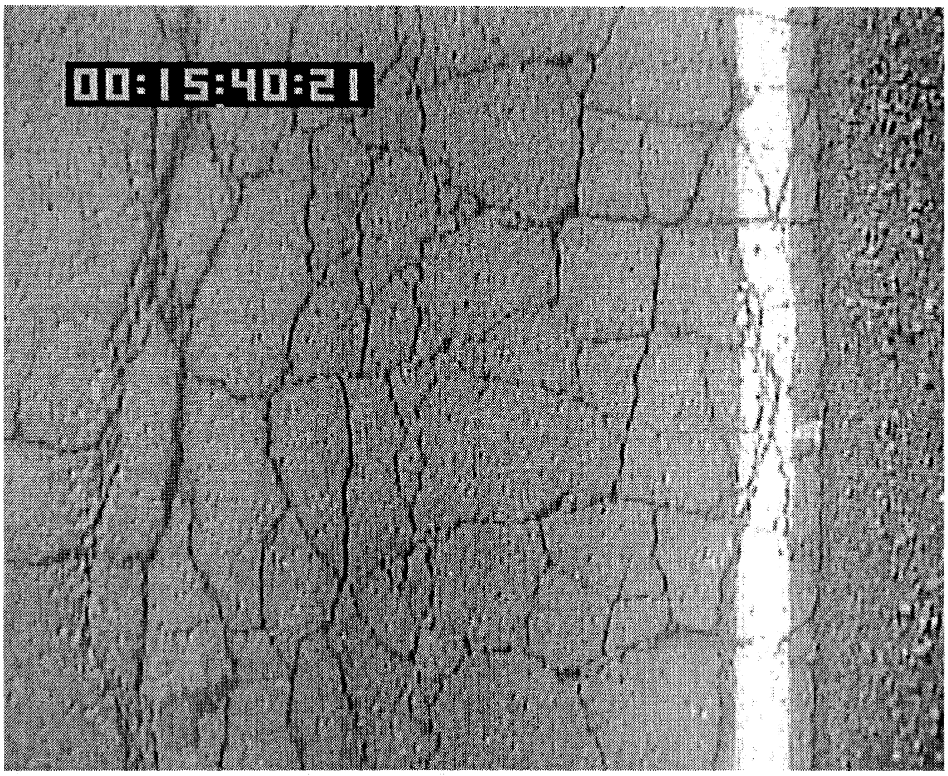

Figure 36. Alligator cracking.

Frost Heave Bump

Bumps caused by frost heave usually extend over a greater longitudinal distance than the footprint of common height sensors. Thus, frost heave and other bumps of similar height and length do not cause significant variations between profilers with different height sensors. Figures 37 and 38 show a bump caused by frost heave and measurements of the bump by several profilers, respectively. The measurements are distinguished in the figure by height sensor type. The profilers all measured a bump of roughly the same shape. Although this type of bump is measured equally by most profilers, its severity varies with lateral position. Thus, the bump may not be measured equally by different drivers, even in the same profiler.

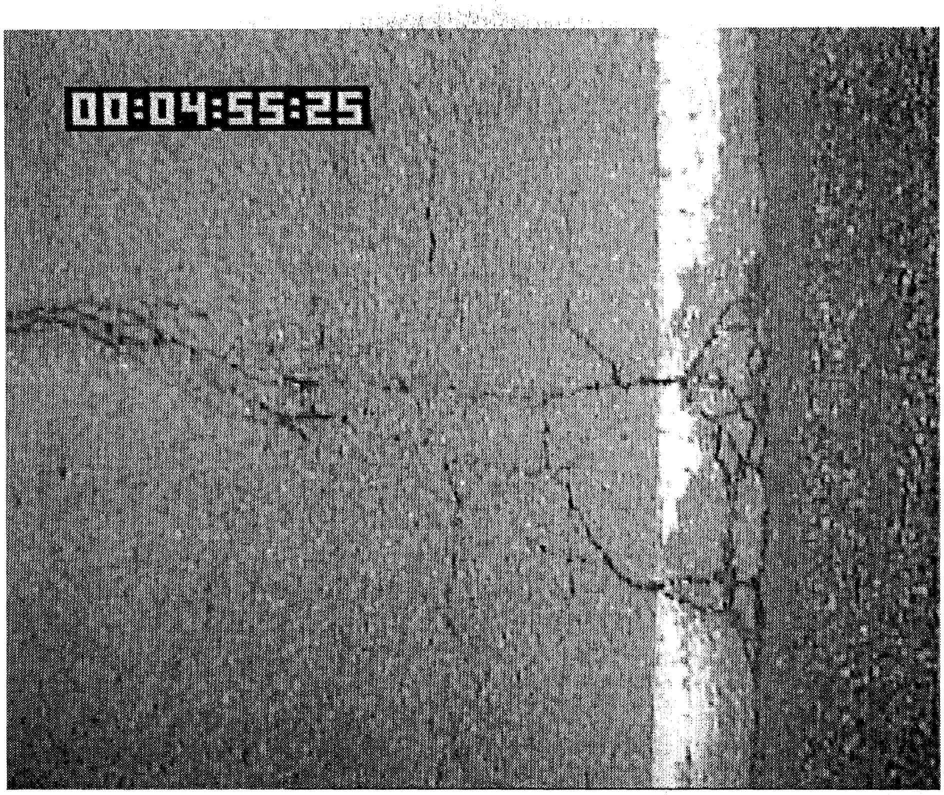

Figure 37. A bump caused by frost heave.

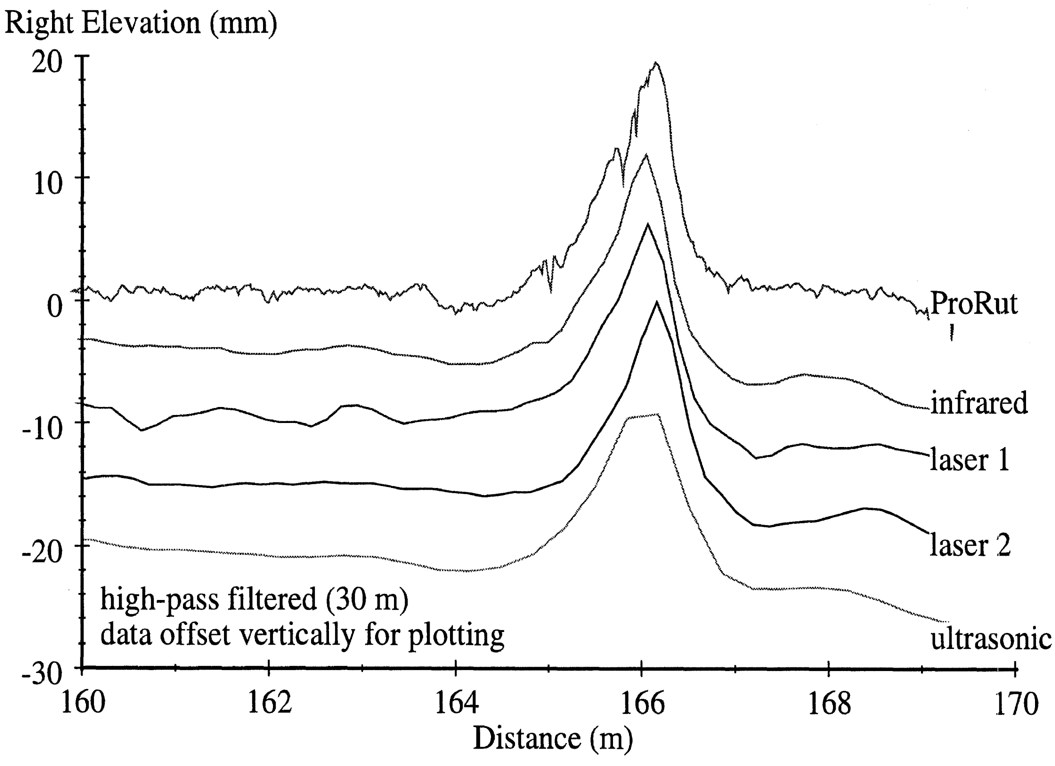

Figure 38. Measurement of a bump by the several profilers.

Curves

Lateral acceleration that results from operating on curves can contaminate accelerometer measurements in a profiler if the accelerometer does not stay vertical. When a vehicle negotiates a curve, it undergoes small levels of lateral acceleration. For example, the *AASHTO Policy on Geometric Design of Highways and Streets* allows highways with superelevation of 4 percent to have curvature that corresponds to a lateral acceleration of 0.15 g if the vehicle is moving at the design speed. (*41*) Highways with superelevation of 10 percent may have curvature that requires lateral acceleration of 0.23 g at the design speed.

The potential error in profile measurement on curves occurs if the vehicle is accelerating laterally and tilts sideways simultaneously. This is pictured below.

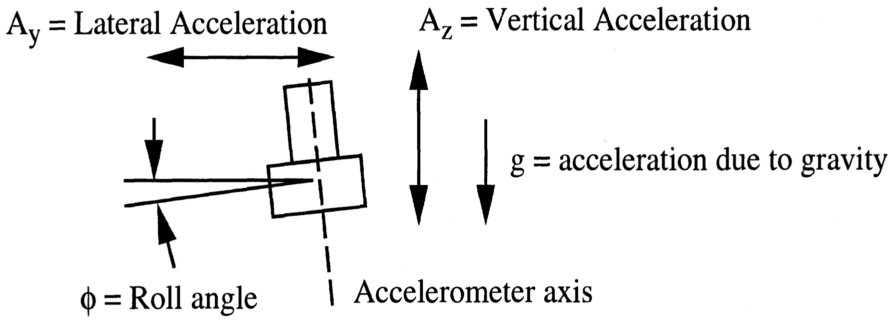

Figure 39. Accelerometer tilting during lateral acceleration.

The acceleration measured by the transducer is

$$A_{meas} = (A_z - g)\cos(\phi) + g + A_y \sin(\phi) \quad (13)$$

In perfect operation, the roll angle ϕ is zero, and the total measurement is equal to A_z. The 1 g offset measured by the accelerometer at rest because of the Earth's gravity is subtracted out by an offset in the electronics, and the output is the acceleration relative to the Earth. If the vehicle is in a turn, and it is tilted to a roll angle of 1 degree, $\cos(\phi)$ is 0.99985. If the legitimate vertical acceleration is 0.25 g, the sum of the first two terms is 0.2498 g. This is only an error of 0.0002 g. The third term represents contamination of the vertical acceleration measurement by a component of the lateral acceleration. For a 0.1 g turn, and a resulting roll angle of 1 degree, this term adds an error of (0.0175)•(0.1) = 0.00175 g. This amount of acceleration error is small, but could be noticeable in the profile of a very smooth section.

A 1 degree roll angle is a reasonable estimate of the tilt of a van during lateral acceleration of 0.1 g. The roll angle is roughly proportional to lateral acceleration. Thus, an aggressive level of lateral acceleration of 0.25 g may cause a 2.5 degree roll angle. In this case, the third term in eq. 13 adds an error of over 0.01 g. This is more than 2 percent of the total range measured on many smooth roads. (See table 3.) An error in acceleration measurement this large will affect the final profile. However, it may take the form of a long drift that makes the plots look bad, but does not change the IRI or RN much. This is because curves are much longer than the longest wavelength of interest in a profile. High-pass filtering also removes the bias in acceleration induced by operating on a curve over an extremely long distance. The greatest potential for error exists in a transition from straight-line operation to a curve. Fortunately, the geometrical layout of highways usually limits the severity of transitions in horizontal curvature.

A small series of tests was conducted on four profilers to quantify the level of error that is possible when a profiler undergoes lateral acceleration. The tests were performed at the GMPG on a smooth asphalt section of smooth macrotexture and fine microtexture. Each of the profilers measured the section three to five times under normal operating conditions (constant speed, no lateral acceleration). Then they measured the section with severe motions to the left and right within the lane. The result was a "zig-zag" test that included peak lateral accelerations of about 0.2 g with rapid transitions from one direction to another. The profilers were able to dodge back and forth about once per second, which is fast enough to contaminate the wavelength range of interest in a profile. The maneuver was structured to represent a series of roughly executed transitions from one severe horizontal curve to another. Of course, these runs contained a series of worst-case events. A profile collected on an actual curve would contain at most two of these events and they would probably not be as severe.

The test affected all four profilers about equally. The lateral acceleration had a strong impact on measurement of very long wavelengths. This is the result of the mechanism described above in which simultaneous tilting of the accelerometer and lateral acceleration of the vehicle contaminates the accelerometer signal. The error in measurement of vertical acceleration, once double integrated to an inertial reference, gives rise to a long-wavelength drift in the profile. Figure 40 shows three measurements made by one of the profilers with no lateral acceleration and another made with peak lateral acceleration of 0.15 g. Although the profiler filters out wavelengths longer than 40 m, the drift of the zig-zag run compared to the others is still obvious.

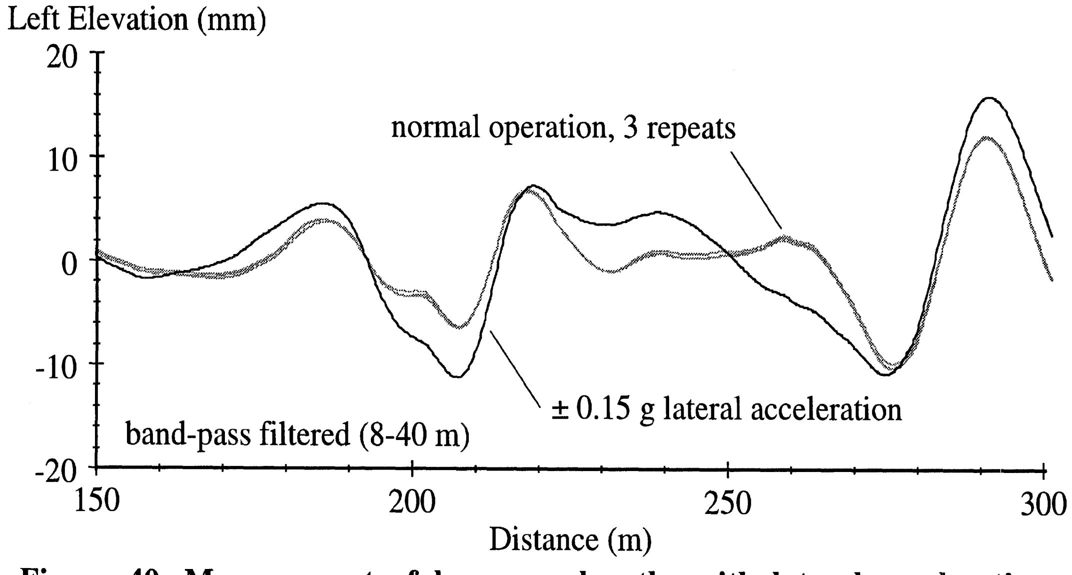

Figure 40. Measurement of long wavelengths with lateral acceleration.

The range of wavelengths from 1.6 to 8 m, which strongly influences both the IRI and RN, was not affected as much. Even with an eager effort by the drivers to induce rapid changes in lateral acceleration, the frequency of the steering input was too low to affect shorter wavelengths. Figure 41 shows the profiles of figure 40, filtered to display wavelengths from 1.6 to 8 m. Qualitatively, the profile measured with lateral acceleration does not agree with the other three profiles as well as they agree with each other. However, the lateral acceleration did not seem to add roughness to the measurements. All of the profilers tested exhibited similar behavior.

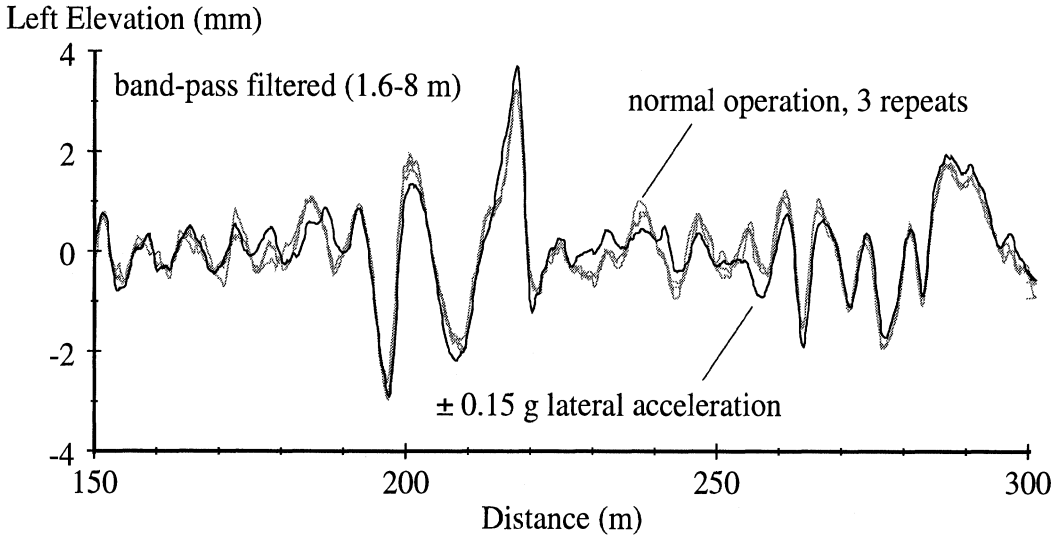

Figure 41. Measurement of medium wavelengths with lateral acceleration.

Table 21 lists the IRI and RN measured in three to five runs with normal operation and one run with lateral acceleration. The table provides the range of values for the normal runs instead of the average to illustrate that the lateral acceleration tests fell within or near the range of the other repeats in most cases. No systematic error exists in the RN, because it depends primarily on short wavelengths, which were not affected by the lateral acceleration. In some of the cases, the IRI was slightly higher with the lateral acceleration than in normal operation. Qualitatively, the driver of profiler number 2 appeared to use the most violent lateral accelerations, and the resulting IRI of the left and right were both a few percent high.

Table 21. Effect of zig-zag on IRI and RN.

	Range in Normal Operation			With Lateral Acceleration		
	IRI (m/km)		Ride	IRI (m/km)		Ride
Profiler	Left	Right	Number	Left	Right	Number
1	0.96-1.07	1.47-1.51	3.90-4.23	1.05	1.63	3.97
2	1.02-1.05	1.54-1.61	4.13-4.16	1.06	1.63	4.14
3	1.01-1.06	1.48-1.49	3.97-4.12	0.96	1.54	4.12
4	1.03-1.12	1.68-1.72	4.27-4.32	1.15	1.65	4.26

The lateral acceleration level used in the tests was relatively high and changed direction much more often than is necessary in highway driving. For network-level profiling of interstate and primary roads, lateral acceleration on curves is not a concern. On secondary roads with significant curvature, errors caused by lateral acceleration can be minimized by reducing speed. (Lateral acceleration on a curve is proportional to the square of speed.) In project-level profiling lateral acceleration under 0.2 g can also be ignored, but extreme lateral movements of a profiler to avoid obstacles may slightly elevate roughness. If such an event occurs, repeat the measurement.

Hills and Grades

Hills and grades affect profiler accelerometer readings by changing their orientation. If an accelerometer is perfectly vertical, it will measure 1 g (about 9.81 m/s^2). When the 1 g offset (for gravity) is subtracted, a reading of zero is the result. If the accelerometer is held steady but tilted by an angle θ, the error is:

$$\text{Error} = (1 - \cos\theta)\bullet 1\text{ g} \qquad (14)$$

If the grade is consistent, the accelerometer's steady position is tilted. Thus, an offset equal to the error in eq. 14 is added to the accelerometer signal. A 12 percent grade causes an error of 0.007 g. Since the accelerometer signal in a typical profile measurement covers a range of at least 0.4 g, this error is small. On a steady grade, it is also constant, so it is usually eliminated by the bias removal in the profile computation algorithm.

Transition from one level of grade to another has a greater potential to contaminate the accelerometer signal, because the error level is not steady and it will not be eliminated in bias removal. The level of error in IRI caused by transition between steady grades was investigated using some limit conditions for highway design in the *AASHTO Policy for Geometric Design of Highways and Streets* (*41*). For example, the *Policy* recommends a maximum grade of 3 percent on freeway built with a design speed of 112 kph. The *Policy* also recommends that the minimum distance to transition a total of 3 percent in grade on a road designed for speeds of 112 kph is 137 m. (This recommendation is set for sight distance. It is expressed as a "K" value, which is the distance that must be covered per 1 percent change in grade.) In an extreme transition from a 3 percent downgrade to a 3 percent upgrade, the offset error in the accelerometer would change from 0.0004 g to zero and back to 0.0004 g again. In this case, the accelerometer bias removal would not eliminate the error. This error adds a very long wavelength curvature to the profile that increases the IRI slightly.

Table 22 lists the error in IRI caused by severe transitions in grade within a 500 m long section. The table includes a range of AASHTO road classes, and lists the maximum allowable grade at a given design speed and the minimum distance recommended for a transition from a downgrade to an upgrade of the level listed. The IRI error listed in the table is the amount added to the IRI of a section 500 m long when the error in accelerometer readings is superimposed on the profile. This is not the roughness added to the section by the transition, it is only the error caused by tilting of the accelerometer. The error is extremely small, except on the 12 percent grade.

Table 22. IRI error on a transition from a downgrade to an upgrade.

Road Class	Terrain	Maximum Grade (%)	Design Speed (kph)	Distance for Transition (m)	IRI Error (m/km)
Freeway	Level	3	112	274.4	0.00015
Arterial	Rolling	5	96	365.9	0.00053
Arterial	Rolling	8	64	292.7	0.0031
Collector	Mountainous	12	48	292.7	0.012

MEASUREMENT ENVIRONMENT

This section discusses the effect of the conditions in which profilers must operate on their performance. These factors, termed the *measurement environment* include all of the aspects of the surroundings that might confound the profile measurement process, but do not relate to the actual shape of the pavement surface. Some examples are weather, surface color changes, and surface contaminants.

If a profile measurement is affected by one of the factors in this section, the resulting change is considered an error. This is a contrast to the previous section on surface shape, in which genuine changes in pavement surface shape may cause inconsistencies in profile measurement that are not errors. For example, the effect of temperature is discussed in both sections. If the air and surface temperature are severely different than the temperature during calibration of ultrasonic height sensors, an error might result. This is considered a direct effect of the measurement environment on profiler performance. On the other hand, if changes in surface temperature throughout a daily cycle cause changes in surface shape it is a legitimate pavement effect. Thus, it is covered under surface shape.

The factors covered in this section generally affect height sensor accuracy in two ways: (1) causing a bias in all measurements by a height sensor (akin to an error in calibration), and (2) causing some extremely erroneous height sensor measurements that appear as spikes in the measured profile. Sensor bias errors are avoided by operating a profiler only under conditions in which it was meant to operate. For example, most height sensor manufacturers will provide a range of air and surface temperatures for which the sensor is valid. Height sensor spikes can often be avoided the same way. Each type of height sensor is prone to bad readings caused by some aspect of the measurement environment. For example, ultrasonic height sensors are prone to spikes in high wind, optical sensors are prone to spikes caused by changes in light and surface reflectivity, and all types of height sensor are prone to spikes caused by surface contaminants. Table 23 lists the factors covered in this section and the types of height sensors that are affected by them.

Profiler operators should know the sensitivities of their equipment to the environment and avoid the adverse conditions. The equipment itself should aid the operator in this regard. If two consecutive height sensor readings are so different that the most likely explanation is a measurement error, the profiler should alert the operator. The operator or the analyst is then free to make a judgment as to the validity of that reading and might elect to remove it. Spikes of extreme magnitude can be eliminated automatically by using a sample and hold algorithm in the profiler that uses the last valid reading until the next valid reading is encountered. In project-level applications or measurement of new construction, where subtle changes in roughness could have serious implications, any spike warning issued by the profiler should render the entire profile measurement invalid and the measurement should be repeated.

Table 23. Effect of measurement environment on height sensors.

Factor	Ultrasonic	Laser	Infrared	Optical
Wind	◍	○	○	○
Temperature	●	◍	◍	◍
Humidity	○	○	○	○
Surface Moisture	●	●	●	●
Surface Contaminants	●	●	●	●
Pavement Markings	○	○	○	●
Pavement Color	○	○	○	—
Ambient Light	○	○	○	●

● - Strong Effect ◍ - Effect Under Unusual Circumstances
○ - Small or No Effect — - Insufficient Information

Wind

Severe winds interact with the host vehicle of a profiler to generate sound that causes invalid ultrasonic height sensor measurements. Huft (*17*) reported that winds exceeding 65 kph oriented at certain angles to the profiler are likely to interfere with ultrasonic height sensor measurements. Severe winds also cause measurement errors if a significant amount of sand, snow, or other surface contaminants pass under the profiler.

Temperature

Extreme air and surface temperatures have the potential to cause errors in height sensor measurements. In laser height sensors, a large temperature gradient along the path of the beam can induce curvature in its path. Still (*42*) studied this phenomenon and found that its effect was negligible for reasonable temperature gradients. Laser sensors are also slightly sensitive to ambient air temperature. Selcom reports in their specifications that their laser sensors operate properly in temperatures ranging from 0 to 40 degrees C (32 to 104 degrees F), and exhibit an error of 0.005 percent of the total range per degree C (a negligible error in profiling applications) (*43*). Most accelerometers operate properly over a much broader range of temperatures.

Ultrasonic height sensors are extremely temperature sensitive. Lawther (*44*) reported that ultrasonic height sensor measurements that pass through a 5.5 degree C temperature gradient will exhibit a bias equal to 4 percent of the distance covered by the gradient. A more comprehensive study was performed in 1992 that focused on performance of an entire profiling system with ultrasonic sensors (*26*). This study found a significant upward trend in IRI with air and surface temperature dramatic enough to render the device useless for roughness measurement in network or project-level applications. There was consistently an upward trend in IRI with air temperature (between 25 and 35 degrees C) with magnitudes of up to 0.03 m/km per degree C. If the results of this study are representative of the temperature sensitivity of profilers with ultrasonic height sensors, it would render them in need of constant calibration (more often than daily) to be sufficient for roughness measurement.

All of the brochures that the authors encountered for optical and infrared height sensors boast of insensitivity to temperature, humidity, and wind. Although these are advertisements, there is no experimental evidence that they are incorrect. An infrared height sensor considered for use in the original ProRut was also found to be insensitive to changes in air temperature (*45*).

Humidity

Humidity (within reasonable limits) is not likely to have a significant effect on laser, infrared, or optical height sensor performance as long as the sensors are clean and free of condensed water. For example, Selcom reports in their specifications that their laser sensors operate properly as long as the humidity is below 90 percent and noncondensing. K.J. Law, Inc. also mentions in their advertising that their infrared sensors are not sensitive to humidity. Since humidity has only a very weak influence on the speed of sound in air, it is unlikely that a significant influence on ultrasonic height sensors exists (*46*).

Moisture in humid conditions may also contaminate the transmission path of the beam in any noncontact height sensor if water condenses on the surface of emitters (such as a laser light source), pick-ups, lenses, or mirrors. This was cited as the cause of reliability problems in a study of profiler performance in Virginia, where conditions are frequently humid (*27*). In such conditions, it is important that the operator check emitters, lenses, and mirrors and clear condensed water from them frequently. (Do not supply power to the sensors when clearing the sensor and related components of moisture and dirt, since direct laser light will damage a person's vision.)

Surface Moisture

Pavement profiling is usually not performed on wet pavements. Certainly, no profiling system is going to function properly if the sensors pass over snow or ice-covered pavement. However, it is probably not unusual to encounter rain in the middle of a day of profiling. The question is: When is the road so wet that profiling should cease?

In a study of profiling with laser sensors Still (*42*) reported that sensor dropout could occur if the surface texture is submerged in water. As suggested by that study, profiling should stop after the surface texture is submerged and may continue "as soon as the surplus water on the road surface has drained away." Profiling should also stop if traffic is causing mist or spray.

Surface Contaminants

Surface contaminants are an unavoidable aspect of the pavement environment. Litter such as garbage, fallen cargo, vehicle parts, leaves, or branches find their way onto the road and interfere with profile measurements. In measurement of new construction, where no traffic is present, contaminants should be removed if they are in the path of the height sensors. In monitoring of in-service roads, it is not practical to remove them, and they cannot always be avoided.

Unfortunately, some surface contaminants can add substantially to the apparent roughness of a section. For example, a piece of tire tread 2.5 cm in height and 2.5 cm wide laying across a wheeltrack adds about 0.09 m/km to the IRI of a section 160 m long. A profiler with a long sample interval may not detect the tread, but if it does, aliasing errors will cause the profiler to misinterpret the tread as a larger disturbance, and the error could be as much as three times as large. The effect of the tread on RN depends on the roughness of the section. On a 160 m long section, it would degrade an RN of 4.00 to 3.87, or an RN of 3.00 to 2.95.

Operators that suspect a contaminant was included in a measurement should always indicate their presence with an event marker. If contaminants such as dirt, snow, or blowing leaves are so abundant on a section that they continuously interfere with the profile measurement, the data should simply not be recorded. Remember, in pavement management, last-year's roughness is a better estimate of the current road condition than a measurement with major errors in it.

Pavement Markings

The change in surface reflectivity caused by white pavement markings on an otherwise dark pavement surface can, in some cases, be interpreted as change in elevation contributing to roughness. Profilers with optical sensors have been sensitive to this phenomenon in the past. Profilers with infrared, laser, and ultrasonic sensors need no special error detection procedures to measure pavement with white markings.

The majority of pavement markings appear along lane edges where they are very unlikely to be encountered during profile measurement. However, some markings that go across the lane, such as those used to indicate stop lines and railroad crossings, appear on secondary roads. These potentially confound profile measurement in two ways: (1) they add roughness to the pavement by virtue of their thickness, and (2) they represent a rapid change in pavement surface color or reflectivity which may cause incorrect height sensor readings.

Markings for a railroad crossing appeared about 92 m after a section measured by five profilers for this study. This was an asphalt concrete section with an IRI of about 1.25 m/km. All of the profiler operators who visited the section included the markings in all five of their measurements. Figure 42 shows one measurement from each of the profilers with a drawing of the markings in the scale of the distance axis of the plot. The profiles were filtered to include only very short wavelength features. All of the measurements by the laser and infrared profilers have distinct peaks ranging in height from 0.75 to 2 mm in the location of the initial transverse stripe, the Rs, and the final transverse stripe. The measurements by the ultrasonic profiler were less consistent. The larger sample interval of the ultrasonic height sensor meant that not every piece of the markings would be detected in every pass. The figure shows a "median" example. The material used to mark this railroad crossing is about 1.25 mm thick. The peaks shown in these measurements at the location of the markings are genuine, and no artificial spikes were induced by the color change.

The change in the IRI of the section caused by these markings was small. Analysis of a roughness profile filtered to show deviations in IRI over very short distances revealed that markings like those drawn in figure 42 will add an average of about 0.03 m/km to a 150 m long section that includes them. In network-level profiling this can be ignored. Measurement of initial roughness for construction acceptance is not likely to be affected either since early measurements of roughness most likely take place before pavement markings are installed. However, if markings are placed before the roughness of a section is measured early in its life, the analyst should be aware that they may appear in the profile.

A second experiment was performed to study the effect of pavement markings at the GMPG on a smooth asphalt section of smooth macrotexture. Four strips of temporary pavement marking tape 1.3 mm thick and 10.2 cm wide were laid out across the lane to form a pavement marking a total of 40.6 cm wide. (In Michigan 61 cm is the width of a typical stop line.) The same set of profilers that measured the road with the railroad crossing made these measurements, and none of them showed spikes induced by the color change. That is, they all measured a bump about 1.3 mm high.

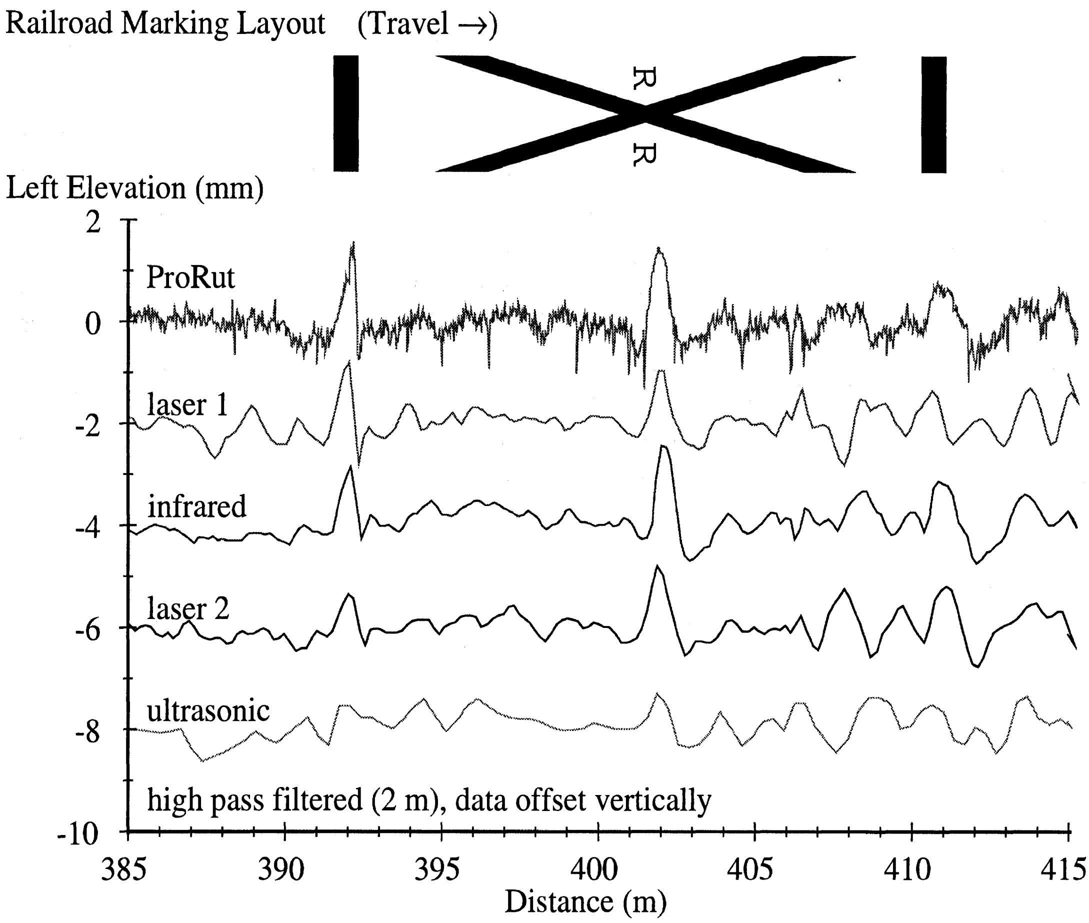

Figure 42. Measurements of pavement markings at a railroad crossing.

As in the experiment at the railroad crossing, the white stripe at the proving grounds did not significantly increase the IRI of the section. The values of RN were also affected very little, as long as the section under study was at least 150 m long. The only circumstances in which pavement markings 1.3 mm thick or less will affect roughness measurement is if the roughness index is sensitive to short wavelengths (like RN) and the sections under study are very short. For example, table 24 shows the RN values for a section 20 m long that included the white stripe and the average value for 3 to 7 measurements of the same section that did not. The RN measured by the laser and infrared profilers dropped 0.2 units or more because of the marking. If short segments are used to identify trouble spots in the pavement, care should be taken at locations with pavement markings.

Table 24. RN of 20 m long sections with markings.

	Without Marking		With Marking
Device	# of runs	RN	RN
ProRut	5	4.19	4.00
laser	5	4.37	4.15
laser	3	4.41	4.10
infrared	7	4.37	4.11
ultrasonic	3	4.48	2.61

One type of device that was not included in our experiments was the optical K.J. Law profilers used in the first eight years of the LTPP study. These profilers introduce a spike in the profile when the sensors obtain a reading on a white pavement marking. In some cases, the mark causes a large upward spike in the profile large enough to introduce a significant bias in the RN computed for a 152.4 m long section. For example, one of the measurements of GPS section 1012 in Maine taken in 1994 had an upward spike in the second and third to last sample that was about 7 mm above the datum created by the surrounding points. This was caused by a marking used to trigger the end of data collection for the section. The RN values for the four measurements without the spike ranged from 3.94 to 3.96. The RN of the measurement with the spike was 3.63. This high sensitivity to spikes in the profile stems from the fact that the RN algorithm is both sensitive to short wavelengths and accumulates roughness using the RMS. Since the IRI is not as sensitive to short wavelengths and accumulates roughness linearly, the IRI of the measurement with the spike was within the range of the other four.

Note that the spike under discussion appeared in two samples of the profile after a moving average of 13 profile points was computed. Thus, the individual height sensor reading that caused the 7 mm spike in the final profile must have indicated an extreme upward change in height before the profile was filtered. It would therefore be reasonable to weed out such changes in height sensor reading by using the previous height sensor reading in place of a reading that is obviously in error.

Pavement Color

Based on the results presented for pavement markings above, it is unlikely that ultrasonic, laser, and infrared sensors are susceptible to errors at a transition in pavement surface color. Each of these devices measured a section with a smooth transition from new asphalt (laid four months before) that was still dark and old PCC. The portion of these measurements that includes the transition is shown in figure 43. Note that the transition occurs at the 150 m mark and is not the bump at the 153 m mark. This is a discontinuity at a slab joint. This figure demonstrates that none of the sensor types tested are sensitive to pavement color change.

Optical height sensors were not investigated in this experiment. However, Claros (*28*) reported that the prototype optical sensor used by K.J. Law in the 1980s showed a change in height reading of about 3.3 mm when exposed to a change from a white surface to a black surface. The test was of a prototype, and it is possible that subsequent versions of the sensor are less sensitive to surface color change. In the case where the sensors encounter a surface that is so dark their light is not reflected, an error will occur. (This is called *lost lock*, and a warning is issued if this occurs.) If the error goes undetected, the roughness of the section will be in error.

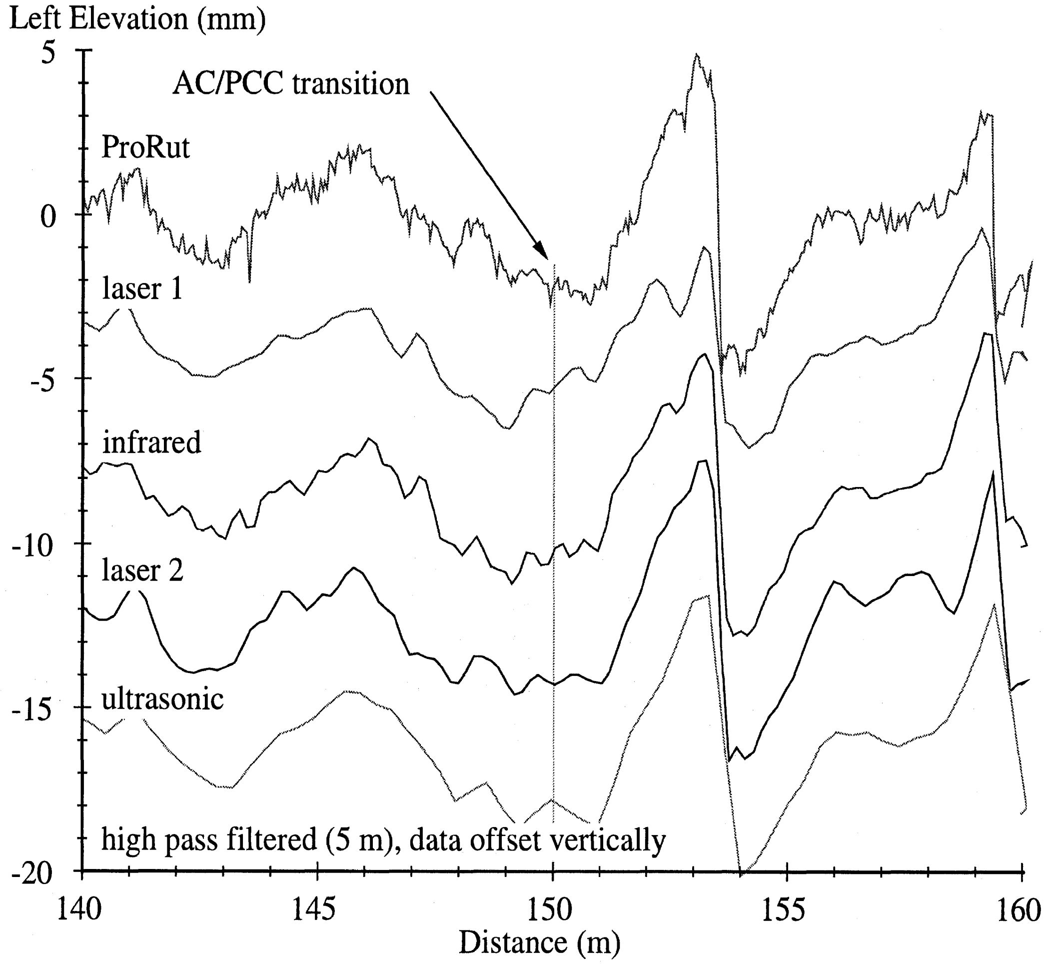

Figure 43. Measurement of an AC to PCC transition.

Ambient Light

The laser, ultrasonic, and infrared height sensors in common use are not affected by changes in ambient light. Optical sensors, however, do not operate properly if the beam is contaminated by sunlight. Exposure of the optical height sensor beam to even a small amount of sunlight can induce major errors in the collected profile. To eliminate this error source, K.J. Law profilers with optical sensors are fitted with a shroud that keeps the environment around the optical sensors in the shade at all times. If the shroud is in good repair, no errors should result.

PROFILER OPERATION

This section covers the quantifiable aspects of the manner in which a profiler is driven and operated. These factors are all under the control of the people using the profiler. Some of them interact with the pavement surface shape to affect the measured profile. These are considered sources of variation instead of error. For example, the path a profiler takes over a section has a strong influence on the roughness it measures because of transverse variations in profile. Two measurements that follow a different path can produce equally valid but different results. The starting point of a section also determines what features are included in a measurement. Some steps can be taken to eliminate the variations caused by these factors, and alerting drivers and operators to the fact that this is important is likely to help.

Other aspects of profiler operation that are under the driver's control can lead to errors. Driving at speeds outside of the recommended range for a profiler or aggressive braking can cause invalid measurements. Speed and acceleration are particularly relevant to profiler drivers who must cover significant distance every day or profile in confined areas. Drivers do not always have complete control over their speed, but should know when a measurement is no longer valid because of low speed or excessive deceleration.

In the best case, the findings presented in this section could be used to enhance profiling technology and aid operators and drivers in the profiling process. Whenever possible, profilers should automatically recognize conditions that render a profile invalid. Visual displays can also help drivers better control lateral and longitudinal positioning of measurements, as long as they do not divert their attention from safety. All of the factors discussed in this section should be understood by drivers and operators and their supervisors to ensure reliable profiling practices.

Operating Speed

The response of a vehicle to road roughness and a user's perception of the road is directly linked to travel speed. Response-type road roughness measuring systems, which produce a roughness value that is proportional to some vehicle response (usually suspension stroke), provide an output that is speed dependent. In contrast, the output of a profiler is a static property of the road. It does not depend on operating speed. Inertial profilers have to operate at some speed to function, but the profile it measures should depend only on the properties of the road at the time of the measurement and the particular path the profiler takes. If the output of a profiler depends heavily upon its operating speed, it is not valid.

Most profilers are valid over a broad range of operating speed and can tolerate modest and even aggressive speed changes during a profile measurement. Speed changes that arise in common profiling situations are discussed in the next section. The range of valid operating speed depends on the design of the profiler and the range of wavelengths that must be measured correctly. The manufacturer usually specifies the range of speed in which valid profile data can be collected.

Maximum Speed

The maximum speed at which a profiler may operate is limited by its data collection rate. Fortunately, computer speed has improved so much in recent years that data collection rate is a lesser concern than in the past. Most high-speed laser, optical, and infrared profilers currently on the market collect profile at sample intervals of 25 mm or less up to speeds well above 100 kph, even if they have real-time displays of sensor signals, computed profile, and computed roughness. Thus, they can usually be operated on an interstate without slowing traffic.

The operating speed of profilers with ultrasonic sensors is limited by echoing of the acoustic ping. The ping must travel from the sensor to the road surface and back for each reading. This takes about 0.002 s. Unfortunately, multiple echoes of the ping last much longer, such that the sensor can only make a measurement every 0.01 s (*17*). At a travel speed of 109 kph, this is only one sample every 300 mm. At this sampling rate, the lack of anti-aliasing filters renders measurement of wavelengths below about 2 m completely invalid, particularly on roads with coarse macrotexture and rough megatexture. To sample the road every 75 mm, the profiler must slow to 27.2 kph.

Operating speed is also limited on very rough roads if the profiler bounces or pitches excessively. A combination of the roughness of the road and high speed can cause a profiler to respond so dramatically that the height sensor reading goes out of range. This is not likely to occur on interstate or primary roads. However, profilers with bumper-mounted sensors may be prone to this difficulty on rough secondary roads.

For example, a pair of profilers of the same make with bumper-mounted laser sensors measured a rough section with a very large dip near the end. The speed limit of this road is 64 kph, but the prevailing traffic speed over the dip was usually slower. One of these profilers measured this section at 64 kph five times and never reported an invalid height sensor measurement. Figure 44 shows a portion of these five measurements (labeled "profiler A") that includes the dip. The other profiler measured the section at 56 kph, 48 kph, 40 kph, and 32 kph. The measurement at 32 kph is the only one that did not cause the profiler to issue a warning to the user and mark 1 to 3 m of the profile as invalid. Two of these measurements (labeled "profiler B") are shown in figure 44. The measurement made at 56 kph includes the portion of the profile that was computed from invalid height sensor measurements. Since the profiler marked this portion as invalid it can be removed. Of course, this section is so rough that the extra bump caused by the invalid sensor readings did not change the IRI or RN by a significant percentage.

The invalid height sensor readings on the dip described above occurred when the distance between the height sensor and the ground exceeded the total sensor range. Of five profilers that measured this section, only one experienced this difficulty. Since another profiler of the same make did not, the likely explanation is that one of the vehicle's static position was not in the center of the height sensor range. This occurs when the sensors are not mounted properly or the suspension springs have experienced excessive wear. A way to help avoid this kind of sensor error on rough roads is to check the sensor mounting position and perform suspension and shock absorber maintenance on a regular basis.

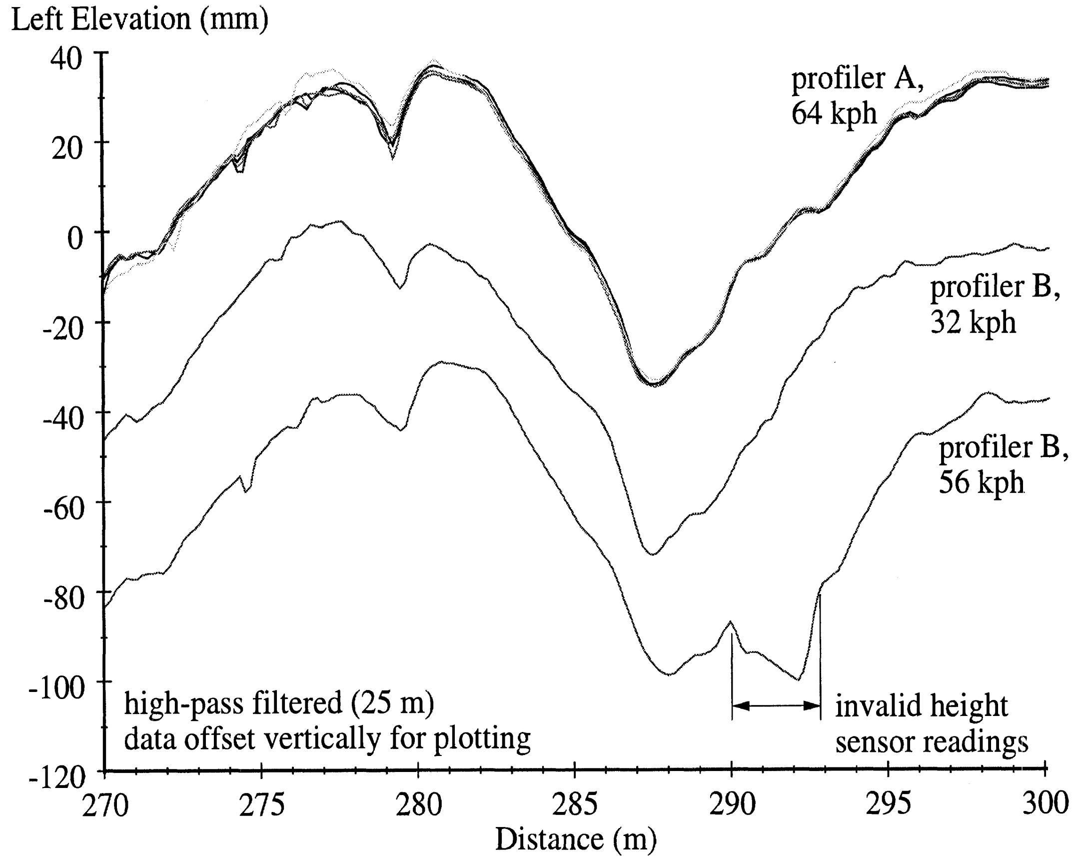

Figure 44. Measurement of a dip that caused invalid height sensor readings.

Minimum Speed

The minimum speed at which a profiler should operate is dictated by the longest wavelength it needs to measure. An inertial profiler uses an accelerometer to sense vertical movement of the vehicle and establish an inertial reference. The amplitude of the accelerometer signal decreases rapidly as wavelength increases. At some cutoff wavelength, the amplitude of the accelerometer signal is so low that it is masked by sensor noise. (This is why common profilers all have a long-wavelength limit and cannot measure topography accurately.) The cutoff wavelength gets shorter at lower speeds, and at some low speed a portion of the wavelength range of interest is affected. Most profiler manufacturers are well aware of this phenomenon and provide a low speed limit to the customer. A common low speed limit of a profiler is 25 kph, but some models can measure valid profile at operating speeds as low as 15 kph.

Effect of Operating Speed on Repeatability

The 1993 RPUG experiment included a study of the effect of operating speed on measured profile (*11*). Thirty-four profilers measured up to eight pavement sections five times at a speed near 80 kph and five times at a speed near 64 kph. (Some of the profilers measured at 72 kph and 56 kph instead). An analysis was performed to determine if modest changes in speed had a systematic effect on measured roughness values. Statistical results covering this aspect of the experiment are listed in Appendix C. Overall, very few of the profilers exhibited any bias in IRI between the two measurement speeds. The statistics hinted that a moderate effect of speed occurred in profilers with ultrasonic height sensors on one section of coarse macrotexture. This pavement section was so problematic to ultrasonic profilers that higher speed increased the likelihood of major sensor errors.

RN values computed from the RPUG experiment were not sensitive to operating speed over the range covered on most of the profilers. A few isolated cases of a major bias with speed appeared in profilers that measured RN with large errors at either speed.

Speed Changes

Changes in speed affect profile measurement in two ways. First, in the course of accelerating or decelerating, the speed might violate the maximum or minimum speed limit for proper operation of the profiler. This is a practical consideration when profiling in heavy traffic. Profilers must often operate in situations that include bringing the vehicle to a dead stop:

- when a stop signal is encountered in urban areas;
- in network monitoring applications, when the driver must stop occasionally at the roadside as part of the measurement routine, then resume measurement without doubling back; or
- in monitoring of new construction, when limited distance is available ahead of a road section.

Study of these conditions is a matter of learning how much lead-in and lead-out distance must be ignored because of excessive measurement error. Certainly, any length of road that is measured outside the speed limits of a profiler should be automatically ignored.

Second, the longitudinal acceleration (or deceleration) can contaminate the inertial reference if the accelerometer does not stay vertical. This occurs during braking or heavy acceleration, the pitch angle of a vehicle can be much more than one degree. A potential problem exists when the accelerometer is tilted and the vehicle is undergoing longitudinal acceleration, as shown in figure 45.

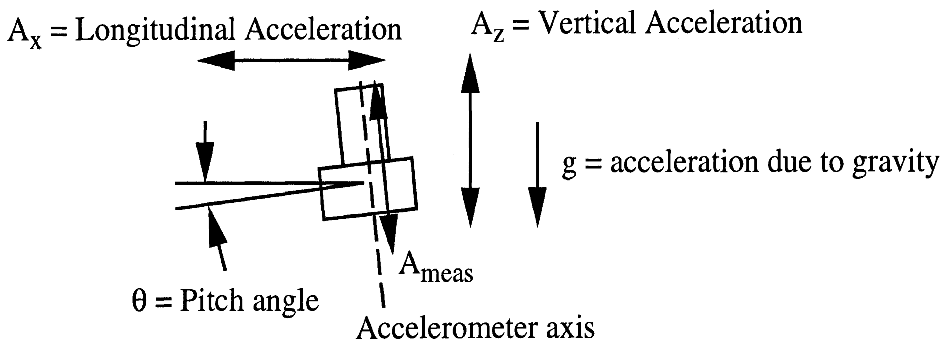

Figure 45. Accelerometer tilting during braking.

The acceleration measured by the transducer is

$$A_{meas} = (A_z + g)\cos(\theta) - g + A_x \sin(\theta) \qquad (15)$$

In perfect operation, the pitch angle θ is zero, and the total measurement is equal to A_Z. The 1 g offset measured by the accelerometer at rest because of the Earth's gravity is subtracted out by an offset in the electronics, and the output is the acceleration relative to the Earth. For a 1 degree pitch angle, cos(θ) is 0.99985. Even if the acceleration is 0.25 g, the sum of the first two terms is 0.2498 g. This is only an error of 0.0002 g. The third term represents contamination of the vertical acceleration measurement by a component of the longitudinal acceleration. For braking of 0.1 g and a resulting pitch angle of 1 degree, this term adds an error of (0.0175)(0.1) = 0.00175 g. This amount of acceleration error is small, but could be noticeable in the profile of a very smooth section.

A 1 degree pitch angle is a reasonable estimate of the pitch angle that might result during moderate braking of 0.1 g, and might even be a conservative estimate for a typical van. Both the longitudinal acceleration and the pitch angle are roughly proportional to braking effort. Thus, the error is roughly proportional to the braking effort squared. For example, with a 2 degree pitch and 0.2 g deceleration, the vertical acceleration error is 0.007 g. An error in acceleration measurement this large will affect the final profile. However, it may take the form of a long drift that makes the plots look bad, but does not change the IRI or RN much. The contribution of this phenomenon coupled with potential operation below the low-speed limit of a profiler was investigated experimentally.

A series of tests were conducted on five profilers to study the effect of variations in speed throughout a profile run. They were intended to represent common traffic situations that might arise in network-level profiling or measurement of roughness for acceptance of new construction. The tests were performed at the GMPG. The section was a smooth asphalt of smooth macrotexture and fine microtexture.

Eight different situations were tested with deliberate speed changes. Three to five constant speed runs were also made to serve as a reference and provide an idea of the repeatability expected in each profiler in more ideal operation. Table 25 lists the test conditions. All of the measurements from a given profiler were made within two hours. All of the profiles are synchronized longitudinally, so no positioning errors were expected. The lane was also rather narrow (about 2.5 m wide) and a different color than other lanes, so only moderate lateral tracking errors were expected. Cases S01-S07 were tested with five profilers: (1) an infrared profiler manufactured by K.J. Law and owned by the Ohio DOT (infrared), (2) a laser profiler manufactured by International Cybernetics Corp. (ICC) and owned by the Ohio DOT (laser 1), (3) a laser profiler manufactured by ICC and owned by the Pennsylvania DOT (laser 2), (4) an ultrasonic profiler manufactured by ICC and owned by the Pennsylvania DOT (ultrasonic), and the ProRut. Case S08 was only tested with laser 2.

The tests listed in table 25 were carried out by experienced drivers. However, the speed variations were not strictly controlled so the acceleration levels are estimates, rather than precise measurements. For example, figure 46 shows the speed profile of the ProRut in the moderate braking case (S02). The speed profile achieved in the run is not exactly that listed in table 25, but the basic spirit of the description was followed, and the average deceleration during the slow down was about 0.1 g.

Table 25. Speed change tests conducted at the GMPG.

Case	Simulated Situation	Test Condition
N01-N05	Typical	Maintained constant speed, 80 kph.
S01	Coast down (approaching slower traffic)	Began the run at 80 kph, let off the gas pedal and coasted down over the entire section (average deceleration of about 0.025 g, traveling about 60 kph at the end).
S02	Moderate braking (to avoid traffic)	Drove 80 kph until the 135 m mark, slowed to 48 kph with moderate braking (about 0.1 g), and continued at 48 kph until the end.
S03	Heavy braking (cutoff in traffic)	Drove 80 kph until the 135 m mark, slowed to 48 kph with heavy braking (at least 0.2 to 0.3 g), and continued at 48 kph until the end.
S04	Gentle speed-up (after clearing traffic)	Drove 48 kph until the 135 m mark, accelerated gently (about 0.05 g) until the end (usually almost reached 80 kph).
S05	Heavy acceleration	Drove 48 kph until the 135 m mark, accelerated heavily (about 0.15 g) to 80 kph, and continued at 80 kph until the end.
S06	Operating from a dead stop (profiling a new section with no lead-in)	From a dead stop at the beginning of the section accelerated heavily (floored it) to 80 kph. Reached 80 kph at the 160 m mark then continued at constant speed (averaged 0.15 g during acceleration).
S07	Operating from a rolling start (starting from the shoulder)	Rolled over the section start at 20 kph then accelerated heavily to 80 kph in the first 160 m and continued at constant speed. (Averaged about 0.125 g during acceleration.)
S08	Profiling through a stop (at a stop sign)	Drove 80 kph at the start of the section. Treated the 450 m mark as a stop sign.

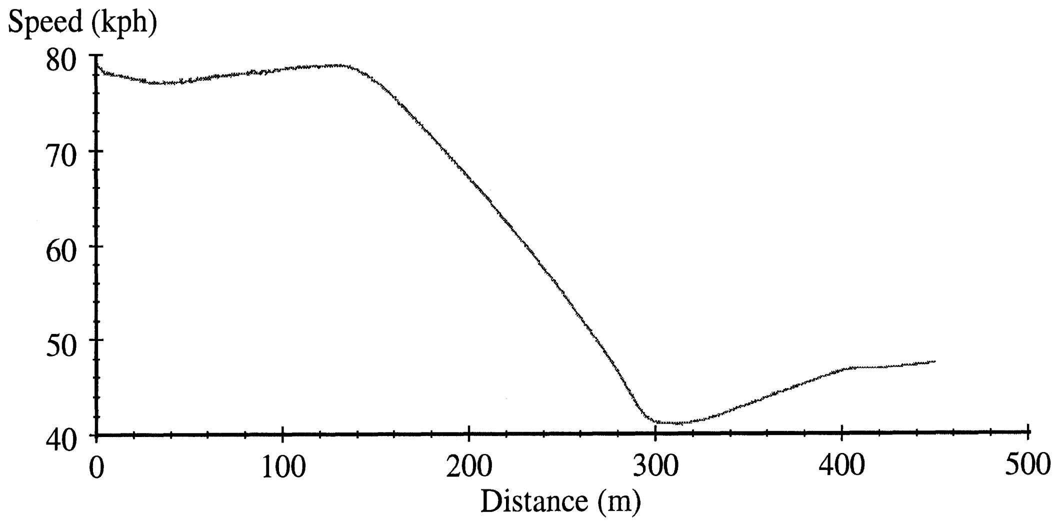

Figure 46. Speed profile of the ProRut during the moderate braking test.

The speed changes listed in table 25 had a strong impact on measurement of very long wavelengths in all of the profilers. This is the result of the mechanism described above in which simultaneous tilting of the accelerometer and longitudinal acceleration (or deceleration) of the vehicle contaminates the measurement. The error in measurement of vertical acceleration, once double integrated to an inertial reference, gives rise to a long-wavelength drift in the profile. Figure 47 shows a measurement of one of the profilers in the moderate braking case with five constant-speed repeats in the background. Although the profiler filters out wavelengths longer than 91 m, the drift of the braking run compared to the others is still obvious. All of the profilers tested exhibited this behavior to some extent.

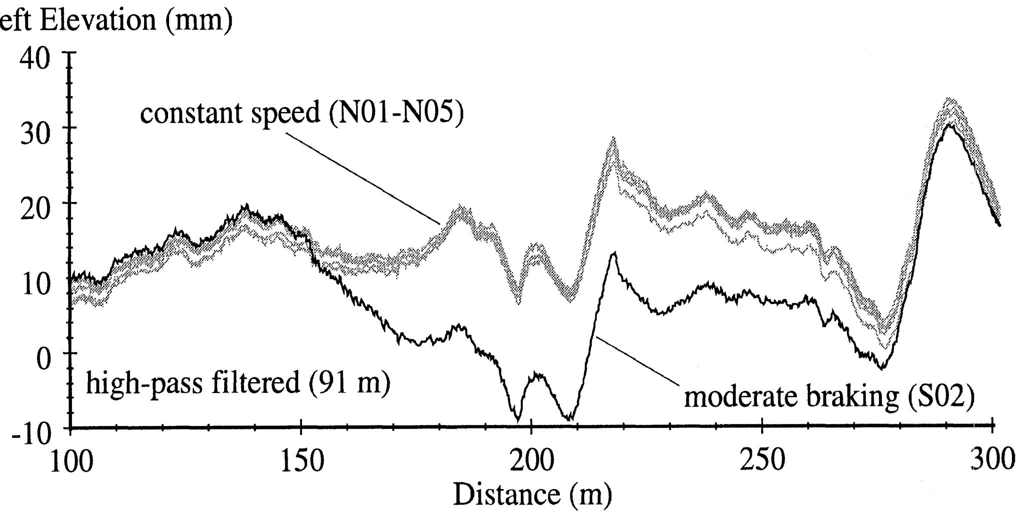

Figure 47. Measurement of very long wavelengths in moderate braking.

In most of the cases listed in table 25, the "long" wavelength range of 8 to 40 m was affected. In severe cases, identified below, wavelengths shorter than 8 m were also affected. Agreement with the reference runs (N01-N05) was studied qualitatively using plots of profile from cases S01-S08 and quantitatively using the IRI, RN, and an "IRI correlation" coefficient. The IRI correlation coefficient is a -1 to 1 rating of the agreement of the profiles after the IRI filter has been applied. It effectively tells you if the IRI values should agree, and weeds out cases where agreement between IRI values is due to compensating error. This rating method is described in a recent FHWA report (*10*).

Although the section used in these experiments was 450 m long, the primary effect of each case usually occurs within a shorter range. Thus, plots and statistics are given over smaller subsections.

Reference Measurements

Table 26 provides the IRI and RN of the measurements over a subsection ranging from 150 to 300 m. The table also lists the IRI correlation coefficient between the first reference measurement and the others for each profiler. These demonstrate the repeatability expected in normal (constant speed) operation. Each profiler exhibited a different level of repeatability among the reference runs, and they did not all agree on the value of IRI and RN of the section. It is a confounding circumstance that we could not avoid all sources of variation besides speed changes during the experiment. However, the effect of a speed change can be judged by agreement of each run to the reference runs.

If a speed change results in a profile more different from the reference runs than they are from each other, the difference is deemed a speed change effect. Subsequent profile plots in this section will show the reference measurements in the background. Correlation of a run to the first reference repeat that is as high as that of the other reference measurements indicates that the speed change does not effect IRI measurement, even if the plots are different. The subsection covered in table 26 is where the primary effect of cases S01-S05 is expected, so statistics are given for these runs.

Coast Down (Case S01)

The average deceleration during the coast-down test was about 0.025 g. All five profilers measured as reliably during the coast-down tests as they did during the reference repeats. Table 26 shows that the coast down measurements of each profiler produced IRI and RN values that fell within the range of the reference runs. These measurements also correlated with the reference about as well as they did with each other.

Braking (Cases S02 and S03)

Moderate braking (of about 0.1 g) and heavy braking (of 0.2 g or more) consistently affected the long wavelength range. Figure 48 compares the long wavelength content of a heavy braking run with the reference repeats. The drift that occurs directly after the brakes are applied was present in the heavy braking runs of all five profilers. Heavy braking also affected shorter wavelengths (relevant to measurement of IRI and even RN), but to a much smaller extent.

Correlation to the reference runs in the braking tests was often slightly lower than that of the constant speed runs, and some of the IRI and RN values were off, but rarely by more than 10 percent. This is probably because the primary effect of the braking was on wavelengths longer than those of interest in the measurement of IRI and RN. Nevertheless, the plots suggest that deceleration of more than 0.1 g should be avoided whenever possible. These tests did not include a drop in speed below 40 kph so they are tests of the effect of deceleration, but they are not tests of low-speed performance.

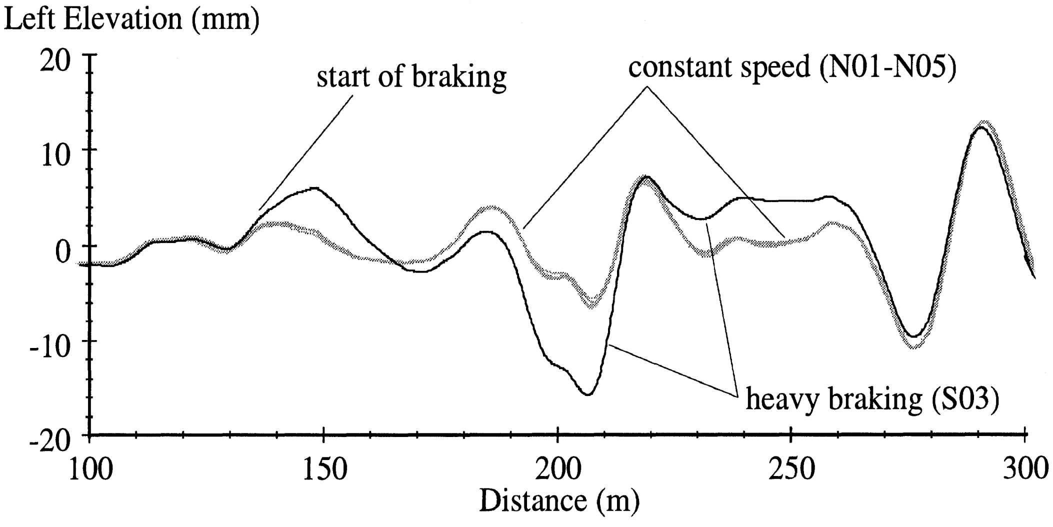

Figure 48. Effect of heavy braking on measurement of long wavelengths.

Table 26. IRI, RN, and correlation to a constant-speed run.

Case	IRI Correlation to reference measurement		IRI (m/km)		Ride Number
	Left	Right	Left	Right	
infrared					
N01-N05	0.90-0.97	0.85-0.99	1.01-1.05	1.53-1.71	4.17-4.23
S01	0.92	0.89	1.03	1.67	4.22
S02	0.87	0.95	1.00	1.53	4.24
S03	0.86	0.92	1.03	1.53	4.24
S04	0.88	0.97	0.96	1.54	4.25
S05	0.85	0.93	1.00	1.52	4.24
laser 1					
N01-N05	0.76-0.91	0.86-0.97	0.95-1.05	1.45-1.50	4.09-4.29
S01	0.86	0.92	0.99	1.47	4.17
S02	0.80	0.85	1.03	1.54	4.02
S03	0.80	0.83	1.01	1.55	4.15
S04	0.87	0.90	0.96	1.47	4.31
S05	0.90	0.87	1.00	1.48	4.29
laser 2					
N01-N03	0.77-0.78	0.87-0.88	1.00-1.06	1.48-1.50	3.97-4.12
S01	0.78	0.86	1.00	1.41	4.21
S02	0.76	0.91	1.01	1.55	4.02
S03	0.68	0.85	1.17	1.59	3.94
S04	0.83	0.92	1.00	1.50	4.13
S05	0.80	0.90	1.00	1.53	4.15
ultrasonic					
N01-N03	0.80-0.82	0.88-0.90	1.03-1.12	1.68-1.72	4.27-4.32
S01	0.81	0.92	1.13	1.72	4.29
S02	0.79	0.87	1.08	1.67	4.29
S03	0.77	0.84	1.10	1.66	4.23
S04	0.82	0.88	1.10	1.67	4.28
S05	0.79	0.79	1.14	1.78	4.20
ProRut					
N01-N05	0.97-0.99	0.92-0.98	0.91-0.93	1.56-1.66	4.20-4.21
S01	0.98	0.97	0.92	1.61	4.20
S02	0.92	0.95	0.92	1.60	4.19
S03	0.89	0.84	0.96	1.41	4.16
S04	0.92	0.82	0.94	1.71	4.17
S05	0.88	0.91	0.94	1.56	4.20

Acceleration (Cases S04 and S05)

Moderate and heavy acceleration only affected measurements of long wavelengths. The effect was not as significant as that of the braking tests, because the acceleration levels were lower. (See figure 49.) The statistics in table 26 for the acceleration tests did not always fall within the range of the reference runs. However, all of the profilers measured well enough to suggest that network-level profiling measurements that include heavy acceleration do not need to be flagged as suspect or repeated.

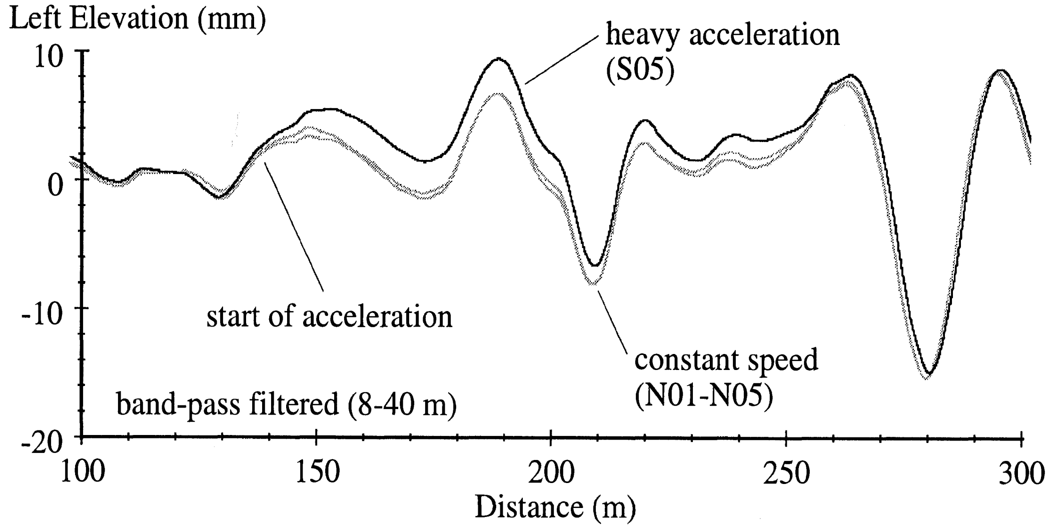

Figure 49. Effect of heavy acceleration on measurement of long wavelengths.

Dead Stop and Rolling Start (Cases S06 and S07)

Profiling from a dead stop or a rolling start influences profile measurement because the profiler must operate below its lower cutoff speed at the start of the run and the vehicle must accelerate during the measurement. The low-speed operation of all five profilers gave rise to major errors in the long and medium wavelength range in the first 50 m of the profile. Figure 50 shows the long-wavelength range of the dead stop run for the profiler designated laser 1. The reference measurements are shown in the background. With the exception of the infrared profiler and the ProRut, the effect was quite dramatic and caused a large "hill" at the start of the profile, as shown. In all five profilers, the dead stop and rolling start runs also contaminated the medium and shorter wavelengths enough to render some distance at the start of the run unusable. (See figure 51.)

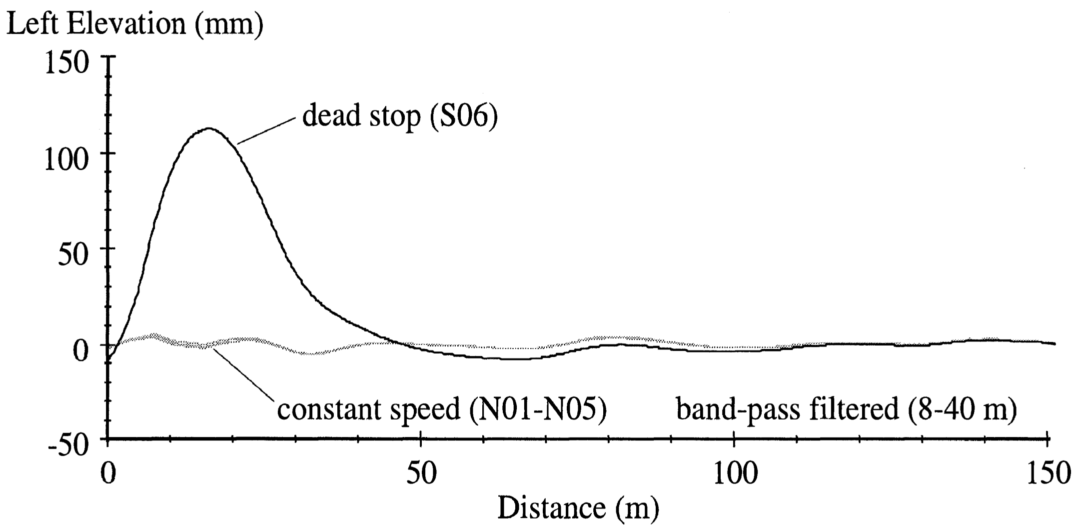

Figure 50. Effect of operating from a dead stop on long wavelength measurement by profiler laser 1.

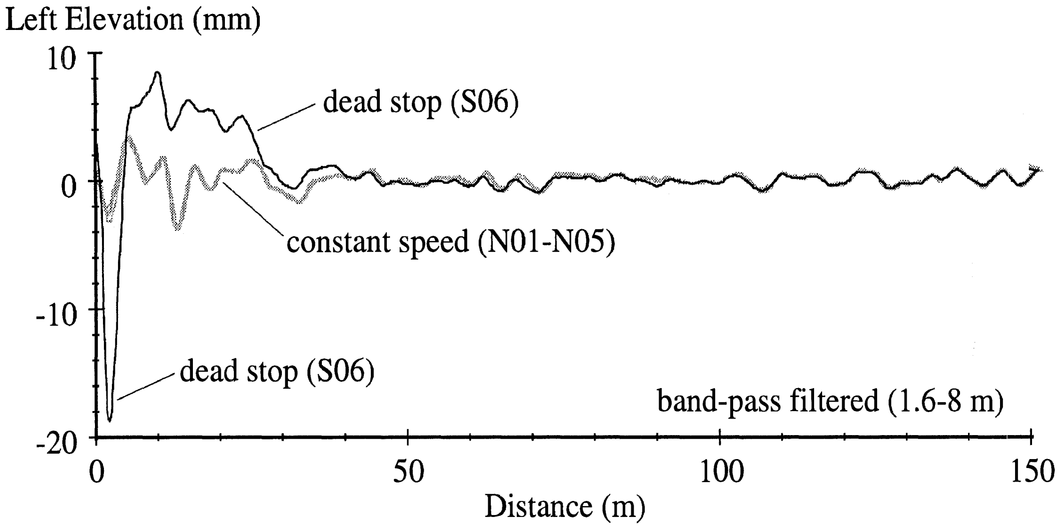

Figure 51. Effect of operating from a dead stop on medium wavelength measurement by the profiler laser 1.

Although the minimum speed of the profilers was reached in the first 50 m or so, the acceleration needed to reach the final speed of 80 kph contributed to error to a lesser extent in the next 100 m of the profile. (All of these profilers reached their final speed and stopped accelerating near the 150 m mark.) Table 27 provides statistics for the first 150 m long subsection of the profile. In all cases, agreement of the dead stop and rolling start runs was unacceptable over the first 150 m long subsection. The correlation values were very low and any agreement in IRI or RN is coincidence.

Detailed study of the profiles from the dead stop and rolling start runs was conducted to find out how much distance must be covered before the measurement is valid. The minimum operating speed of the profiler must certainly be reached, and the acceleration should not be greater than 0.15 g. The distance will also depend heavily on the filtering used within the profile computation algorithm. Most profilers incorporate a high-pass filter with a cutoff of 91 m or longer in their profile computation. The effect of accelerometer errors like those imposed by low-speed operation or excessive acceleration can affect profile far beyond the location of bad readings by misleading the initialization of the high-pass filter. Worse yet, if no initialization is used, errors may extend over a long distance.

Figure 52 shows the IRI correlation coefficient of the dead stop test by the infrared profiler to a constant-speed test for 50 m long portions of the left side. In the figure, each point represents the correlation of a piece of the dead stop test (S06) starting at the location given on the horizontal axis to a section of a constant-speed run over the same piece of road. When the correlation rises to the level exhibited by a pair of constant-speed runs (0.90 to 0.97 in this case), we may assume that the profiler is operating properly. The infrared profiler shows good agreement as early as the 40 m mark. This means that only the first 40 m must be ignored if the profiler operates from a dead stop and accelerates hard to its final speed. In this case, the lower speed limit of the profiler (24 kph) was barely reached before valid profile was being collected.

Table 27. IRI, RN, and correlation to a constant-speed run.

Case	IRI Correlation to reference measurement		IRI (m/km)		Ride Number
	Left	Right	Left	Right	
infrared					
N01-N05	0.90-0.97	0.89-0.98	0.92-0.95	0.98-1.02	4.07-4.09
S06	0.05	0.07	0.94	0.99	3.73
S07	0.18	0.15	0.72	0.89	4.20
laser 1					
N01-N05	0.80-0.86	0.79-0.86	0.99-1.11	1.03-1.12	3.83-4.06
S06	0.27	0.05	1.59	1.70	2.83
S07	0.71	0.71	0.83	1.32	4.17
laser 2					
N01-N03	0.80-0.86	0.81-0.89	1.10-1.29	1.26-1.43	3.46-3.56
S06	-0.22	0.68	2.32	1.46	3.04
S07	-0.29	-0.03	1.71	1.06	3.59
ultrasonic					
N01-N03	0.76-0.76	0.68-0.69	1.09-1.12	1.13-1.25	4.13-4.18
S06	0.46	0.54	1.31	1.29	3.94
S07	0.19	0.68	0.99	1.68	3.81
ProRut					
N01-N05	0.97-0.99	0.82-0.96	0.83-0.86	0.98-1.07	3.98-4.02
S06	0.79	0.18	0.93	1.65	3.67

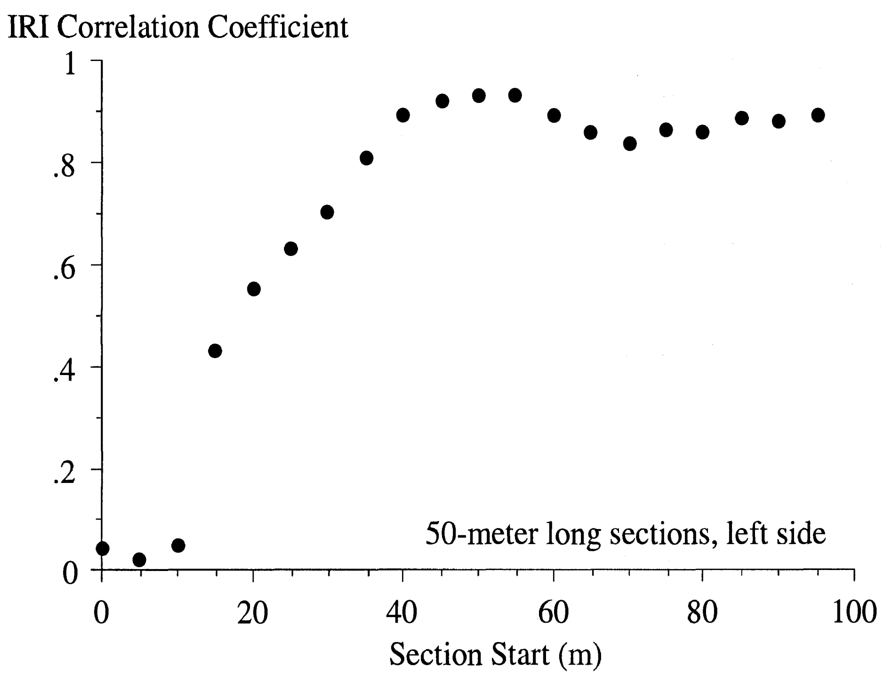

Figure 52. Agreement of 50 m long sections of the dead stop test to a reference measurement, infrared profiler.

The ProRut began to collect valid profile after about 60 m. Unfortunately, this was not the case with the others. The other three profilers all traveled 150 m before they began to operate as they would at constant speed. This is almost the distance it took to reach their final speed of 80 kph. This is believed to be a consequence of residual contamination of the filters in the profile computation algorithm by the first 50 m of the measurements.

Stop Sign (Case S08)

In this experiment, conducted only with profiler laser 2, the 153 m mark was treated as a stop sign. The test included a combination of deceleration, a complete stop, acceleration, and operating below the valid speed range of the profiler. The long-wavelength content of the profile was affected over a very large range, and the medium wavelengths showed a huge localized spike. (See figures 53 and 54.)

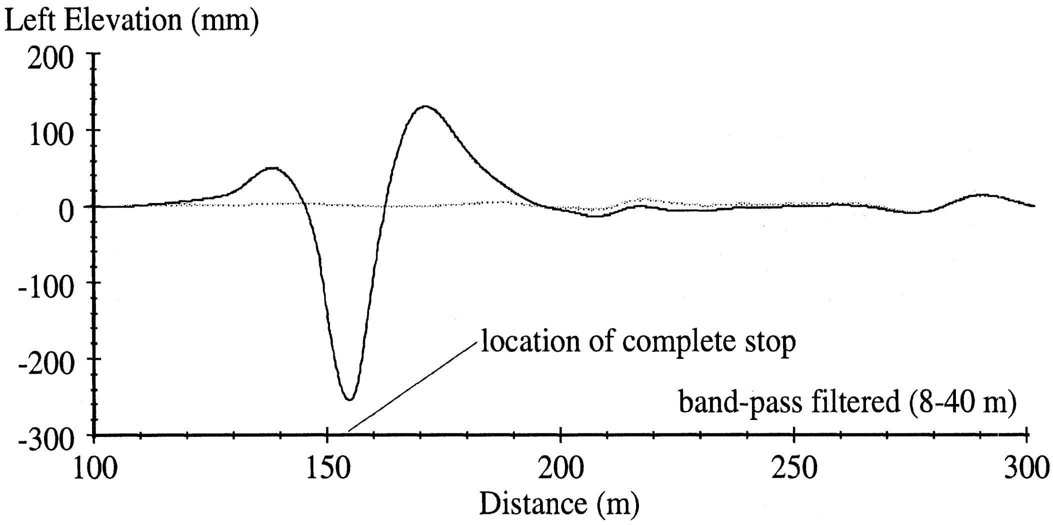

Figure 53. Profiling through a stop, long wavelengths.

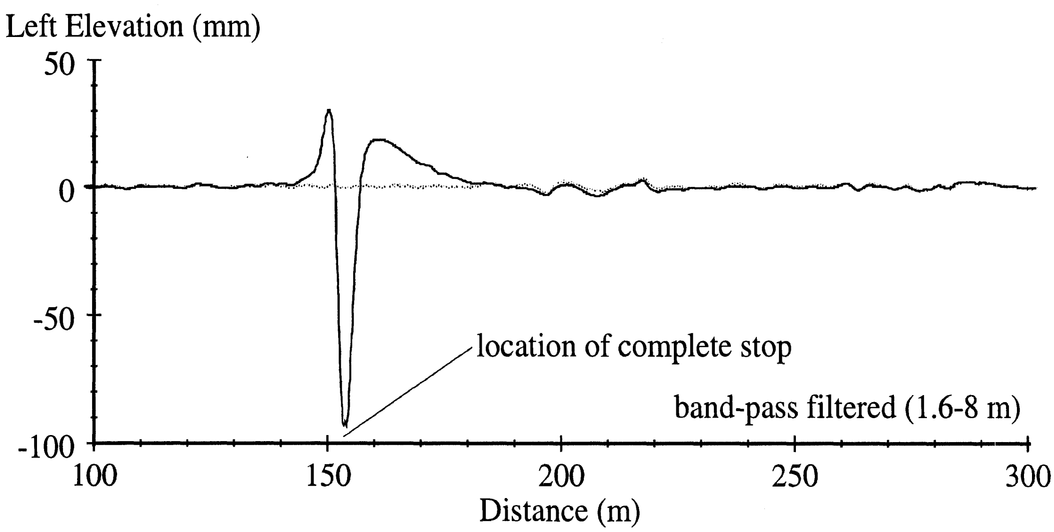

Figure 54. Profiling through a stop, medium wavelengths.

Analysis similar to that of figure 52 was conducted to see how close the vehicle got to the simulated stop sign before it ceased to operate normally and how far beyond the stop sign it traveled before it began to operate normally again. The results are shown in figures 55 and 56. Figure 55 shows the distance beyond the stop sign the vehicle must travel before the results correlate to a constant-speed measurement of the section. The correlation coefficient values were computed for a section that starts at the location given in the figure and ends 50 m beyond that point.

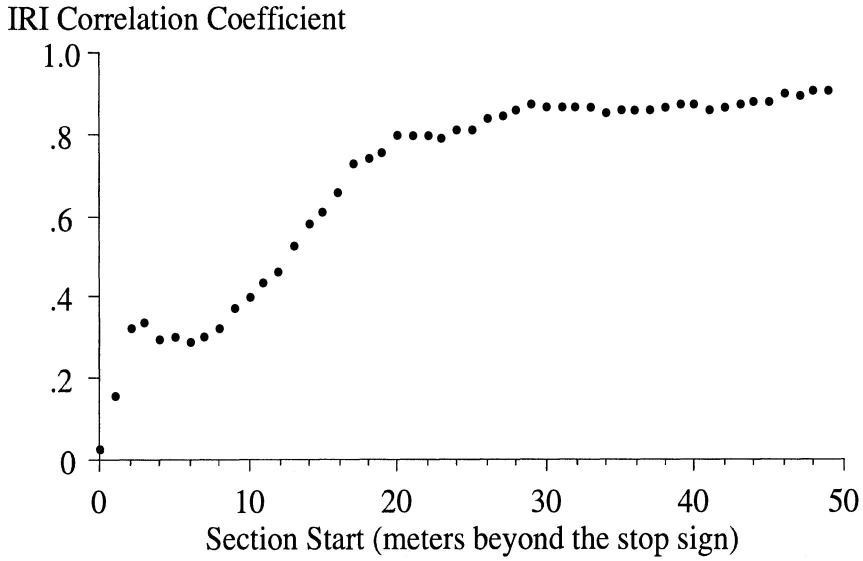

Figure 55. Agreement of 50 m long sections after a stop sign to a reference measurement, profiler laser 2.

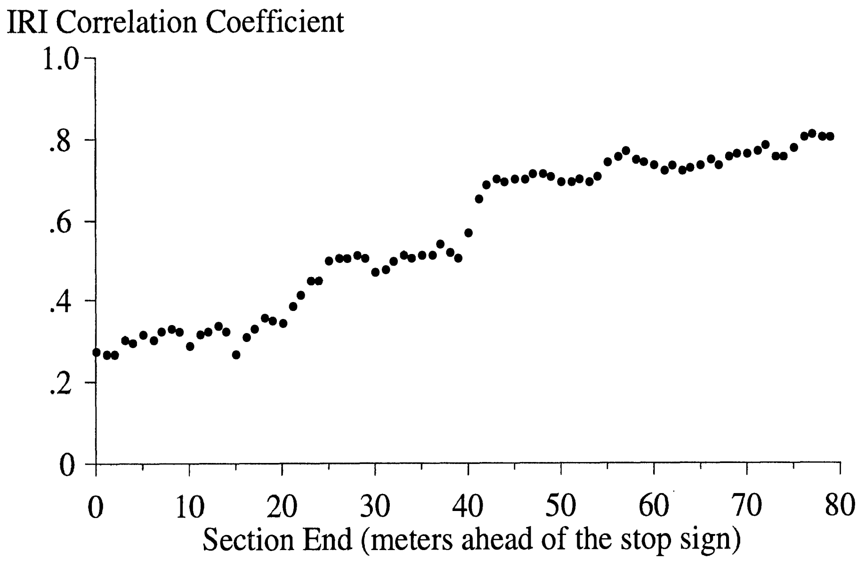

Figure 56. Agreement of 50 m long sections before a stop sign to a reference measurement, profiler laser 2.

Profiler laser 2 appears to operate well as early as 20 m after the stop and very well as soon as 50 m after the stop. This is a significant result. The same device needed to travel 150 m to recover from low-speed operation in the dead stop test. This suggests that continuous running of the data acquisition system and filters through poor speed conditions is preferable to starting internal calculations just before moving the profiler. It also suggests that the filter initialization, and not limitations in the accelerometer, are the culprit in the dead stop test. Thus, it is possible to measure from a dead stop with a shorter lead-in distance if some higher-speed data was collected just before the stop. What is not clear is how long the vehicle can be at rest before the calculations are contaminated and the longer lead-in is needed.

Figure 56 shows the distance ahead of the location of the stop sign at which a 50 m long section must end so that it is measured as it would be in high-speed operation. These data suggest that only about 80 m of profile ahead of the stop sign need be ignored under these circumstances.

Lateral Positioning

Road profile is not a property of a pavement section. Rather, it is a property of one slice of a pavement section at a particular time on a particular day. The "Surface Shape" section of this report demonstrates that a measured profile and the computed roughness value are only a sample of the total roughness picture. The study of transverse variations showed that both IRI and RN vary strongly across a lane on typical pavements. Thus, the particular path that a profiler follows as it passes over a pavement section is expected to influence the measured roughness. The distance from the lane edge to the path followed by the height sensor footprint is the lateral position of the measured profile. Naturally a profiler never follows a path that is perfectly parallel to the lane edge. Drivers generally follow a path near a comfortable lateral position with deviations over some range. Thus, values of lateral position that are discussed here refer to the approximate location of the profile when the profiler followed a straight path within a reasonable tolerance.

In an experiment conducted for this study to characterize transverse variations in profile, a camera and a small monitor were used to aid the driver in holding a required lateral position. (See Appendix D for details.) In transit between sections of interest, all of our drivers wandered within a range of lateral positions wider than 50 cm on straight sections and wider still in heavy traffic or on curves. The lateral position preferred in each case depended on the driver and the traffic in a particular location. (For example, all of our drivers seemed to veer away from a truck in a neighboring lane.) On sections where the drivers were told to hold a given lateral position consistently for 300 m of travel distance, they could do it within a range of 25 cm or less most of the time. Our most experienced driver held within a total range of 15 cm in most of these runs.

In the transverse variations experiment, profiles of seven pavement sections were measured in several lateral tracking positions using the ProRut. The experiment covered so many lateral positions across the lane that the roughness in any position can be estimated within reasonable tolerance. These data were used to estimate the effect of lateral positioning on the roughness that would be measured by a profiler with sensors on both sides. Table 28 provides the results for a profiler with a lateral sensor spacing of 182 cm. The table lists the IRI values the profiler would measure if the vehicle was centered over a position 167 cm from the center of the right edge stripe. (This places the center of the vehicle 175 to 180 cm from the right lane edge.) The table also lists the IRI that this profiler would measure if it were shifted 30 cm in either direction from that central location.

Table 28. Variations in IRI with lateral position, 182 cm sensor spacing.

	IRI (m/km) with the vehicle:								
	in a central location			shifted 30 cm right			shifted 30 cm left		
Section	right	left	MRI	right	left	MRI	right	left	MRI
new asphalt	0.98	0.85	0.91	1.04	0.82	0.93	0.91	0.82	0.86
AC with thermal cracks	1.22	1.20	1.21	1.64	1.16	1.40	1.25	1.29	1.27
old asphalt	2.63	1.85	2.24	2.62	1.72	2.17	2.04	1.53	1.79
one-year-old PCC	1.41	0.84	1.13	1.59	0.85	1.22	1.12	0.81	0.97
three-year-old PCC	0.58	0.59	0.58	0.66	0.56	0.61	0.62	0.68	0.65
six-year-old PCC	1.75	1.41	1.58	1.98	1.46	1.72	1.69	1.35	1.52
severely faulted PCC	3.83	3.67	3.75	3.88	3.63	3.76	3.75	3.97	3.86

The IRI from the left and right side varies with lateral position of the profiler on all of the sections. The majority of states that measure IRI on the left and the right only retain the mean value (called the MRI) for pavement management (*7, 8*). Thus, the MRI is the value the profiler would use to judge the entire section in a single pass. Table 29 lists the MRI measured on each section in the central position and the percentage change that is caused by a shift of 30 cm to either side. The change in MRI is significant on most of the sections.

Table 29. Variations in MRI with lateral position, 182 cm sensor spacing.

Section	"Central" MRI (m/km)	Percent change with 30 cm shift to the right:	to the left:
new asphalt	0.91	2.0	-5.2
AC with thermal cracks	1.21	15.8	4.8
old asphalt	2.24	-3.1	-20.2
one-year-old PCC	1.13	8.3	-13.9
three-year-old PCC	0.58	4.2	11.4
six-year-old PCC	1.58	9.0	-3.6
severely faulted PCC	3.75	0.1	2.9

The MRI varied with lateral position of the profiler in four ways.

1. Higher roughness to the right: In the new asphalt, one-year-old PCC, and six-year-old PCC, the roughness increased transversely across the lane from left to right. Thus, shifting the profiler to the right increased the MRI and shifting to the left decreased the MRI.

2. Higher roughness near the edges: The three-year-old PCC and AC with thermal cracks are both roughest near the right edge and slightly rougher near the left edge than in the center. The MRI of these sections increased if the lateral position shifted to either side.

3. Roughest in the center: The old asphalt is mildly rutted with longitudinal cracks in the ruts. Any shift from the center of the ruts causes the value of MRI to drop since most of the features that contribute to roughness appear within the ruts.

4. Insensitive to lateral position: The changes in MRI with lateral position of the severely faulted PCC are insignificant relative the total roughness. This section appears to need resurfacing no matter where it is measured. Indeed, it was resurfaced the summer following these measurements.

Table 30 presents the results of the same analysis for the case of a profiler with a 164 cm lateral sensor spacing. The values in this table derive from the same type of analysis as the values in table 29, but the lateral position of the sensors are drawn inward 9 cm. Although the percentages are different, the trends and the overall magnitude of the dependence on lateral position are about the same.

The strong dependence of roughness measurement on lateral positioning of a profiler raises two questions: (1) What lateral position is best? and (2) How can the driver of a profiler control the lateral position? Although seven sections were measured in great detail to address the first of these questions, the sections are by no means a complete representation of pavement surfaces. As such, further measurements are needed to address this issue.

Table 30. Variations in MRI with lateral position, 164 cm sensor spacing.

Section	"Central" MRI (m/km)	Percent change with shift to the right:	to the left:
new asphalt	0.89	4.0	-3.4
AC with thermal cracks	1.21	10.8	4.9
old asphalt	2.15	-0.6	-16.6
one-year-old PCC	1.08	11.7	-10.6
three-year-old PCC	0.59	1.0	7.9
six-year-old PCC	1.58	6.4	-3.6
severely faulted PCC	3.72	1.3	2.9

The results from the seven sections studied in this project suggest that the best strategy is to drive the profiler so that it is between a position that is perfectly centered in the lane and a position 10 cm to the right of the central lateral position. A lateral sensor spacing of 170 to 180 cm is also recommended. (This is discussed under "Profiler Design.") On rutted pavement, this combination of lateral positioning and lateral spacing will usually place the sensors within the ruts. On pavement without much visible distress or distresses that span the entire lane, a typical automotive ride experience is well represented, and elevated roughness that appears at lane edges but is rarely covered by traffic is ignored. Some pavements have their most significant distress in the wheeltracks. Naturally, the driver should try to track directly over the roughest wheeltrack if it is not too close to the edge, even if it requires a slight deviation from the recommended positioning. (Although many road users will shift their positions to avoid distress, they will still judge the section as poor.) The recommended lateral positioning should also be ignored on sections with rutting so deep it is easily visible. On these sections, drive in the ruts. The driver of a profiler should never move back and forth across a lane during a measurement to avoid or capture various features.

Standardizing the lateral positioning of profile measurement would greatly improve the repeatability of roughness values and would make the comparison of roughness measurements between agencies much more meaningful. On the other hand, maintaining a consistent lateral position is very difficult. The distance covered in most network-level profiling operations prohibits drivers from maintaining a required lateral position at all times or repeating suspect measurements. Of course, simply alerting profiler drivers that lateral positioning is important and providing them instructions would probably lead to significant improvement.

The use of a monitor with a camera pointed at the right edge stripe was very helpful in positioning the profiler properly for a measurement. During the transverse variations experiment, we learned from our most experienced driver that the best method of holding a given lateral position was to use the monitor to position the profiler, then simply focus on the road ahead. Looking at the monitor too often and using it to make constant adjustments hindered the effort to maintain consistency, because the driver made corrections that were too large and too late. Maintaining lateral position in a vehicle is done best when a driver can preview the road ahead (*47*). A monitor and camera setup are most useful if the driver only checks it occasionally and uses it to get a feel for driving in the desired lateral position. The driver must be warned to view the monitor with no more than a glance and maintain focus on the road for safety concerns. (In our experiments with the camera and monitor, the operator looked at the road ahead throughout each measurement to assist the driver.)

The procedures described in this discussion pertain to systems that measure profile in two tracks. The data collected on the seven sections described above suggest that a profiler with five sets of sensors would provide a superior characterization of road roughness. An experienced analyst could use the five profiles to classify many distresses without visual clues. The recommended lateral positioning of the profiler would not change, but the enhanced profiler would measure one profile under the center of the profiler, two profiles about 91 cm from the center, and two profiles about 137 cm from the center. (This profiler would also provide a better measurement of rut depth.) For now, cost and the operational difficulty of driving a vehicle with extensions on the profiler that make it 2.75 m wide prohibit the five-sensor approach.

Triggering

Most profilers include manual and automated triggering systems. In a typical automated triggering system, some stationary landmark with special reflective properties is placed at the desired starting location of the measurement. The passing profiler senses the landmark and initiates data collection. One example of this type of system is mounted on the ProRut. The ProRut triggering system uses infrared retroreflective sensors to detect a stationary target to the right of the profiler or on the road underneath. The target on the right is a cone covered with reflective tape. To place a target underneath the ProRut, a flat plate covered with reflective tape must be attached to the road with temporary adhesive. This system was used to make sets of five auto-triggered measurements of several sections. All sets of repeats were triggered within 50 mm (two reporting samples) of each other. Although we did not test the placement of the section start relative to the triggering landmark, we believe that the offset between the landmark and the starting point of data collection was less than 1 m at highway speed. The accuracy of other automated triggering systems was not investigated in this study, but it is expected that they all function as accurately as the one on the ProRut.

Measurements are manually triggered by striking a key or pushing a button when a landmark is passed. Naturally, manual triggering is not as accurate as automated triggering. The 1992 RPUG experiment compared manually triggered measurements from several profilers (*48*). The measurements frequently varied in starting location by more than 3 m. In measurements made for this study, an experienced operator who was not driving triggered the starting and ending point of highway sections consistently within 1 m. This level of accuracy would probably be harder to achieve if the operator was also driving.

Ten measurements were made on a section with the ProRut to investigate the ability of a driver who was also operating the profiler to manually trigger profile measurements at highway speed. The section starts at a reference post. The measurements were made in the late afternoon in fairly dense but fast-moving traffic. Triggering the start of a measurement was done by striking any key on a keyboard at the instant the reference post passed beyond the back of the passenger side window. Afterward, each measurement was synchronized to an auto-triggered measurement made at the same reference post. The ten manually triggered measurements range in starting location from 5.6 to 10.6 m after the auto-triggered measurement.

The offsets are caused by a combination of two effects. First, a delay exists within the system, such that data collection starts a fraction of a second after the keyboard is struck. The average offset distance was 7.8 m, which corresponds to about 0.25 s of travel time. This delay is probably software related. Second, the range of offsets covers 5 m. This is a consequence of the operator's inability to trigger the measurement consistently. Keep in mind that this was an inexperienced operator who was also driving in dense traffic, so it represents a worst-case performance.

Triggering accuracy has a minor effect on roughness measurement, but it is an important issue when a profile is used to plan corrective action such as patching or grinding. If the profile measurement does not line up properly with landmarks on the road, correction of undesirable features could be done in the wrong location. This is of particular concern when the feature is not easily visible, such as for bumps in new pavement recommended for grinding. Thus, auto-triggering should be used whenever possible in project-level applications. If manual triggering is used, the analyst must be aware of the delay time (and the corresponding distance) in the triggering system and the potential variability in triggering by the operator. Whenever possible, grinding locations should be referenced to a landmark feature (artificial, if necessary) that is obvious in the profile.

Longitudinal Positioning

Longitudinal positioning refers to the placement of the starting and ending point of a profile measurement along the direction of travel. The longitudinal positioning depends on the accuracy of the triggering that initiates the measurement and the accuracy of the distance measuring instrument. In the study of short, isolated sections, triggering accuracy is of primary concern, because it determines the longitudinal positioning of the measured profile directly. The discussion above reports that in manual triggering a delay of 5 m is possible and even an experienced operator can only trigger within a meter of a landmark consistently.

In most profiling applications, long stretches of road are covered in a single long measurement, then the roughness is reported for shorter segments within the total length. In such a case, a small bias in distance measurement builds up and contributes to errors in the longitudinal position of the segments that are downstream of the start of data collection. Four of the test sections used in this study were laid out along 14.3 km of highway. Four profilers measured these sections five times each. All of the profilers were very consistent, but they disagreed with each other on the total distance by as much as 0.4 percent. An error of 0.4 percent in longitudinal distance means that an error of 4 m in starting location of the segments will build up every kilometer of a long measurement. Thus, errors in longitudinal position on the order of 40 m could build up over a 10 km stretch of highway.

Figure 57 shows the variation in the IRI of a new asphalt section with starting location. Each value along the plot represents the IRI of the 150 m long section that starts at the location indicated. A change in IRI of more than 2 percent is possible by moving the starting point less than 3 m from the reference location at zero. In some areas the IRI is not as sensitive to starting location, but it is more sensitive in others. Keep in mind that on a smooth section a single rough feature can influence the overall IRI very easily. Thus, including or ignoring only a short distance because of errors in longitudinal position may cause significant variation in the IRI. However, few rough features are found on smooth sections, so some segments will not be as sensitive to errors in longitudinal position. Since the new asphalt has very little short-wavelength roughness, the RN is no more sensitive to errors in longitudinal position than the IRI.

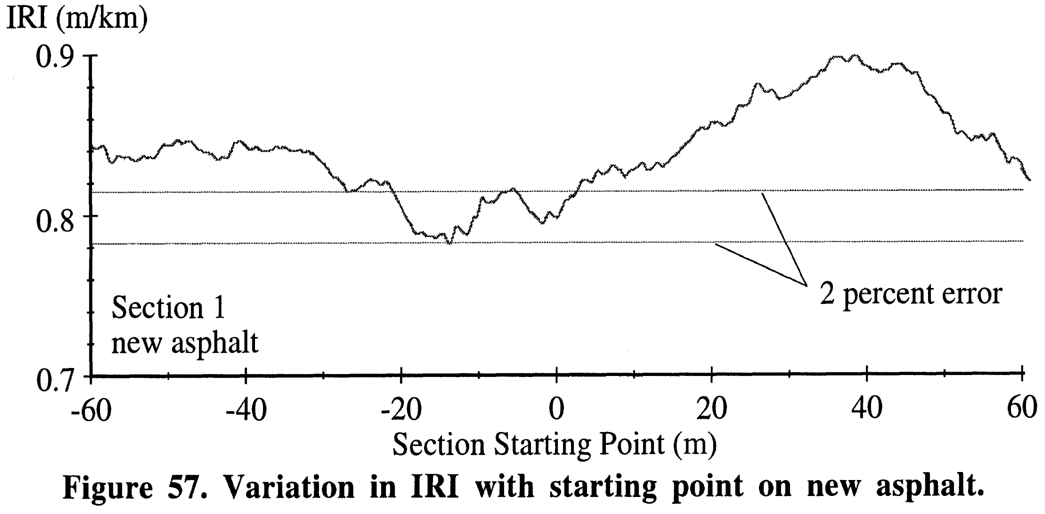

Figure 57. Variation in IRI with starting point on new asphalt.

Figure 58 shows the variation in IRI of severely faulted PCC with starting location. An error in IRI of more than 2 percent is possible by moving the starting point only 2 m ahead of the reference location at zero. Overall, the IRI of this section is more sensitive to changes in starting location because a transverse crack with faulting appears every 2 to 6 m throughout the section. These faults contribute significantly to the IRI of a segment that includes them. Thus, small changes in starting position that influence the number of faults that appear in a segment impact the IRI significantly and the RN tremendously. It is common on this section that movement of the starting point of less than 5 m changes the RN by more than 10 percent.

Many profilers used in network-level surveys now allow the operator to enter event marks at locations of interest throughout a measurement. This feature can be used to eliminate some of the variations in roughness caused by errors in longitudinal positioning. In a project-level measurement, where the specific location of roughness hot spots may be important, the operator should enter an event mark at landmarks such as reference posts, cross streets, overpasses, or bridges. These event marks would allow the landmarks to be used as reference points and to shorten the total distance over which distance measurement errors build up. This procedure would improve the accuracy of longitudinal positioning in long measurements significantly, but is still subject to errors in location associated with manual triggering. In network-level profiling where the overall roughness of long stretches of road is of greater concern, event marks do not need to be entered as frequently. However, they should still be used every 10 km or so to reset the location of the measurement.

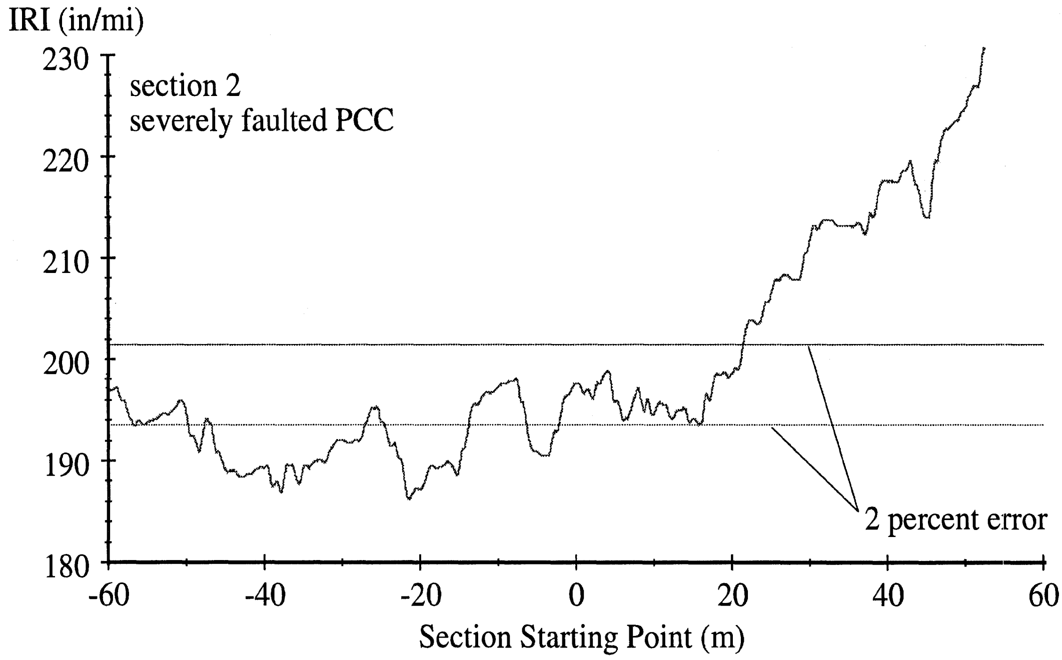

Figure 58. Variation in IRI with starting point on faulted PCC.

Segment Length

Most profiling operations for monitoring of road condition are done by covering very long stretches of road in a single measurement and reporting roughness values for shorter segments at regular intervals. This reporting interval is the segment length for each roughness value. Another common strategy in network-level profiling is to report roughness on sections of homogeneous construction and maintenance history. In this case, the segment length varies over the road network. In North America, the segment length preferred by state and provincial agencies for reporting of roughness is 0.16 km. The length varies from 16 m to 1.6 km (*7*).

The segment length has a strong impact on the interpretation of a roughness value. The IRI of a very long section provides a single number that functions as a summary value. A single value has the advantage that it is easy to interpret, but a shorter section that is very rough could go unnoticed because its roughness is averaged out.

Figure 59 shows the IRI of short segments of a 1.3 km long section with an overall IRI of 1.96 m/km. The section is an AC overlay on PCC with patches scattered throughout and some locations where joint distress has reflected through the overlay. When the section is split into 160.9 m long segments, the IRI fluctuates somewhat from the average. The roughest segment (which is 3.50 m/km) includes significant distress, but only stands out if a short segment length is used. If an even shorter segment length of 40.2 m is used the fluctuations grow and the location of the worst distress can be pinpointed.

A short segment length is useful because it helps locate very rough spots in the road. In the case of the IRI, values from adjacent segments of equal length can be averaged to recover the IRI of a longer segment. Unfortunately, roughness indices that are computed using an RMS, like RN, cannot be averaged this way so it is less convenient to combine roughness values from short segments. A short segment length is also cumbersome because it generates so many numbers to manage. A clever data management strategy is to use two segment lengths. Report roughness of the entire road network for longer segments. Concurrently, compute roughness for short segments, but only retain the value (and the location) if the roughness is very high. This allows the pavement management engineer to identify short trouble spots without managing too much data.

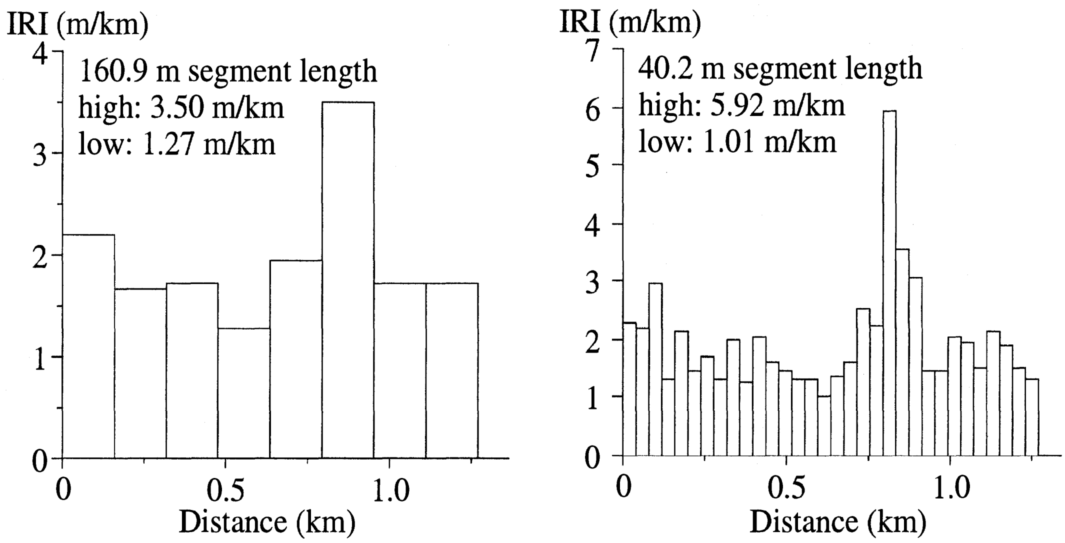

Figure 59. IRI of a smooth section split into short segments.

A roughness profile uses a short segment length to get a continuous description of road roughness (*49*). Rather than providing a single index that summarizes the roughness of a road section, it shows details of how roughness varies with distance. For a given segment length, it is a plot of variations in IRI with longitudinal position. A roughness profile is generated by passing a profile through the IRI filter, then applying a moving average to the result. The baselength of the moving average is the segment length of the roughness profile.

Figure 60 shows the roughness profile of the right wheeltrack of a smooth asphalt road with a railroad crossing near the end. The segment length of the roughness profile is 25 m. That means that any point in the plot represents the IRI of a 25 m long segment that is centered in its location. For example, the railroad tracks fall between the 570 and 575 m mark. The IRI at the 572.5 m mark is about 10.9 m/km. This is the IRI of a 25 m long segment that starts at the 560 m mark and ends at the 585 m mark. A roughness profile with a short segment length helps judge the severity of rough features such as railroad and bridge crossings. The railroad crossing in the pavement shown in figure 60 caused a peak IRI of about 11 m/km. This value can be used to compare the roughness of this crossing to others. The peak value in a roughness profile generated with a short segment length may provide more information about a user's perception of the road than the average IRI of the entire section, since users tend to remember severe features.

The roughness profile is a useful tool for analyzing road condition. If the general condition of longer segments is of interest, apply a moving average with a long baselength (the baselength and segment length are equal). A roughness profile with a short segment length has several potential applications, such as identification and rating of trouble spots on in-service pavement or identification of grinding locations within newly constructed pavement.

Overall, the level of variation in roughness values and their interpretation is heavily linked to the segment length. The optimum length depends on the application. However, it is important that roughness values are only compared if they were generated using the same segment length.

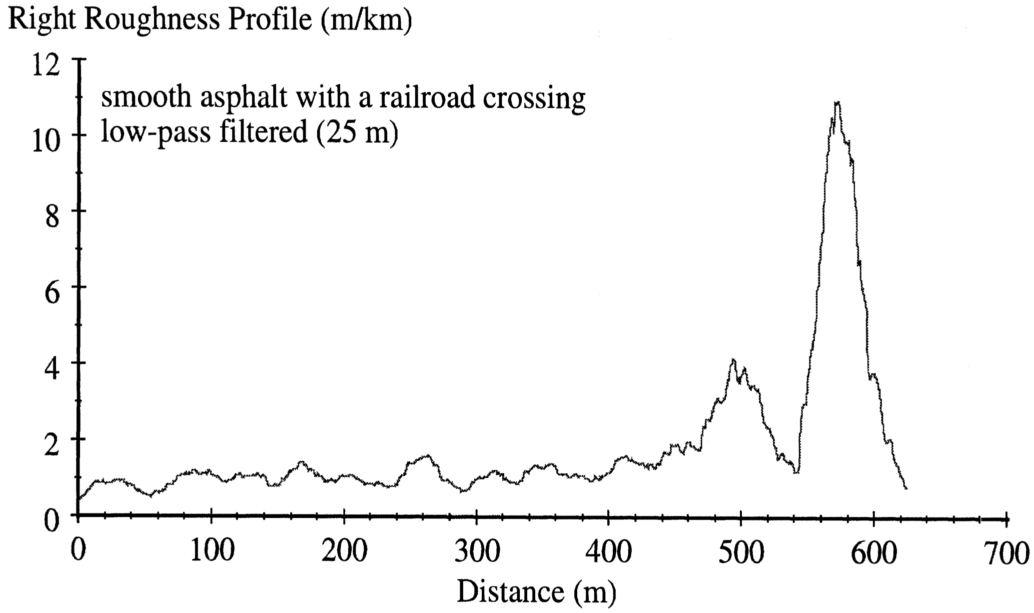

Figure 60. Roughness profile of smooth asphalt with a railroad crossing.

Frequency of Data Collection

Successful monitoring of pavement roughness involves repeated measurement over the life of a road. Logistical and budgetary constraints usually dictate that large road networks can only be covered once per year or less. Currently, the interstate and other portions of the primary road network in most states are covered annually, but several states can only monitor these roads every two or three years (*7, 8*). Even the states that can afford annual monitoring often measure roughness in just one lane or in only one direction on two-lane roads and both directions, but only the outside lane on four-lane roads.

Analysis of the progression in IRI of LTPP study sections revealed that roughness grows very slowly on pavements smoother than 1.6 m/km (*50*). Therefore, monitoring of most smooth pavement yields little new information. Unfortunately most smooth stretches of road must be traversed anyway to reach the rough sections. Besides, the few smooth sections in a road network that increase in roughness quickly are of great interest.

Timing of profile measurements is also important. Some examples were found in the LTPP study data where the roughness of sections increased tremendously for only a month or two then returned to normal for the rest of the year. Fortunately, this usually occurs in the dead of winter when the weather probably prevents profiling activities anyhow. If profiling in freezing weather cannot be avoided, pavement managers should be aware of the timing of the measurements. To reduce the significance of variations in roughness of PCC pavements that occur in daily and yearly cycles, a road network should be monitored with the same plan every year. That is, managers should try to make sure that each district, region, or county is covered at about the same date (within weeks) every year.

Occasionally, circumstances arise that may require some roads to be monitored more frequently than usual. Natural disasters such as flooding may cause part of the road network to deteriorate rapidly. New mining or logging operations may appear in a previously rural area where pavements were not designed for dense heavy truck traffic. In these cases, managers may alter their monitoring plan to cover the affected roads more frequently.

Profiler Sanity Checks

The operator of a profiler should perform regular sanity checks of its measurements. Most profilers display sensor signals and profile elevation values numerically or graphically. The operator should check these displays periodically to make sure the profiler is providing plausible output. This is a burden, but a lesser burden than repeating several days of work or covering a large portion of the road network only to find out the data is useless. An operator who is familiar with a particular kind of profiling equipment knows the approximate value of roughness to expect on a particular road. (Many operators are expert roughness meters by virtue of their experience.)

A useful procedure for checking the accuracy of a profiler is to use it on a few sections regularly. An operator or manager should designate a few sections near the home base location of a profiler. The operator can measure one of these sections that is near the route the profiler is taking for the day to check its operation. At the very least, this should be done once per week. The roughness values and the profiles of these sections can be compared to a previous measurement to make sure the profiler is working consistently.

PROFILER DRIVER AND OPERATOR

The driver and operator of a profiler have a tremendous influence on the quality of profile data. Drivers control the lateral positioning of the host vehicle, which affects the measured roughness significantly. It is also up to them to control the speed of the profiler (which can rarely be held constant in mixed traffic), stay in the correct lane, and devote adequate attention to safety. The operator (who is often the driver as well) must prepare the profiler at the start of a day to make sure it is working properly, find data collection landmarks and trigger the system, conduct quality control during measurements, and often do on-the-spot maintenance. The operator must also make constant judgment calls in adverse conditions as to whether valid profile can be measured.

It is definitely better to use a two-person crew than one person to collect profile. This leaves one person free to worry about driving and safety, and the other free to ensure that quality data is collected. A good way to help ensure quality data is to use the same profiling crew every year. Experienced drivers and operators have several advantages.

- They are familiar with the equipment.
- They usually already know what conditions lead to measurement error. (A new crew has not yet learned from mistakes.)
- They are more likely to recognize errors, because experienced profiler operators can usually guess the roughness of a road with reasonable accuracy.
- They have hopefully already made a habit of good measurement practices.
- They can better protect and maintain the equipment.
- They know the road system well.

It is not always possible to employ experienced drivers and operators, so managers must help them along in developing good (and safe) habits. New drivers and operators should spend the first several days in a profiler under supervision. (Hopefully, an experienced profiler user is available to ride along.) This way, someone is available to help them learn the routine, and to provide an example of how to make decisions when unusual things happen. Even the most well-written manual or instructions cannot cover everything that a driver and operator will encounter on the road. A new driver and operator do not always have the experience to do what a manager would suggest.

Drivers and operators from Ohio, Pennsylvania, and Minnesota all visited Michigan to participate in this study. All of them were knowledgeable about profiling and were genuinely interested in doing a quality job, and they all had something to teach us about good measurement practice. As a consequence of their experience in network-level profiling, where huge distance is covered, they seemed to find a quicker way to finish a set of measurements than we planned, but never compromised the quality of the data. They also seemed interested in what affects the accuracy of roughness measurement. (Some of the studies reported in this chapter were prompted by suggestions from profiler operators.) If a profiling crew knows what can be done to improve the quality of their measurements, they will try to do it. Thus, it seems prudent to pass along any information in this chapter that might be of help to them.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATION

Over the past several decades, road profiling technology has evolved from a research tool to a routine surveying tool for tracking the roughness condition of highway networks. This, coupled with the development of standardized roughness metrics such as the International Roughness Index and the Ride Number, has made it possible for the highway and highway-user communities to know the state of the networks on an ongoing basis. Such information serves not only the highway community as a data source for decision making on maintenance and rehabilitation, but also serves the various interest groups peripheral to the highway community with objective information about its condition.

As profiling devices have become more common and distributed among the state users, disparities in performance have been observed. In part, this derives from the lack of standards by which to test system performance, and variations in design and hardware. Early evidence of these problems motivated efforts to quantify the differences between profiling devices and discover their sources in exercises such as the Ann Arbor Road Profilometer Meeting and the annual meetings of the RPUG.

As our understanding of profiling systems has evolved, we now realize that differences arise from two sources that can be better controlled.

- System performance—The various makes and designs of profiling devices have different performance capabilities due to the way in which the road surface is sensed (sensor footprint), the interval at which the surface is sampled, and the way the data are processed to determine the profile and roughness values. Some of these differences are caused by deficiencies in system design, but others are simply a matter of a lack of standardization. Since the road profile is a continuous function that is digitally sampled, the process used will affect the results, and until there is a well-defined standard for measurement of road profile, these differences will exist.
- Operator practices—The operators of profiling equipment differ in their practices in ways that may affect the measurement of profile and the resulting roughness value. Some of the variations are inherent to the measurement process, such as where the profile is started, and where in the wheeltrack the measurement is made. Other factors arise from the practical problems of making measurements on public roads. For example, operators must sometimes adjust driving practices to accommodate other traffic, forcing them to slow down or even stop at times or to vary in lane position. These problems are most often encountered in network surveys where many km of measurement are required, and the operator is faced with the choice of turning around to repeat the measurement of a section or accepting the fact that a small portion of the measured data is erroneous.

Other sources of difference were identified that do not lend themselves to better control. Dominant among these is the fact that the profile (and hence the roughness) of a road section does not have a single value but varies across a lane and with time. Depending on construction, rigid pavements can vary in roughness on a daily cycle due to temperature gradients; all pavement types may exhibit seasonal variation in roughness; and, of course, pavement roughness varies over years with deterioration. It is often difficult to plan for daily and seasonal changes. If annual surveys of a road section could be scheduled for the same date and time each year, presumably the year-to-year comparisons of roughness would be more meaningful. However, this may be difficult or impossible to accomplish. Even if an identical schedule was achieved each year, climatic conditions are never the same in consecutive years.

Given the existence of these sources of variation, there will always be some lack of precision associated with roughness measurements. However, there are steps that can be taken to reduce the magnitude of variations arising from the equipment and operators. The options for improvement fall within the areas of responsibility of all involved—from the federal level down to the operators and manufacturers of the equipment. Some suggested interventions are described here. Detailed instructions for improving the quality of roughness measurements, based on this research, are provided in an the *Operational Guidelines* that accompany this report.

HIGHWAY ADMINISTRATORS

The findings from this research project bring into focus roles for both federal and state highway administrators to improve the technology for measuring road roughness by high-speed profiling devices.

Federal Highway Administrators

The FHWA has mandated that states survey the roughness condition of portions of their highway networks on an annual basis. In compiling the roughness statistics from network surveys, random variations in individual measurements do not influence the overall statistics for the network. However, if one state's survey system produces roughness measures that are systematically and significantly different than those of another state, the state-to-state comparison of roughness statistics will not be valid.

It has become clear that despite efforts to standardize road profile measurement practices to date, the process has not been completely successful and systematic differences between profilers exist. Current proposed standards are not yet concise enough to eliminate differences between systems that nominally meet the standards, nor is it clear that the proposed standards are sufficient to define a methodology that is robust enough to avoid certain error sources. Thus, the roughness data being acquired for the HPMS should be viewed as having a high degree of variability that should be recognized in any policy-making based on this information.

Consequently, the FHWA should anticipate a continuing need to develop profiling technology and practices further as a step in improving the quality of the roughness database in these programs. The federal government should take a lead role in promoting improvements in measurement technology. Specific actions that could help advance the state of practice are:

- Encourage the development of a standard process for verifying profiler accuracy.

- Discourage the use of profilers with ultrasonic height transducers.
- Continue support for research on profiling technology to solve some of the remaining problems affecting measurement accuracy. (See "Suggested Research," Chapter 4.)
- Require measurement of roughness on both wheeltracks to better quantify the condition of the highway.
- Support the RPUG as a forum for practitioners to exchange information and learn more about the latest developments in technology.
- Provide continuing support for efforts to standardize road profile measurement technology through the American Association of State Highway and Transportation Officials (AASHTO) in cooperation with the American Society for Testing and Materials (ASTM), or the Society of Automotive Engineers (SAE).
- Support annual presentation of the short course "Measuring and Analyzing Road Profiles," inasmuch as it is the only comprehensive continuing education course available to practitioners.
- Support further development of the short course to cover the results of this project.

The research conducted here has revealed many new sources of error that had not been obvious when the short course was originally prepared. Consequently, the course should be updated with this new information, and provisions should be made for regular review and upgrading of the material as a routine part of its annual presentation.

Employees at state highway departments often have difficulty participating in standardization efforts that require funding for travel. For this reason, their interests are poorly represented in efforts to standardize profiling techniques such as those in ASTM. However, the majority of state highway departments and transportation agencies are routinely represented at RPUG meetings. For this reason, the RPUG is suggested as the organization to provide a venue for maintenance and updating of the *Operational Guidelines* and other profiling standards in the future. As users become more cognizant of the nuances of operation that can reduce measurement quality, undoubtedly the guidelines will evolve. RPUG is the logical organization to collect these observations and make the latest guidelines available to users on an annual basis. However, the success of this process requires that AASHTO, ASTM, or SAE work concurrently with RPUG organizers.

State Highway Administrators

Road profilometry is a highly technical activity, subject to very subtle error sources not obvious to the untrained. Within state highway departments, roughness data quality can be improved by instituting certain administrative practices as follows:

- Enlist technically qualified personnel to oversee profiling operations, preferably an engineer trained in digital signal acquisition and processing methods.
- Establish policies that will encourage development of an experienced operating crew able to detect when invalid profile information is being obtained and diagnose the source of error.

- Encourage and support participation of the profiling crew in the annual RPUG meetings so that they benefit at first opportunity from the newest discoveries of problem areas.
- Encourage and support participation of the chief technical person in road profiling standardization efforts through the AASHTO, ASTM, and/or SAE.
- Make the necessary budget provisions to allow the operating crew to obtain extracurricular training, such as the annual short course "Measuring and Analyzing Road Profiles."

Administrators should also recognize that accurate profiling equipment is worth the investment. The *Operational Guidelines* that accompany this document list several aspects of equipment design and performance that are needed to produce reliable roughness measurements. Make sure these performance requirements appear in specifications for new equipment. Compromising on the cost of a profiler is false economy both due to the hidden costs of personnel time lost while compensating for profiler shortcomings and due to compromise in the validity of the roughness database in a pavement management system. The original move from response-type road roughness measuring systems was motivated by the superior repeatability and time-stability possible with profilers. Unless a profiler provides these qualities, they only differ from response-type systems in cost.

OPERATORS AND ANALYSTS

In routine operation of a profiling system there are a number of ways in which the quality of the data may be affected by operating practices. The *Operational Guidelines* that accompany this report provide a detailed discussion of specific practices that can reduce the variability of profile data. It is very important that each agency become familiar with these *Operational Guidelines* and expand them to a rigorous set of guidelines specific to their operations, taking into account the type of equipment and circumstances peculiar to the agency.

For operators, perhaps the most important issues are to develop consistent practices for maintaining acceptable speeds and position in the roadway during measurement. These types of practices need to become routine. Development of agency-specific guidelines as well as an operator's checklist are means to increase consistency that will improve the quality of roughness data, particularly when different profiler operators are involved. An example of such a guideline is the LTPP Manual for Profile Measurements, Operational Field Guidelines that is used for collecting data at LTPP test sites (*51*).

At the same time, the analysts that use the data for project-level and network-level monitoring should become familiar with the procedures used in profile measurement, even to the extent of accompanying the crew occasionally on surveys. The goal is to develop first hand knowledge of how the equipment is used, its capabilities, and the environment in which it operates. At the most basic level, the analyst that uses the data should be knowledgeable about the repeatability that can be achieved by the equipment on various types of road surfaces, so that reasonable conclusions are drawn from data analysis.

Going beyond these details, it is suggested that those responsible for roughness measurement within a state highway department or transportation agency be aware that they are involved in rather complex technology.

Network Surveys

In network surveys, the primary concern of operators should be to ensure that valid data are being acquired and that questionable data are discarded or at least flagged with a warning. Considering the long and routine hours involved in network surveys, that means that operators need to be aware of those circumstances in which departure from normal practices may compromise the validity of measurements. The *Operational Guidelines* provide some practical advice on which driving deviations (e.g., in response to traffic conflicts, etc.) affect data integrity and how to judge when they are serious. Operators should become familiar with those advisories and develop operating practices appropriate to their equipment.

Project Surveys

Project surveys are distinguished from network surveys in two fundamental ways: (1) the distance that must be covered is usually much smaller, and (2) the end use of the data requires better measurement accuracy. With this in mind, it is both essential and practical to conduct project-level measurements with more rigorous practices. Therefore, aspects of profiler design or operation that are less than ideal in network surveys may not be tolerable in project surveys because of the trade-offs between accuracy and efficiency. In other words, adhere more strictly to the *Operational Guidelines* in project surveys. Operators should train themselves to recognize circumstances that degrade the quality of profile measurement. Measurements that are suspect should be repeated, and any adverse profiling conditions (such as bad weather) should prompt operators to postpone their measurements.

Construction Acceptance Surveys

In some states, profilers have replaced other technology (such as profilographs) as a tool for measurement of new construction. This has the advantage that roughness values on a consistent scale will be available throughout the life of a pavement. However, measurement of very smooth pavement requires more accurate equipment and more careful measurement procedures than network-level and project-level surveys. To further complicate matters, roughness values measured on new construction are often used to determine incentive payments and disincentive penalties for construction quality. To serve this purpose, roughness values must be measured on new construction without bias and with very little random error.

Although this study did not focus on measurement of roughness of new construction, many of the findings are applicable to construction acceptance surveys. In particular, the following aspects of profiler system design require improved performance in construction acceptance surveys:

- Current height sensors, accelerometers, and on-board electronics are challenged in measuring the low level of roughness found on new construction.

- The processing algorithms in profilers used for construction acceptance should scan sensor signals rigorously for potential erroneous readings. In particular, all of the suggestions listed in the "Automated Error Checking" section of Chapter 2 should be implemented.
- Profilers used in construction acceptance should employ special filters to ignore downward spikes that appear in a profile at joints in PCC pavements.

In addition, measurement of new construction requires more careful operator practices than network-level and project-level surveys. The following practices are suggested to operators of profilers in construction acceptance surveys:

- Never operate in adverse weather conditions, such as rain or snow.
- Never operate on pavement that is wet or pavement with surface contaminants such as dirt or gravel.
- Insofar as possible, operate at constant speed during data collection.
- Perform frequent checks to ensure that sensors are operating properly.
- Strictly follow instructions for calibration of height sensors, accelerometers, and the distance measuring system.
- Attempt to drive in a consistent lateral position.
- Make repeat measurements, initiating data collection at a known landmark with an automated triggering system.

Depending on the amount of new construction under the supervision of an agency, it is suggested that the profiles are stored in addition to the roughness values. The profile of a section that produced a roughness value that is suspect or unusually high can be examined for errors. In the best case, this would take place as a quality control check directly after the measurement.

The suggestions made here are extrapolated from the study of profiling of pavement in service and in open traffic. As such, many of the issues listed here appear in the suggestions for future research in the area of monitoring of new construction.

PAVEMENT MANAGEMENT ENGINEERS

This study did not specifically address the role of roughness measurements in pavement management systems. However, the research demonstrated that yearly measurements of road profile do not define the roughness of the road within very tight tolerance. In particular, road profiles change over daily and yearly cycles, and vary with lateral positioning of a profiler. Thus, the yearly roughness values provided by profiling operations are merely a statistical sampling of the road condition. Pavement management engineers should be aware of the tolerances within which roughness values were measured, whether the variations are caused by changes in road shape or random error associated with the profiling equipment and procedures in use.

The variation observed in the seasonal data of the LTPP program clearly indicated that rather large changes in roughness can be observed in the winter in freezing climates. It may prove beneficial to track the magnitude of these changes in a pavement management system.

PROFILER MANUFACTURERS

Many of the advances in profiling technology will require changes and improvements to profiling hardware. These are the responsibility of profiler manufacturers. Some aspects of profiler design, such as proper use of anti-aliasing filters, are essential to their performance. Our understanding of some aspects of profiler configuration are not yet adequate to prescribe the best design for a profiler. However, a broad initiative under the the AASHTO Joint Task Force on Pavements, Subcommittee on Pavement Condition Protocols, is currently underway to standardize those aspects of profiler design that cause two valid profilers to disagree. Profiler manufacturers should assist in this process by incorporating the standards into new designs and offering to retrofit old models as a service option.

One of the most direct ways that manufacturers can aid in eliminating sources of error is to provide more on-board diagnostics with the equipment. Although some systems already include some diagnostic features, all should have certain minimum diagnostics as follows:

- Height Sensor—It is possible to operate a profiler without knowledge that the height sensor is not functioning correctly and still obtain a measure of a profile and roughness. Simple problems such as wiring faults, covers over the sensors, etc. may be the cause. A profiler should provide a means of checking that a dynamic signal is present and that it remains in range. Ideally, the computer should monitor the height sensor signal, alert the operator when it is not functioning or when it is overranging, and mark data files when the signal is in error.
- Accelerometer—The accelerometer may experience functional problems similar to that of the height sensor. The computer should monitor accelerometer operation, alert the operator when a malfunction occurs, and mark data files in which questionable data have been entered.
- Speed—All profilers operate properly within a range of speeds. If the limits of that range are violated, a profiler should automatically suspend data collection and warn the operator.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

The factors that affect measurement of longitudinal road profile and computation of the International Roughness Index and Ride Number have been systematically examined. Information from the literature and from experimental tests have been used to evaluate the way in which these factors influence the measurements and prevent two profilers from obtaining the same result on the same road. The findings from this examination have been translated into a set of *Operational Guidelines* for profile measurement contained in a separate document that accompanies this report. The *Operational Guidelines* provide a condensation of the observations and findings from the research. If they are applied in routine measurements they will help improve profiler accuracy and repeatability, even though it is not possible to eliminate all sources of variation. Conclusions relevant to the *Operational Guidelines* are contained in this section.

Other observations have emerged from this research that go beyond the realm of the *Operational Guidelines*. The opportunity for careful review of current technology in profiling has made evident a number of shortcomings in the hardware and data analysis methods. Suggestions for research to improve the technology are provided with the expectation that more precise and robust profiling practice will result when they are implemented.

CONCLUSIONS

The systematic study of factors that affect profiler accuracy and repeatability revealed several results that are very significant to profiling practice.

- A profiler must apply anti-aliasing filters to the height sensor and accelerometer signals to measure IRI and RN accurately. Failure to do so will result in errors in IRI of 2 to 10 percent and errors in RN of 10 to 50 percent on typical roads and much larger errors on roads with coarse macrotexture or severe cracking.
- A sample interval of 167 mm or less is required for accurate measurement of IRI.
- A sample interval of 50 mm or less is required for accurate measurement of RN.
- Pavements exhibit significant transverse, seasonal, and daily variations in roughness. Thus, a single roughness measurement, no matter how accurate, must be considered only as a statistical sampling of the roughness.
- Transverse variations in roughness account for a significant amount of the variation that has been observed between repeat measurements of profilers in past studies. Typical variations in lateral positioning may cause repeat measurements of IRI to vary up to 20 percent on a section 300 m long.
- Profilers should, at a minimum, measure roughness in two wheeltracks.

- Height sensor footprint has a strong influence on the way a profiler measures cracks and open joints. Proper use of anti-aliasing filters improves the accuracy of profilers on pavements with these features, as well as the agreement between measurements obtained with different types of height sensors.
- Moderate acceleration and deceleration of less than 0.15 g can be tolerated in network-level measurements of profile, but should be avoided in project-level measurements. (This level of acceleration is approximately equivalent to changing speed at a rate of 5 kph per second, or 3 mph per second.)
- Profilers with ultrasonic height sensors do not make reliable measurements of IRI or RN. Ultrasonic sensors should be replaced.
- Display of sensor signals and automated error checking in a profiler would significantly reduce instances of major measurement errors.
- The phase shift incident to computing profile as the sensor signals are collected causes long wavelength features to be displaced longitudinally. This has no significant effect on roughness values, but may lead to errors in locating roughness features (e.g., "must grind" areas).

The fact that two devices do not measure the same profile and roughness value on the same road section, or the fact that a particular profiler cannot precisely replicate its measurements is not necessarily indicative of errors. The roughness of a road surface is a three dimensional property that depends on the path taken along the road and the longitudinal range of the measurement. Roughness also varies throughout the day on a short-term basis, with the seasons over a yearly cycle, and with pavement wear over the longer term. Thus, a road has no unique profile or roughness value. Rather, it depends on exactly when and where the measurement is made. Thus, highway engineers should view a roughness measurement made by a profiler as a statistical property for which limited sampling produces only an estimate of the true roughness.

This being the case, it is important to exercise control over measurement procedures that are appropriate to the end use of the data. For example, in routine surveys of network roughness condition, daily and seasonal variations are not critical, as they will tend to average out in compiling overall statistics for the total road network. On the other hand, if annual data are used in a pavement management system to project maintenance needs, the prediction may be improved by attempting to be consistent in the timing of the measurements (daily and by season).

Beyond these considerations, there are other controls that can be placed on profiling activities to improve the quality of the data. A number of these controls relate to the specific procedures used in the operation of the equipment and are addressed in the accompanying *Operational Guidelines*.

SUGGESTED RESEARCH

Despite several decades of development, road profiling technology is not yet fully mature. Though the steps in measuring profile seem straightforward, there are subtle ways in which equipment differences and error sources can creep into the process. Some of the errors arise from the measurement equipment and others relate to the capabilities of the driver and operator.

In order to reduce systematic differences between road profiling systems, it is recommended that the FHWA continue to support research to develop road profiling technology beyond today's level of knowledge. The suggested research should focus more on road surface sensing technology. The research should develop a concise method for processing the raw sensor measurements (accelerometers and height sensor signals) into profiles that are accurate for predicting roughness values (as well as vehicle performance) and cross profile characteristics.

Technical issues that still need to be better understood and addressed are:

- Determining how to sense the road surface to detect a surface datum similar to that which would be seen by a tire.
- Determining whether spot (laser) sensors and area (infrared and optical) sensors can give equivalent performance.
- Developing standardized methods for dealing with cracks in the pavement and distinguishing them from bumps.
- Eliminating the phase shift caused by the integration process to properly locate bumps in new construction.

If profilers find widespread use in construction acceptance surveys, three technical issues that warrant further require research are:

- Determining the precision and accuracy requirements of height sensors and accelerometers on very smooth pavement.
- Developing algorithms for removing narrow downward spikes in a profile.
- Developing adequate sensor specifications for low-speed profiler operation.

Beyond the goals of improving the technology for profiling, the findings from this research suggest other avenues for research to improve the effectiveness and efficiency of pavement management.

- The IRI and RN currently interpret narrow downward spikes with the same significance as an upward spike of the same shape, even though narrow downward spikes are generally enveloped by vehicle tires. The interpretation of downward spikes involves a trade-off between ignoring them because they do not affect vehicle motion or including them because they provide information about pavement condition.
- Studies of transverse variation in roughness on a limited set of pavements provided great insight into road roughness characteristics and helped explain the lack of repeatability observed in past research. An experiment that provides measurement of a more complete set of pavement surfaces in twenty or more wheeltracks would provide a better understanding of roughness variations.

- It has become apparent that some of the roughness databases (LTPP, RPUG, etc.) contain erroneous measurements that often lead to incorrect observations and conclusions. The exercise of scrutinizing and analyzing these databases has resulted in new methods for screening data for errors. It is suggested that a program be established to apply these tools to the LTPP database with the goals of identifying erroneous profiles and demonstrating methods for more comprehensive analysis of the database.

- Plotting and filtering tools are available that help identify specific pavement distress features. As our experience grows in profile analysis, it is increasingly practical to use profile for identification of certain types of distress. Research should continue to develop algorithms that identify common pavement distress types (i.e., faulting, slab tilt, and curling of PCC).

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APPENDIX A
DATA SOURCES

This appendix describes the data used in the analyses in Chapter 2. Four major data sources were used in this research:

1. measurements of roads in southeastern Michigan by the ProRut,
2. measurements of roads in southeastern Michigan by visiting profilers from Minnesota, Ohio, and Pennsylvania DOT,
3. data from RPUG experiments in 1993 and 1994, and
4. LTPP GPS data.

The ProRut was available for ten months from July 1997 until April 1998. Whenever an experiment required only one profiler, the ProRut was used. The visiting profilers were needed for several experiments that required a diversity of profiler designs, particularly in the study of factors that interact with height sensor type. The operators and analysts who visited from Minnesota, Ohio, and Pennsylvania also provided tremendous insight into the profiling process. RPUG data provided useful demonstrations of error sources that were already understood when the research began, but required clear explanation. The RPUG experiments also covered a broader range of profiler designs than was logistically possible in our experiments. LTPP data provided a means of investigating seasonal and daily variations in profile on a diversity of roads in a diversity of environmental conditions.

TEST SECTIONS

Twenty sections were selected for use in this project. Seventeen of them were of in-service roads near Ann Arbor, Michigan. These sections covered a variety of examples of common distress types and some special surface properties intended to challenge profiler height sensors. Three more sections were measured at the GMPG interior noise loop. These sections provided some examples of coarse and fine macrotexture and a traffic-free environment in which to conduct special tests.

Tables A-1 through A-3 list pertinent information about the sections. The distress column provides the properties of each section that had the most to do with their selection, and some others that were important in the analysis of their profiles. Sections 1 and 2 were used in more studies than any of the others. These sections are given the nicknames "new asphalt" and "severely faulted PCC." This is because they represent two extremes. Section 1 is a new asphalt overlay with almost no short-wavelength roughness. Section 2 is a severely faulted PCC pavement with a very high level of short-wavelength roughness.

Table A-1. Location of test sections.

Section	Road	Section Location
01	M-14	East of the US-23 interchange. Starts at speed limit sign.
02	M-14	Starts at MP 11.
03	M-14	Starts at MP 16.
04	M-14	Starts east of the Ridge Rd. overpass, end ahead of the Beck Road exit.
05	Plymouth Rd.	Starts 0.6 km west of M-153.
06	Beck Rd.	Starts about 0.44 km south of Grand River.
07	Beck Rd.	Starts 0.16 km south of 10 Mile Rd. Ends at a fire hydrant between Iroqusis and Edinburgh Rd.
08	Beck Rd.	Starts 0.4 km south of 9 Mile Rd.
09	5 Mile Rd.	Between Ridge Rd. and Napier Rd.
10	5 Mile Rd.	Between Napier Rd. and Ridge Rd.
11	Ecorse Rd.	Starts 0.6 km west of Beck Rd. Ends east of Denton Rd.
12	I-94	Starts 0.16 km east of MP 188.
13	I-94	Starts at MP 146.
14	I-94	Starts at MP 161.
15	US-23	Starts at MP 16.
16	M-14	Between Section 1 and 2.
RR	5 Mile Rd.	East of Section 10.
G1	GMPG INL	Starts at transition to textured surfaces.
G2	GMPG INL	Starts at transition to textured surfaces.
G3	GMPG INL	Starts at transition to textured surfaces.

GMPG INL – General Motors Proving Grounds Interior Noise Loop MP - Milepost

Table A-2. Description of test sections.

Section	Length (m)	Speed Limit (kph)	Lane	Lanes	Type
01	300	112	Outside, Eastbound	4, Divided	AC
02	300	112	Outside, Eastbound	4, Divided	PCC
03	300	112	Outside, Eastbound	4, Divided	PCC
04	260	112	Outside, Eastbound	4, Divided	PCC
05	335	80	Westbound	2, Undivided	AC
06	390	64	Southbound	2, Undivided	AC
07	335	64	Southbound	2, Undivided	AC
08	350	64	Southbound	2, Undivided	AC
09	300	80	Westbound	2, Undivided	AC
10	300	80	Eastbound	2, Undivided	AC
11	365	88	Outside, Westbound	4, Divided	PCC
12	300	112	Outside, Eastbound	6, Divided	PCC
13	300	112	Outside, Eastbound	4, Divided	PCC
14	300	112	Outside, Eastbound	4, Divided	AC
15	300	112	Outside, Southbound	4, Divided	PCC
16	300	112	Outside, Eastbound	4, Divided	AC/PCC
RR	550	80	Eastbound	2, Undivided	AC
G1	450	80	Left	3, Loop	PCC
G2	450	80	Center	3, Loop	AC
G3	450	80	Right	3, Loop	AC

Table A-3. Description of test surfaces.

Section	Surface Type, Distress
01	New asphalt. Overlay of PCC placed in July 1997. Very smooth, very dark. No seal coat. Low roughness in the short-wavelength range. Two closely spaced core samples were taken on the right side of the lane about 800 m into the section. The area around these core samples was a depression about 13 cm wide, more than 15 cm long, and about 10 mm deep.
02	Severely faulted PCC. High severity faulting and medium severity spalling. Slabs 21.3 m long. At least 7seven transverse cracks appear between each joint. Slab pieces tilted. PCC shoulder.
03	Medium severity transverse cracking. Mild spalling. PCC shoulder.
04	High severity transverse cracking. Mild spalling. PCC shoulder.
05	Medium to high severity transverse cracking. Some bumps in section likely to be caused by frost heave.
06	Rutting and medium severity alligator cracking.
07	Rutting and high severity alligator cracking.
08	Medium severity alligator cracking.
09	Medium severity transverse cracking and longitudinal cracking. Most cracks sealed. Mild rutting.
10	Low severity transverse cracking. Most cracks sealed.
11	Low to medium severity faulting. A few slabs have transverse cracks. One slab was replaced with a large asphalt patch in late September 1997. Slabs 5.5 m long, joints between them opened about 10 mm. Smooth finish (no tining).
12	Three-year-old concrete. Very smooth, no visible distress. Grinding has been performed in right wheeltrack from 150 to 157 m into section, in left WP from 150 to 198 m into section. Slabs are 8.2 m long. Tined. Joints opened 10 to 15 mm. Joints are sealed, sealant is about 10 mm deep. PCC shoulder.
13	One-year-old concrete. Slabs are 12.5 m long. Very tight cracks in the middle of the slabs. Very smooth. Tined. Bituminous shoulder. Joints opened 10 to 15 mm. Joints are sealed, sealant is about 10 mm deep. PCC shoulder.
14	Asphalt concrete with dips that spanned the lane, about 10 cm long along the right edge.
15	Six-year-old jointed PCC. Slabs are an average of 12.5 m long. No major distresses. Midpanel cracks that were very tight. Half-slabs curled upward. Tined. Joints opened about 10 mm. Joints are sealed, but sealant is 10-mm deep. (Huge punchout now present in the section developed in the spring of 1998.) Bituminous shoulder.
16	Transition from dark (new) asphalt to old PCC.
RR	Continuation of section 10 that includes a railroad crossing. The crossing is on a very large bump.
G1	PCC of very coarse macrotexture, protruding rocks up to 40 mm in diameter. Lane 2.44-m wide.
G2	Asphalt concrete of extremely fine macrotexture. Lane 2.44-m wide. Probably the designated "quiet" surface.
G3	Chip-sealed asphalt concrete. Lane 2.44-m wide. Stones 3 to 6 mm in diameter.

PRORUT

The Turner-Fairbanks Highway Research Center loaned the ProRut to this project for ten months. The ProRut was the work-horse profiler of the project, and it was used in all experiments that required only one device. It was also used to help search for sections with a desired roughness level. The ProRut is fitted with Selcom laser sensors on each side spaced about 181 cm apart. These are used for roughness measurement. A third sensor is mounted in the center of the vehicle for measurement of a three-point rut depth. The sensors are between the axles near the longitudinal center of the vehicle. The ProRut can collect profile at speeds in excess of 120 kph and has an adjustable sample interval (larger than 10 mm). In addition to profile it provides rut depth, a speed record, and the individual height sensor and accelerometer signals. Triggering of data collection can be either manual or automatic. Auto-triggered data collection starts when a photocell detects a landmark with reflective tape (either to the right of the vehicle or underneath it). The ability of the ProRut to provide individual sensor signals and collect data at a short sample interval made it very useful in studies that required special details.

Experiments for study of the following factors were performed with the ProRut:

- Sample Interval—Collected profile with a very short (25 mm) sample interval on all sections to help quantify the effect of sample interval on roughness.
- Automatic Error Checking—Studied individual sensor readings from the ProRut to help formulate strategies for automatically detecting errors. Computed profiles with individual sensor signals.
- Height Sensor—Quantized sensor signals to study the effect of height sensor resolution on the accuracy of roughness.
- Longitudinal Distance Measurement—Ran the ProRut at various levels of tire inflation pressure to gauge the effect on distance measurement. Varied the value of sample interval in twelve ProRut measurements to simulate distance measurement errors and study the effect on roughness.
- Lateral Sensor Spacing, Transverse Variations, and Lateral Positioning—Measured seven sections in at least twenty-two lateral positions each. This was a major experiment. It is described in detail in Appendix D.
- Triggering—Tested the ability of an operator to trigger accurately at a landmark while driving in heavy traffic.
- Longitudinal Positioning—Demonstrated the effect of longitudinal positioning errors on IRI and RN of segments of fixed length.
- Segment Length—Demonstrated the effect of segment length on roughness variations using long measurements.

VISITING PROFILERS

Five profilers from three state DOTs visited to make measurements for this study. The ProRut also participated in most of the experiments that included these profilers. Mainly, the visiting profilers were included to cover a range of common height sensor types, but it also turned out to be valuable to observe experienced profiler operators and ask them questions, and to see the kind of features that are available in commercial profilers. The profilers that participated are listed in table A-4. All of these profilers use sensors that are mounted in front of the front bumper.

Table A-4. Visiting profilers.

Owner	Manufacturer	Height Sensor Type	Sample Interval (mm)
Ohio DOT	ICC	laser	165
Ohio DOT	K.J. Law, Inc.	infrared	152
Pennsylvania DOT	ICC	laser	170
Pennsylvania DOT	ICC	ultrasonic	338
Minnesota DOT	PathWay	laser	—
FHWA	FHWA (ProRut)	laser	10-100

The profilers from the Ohio DOT and Pennsylvania DOT measured all of the sections listed in table A-1 several times. The profiler from the Minnesota DOT did not visit the GMPG. This profiler performed video surveys of sections 1 through 16 and RR. This proved very helpful in studying the effect of distress on profile and identifying the source of anomalous features in measured profiles.

Experiments for study of the following factors were performed with most or all of the profilers listed in table A-4:

Longitudinal Distance Measurement—Compared the distance between the starting point of sections 1 and 4 to test the distance measurement instruments.

Distress—Used the PathWay video log to find examples of the way each type of height sensor treats various forms of distress.

Pavement Markings—Checked the profilers for sensitivity to pavement markings on section RR, and on fabricated markings at the GMPG.

Pavement Color—Checked the profilers for sensitivity to pavement color at the transition from asphalt concrete to PCC on section 16.

Profiler Operator—Learned about common operator practices and abilities from the visitors.

Curves—Used the traffic-free environment the GMPG to operate profilers with extreme steering inputs and lateral acceleration.

Speed Changes—Used the traffic-free environment at the GMPG to operate profilers with acceleration and deceleration that might take place in common profiling situations.

Surface Texture—Measured sections that represented different levels of macrotexture at the GMPG.

RPUG DATA

Calibration studies were conducted prior to RPUG meetings in 1993 and 1994. Four regional calibration locations were established in Mississippi, Nevada, Pennsylvania, and South Dakota. State highway agencies and private agencies were invited to run their profilers on the test sites in any of these regions. The Dipstick was also used to make reference measurements at each of these sites. Most of the data from these experiments were available for use in this project. A tremendous diversity of profilers participated in these studies. Thus, the data were used to investigate the performance of a broad range of equipment and to demonstrate differences among profilers. A more detailed description of the 1993 RPUG experiment and statistical results are provided in Appendix C. The factors investigated using RPUG data are:

- Accuracy and Repeatability—Demonstrated the accuracy and repeatability of common profilers in use in the early 1990s.
- Profile Computation Algorithm—Demonstrated the utility of high-pass filtering in getting informative plots.
- Longitudinal Distance Measurement—Studied the accuracy of the distance measurement instrument in common profilers.
- Surface Texture—Used to estimate the bias in roughness characteristic of each height sensor type on sections of coarse macrotexture.
- Operating Speed—Showed that common profilers are not sensitive to modest variations in operating speed.

LTPP GPS DATA

The objectives of the LTPP program are to (1) evaluate existing design methods; (2) develop improved design methods and strategies for the rehabilitation of existing pavements; (3) develop improved design equations for new and reconstructed pavements; (4) determine the effects of loading, environment, material properties and variability, construction quality, and maintenance levels on pavement distress and performance; (5) determine the effects of specific design features on pavement performance; and (6) establish a national long-term pavement database to support future needs.

To accomplish the described goals, the LTPP program was divided into two complementary programs. The first program, called General Pavement Studies (GPS), uses in-service pavement test sections in either their original design phase or in their first overlay phase. The second program, called Specific Pavement Studies, investigates the effect of specific design features on pavement performance.

Under the GPS program of the LTPP study, more than eight-hundred test sections were established on in-service pavements all over the United States and Canada. The GPS sections generally represent pavements that incorporate materials and structural designs used in standard engineering practices. Each GPS section is 152 m in length and is located in the outside traffic lane. The data collected at the GPS sections include climatic, material properties, traffic frequency, deflection, profile, distress, and friction data. In the LTPP program a seasonal monitoring program has been established to study the seasonal effects on pavements. Several GPS test sections have been included in this program. They are profiled four times per year (once per season). These data were used to study seasonal roughness variations.

The profile data that were collected at GPS sections and had cleared LTPP data quality checks by January, 1998 were used in some analyses that were performed for this study. Overall, the factors studied with LTPP profile data were:

- Number of Sensors—Demonstrated the advantage of two sets of sensors over one.
- Daily Variations—Quantified the range of roughness expected throughout the day on jointed PCC.
- Seasonal Variations—Quantified the range of roughness possible throughout the year, primarily on asphalt concrete with a granular base.

APPENDIX B
INTERNATIONAL ROUGHNESS INDEX AND RIDE NUMBER

This appendix provides some background about the International Roughness Index (IRI) and the Ride Number (RN). Information relevant to the analysis of errors in IRI and RN is also provided. A more comprehensive description of the IRI and RN can be found in (*1-3*).

INTERNATIONAL ROUGHNESS INDEX

Almost every automated road profiling system includes software to calculate the IRI. The IRI is a continuation of the "in/mi" roughness statistic in use in the highway community since the 1920s to describe road roughness. It was developed originally as a scale for calibrating response-type road roughness measuring systems (*4*). Mathematical models of the vehicle and road meter were developed and tested, and shown to provide the same type of "in/mi" index as a mathematical function of the longitudinal profile.

Because response-type road roughness measuring systems were common, the index was tailored to correlate well with the output of these systems. The filter is based on a mathematical model called a quarter-car. The quarter-car filter calculates the suspension deflection of a simulated mechanical system with a response similar to a passenger car shown in figure B-1. The simulated suspension motion is accumulated and divided by the distance traveled to give an index with units of slope (m/km, in/mi, etc.). The form of data reduction emulates a perfect road meter. The IRI is essentially a computer-based "virtual response-type system." Several years of research reported in NCHRP Report 228 were spent to develop a profile index that built on the fifty years of experience accumulated by the states and others using "in/mi" roughness indices.

Development and testing of the IRI was continued by the World Bank. In 1982, the World Bank initiated a correlation experiment in Brazil to establish correlation and a calibration standard for roughness measurements (*5*). In processing the data, it became clear that nearly all roughness measuring instruments in use throughout the world were capable of producing measures on the same scale, if that scale were suitably selected. A number of methods were tested, and the "in/mi" calibration reference from NCHRP Report 228 was found to be the most suitable for defining a universal scale.

Several years of additional development were spent testing computation methods for a variety of profiling methods and step sizes. Example computer algorithms were published, and guidelines were written, reviewed, and published to define a reference measure that was called the International Roughness Index. The guidelines published by the World Bank explained how to measure IRI with a variety of equipment (*1*).

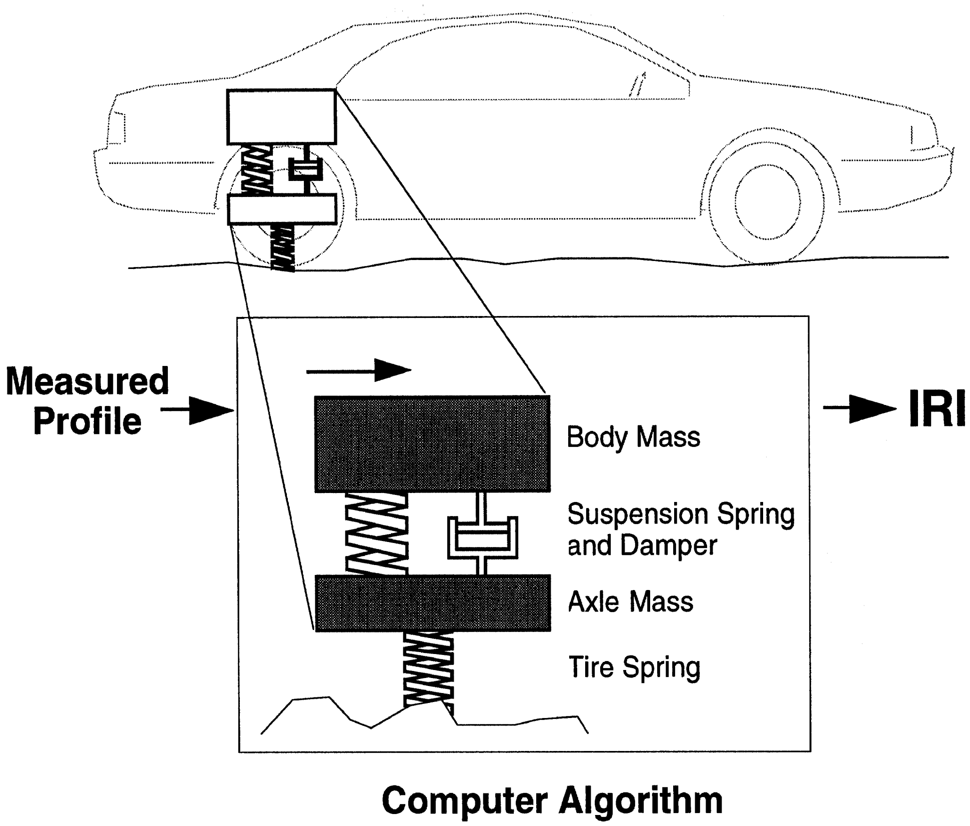

Figure B-1. Quarter-car model for IRI.

The IRI was designed to be reproducible, portable, and stable with time. It was the first widely used profile index where the analysis method is intended to work with different types of profilers. IRI is defined as a property of the true profile, and therefore it can be measured with any valid profiler. The analysis equations were developed and tested to minimize the effects of some profiler measurement parameters such as sample interval.

The IRI is a general pavement condition indicator that summarizes the roughness qualities that impact vehicle response and is most appropriate when a roughness measure is desired that relates to overall vehicle operating cost, overall ride quality, dynamic wheel loads (that is, damage to the road from heavy trucks, and braking and cornering safety limits available to passenger cars), and overall surface condition.

IRI is influenced primarily by roughness in wavelengths ranging from 1.33 to 30 m. The wave number response of the IRI quarter-car filter is shown in figure B-2. The amplitude of the output sinusoid is the amplitude of the input, multiplied by the gain shown in the figure. The gain shown in the figure is dimensionless. Thus, if the input is a sinusoid with an amplitude that is slope, the output is the product of the input amplitude and the value taken from the plot.

The IRI filter has maximum sensitivity to slope sinusoids with wave numbers near 0.066 cycles/m (a wavelength of about 15 m) and 0.45 cycles/m (a wavelength of about 2.2 m). The response is down to 0.5 for 0.033 cycles/m and 0.75 cycles/m wave numbers which correspond to wavelengths of 30 m and 1.33 m, respectively. However, there is still some response for wavelengths outside this range.

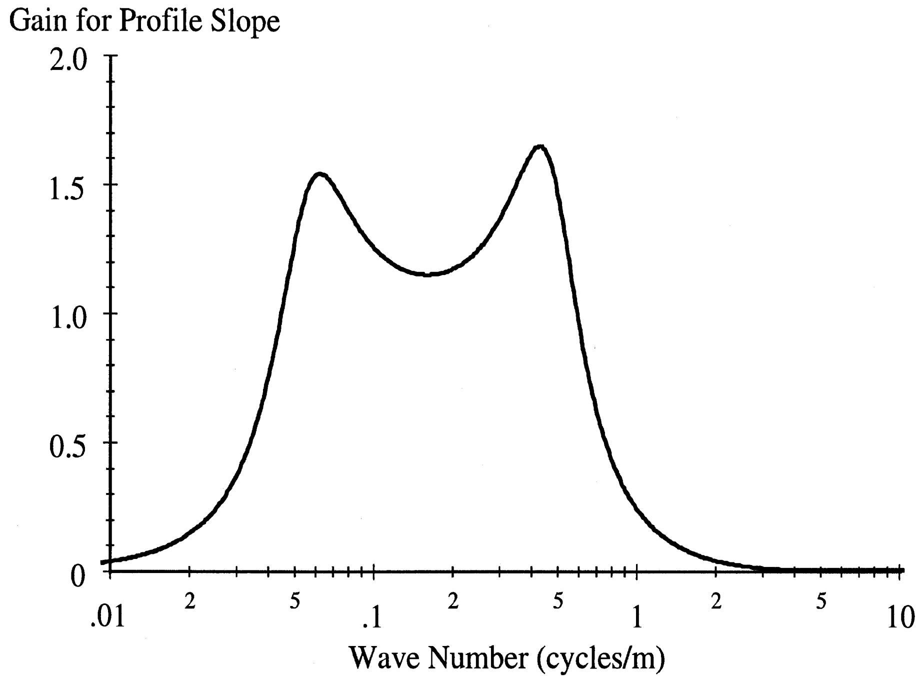

Figure B-2. IRI filter response.

The IRI scale is linearly proportional to roughness. If all of the elevation values in a measured profile are increased by some percentage, then the IRI increases by exactly the same percentage. An IRI of 0.0 means the profile is perfectly flat. There is no theoretical upper limit to roughness, although pavements with IRI values above 4 m/km usually cause traffic to slow below typical highway speed and pavement with IRI values greater than 8 m/km are nearly impassable except at speeds below 60 kph.

The IRI is calculated for a single profile. If a profiler measures several profiles simultaneously, then there is an IRI for each. The IRI standard does not specify how you locate the line on a road that defines the profile. Any possible line on the ground has an associated IRI. Usually, the IRI is measured in one track on the left side of a lane and one track on the right. If the two values are averaged, the result is called the MRI.

As part of the IRI calculation procedure, the profile is filtered with a moving average with a 250 mm baselength. The moving average is a low-pass filter that smoothes the profile. The computer program does not apply the filter unless the profile interval is shorter than 167 mm.

The 250-mm moving average filter should be omitted if the profile has already been filtered by a moving average or with an anti-aliasing filter that attenuates wavelengths shorter than 0.6 m. For example, Profilometers by K.J. Law detect elevation values at intervals of 25 mm, apply a 300-mm moving average filter, and store the result at 150 mm intervals. The filter used prior to storing the profile is very similar to the one used in the IRI, and therefore the moving average in the IRI should not be applied.

The profile is further filtered with a quarter-car simulation. The quarter-car parameters are specified as part of the IRI definition, and the simulated travel speed is specified as 80 kph. The parameters are:

$$\frac{k_s}{m_s} = 63.3\ (s^{-2}) \qquad \frac{k_t}{m_s} = 653\ (s^{-2}) \qquad \frac{c}{m_s} = 6\ (s^{-1}) \qquad \frac{m_u}{m_s} = 0.15\ (-) \qquad \text{(B-1)}$$

where k_s is the spring rate, m_s is the sprung mass, k_t is the tire spring rate, c is the damper rate, and m_u is the unsprung mass. The values listed in eqs. B-1 are called the "Golden Car" parameters.

The filtered profile is accumulated by summing absolute values and then is divided by the profile length. The resulting IRI statistic has units of slope. As a user, you can express the slope in any appropriate units. The most common choices are in/mi (multiply slope by 63,360) and m/km (multiply slope by 1000). The result is the theoretical equivalent of the output from response-type road roughness measuring systems that used to produce inches of suspension stroke per mile of travel.

Details of the IRI are handled in computer software. The analysis is applied to a single profile, the profile is filtered (twice), the filtered result is accumulated, and finally divided by the length of the profile. The IRI is linearly related to variations in profile, in the sense that if all of the elevation values in the profile are doubled, the resulting IRI will also be doubled. The source code for computing the IRI appears on the web at

`http://www.umtri.umich.edu/erd/roughness/iri_rn.txt`

RIDE NUMBER

For decades, highway engineers have been interested in estimating the opinion of the traveling public of the roughness of roads. The PSI scale from the AASHO Road Test has been of interest to engineers since its introduction in the 1950s (*6*). However, direct collection of subjective opinion in the form of mean panel rating is too expensive, and provides no continuity from year to year. RN is a profile index intended to indicate rideability on a scale similar to PSI.

RN is the result of NCHRP research in the 1980s. The NCHRP sponsored two research projects by Dr. Michael Janoff in the 1980s that investigated the effect of road surface roughness on ride comfort (*7, 8*). The objective of the research was to determine how features in road profiles were linked to subjective opinion about the road from members of the public. During two studies, spaced at about a five-year interval, mean panel ratings (MPR) were determined experimentally on a 0 to 5 scale for test sites in several states. Longitudinal profiles were obtained for the left- and right-hand wheeltracks of the lanes that were rated.

Profile-based analyses were developed to predict MPR. A method was developed in which power spectral density (PSD) functions were calculated for two longitudinal profiles and reduced to provide a summary statistic called PI. The PI values for the two profiles were then combined in a nonlinear transform to obtain an estimate of MPR.

RN is an estimate of MPR. The mathematical procedure developed to calculate RN is described in NCHRP Report 275, but not in complete detail. Software for computing RN with the PSD method was never developed for general use.

In 1995, some of the data from the two NCHRP projects and a panel study conducted by the Minnesota DOT were analyzed again in a pooled-fund study initiated by the FHWA (*3*). The objective was to develop and test a practical mathematical process for obtaining RN. The method was to be provided as portable software similar to that available for the IRI, but for predicting MPR rather than IRI. The profile data in the original research were obtained from several instruments. Most were measured with a K.J. Law Profilometer owned by the Ohio DOT and are thought to be accurate. A few other test sites were profiled with instruments whose validity has been questioned. The new analyses were limited to 140 test sites that had been profiled with the Ohio DOT system and the new data from Minnesota.

A new profile analysis method was developed that is portable to many devices. The software was tested on profiles obtained from different systems on the same sites, and similar values of RN were obtained. It predicts MPR slightly better than previously published algorithms. The new RN analysis method shares features with the IRI. It uses the same filtering method, which has been demonstrated to work with sample intervals ranging from 0 up to about 250 mm.

RN uses the 0 to 5 PSI scale. The 0 to 5 scale for present serviceability was used because it is so familiar to the highway community. However, the methods used in the NCHRP research were not the same as used in the prior tests, such as the AASHO Road Test. (The newer methods are based on a better understanding of psychological scaling than existed when the early tests were done and only seek to judge rideability. Most prior efforts also tried to cover general pavement condition.)

RN is a nonlinear transform of an RMS statistic. Keeping with the naming convention of Janoff and others, the index used in the RN analysis is called PI. PI generally ranges from 0 (a perfectly smooth profile) to positive values that increase with roughness. PI is transformed to a scale that goes from 5 (perfectly smooth) to 0 (the maximum possible roughness). The experimental data examined in the FHWA study validate the scale for values from 1 to 4.5.

The choice of scale creates a highly nonlinear relationship between profile variations and RN. If the RN is known for a profile, and the values of elevation are all doubled to increase roughness by a factor of 2, the RN will go down. However, the amount that RN decreases cannot be determined simply.

Nonlinearity limits some applications of RN. The nonlinearity poses no problem for the collection of roughness information to describe the condition of a road network. For roughness collected on a per-km basis (or any standard length), profile indices are converted to the 0 to 5 scale and entered into the database. However, some advanced capabilities of the IRI are difficult to apply to RN. The problem is that RN values for adjacent sections of profile cannot be averaged in the same way as IRI. For example, if one km has an RN value of 3 and the next has an RN of 4, the RN for the 2 km segment is not 3.5. (It is about 3.37.)

PI and RN are sensitive to shorter wavelengths than the IRI. Figure B-3 shows the sensitivity of RN. As in the earlier section on IRI, this shows the response of the PI for a slope sinusoid. If given a sinusoid as input, the RN filter produces a sinusoid as output.

The amplitude of the output sinusoid is the amplitude of the input, multiplied by the gain shown. The maximum sensitivity is for a wave number of 0.168 cycles/m, which is a wavelength of about 6 m. The response is down to 0.5 for 0.088 cycles/m and 2.6 cycles/m wave numbers which correspond to wavelengths of about 11.4 m and 0.38 m, respectively. However, there is still some response for wavelengths outside this range. The figure shows that the RN analysis has a low sensitivity to wavelengths from 12 to 30 m, where the IRI has high sensitivity.

The above descriptions of the RN background and properties are intended to give an idea of how to interpret the RN scale. As implemented in new software, RN is rigorously defined as a specific mathematical transform of a true profile. The specific steps taken in the computer program to compute RN are listed below.

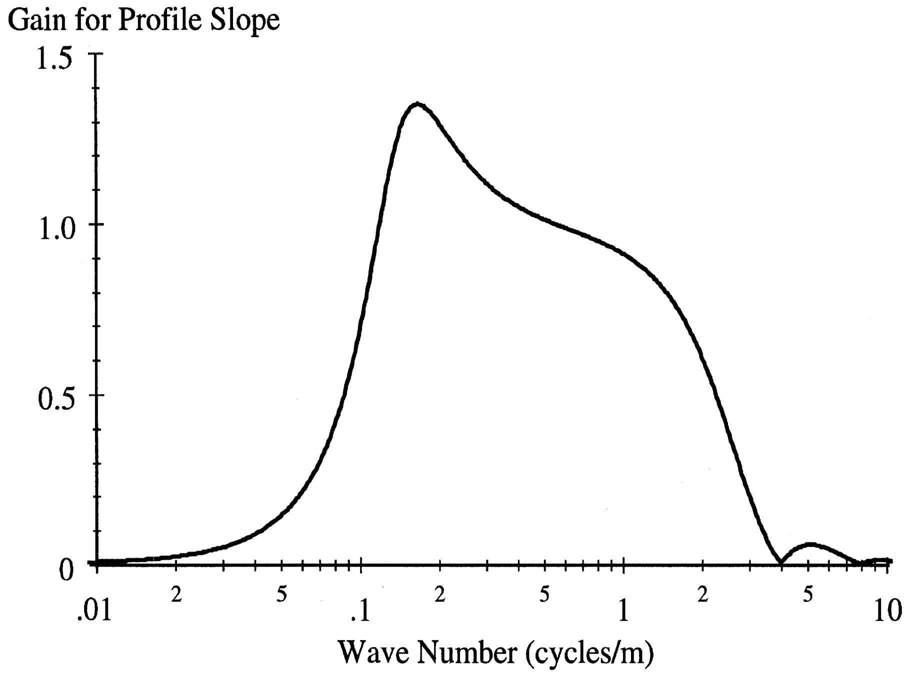

Figure B-3. RN filter response.

RN is calculated from two profiles. Ideally it is calculated from the profiles in the left and right wheeltracks used by automobile traffic. Each profile is processed independently and the results are combined in the last step. RN can also be calculated for a single profile if only one is available, but the results provide a much more crude estimate of MPR.

The profile is filtered with a moving average with a 250 mm baselength. The moving average is a low-pass filter that smoothes the profile. The computer program does not apply the filter unless the profile interval is shorter than 167 mm.

The 250-mm moving average filter should be omitted if the profile has already been filtered by a moving average or with an anti-aliasing filter that attenuates wavelengths shorter than 0.6 m. For example, Profilometers by K.J. Law detect elevation values at intervals of 25 mm, apply a 300-mm moving average filter, and store the result at 150 mm intervals. The filter used prior to storing the profile is very similar to the one used in the RN, and therefore the moving average in the RN algorithm should not be applied.

The profile is further filtered with band-pass filter. The filter uses the same equations as the quarter-car model in the IRI. However, different coefficients are used to obtain the sensitivity to wave number shown in figure B-3. The quarter-car parameters for the RN filter are

$$\frac{k_s}{m_s} = 5120\ (s^{-2}) \qquad \frac{k_t}{m_s} = 390\ (s^{-2}) \qquad \frac{c}{m_s} = 17\ (s^{-1}) \qquad \frac{m_u}{m_s} = 0.036\ (-) \qquad \text{(B-2)}$$

The filtered profile is reduced to yield an RMS value called PI, that should have units of dimensionless slope (ft/ft, m/m, etc.). PI is then transformed to RN.

RN is defined as an exponential transform of PI according to the equation

$$RN = 5e^{-160(PI)} \qquad \text{(B-3)}$$

If a single profile is being processed, its PI is transformed directly. If two profiles for both the left and right wheeltracks are processed, values for the two are averaged with the following equation, and then the transform is applied.

$$PI = \sqrt{\frac{PI_L^2 + PI_R^2}{2}} \qquad \text{(B-4)}$$

Details of RN calculation are handled in computer software. The analysis is applied to two profiles, each profile is filtered (twice), the filtered result is accumulated, and cast onto the familiar PSI scale. The source code for computing RN appears in ASTM Standard 1489-96, "Standard Practice for Computing Ride Number of Roads from Longitudinal Profile Measurements Made by an Inertial Profilers." Unfortunately, the source code provided in this standard includes transcription errors. (In subroutine `SETSTM`, a carriage return is missing at the end of the `DIMENSION` line. In subroutine `INVERT`, the line "`DO I = 1, N`" should appear just after the `DIMENSION` line.) Correct, heavily tested code for computing RN appears on the web at

`http://www.umtri.umich.edu/erd/roughness/iri_rn.txt`

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APPENDIX C

ANALYSIS OF 1993 RPUG DATA

This appendix presents analyses that were performed on data from the 1993 RPUG experiment. In the 1993 RPUG experiment several profilers that normally operate in North America made multiple measurements of a small set of test sections. The experiment covered devices operated by state departments of transportation, LTPP regional contractors, profiler manufacturers, and other private operators. In each of four regions, profilers measured up to eight sections as many as ten times each. These measurements took place five years before this report was written. Although the state of profiling practice has improved since then, the 1993 RPUG data remain the largest source of measurements from multiple profilers on the same sections.

These data were used in this research to study the capabilities of common profilers in use in North America. Usually, the results were used as a foundation for discussion of new experiments. The 1993 RPUG experiment served as the primary source of data in cases where a new experiment was either not warranted or not practical. The factors investigated using these measurements were (1) the accuracy of longitudinal distance measurement, (2) the repeatability of profilers from the experiment, (3) the agreement of profilers with a reference measurement, (4) the level of bias caused by coarse surface texture, and (5) the effect of operating speed on repeatability.

This appendix provides only the information pertinent to discussions within the main body of the report. A more detailed description of the 1993 RPUG experiment and the results was distributed after the 1993 RPUG meeting (*1*).

THE RPUG EXPERIMENT

The RPUG experiment took place in four regions in the U.S. In each region, a state DOT prepared up to eight test sections 160.9 m long. These sections, described in table C-1, were selected to cover range of surface type, roughness, and surface texture. Each profiler that participated in the study measured the sections in the region in which it operates. In most cases, the profilers measured each section ten times. Usually, five measurements were made at a speed near 80 kph and five were made at a speed near 64 kph. The sections were also measured using a Dipstick to provide a reference roughness value. Overall, 34 profilers took part in the study and more than 2400 measurements were made. Table C-2 lists the profilers covered in this appendix. The table provides an instrument number for each profiler that is used to identify them throughout this appendix. The table also lists the sensor type, sample interval, and manufacturer. If South Dakota is listed as the manufacturer, it means that the profiler was built in-house by a state highway agency.

Table C-1. Sections measured in the 1993 RPUG experiment.

Region	Section Number	Pavement Type	IRI Left Wheeltrack (m/km)
Mississippi	1	Asphalt Concrete	1.25
	2	Composite	0.89
	3	Composite	2.55
	4	Asphalt Concrete	3.41
	5	Portland Cement Concrete	2.94
	6	Portland Cement Concrete	1.28
	7	Portland Cement Concrete	2.72
	8	Portland Cement Concrete	1.69
Nevada	1	Asphalt Concrete	2.79
	2	Asphalt Concrete	0.80
	3	Asphalt Concrete	3.55
	4	Portland Cement Concrete	1.78
	5	Portland Cement Concrete	1.69
	6	Portland Cement Concrete	1.10
Pennsylvania	1	Asphalt Concrete	2.61
	2	Asphalt Concrete	1.06
	3	Asphalt Concrete	2.13
	4	Asphalt Concrete	2.36
	5	Portland Cement Concrete	2.78
	6	Portland Cement Concrete	3.23
	7	Portland Cement Concrete	1.89
	8	Portland Cement Concrete	1.40
South Dakota	1	Asphalt Concrete	3.89
	2	Asphalt Concrete	1.30
	3	Asphalt Concrete	1.42
	4	Asphalt Concrete	1.09
	5	Portland Cement Concrete	1.54
	6	Portland Cement Concrete	1.37
	7	Portland Cement Concrete	1.73
	8	Portland Cement Concrete	1.45

Table C-2. Devices that participated in the 1993 RPUG experiment.

Region	Inst. #	Make	Model	Sensor Type	Sample Interval (mm)	Tracks	Number of Measurements
M	MDS	Dipstick		I	305	B	8
	M01	ICC	MDR 4090	U	327	L	80
	M02	ICC	MDR 4087	U	332	B	79
	M03	ICC	MDR 4087 L	L	165	B	58
	M05	Pave Tech		U	263	B	80
	M06	K.J. Law	6900 DNC	O	152	B	100
N	N03	ICC	MDR 4090	U	326	B	59
	N04	ICC	MDR 4097	U	328	B	59
	N06	ICC		U	302	B	60
	N07	ICC	MDR 4090 L	L	160	B	61
	N08	K.J. Law	690 DNC	O	152	B	60
	N09	K.J. Law	6900 DNC	O	152	B	58
P	PDS	Dipstick		I	305	B	8
	P01	ProRut		L	50	B	80
	P02	ICC	MDR 4090	U	333	B	80
	P03	ICC		U	331	B	80
	P04	ICC	4900 LaserSDP	L	101	B	80
	P05	K.J. Law	690 DNC	O	152	B	80
	P06	ICC	MDR 4097	U	319	B	78
	P07	K.J. Law	6900 DNC	O	152	B	80
	P08	ICC	MDR 4087 L	L	165	B	74
	P73	ICC	MDR 4195	U	342	B	80
	P74	ICC	MDR 4195	U	342	B	79
	P75	ICC	MDR 4195	U	343	B	80
	P76	ICC	MDR 4195	U	340	B	80
S	SDS	Dipstick		I	305	B	8
	S01	ICC		U	323	B	65
	S02	South Dakota		U	305	L	80
	S03	Pave Tech		U	331	L	80
	S04	South Dakota		U	305	L	77
	S05	K.J. Law		O	152	B	47
	S06	South Dakota		U	305	L	79
	S08	K.J. Law	6900 DNC	O	152	B	77
	S10	ARAN	4300 LaserSDP	L	204	B	58
	S11	Pave Tech		U	335	B	40
	S12	South Dakota		U	305	L	80

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota
I - Inclinometer O - Optical U - Ultrasonic L - Laser
L - Left B - Both (Left and Right)

LONGITUDINAL DISTANCE MEASUREMENT

The 1993 RPUG tests were designed to eliminate errors in longitudinal positioning of the measurements. To help maintain a consistent starting position in each measurement, an artificial bump was placed on the road before and after each section. The bumps were about 6 mm high, 0.46 m long, and were located 30.5 m upstream and 15.2 m downstream of the section of interest. The data files used in the analyses reported in this appendix were lined up using cross-correlation rather than the bumps in the profile. This method is described in a recent FHWA report (*2*). The result of the cross-correlation program was that the "zero" location of every file was reset to match a reference measurement, usually by the Dipstick. Since the sections were all 160.9 m long, the bumps should appear 206.7 m apart at the longitudinal locations –30.48 and 176.17 m. This was used to check the procedure for lining up the sections.

The distance between the bumps measured by each profiler was also used to gauge the accuracy of their longitudinal distance measurement. Not all of the measurements included enough profile surrounding the section of interest to contain both bumps. Some other measurements were long enough, but no bump appeared in the expected location. (These cases prompted some plotting to make sure the section was lined up properly.) Naturally, the measurement of longitudinal distance was only checked on measurements where both bumps appeared clearly in the profile. Table C-3 lists the results for each profiler. The table lists the number of measurements that included both bumps, the average distance between them, and the error in percent. The table also lists the average offset level in units of length. A negative offset means the profiler underestimated the distance and a positive offset means the profiler overestimated the distance. In most cases, the offset error (or bias) in longitudinal distance measured by a profiler was consistent from run to run. Thus, the average offset error represents the value expected in a single run. The offset error is listed side-by-side with the sample interval to identify cases where the error was not much larger than the sample interval.

Table C-3 demonstrates that most profilers measure longitudinal distance fairly accurately. Twenty-one of the thirty profilers measured the distance between the bumps consistently within two profile samples. Since each bump can only be detected in the profile within one sample, these twenty-one devices are considered correct. Three of the profilers exhibited an error level greater then 1 m, or about 0.5 percent. This is more serious: A bias in longitudinal distance measurement of 0.5 percent or more should prompt recalibration of the distance measurement instrument.

The profilers that exhibited the greatest error in longitudinal distance measurement may have slowed down significantly over the bumps to avoid damage to the vehicle, or simply because the bumps were not within the section of interest in the study. If the error was caused by extremely low-speed operation, it is of lesser concern because it does not represent typical operation of the profilers.

Table C-3. Longitudinal distance measurement accuracy.

Region	Inst. Number	Number of Measurements	Average Separation (m)	Percent Error	Offset (mm)	Sample Interval (mm)
M	M01	73	206.15	-0.25	-509	327
	M02	76	208.35	0.82	1700	332
	M03	50	206.14	-0.25	-518	165
	M05	72	206.40	-0.12	-258	263
	M06	99	207.19	0.26	539	152
N	N04	59	206.51	-0.07	-149	328
	N08	60	206.74	0.04	88	152
	N09	57	207.75	0.53	1094	152
P	P01	79	206.41	-0.12	-242	50
	P02	80	206.66	0.00	8	333
	P03	80	207.34	0.33	683	331
	P04	76	206.85	0.09	193	101
	P05	70	206.79	0.07	137	152
	P06	68	206.61	-0.02	-47	319
	P07	80	206.62	-0.02	-34	152
	P08	74	206.24	-0.20	-415	165
	P73	79	206.72	0.03	62	342
	P74	79	206.59	-0.03	-62	342
	P75	80	206.53	-0.06	-128	343
	P76	80	206.69	0.02	32	340
S	S01	64	206.18	-0.23	-474	323
	S02	78	206.46	-0.09	-191	305
	S03	55	206.46	-0.09	-194	331
	S04	65	206.57	-0.04	-80	305
	S05	47	206.51	-0.07	-139	152
	S06	70	205.87	-0.38	-786	305
	S08	77	206.48	-0.09	-176	152
	S10	53	203.21	-1.67	-3444	204
	S11	40	206.40	-0.12	-256	335
	S12	70	206.63	-0.01	-22	305

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota

REPEATABILITY

The repeatability of a profiling device is its ability to produce the same result in multiple runs with minimal random error. It is very important that a profiler measure roughness with reasonable repeatability, since a device that is not repeatable has no hope of being accurate. A lack of repeatability also suggests that a random error source is present in the measurement. The main body of the report discusses some aspects of the pavement surface shape that affect repeatability through no fault of a profiler. Transverse, longitudinal, and temporal variations in pavement roughness may introduce scatter into a set of measurements, even if a perfectly repeatable profiler was used.

The goal of this section is to present statistics that summarize the level of repeatability of common profilers. The 1993 RPUG data are a good source for judging repeatability without the confounding influence of variations in pavement roughness with time and position. Each profiler visited each section once and made all of the measurements of a section in a short time span, so variations in roughness with time should not affect the results. The measurements are also lined up longitudinally. Although the lateral position of the profilers was not strictly controlled, paint marks were placed every 7.6 m along the left wheeltrack of each section to help guide the drivers along a similar path. At the very least, these paint marks reminded the drivers of the importance of consistent lateral positioning in the experiment.

International Roughness Index

Most of the profilers listed in table C-2 measured all of the sections in their region ten times. To quantify the scatter exhibited by a profiler, each IRI value was normalized by the average of the ten measurements on a given wheeltrack of a given section. For example, the ProRut measured eight sections ten times each. The IRI was computed for the left and right wheeltrack in each measurement, for a total of 160 roughness values. Each set of ten measurements from one side of a section was normalized by their average, and the values on all sixteen wheeltracks were compiled into a histogram, shown in figure C-1. Of course, the average of the 160 values in the figure is 1. The scatter is an indication of the level of repeatability. The standard deviation of the values in the figure is 0.027. This means that about 68 percent of the measurements by the ProRut were within 2.7 percent of the prevailing average for a given wheeltrack. A more relevant way to summarize the performance than the standard deviation is to set a limit for the scatter and see how many measurements fall within the limit. For example, the histogram shows that most of the roughness values (150 out of 160) measured by the ProRut are within 5 percent of the section average. If the limit is set a 2 percent, only 101 of measurements "pass."

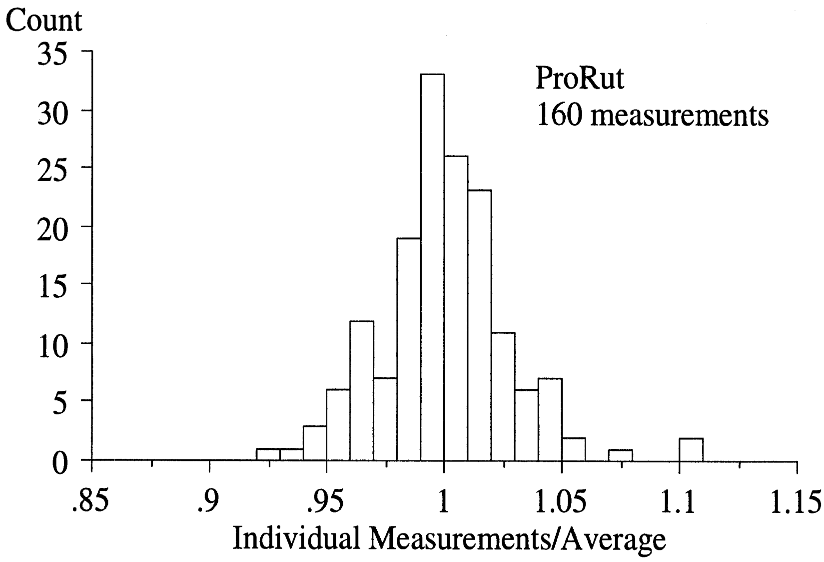

Figure C-1. Repeatability of the ProRut.

IRI values from all of the profilers were compiled in this fashion as a means of characterizing each profiler's repeatability. The results should not be interpreted too precisely, since not every profiler made the same set of measurements. Not all of the profilers within a region measured all of the sections exactly ten times. Some profilers, usually the South Dakota type, measured only the left wheeltrack. Each region had a unique set of sections, so only comparisons of major trends should be made across all of the regions. Nevertheless, some of the trends are so strong that they are meaningful.

Table C-4 summarizes the results. The table provides the standard deviation, the number of measurements within 2 percent of the average, and the number of measurements within 5 percent of the average. The standard deviation is expressed as a percentage. For example, the standard deviation for the histogram in figure C-1 would be listed as 2.7 percent, rather than 0.027.

Table C-4. Repeatability of profilers in measurement of IRI.

Region	Device	Sensor Type	Number of Meas.	Std. Dev. (%)	Within 2 Percent (Count)	Within 2 Percent (%)	Within 5 Percent (Count)	Within 5 Percent (%)
M	M01	U	80	4.77	26	32.5	59	73.8
	M02	U	158	4.74	61	38.6	126	79.7
	M03	L	116	3.59	62	53.4	99	85.3
	M05	U	160	7.80	48	30.0	95	59.4
	M06	O	200	1.92	162	81.0	194	97.0
N	N03	U	118	6.65	35	29.7	66	55.9
	N04	U	118	6.63	39	33.1	81	68.6
	N06	U	120	5.64	37	30.8	83	69.2
	N07	L	120	4.15	71	59.2	106	88.3
	N08	O	120	3.59	76	63.3	109	90.8
	N09	O	116	3.49	59	50.9	100	86.2
P	P01	L	160	2.72	101	63.1	150	93.8
	P02	U	160	3.76	72	45.0	132	82.5
	P03	U	160	3.87	69	43.1	130	81.3
	P04	L	160	3.80	92	57.5	136	85.0
	P05	O	160	1.86	117	73.1	159	99.4
	P06	U	156	7.46	63	40.4	114	73.1
	P07	O	160	2.57	116	72.5	151	94.4
	P08	L	146	2.37	88	60.3	142	97.3
	P73	U	159	3.84	80	50.3	141	88.7
	P74	U	158	3.00	91	57.6	143	90.5
	P75	U	160	3.20	74	46.3	142	88.8
	P76	U	160	2.28	102	63.8	155	96.9
S	S01	U	130	3.57	71	54.6	112	86.2
	S02	U	80	7.62	23	28.8	44	55.0
	S03	U	80	10.60	12	15.0	33	41.3
	S04	U	77	5.65	30	39.0	53	68.8
	S05	O	94	5.47	68	72.3	87	92.6
	S06	U	79	4.78	37	46.8	66	83.5
	S08	O	154	1.63	131	85.1	152	98.7
	S10	L	116	2.49	63	54.3	113	97.4
	S11	U	80	5.09	31	38.8	63	78.8
	S12	U	80	7.46	25	31.3	49	61.3

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota
O - Optical U - Ultrasonic L - Laser

The number of measurements within 2 percent of the average can be thought of as a gauge of a profiler's ability to function as a reference device. Specific definitions aside, a profiler that claims to be "Class 1" should be able to repeat a measurement of IRI within 2 percent on a section 160.9 m long. On the other hand, only slight deviations in lateral positioning of the measurement can cause changes in IRI larger than that. Thus, a profiler may be Class 1 capable, but the combination of profiler, operator, operational procedures, and surface type may not. Of course, the performance of the overall combination of these things is a more informative measure of how a profiler is likely to work in practice. Besides, if a profiler does not include any features that aid a driver in holding a consistent lateral position, why should the resulting variations not reflect on the profiler's probable performance in the field? The same could be said for triggering, detection of bad readings, operating outside the valid speed range for the profiler, etc.

Only two of the profilers measured IRI within 2 percent of the average more then three-fourths of the time. These were both K.J. Law profilers in use in the LTPP study.

The number of measurements within 5 percent of the average is a gauge of a profiler's sufficiency for use in network-level profiling. Meeting this requirement means that a profiler can measure a long stretch of road just once (as is usually the case in network monitoring) with confidence that IRI values of 160.9 m long segments are probably within 5 percent of the value that the profiler would measure in several repeats. Five percent is not very restrictive, but network-level profiling does not require a high level of precision. Besides, the roughness of most roads varies more than 5 percent between network monitoring visits.

Keep in mind that the level of repeatability in percent, as expressed in this discussion, is tied very closely to the segment length. The variations in IRI would be much lower if the segment length were 1.6 km, rather than 161 m, and most of these profilers would meet the 5 percent sufficiency requirement just described.

The broad range of performance exhibited by these profilers can be attributed largely to sensor technology. Table C-5 summarizes the performance of four broad types of profilers: (1) agency-built ultrasonic, (2) commercially built ultrasonic, (3) laser, and (4) optical. Strictly speaking, the normalized roughness values from different regions should not be mixed, because the differences in the test sections gives them different meaning, but they are combined anyway to illustrate the large disparity in performance between the profiler types.

Table C-5. Repeatability of profiler types in measurement of IRI.

Profiler Type	Number of Meas.	Std. Dev. (%)	Within 2 Percent (Count)	Within 2 Percent (%)	Within 5 Percent (Count)	Within 5 Percent (%)
Optical	923	2.95	670	72.6	877	95.0
Laser	818	3.23	477	58.3	746	91.2
Ultrasonic, Commercial	2157	5.32	911	42.2	1675	77.7
Ultrasonic, Agency-built	316	6.47	115	36.4	212	67.1

The profilers with ultrasonic sensors were much less repeatable than the others, and do not appear to be acceptable for measuring IRI. Commercially built ultrasonic profilers performed much better than the agency-built profilers, but only a handful of ultrasonic profilers from Pennsylvania exhibited acceptable repeatability for network-level roughness measurement. The profilers with laser sensors were very often within 5 percent of the average, but did not pass the "reference device" test of repeating IRI within 2 percent consistently. Optical profilers performed the best, and were all sufficient for network-level applications.

The difference between the laser and optical profilers is most likely the sensor footprint. The diameter of the footprint of laser sensors ranges from 1 mm to 5 mm. The optical profilers use a rectangular footprint that is 6 mm long and by 150 mm wide. This large footprint means that the optical profilers are much less prone to variations caused by short features in the road that a laser profiler might capture in one run but miss in another, such as a narrow crack. The large footprint of the optical height sensor also averages out coarse texture, which is a physical form of anti-alias filtering. The width of the optical height sensor footprint probably also reduces variations in roughness caused by inconsistency in lateral positioning from run to run. With aggressive anti-alias filtering and spike detection, sensors with a very small footprint should be able to perform as well as the optical profilers did in the RPUG experiment.

Ride Number

The same statistics presented in table C-4 were also compiled for the RN. RN is defined as an index computed from profiles in two wheeltracks (*2*). Thus, only profilers that measured two wheeltracks are included in the analysis. In addition, bias in the analysis caused by the nonlinearity of the 0 to 5 scale was avoided by compiling statistics on the PI used to compute RN, rather than the RN itself. Table C-6 provides the results.

Two optical profilers (P05 and S08) and one laser profiler (P08) stood out as the most repeatable in measuring RN, but some of the others were not even repeatable enough for network-level measurements. About half of the ultrasonic profilers measured RN with good repeatability, but they also measured RN with a significant downward bias.

ACCURACY

The accuracy of a profiling device is its ability to produce a result that is near the truth without bias. This is an illusive concept. No profiler measures the true profile in the sense that they are all limited to a finite waveband. For example, profilers do not measure topography or texture well, so some part of the true shape of the road is missed. On the other hand, it is possible for a profiler to measure the range of wavelengths of interest for computing IRI or RN correctly. The goal of this section is to present statistics that summarize the accuracy level of the profilers in the 1993 RPUG experiment.

All of the test sections in Mississippi, Pennsylvania, and South Dakota were measured with a Dipstick. The roughness values from these measurements are used as reference values for assessing the accuracy of the inertial profilers. All of the measurements covered the same longitudinal range as the Dipstick measurements. Although the lateral position of the profilers was not strictly controlled, paint marks were placed every 7.6 m along the left wheeltrack of each section to help guide the drivers along a similar path. Since the experiment took place over a few months, changes in roughness of these sections with time may bias the roughness values.

Table C-6. Repeatability of profilers in measurement of RN.

Region	Device	Sensor Type	Number of Meas.	Std. Dev. (%)	Within 2 Percent (Count)	Within 2 Percent (%)	Within 5 Percent (Count)	Within 5 Percent (%)
M	M02	U	79	7.45	25	31.6	51	64.6
	M03	L	58	5.96	32	55.2	45	77.6
	M05	U	80	28.03	8	10.0	24	30.0
	M06	O	100	4.73	62	62.0	90	90.0
N	N03	U	59	10.42	8	13.6	20	33.9
	N04	U	59	6.27	16	27.1	35	59.3
	N06	U	60	6.84	15	25.0	36	60.0
	N07	L	60	3.60	35	58.3	52	86.7
	N08	O	60	12.09	18	30.0	31	51.7
	N09	O	58	8.19	23	39.7	31	53.4
P	P01	L	80	2.79	56	70.0	73	91.3
	P02	U	80	3.67	39	48.8	68	85.0
	P03	U	80	4.23	35	43.8	68	85.0
	P04	L	80	2.87	51	63.8	75	93.8
	P05	O	80	1.76	64	80.0	79	98.8
	P06	U	78	35.64	4	5.1	27	34.6
	P07	O	80	9.55	28	35.0	50	62.5
	P08	L	73	2.36	48	65.8	70	95.9
	P73	U	79	14.19	34	43.0	65	82.3
	P74	U	79	4.00	39	49.4	66	83.5
	P75	U	80	3.59	31	38.8	64	80.0
	P76	U	80	2.61	47	58.8	75	93.8
S	S01	U	65	3.36	37	56.9	57	87.7
	S05	O	47	20.31	26	55.3	36	76.6
	S08	O	77	3.51	58	75.3	75	97.4
	S10	L	58	2.71	37	63.8	51	87.9
	S11	U	40	5.93	19	47.5	30	75.0

M - Mississippi   N - Nevada   P - Pennsylvania   S - South Dakota
O - Optical   U - Ultrasonic   L - Laser

The IRI values computed for all of the measurements in Mississippi, Pennsylvania, and South Dakota were normalized by a reference value from the Dipstick. For example, the ProRut measured eight sections ten times each. The IRI was computed for the left and right wheeltrack in each measurement, for a total of 160 roughness values. The bias between all of these roughness values and the corresponding value from the Dipstick were compiled into a histogram, shown in figure C-2.

The average of the 160 values in the figure is 9.4, which means that the ProRut measured IRI an average of 9.4 percent higher than the Dipstick. This is an overall estimate of the bias between the ProRut and the Dipstick. The average bias level represents the accuracy of the ProRut if the Dipstick is accepted as a reference. The RMS error was 12.3 percent. The RMS error penalizes a profiler for bias and scatter, so it delineates a combination of the accuracy and repeatability problems in a profiler. All profilers will have some level of RMS error. For network-level applications, a combination of no bias and an RMS error under 5 percent is preferred.

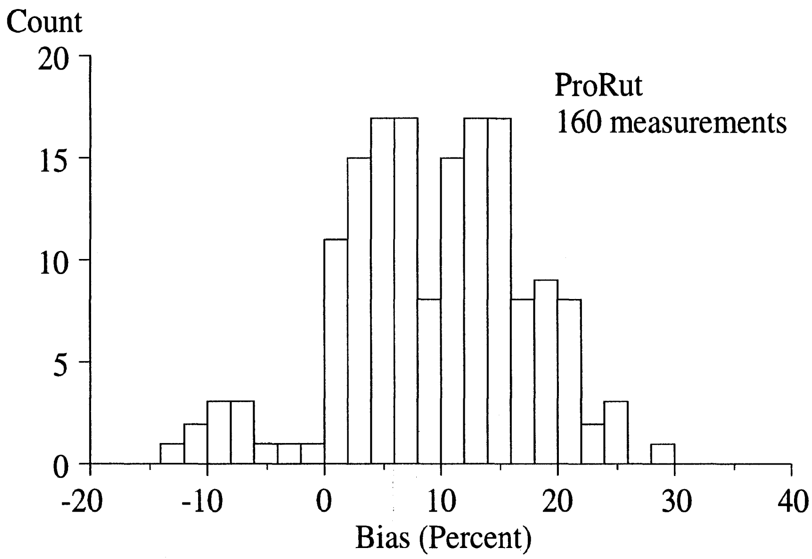

Figure C-2. Bias in IRI by the ProRut.

Bias errors can exist for several reasons: aliasing errors caused by narrow cracks or coarse surface texture, spikes in the sensor signals caused by the environment, variations in lateral tracking that consistently place a profiler on a path other then the one measured by the reference device, or changes in the road surface between the day of the reference measurement and the day of the other tests. The RMS error should include all of the factors that confound profiler measurement, including the factors just listed and everything that degrades the repeatability of a set of measurements.

IRI values from all of the profilers in Mississippi, Pennsylvania, and South Dakota were compared to Dipstick values as a means of characterizing each profiler's accuracy and RMS error level. The results are listed in table C-7. The results should not be interpreted too precisely, since not every profiler made the same set of measurements. Not all of the profilers within a region measured all of the sections exactly ten times. Some profilers, usually the South Dakota type, measured only the left wheeltrack. Each region had a unique set of sections, so only comparisons of major trends should be made across all of the regions. Nevertheless, some of the trends are so strong that they are meaningful.

Very few devices stood out as agreeing with the Dipstick measurements very well. The few promising numbers in table C-7 are listed in bold. The bias and RMS error of these devices was heavily linked to the sensor type. Figures C-3 through C-6 show the histograms for all measurements by four broad types of profiler: (1) agency-built ultrasonic, (2) commercially built ultrasonic, (3) laser, and (4) optical. Table C.8 also provides summary statistics. All of the histograms are shown on the same scale for comparison. The optical profilers had the lowest bias and RMS error, followed by the laser profilers. As described in the section on repeatability, the large footprint of the optical sensors is probably the reason optical profilers in the RPUG study were generally more accurate than laser profilers.

Table C-7. Accuracy of profilers in measurement of IRI.

Region	Device	Sensor Type	Number of Meas.	Bias (%)	RMS Error (%)	Within 5 Percent (Count)	(%)
M	M01	U	80	11.4	14.8	19	23.8
	M02	U	158	21.3	26.9	21	13.3
	M03	L	116	**5.1**	10.8	38	32.8
	M05	U	160	9.3	15.9	46	28.8
	M06	O	200	**4.7**	**8.4**	77	38.5
P	P01	L	160	9.4	12.3	36	22.5
	P02	U	160	30.1	34.8	0	0.0
	P03	U	160	27.3	32.3	0	0.0
	P04	L	160	12.0	16.3	37	23.1
	P05	O	160	11.0	14.9	27	16.9
	P06	U	156	32.4	39.0	0	0.0
	P07	O	160	11.3	13.3	19	11.9
	P08	L	146	9.5	11.5	40	27.4
	P73	U	159	25.7	31.7	4	2.5
	P74	U	158	23.7	27.9	5	3.2
	P75	U	160	21.1	26.8	13	8.1
	P76	U	160	22.6	28.3	3	1.9
S	S01	U	130	44.8	62.3	23	17.7
	S02	U	80	18.9	29.2	24	30.0
	S03	U	80	42.4	68.5	27	33.8
	S04	U	77	51.1	70.4	18	23.4
	S05	O	94	**-0.3**	**7.6**	70	**74.5**
	S06	U	79	50.6	71.7	16	20.3
	S08	O	154	**2.9**	**7.3**	83	**53.9**
	S10	L	116	13.7	19.1	33	28.4
	S11	U	80	36.0	51.0	8	10.0
	S12	U	80	51.8	77.3	19	23.8

M - Mississippi   N - Nevada   P - Pennsylvania   S - South Dakota
O - Optical   U - Ultrasonic   L - Laser

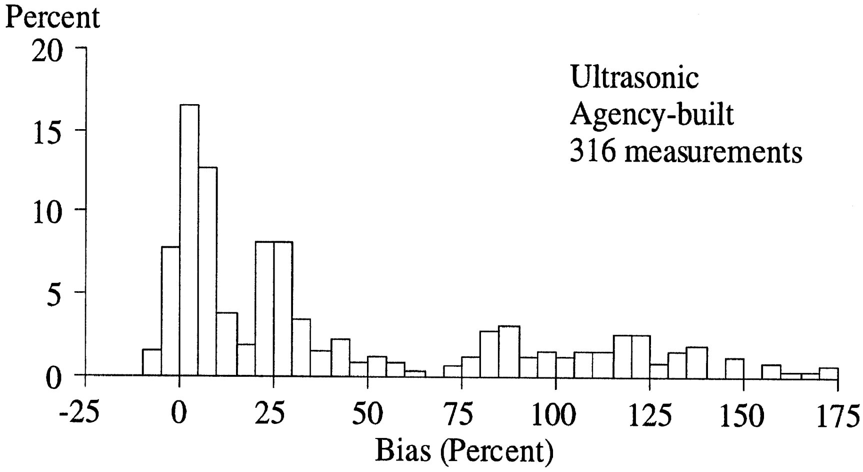

Figure C-3. Bias in agency-built ultrasonic profilers from the RPUG.

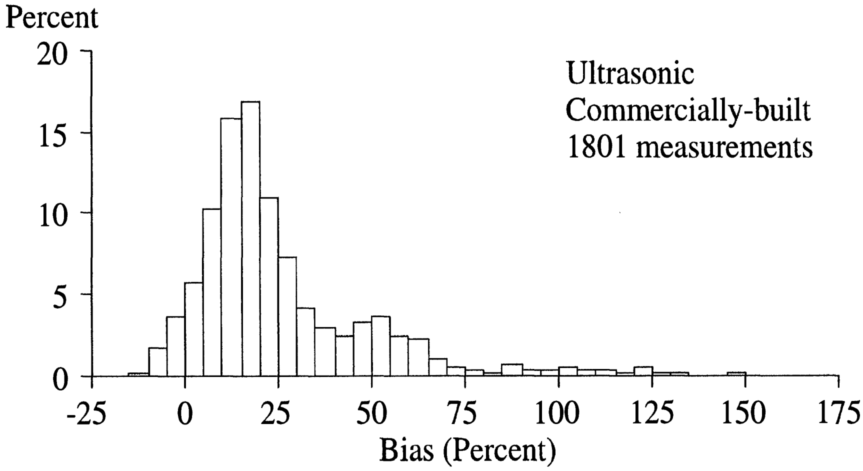

Figure C-4. Bias in commercial ultrasonic profilers from the RPUG.

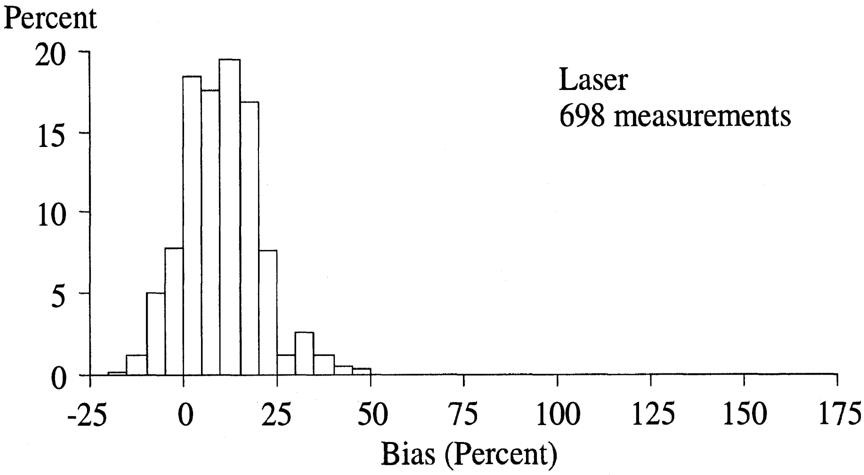

Figure C-5. Bias in laser profilers from the RPUG.

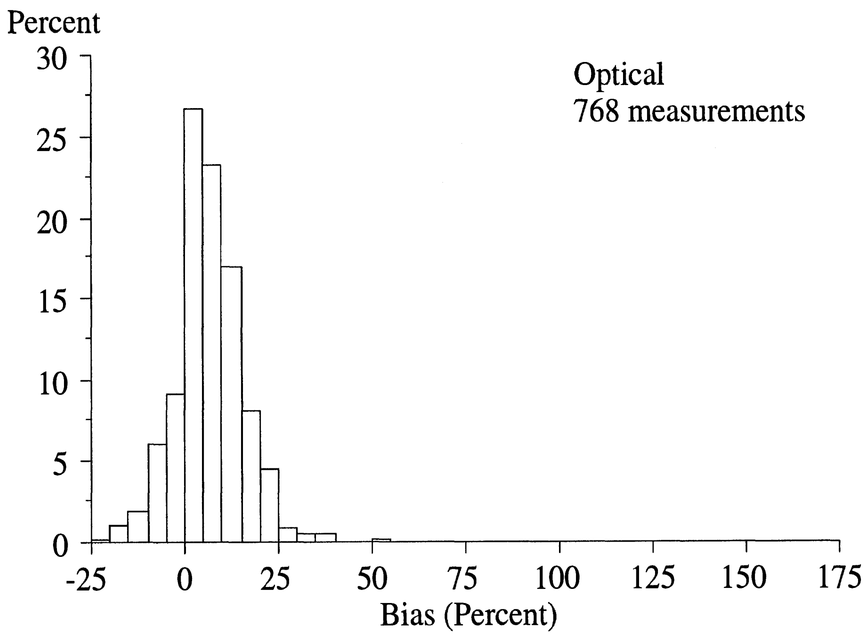

Figure C-6. Bias in optical profilers from the RPUG.

The scatter and bias of the laser and optical profilers compared to the Dipstick measurements are caused by lateral tracking variations, sensing of short features that the Dipstick ignores, the lack of aggressive measures to avoid aliasing errors, and problems inherent in using noncontact sensors in an uncontrolled environment at high speed. This project set out to understand all of these sources of error and variation and suggest ways to eliminate them. Indeed, these issues are covered in the main body of the report.

The ultrasonic profilers, both agency-built and commercial, measured IRI with huge bias and scatter. In contrast to the laser and optical sensors, ultrasonic sensors are not sufficient for the job of measuring IRI. Some of the commercial ultrasonic profilers performed well on most sections, but horribly on sections with coarse surface texture. This is why the histograms in figure C-3 and C-4 extend so far to the right. If IRI values are to be compared from agency to agency or year to year, ultrasonic sensors must be replaced.

Table C-8. Accuracy of profiler types in measurement of IRI.

Profiler Type	Number of Meas.	Bias (%)	RMS Error (%)	Within 5 Percent (Count)	Within 5 Percent (%)
Optical	768	6.4	10.9	276	35.9
Laser	698	10.0	14.2	184	26.4
Ultrasonic, Commercial	1801	26.1	36.4	169	9.4
Ultrasonic, Agency-built	316	43.0	65.0	77	24.4

SURFACE TEXTURE

Coarse surface macrotexture has the potential to cause an upward bias in roughness. For example, on a pavement with a fresh chip seal height sensors with a small footprint may detect the top of a piece of protruding aggregate in one sample and miss the aggregate in another. If the sample interval is too large or a profiler operates without anti-aliasing filters, the texture could erroneously appear in the final profile as deviations with a long enough wavelength to affect the IRI or RN. Laser sensors sample fast enough to allow surface texture to be recognized and averaged out using anti-alias filters. Optical height sensors have a footprint so large that coarse texture is probably averaged out.

Ultrasonic sensors have a footprint that is 50 to 100 mm in diameter. This footprint is large enough to average out texture, but ultrasonic height sensors do not work this way. They register a reading as soon as the reflected acoustic wave is first detected, so they actually detect the highest point within the footprint. There is no way to average these deviations out, because a reading can only be taken about 3 or 4 times per meter at highway speed. This causes a major bias in roughness measurement on roads with coarse texture.

For example, sections 3 and 4 in Pennsylvania were asphalt surfaces with chip seals. These two sections had very coarse surface texture compared to the others. Table C-9 lists the texture depth from ASTM sand patch tests of sections 1 through 8 in Pennsylvania. All of the profilers with ultrasonic sensors measured IRI with an extreme bias on sections 3 and 4. Figure C-7 shows a histogram of all of the measurements by ultrasonic profilers in Pennsylvania. There is a group of measurements with a bias around 20 percent, but a second, smaller group with a bias of about 55 percent. The group with a bias around 55 percent is mostly measurements of sections 3 and 4.

Table C-9. Bias in profilers by section in Pennsylvania.

Surface Type	AC Without Chip Seal		AC With Chip Seal		Portland Cement Concrete			
Section Number	1	2	3	4	5	6	7	8
Macrotexture Depth (mm)	0.65	0.53	1.78	1.39	0.66	0.58	0.53	0.69
Bias, Optical Profilers (%)	16.5	-1.6	6.1	8.1	9.6	12.4	19.5	18.3
Bias, Laser Profilers (%)	15.3	5.9	4.8	5.0	3.2	11.6	16.8	19.9
Bias, Ultrasonic Profilers (%)	18.3	18.7	54.5	46.1	22.1	12.3	16.2	20.3

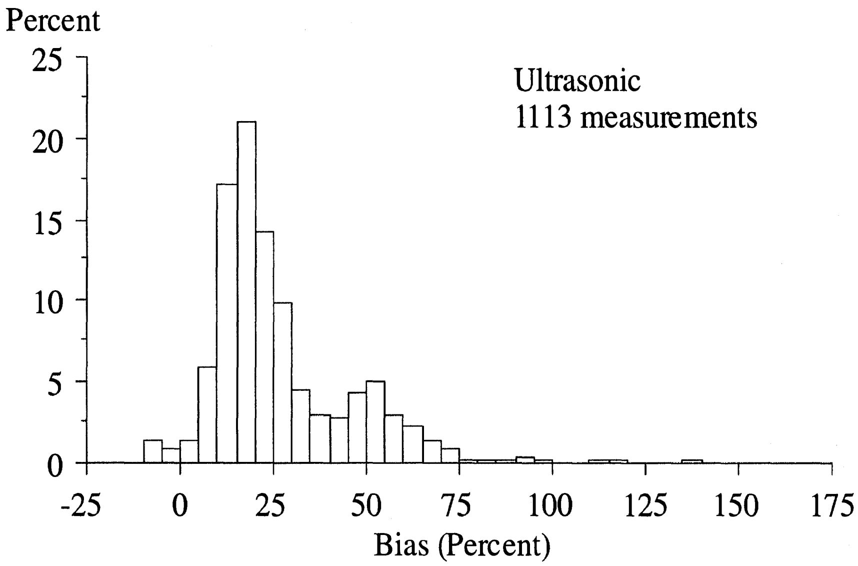

Figure C-7. Bias in ultrasonic profilers from the RPUG in Pennsylvania.

Table C-9 summarizes the bias in IRI compared to the Dipstick on each section in Pennsylvania by height sensor type. The results for the other six sections are also listed for comparison. The ultrasonic profilers had extreme difficulty with sections 3 and 4. In fact, none of their measurements agree with the Dipstick within 5 percent. Their performance is much better on the other sections, but still not acceptable.

The profilers with laser and optical sensors are actually more accurate on sections 3 and 4 than the others. Coarse macrotexture of the kind typical of a chip seal apparently does not cause systematic errors in these profilers. However, all of the laser and optical profilers showed the highest bias on sections 7 and 8. A likely explanation for the elevated roughness is that the laser and optical sensors registered roughness at opened joints (or cracks) that the Dipstick did not. This may also explain the bias in IRI on section 1, which was very rough and probably included narrow forms of distress like cracks that the Dipstick would ignore.

Table C-10 summarizes the bias in IRI compared to the Dipstick on each section in South Dakota by height sensor type. Sections 2, 3, and 4 in South Dakota all had chip seals, and all have high values of macrotexture depth. Profilers with ultrasonic sensors exhibited an extreme bias on these sections. The optical profilers agreed reasonably well with the Dipstick on all of the sections, but the laser profiler did not. Only one laser profiler participated in the study in South Dakota. Most of the bias in its measurements come from large upward spikes that are not caused by coarse texture.

Table C-10. Bias in profilers by section in South Dakota.

Surface Type	Asphalt Concrete				Portland Cement Concrete			
Section Num.	1	2	3	4	5	6	7	8
Macrotexture Depth (mm)	1.08	1.42	1.31	1.33	0.78	0.33	0.67	0.38
Bias, Optical Profilers (%)	-5.3	-1.0	-1.2	2.1	9.3	3.4	4.2	3.5
Bias, Laser Profilers (%)	5.6	20.3	10.6	28.2	12.9	-1.5	6.7	—
Bias, Ultrasonic Profilers (%)	4.3	104.5	59.7	107.6	17.2	5.9	16.9	11.8

OPERATING SPEED

Most of the profilers listed in table C-2 performed ten or more measurements of each section: five measurements at a speed near 80 kph (called higher speed repeats) and five more at a speed near 64 kph (called lower speed repeats). In a few isolated cases, measurements were made at speeds of 72 kph and 56 kph instead. This matrix of runs was intended to reveal any bias in roughness measurement caused by modest variations in operating speed. Tables C-11 through C-14 list the ratio of the MRI measured at the higher speed to the MRI measured at the lower speed. (MRI is the average of the IRI from the left and right wheeltrack.) Each value in the tables represents the average of the higher speed repeats divided by the average of the lower speed repeats on a particular section by a particular profiler. In most cases, exactly five measurements of each section at each speed were made. A value is only listed if at least four measurements at each speed were available. A table is provided for each region, since each region used a distinct set of sections. (In other words, section 1 in South Dakota is not the same as section 1 in Pennsylvania, etc.)

Table C-11. Speed sensitivity of profilers in Mississippi.

	Average MRI at high speed/Average MRI at low speed							
	Asphalt Sections				Concrete Sections			
Device	1	2	3	4	5	6	7	8
M02	1.06	1.08	1.05	1.01	1.06	0.97	0.97	1.01
M03	—	—	0.97	—	1.02	1.04	—	0.99
M05	1.03	0.96	1.01	1.03	1.02	1.00	1.05	1.14
M06	1.02	1.01	0.99	1.03	1.00	0.99	1.01	1.01

Table C-12. Speed sensitivity of profilers in Nevada.

	Average MRI at high speed/Average MRI at low speed					
	Asphalt Sections			Concrete Sections		
Device	1	2	3	4	5	6
N03	1.06	1.03	1.06	1.12	1.10	1.01
N04	1.08	1.07	1.15	1.01	1.04	1.01
N06	1.11	1.11	1.03	1.01	1.00	0.99
N07	0.98	0.97	0.96	1.01	0.99	0.99
N08	1.00	1.01	0.97	1.05	1.02	1.00
N09	0.97	1.01	1.03	1.07	0.97	1.00

Table C-13. Speed sensitivity of profilers in Pennsylvania.

	Average MRI at high speed/Average MRI at low speed							
	Asphalt Sections				Concrete Sections			
Device	1	2	3	4	5	6	7	8
P01	1.00	1.01	0.99	0.98	0.99	0.97	1.05	0.99
P02	1.04	1.06	0.96	**1.12**	1.04	0.98	1.02	1.00
P03	1.05	0.98	0.95	**1.08**	1.05	0.99	0.99	1.03
P04	0.99	0.92	0.98	0.93	0.97	1.00	0.98	0.95
P05	1.05	1.00	1.00	1.00	1.02	1.03	1.04	1.03
P06	1.02	0.97	1.02	**1.26**	1.03	1.02	1.04	0.98
P07	1.00	1.07	1.01	1.00	1.00	0.99	0.98	1.01
P08	1.04	1.05	1.02	0.94	1.01	1.02	1.01	1.02
P73	0.99	1.01	0.98	**1.12**	0.98	0.97	1.00	1.01
P74	1.00	1.00	0.99	**1.08**	1.01	0.99	0.98	1.00
P75	1.02	1.03	0.99	**1.08**	0.99	0.98	0.98	0.99
P76	0.99	0.98	1.00	**1.03**	1.00	1.00	1.00	0.98

Table C-14. Speed sensitivity of profilers in South Dakota.

	Average MRI at high speed/Average MRI at low speed							
	Asphalt Sections				Concrete Sections			
Device	1	2	3	4	5	6	7	8
S01	—	0.98	1.05	1.02	1.02	—	1.01	—
S08	1.01	0.99	1.01	1.02	1.01	0.99	1.02	1.00
S10	1.01	0.99	0.99	0.99	0.98	—	—	—

Table C-15 summarizes the results for each profiler organized by sensor type. The table lists the average of the values given for all sections in tables C-11 through C-14 and the minimum and maximum. Keep in mind that profilers from different regions encountered different sections and not all profilers covered all sections, so only major trends are likely to have significant implications about the effect of operating speed. Very few of these devices showed an overall bias with operating speed that was more significant than the scatter they exhibit within a given speed. (That is, the average listed in table C-15 rarely accounts for most of the standard deviation listed in table C-4, and the scatter within repeats at the two speeds overlap each other.)

In general, the profilers with ultrasonic sensors measured higher MRI values at the higher speed. This is because a sensor error that drives up the roughness is more likely to occur at higher speed. This explains why the averages in table C-15 for ultrasonic sensors are generally greater than one, although the trend is weak. One example that stands out (if for no other reason, because they are in bold type) is that all of the profilers with ultrasonic sensors measured MRI values that were significantly higher at the higher speed on Pennsylvania section 4. (See table C-14.) This is not the section with the highest macrotexture depth, but its texture did seem most problematic to profilers with ultrasonic sensors.

A few other weak trends exist with speed, but most of them are not systematic. In most of the cases of extreme values in tables C-11 through C-14, a single anomalous value from one measurement skewed the average for one of the speeds, rather than a systematic bias in all repeats. The only other case of a systematic bias with speed was exhibited by profiler P04. It produced lower MRI at the higher speed on all sections. We do not have an explanation for this.

Table C-15. Summary of trends in MRI with operating speed.

Sensor Type	Device	Average	Minimum	Maximum
Laser	M03	1.00	0.97	1.04
	N07	0.98	0.96	1.01
	P01	1.00	0.97	1.05
	P04	0.97	0.92	1.00
	P08	1.01	0.94	1.05
	S10	0.99	0.98	1.01
Optical	M06	1.01	0.99	1.03
	N08	1.01	0.97	1.05
	N09	1.01	0.97	1.07
	P05	1.02	1.00	1.05
	P07	1.01	0.98	1.07
	S08	1.01	0.99	1.02
Ultrasonic	M02	1.03	0.97	1.08
	M05	1.03	0.96	1.14
	N03	1.06	1.01	1.12
	N04	1.06	1.01	1.15
	N06	1.04	0.99	1.11
	P02	1.03	0.96	1.12
	P03	1.01	0.95	1.08
	P06	1.04	0.97	1.26
	P73	1.01	0.98	1.12
	P74	1.01	0.98	1.08
	P75	1.01	0.98	1.08
	P76	1.00	0.98	1.03
	S01	1.02	0.98	1.05

Table C-16 shows a summary for trends in RN with operating speed compiled in the same manner as MRI in table C-15. Very few of the profilers are speed sensitive. A few of the ultrasonic profilers appeared speed sensitive on sections of coarse macrotexture, but the RN values were so far off at both speeds that the trend is not worth examination.

Table C-16. Summary of trends in RN with operating speed.

Sensor Type	Device	Average	Minimum	Maximum
Laser	M03	1.01	0.99	1.06
	N07	1.00	1.00	1.01
	P01	0.99	0.96	1.00
	P04	1.00	0.96	1.02
	P08	0.99	0.97	1.01
	S10	1.02	0.99	1.04
Optical	M06	1.01	0.98	1.09
	N08	0.98	0.89	1.10
	N09	0.95	0.90	1.00
	P05	0.99	0.97	1.00
	P07	1.00	0.95	1.09
	S08	1.01	1.00	1.02
Ultrasonic	M02	0.99	0.91	1.05
	M05	1.01	0.85	1.13
	N03	0.93	0.88	1.00
	N04	0.98	0.93	1.04
	N06	0.97	0.92	1.00
	P02	1.00	0.96	1.04
	P03	0.99	0.96	1.02
	P06	0.87	0.50	1.03
	P73	0.98	0.73	1.04
	P74	1.00	0.97	1.02
	P75	1.00	0.96	1.05
	P76	1.00	0.98	1.02
	S01	0.98	0.92	1.00

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2. Sayers, M. W. and Karamihas, S. M., "Interpretation of Road Roughness Profile Data." Federal Highway Administration, *FHWA/RD-96/101* (1996) 177 p.

APPENDIX D
TRANSVERSE VARIABILITY EXPERIMENT

This appendix provides detailed results from the transverse variability experiment. The results of this experiment are used in chapter two to cover the issues of transverse variability, lateral positioning, and lateral sensor spacing. The experiment is described briefly, then plots of IRI and RN versus lateral tracking position on all of the sections tested are provided.

Seven sections were measured in this experiment. A camera, aimed at the pavement to the right, was mounted on a roof rack attached to the ProRut to monitor its lateral position. The position of the ProRut was displayed for the driver on a monitor marked to show the lateral separation between the right height sensor footprint and the center of the right edge stripe. Before each day of testing, a piece of wood, marked every 0.15 m along its length, was used as a calibration gauge to ensure that the marks on the screen gave correct readings for the angle of the camera.

The monitor served as a guide for the driver. In general, the driver would use the monitor ahead of the section of interest to get the vehicle in the correct tracking location. Once in the desired position the driver would focus only on the road and simply try to hold the vehicle steady. We found that using the monitor to make adjustments during a test actually hindered the effort to maintain a constant tracking position. To further aid the driver, all of the sections were straight and had very visible markings along the right edge.

The video was also recorded and used after each run to judge the lateral position of the sensors at one second intervals. In each run, the driver attempted to hold the lateral position within a range of less than 20 cm, but a total range of 30 cm was considered acceptable. In general, drivers were able to make at least seven acceptable runs in ten tries.

Each section was tested in two stages. In the first stage, the section was measured in several lateral positions spread out over the entire lane. In the second stage, the section was measured several times in a position that the driver considered central. Often, the position was to the right of the center of the lane, but seemed to be in the tracking position of the prevailing traffic. These "central repeats" are used to determine the level of repeatability that is possible with control over the lateral placement of a profiler. They also ensure that the trends observed on the first stage of testing are caused by transverse variations in profile, rather than other sources of variation.

Table D-1 lists the sections that were tested. The table identifies the sections by a number and a short designation that appears on the plots. The sections are described in detail in Appendix A. Table D-1 also lists the dates of each stage of the testing and the number of tracks upon which acceptable data was collected. Keep in mind that a single run provides data in two tracks. In general, it was the goal of the first stage of testing to sweep across the entire lane. For example, figure D-1 illustrates the coverage of a section by the runs with variation in lateral position. (The central repeats are not shown.) The figure maps the path of the right height sensor footprint with respect to the center of the right edge stripe. For each line on in the figure, a track with the same path was covered 181.6 cm to the left.

Table D-1. Sections tested in the transverse variability experiment.

		Lateral Variations		Central Repeats	
Number	Designation	Tracks	Date	Tracks	Date
1	new asphalt	16	9-22-97	14	10-29-97
2	severely faulted PCC	18	9-23-97	14	10-29-97
9	old asphalt	26	11-07-97	22	11-07-97
12	three-year-old PCC	20	9-24-97	16	11-07-97
13	one-year-old PCC	18	9-27-97	12	12-01-97
14	AC with thermal cracks	14	9-27-97	20	12-01-97
15	six-year-old PCC	28	9-25-97	22	11-09-97

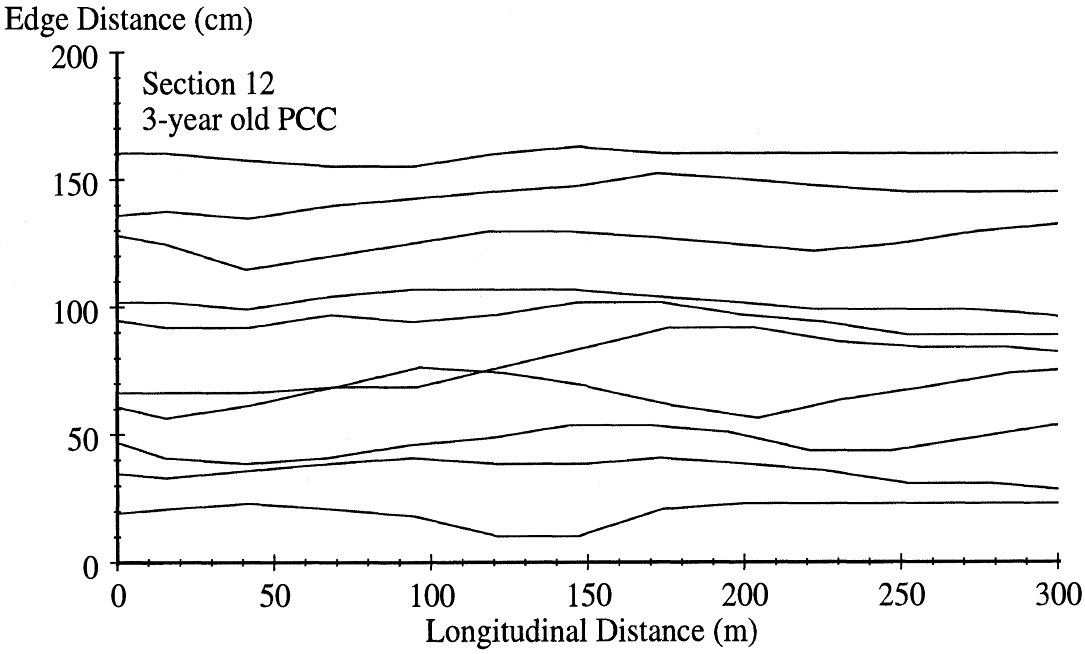

Figure D-1. Coverage of section 12.

The rest of this appendix provides plots of the IRI and RN versus distance from the center of the right edge stripe to the center of the sensor track. The results of the runs from the first stage of testing are distinguished from the central repeats by point type. Section 9 was covered in a single sweep, so all data points appear in the same type.

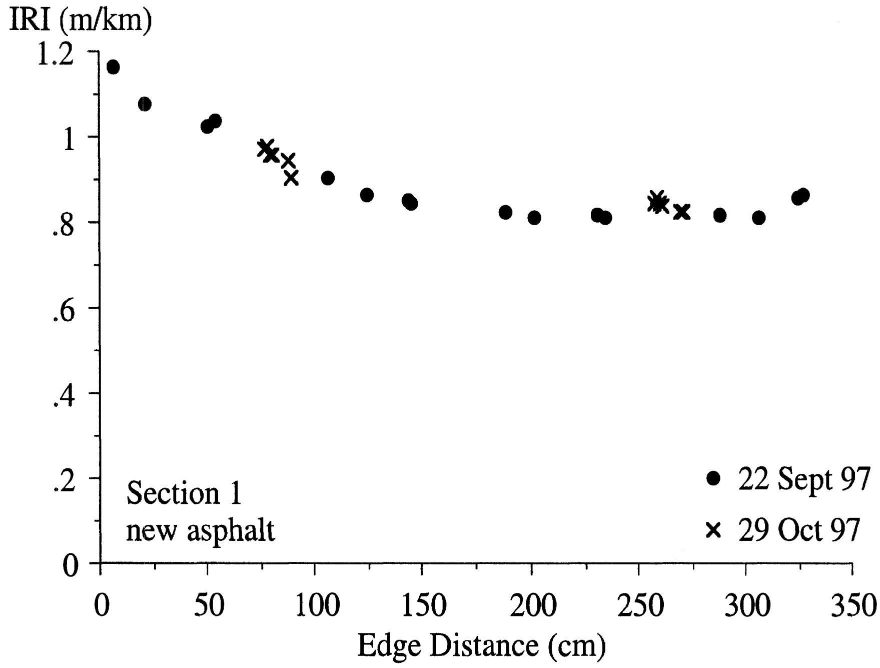

Figure D-2. Transverse variations in IRI of section 1.

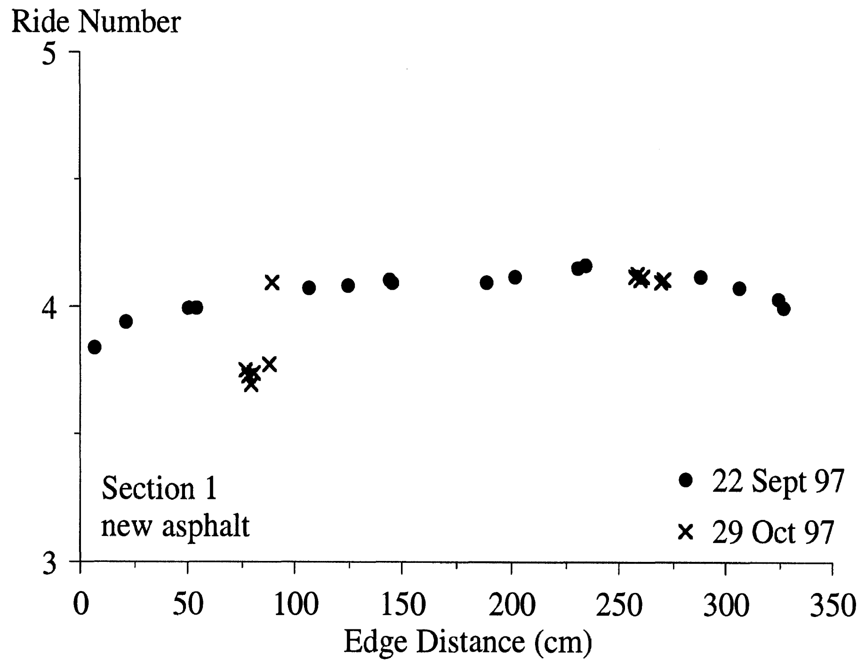

Figure D-3. Transverse variations in RN of section 1.

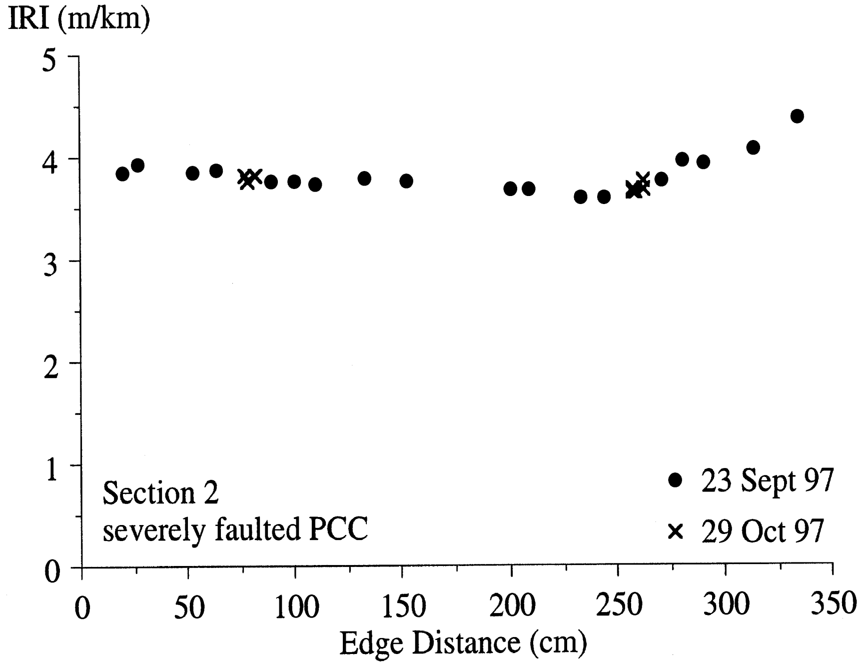

Figure D-4. Transverse variations in IRI of section 2.

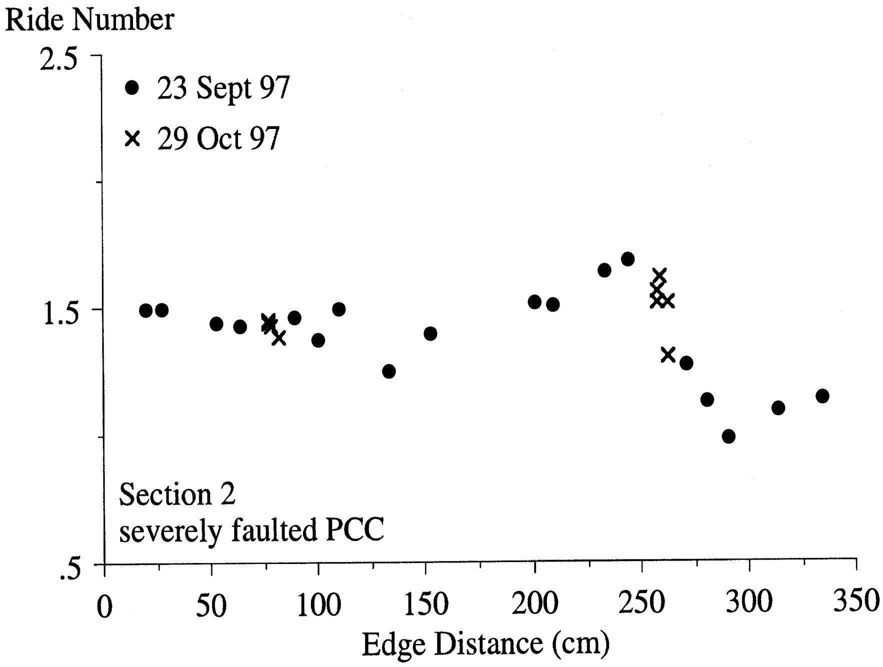

Figure D-5. Transverse variations in RN of section 2.

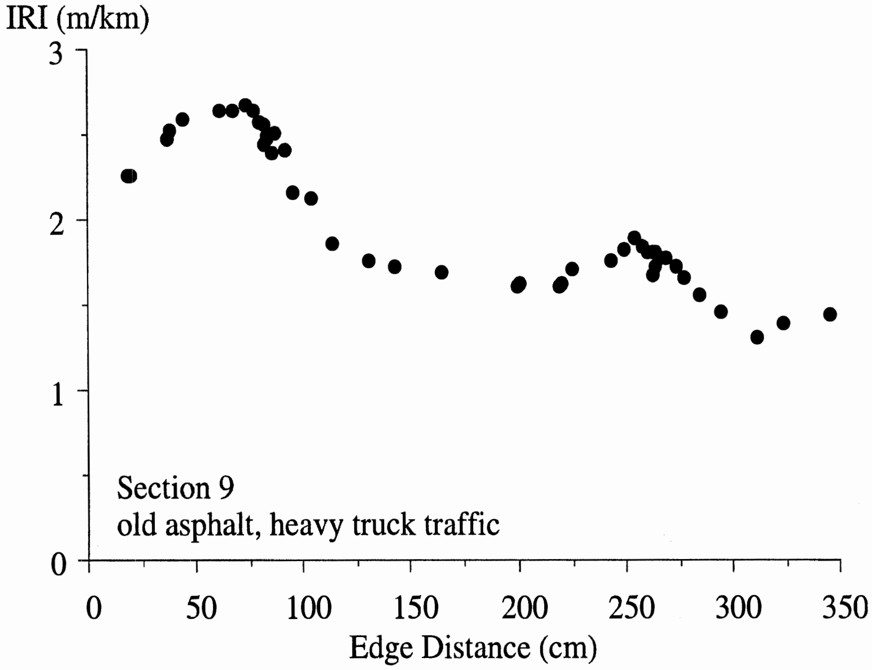

Figure D-6. Transverse variations in IRI of section 9.

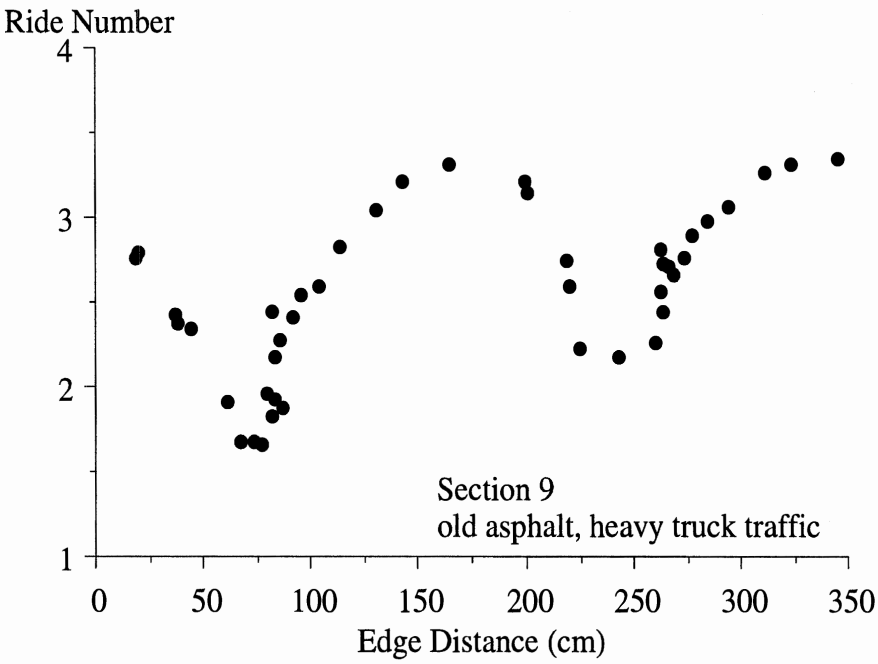

Figure D-7. Transverse variations in RN of section 9.

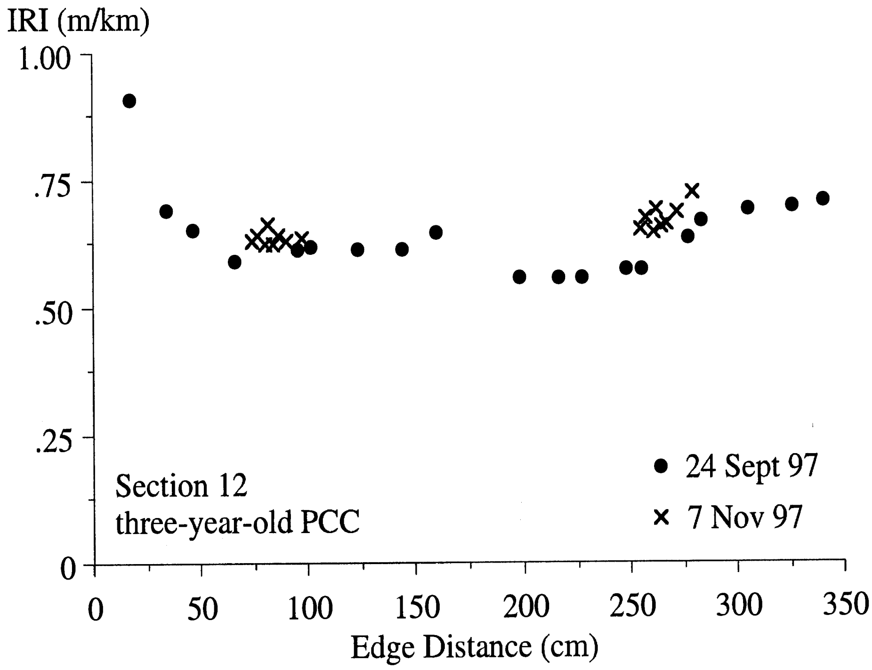

Figure D-8. Transverse variations in IRI of section 12.

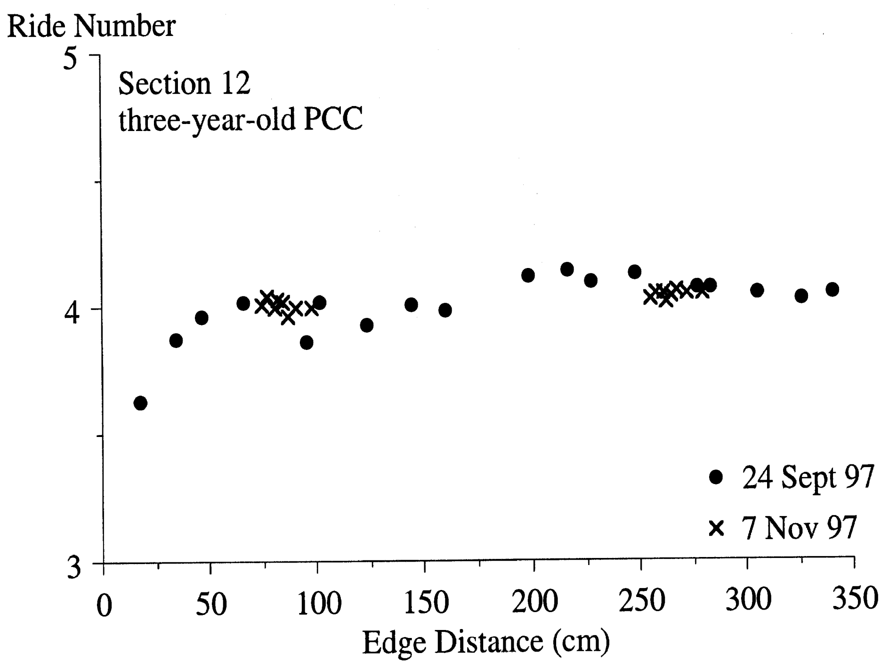

Figure D-9. Transverse variations in RN of section 12.

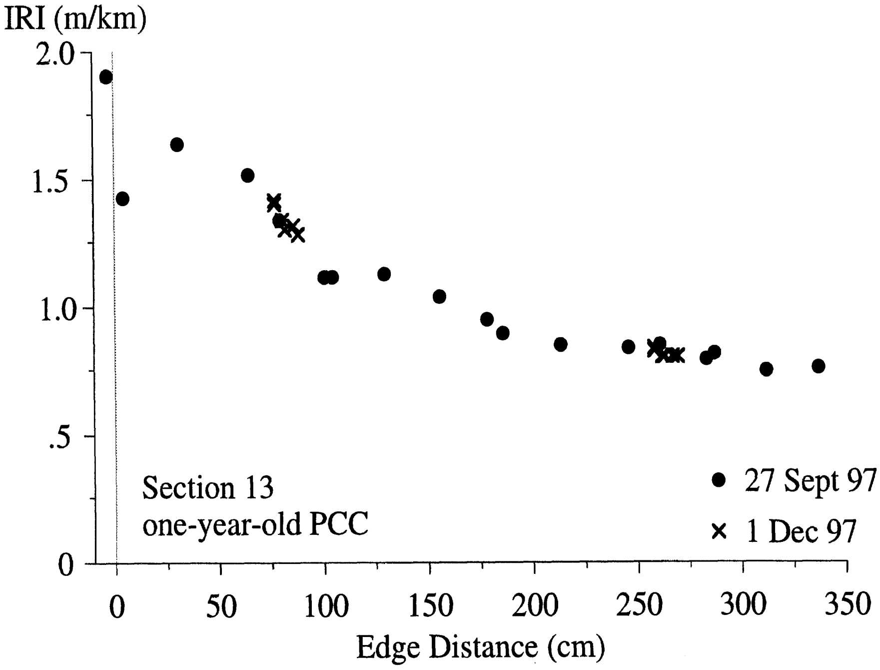

Figure D-10. Transverse variations in IRI of section 13.

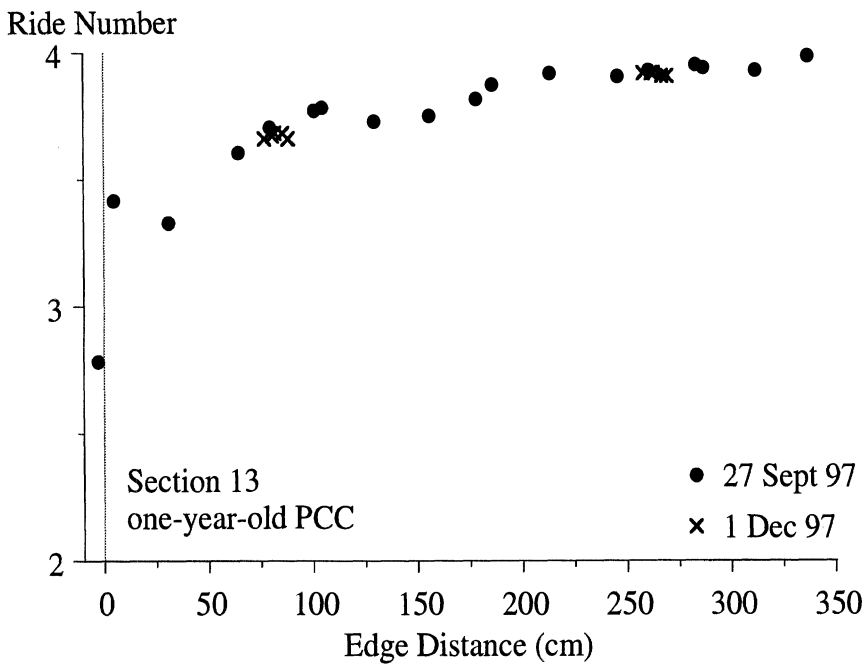

Figure D-11. Transverse variations in RN of section 13.

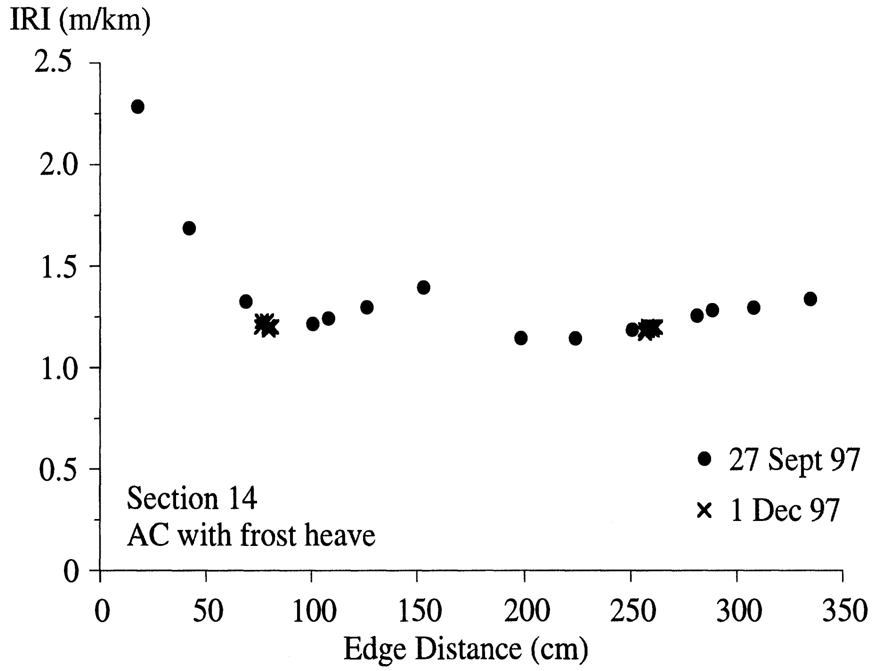

Figure D-12. Transverse variations in IRI of section 14.

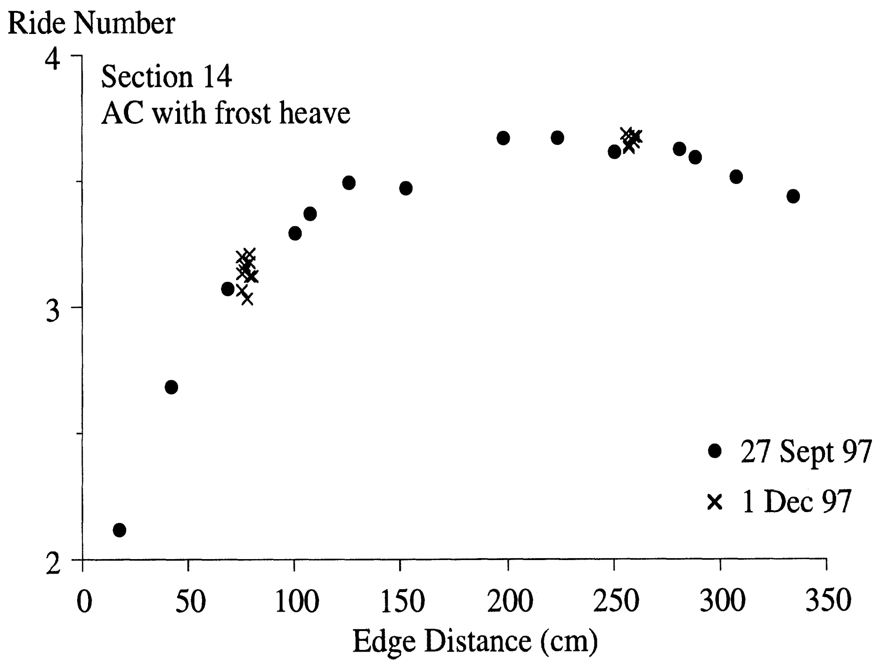

Figure D-13. Transverse variations in RN of section 14.

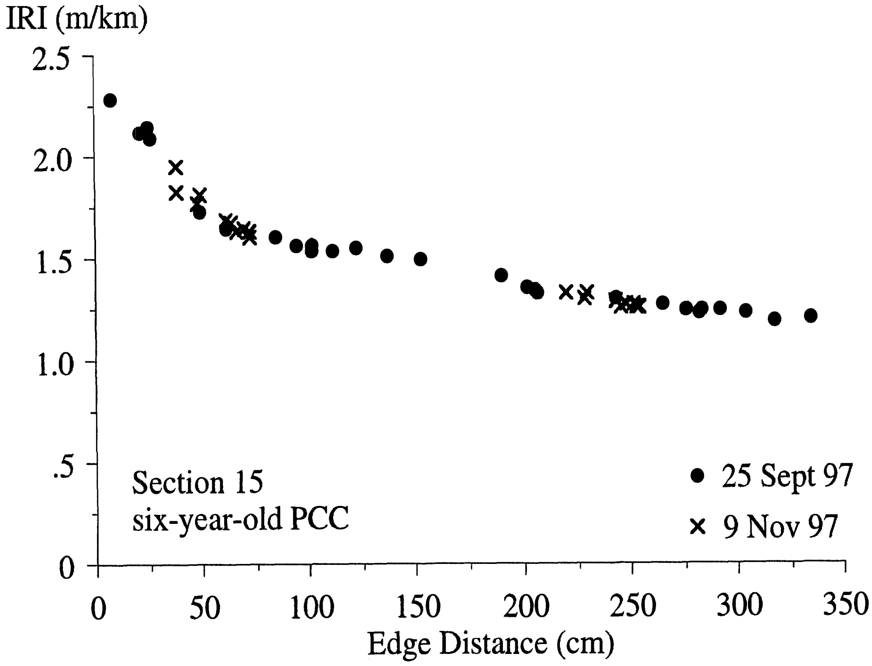

Figure D-14. Transverse variations in IRI of section 15.

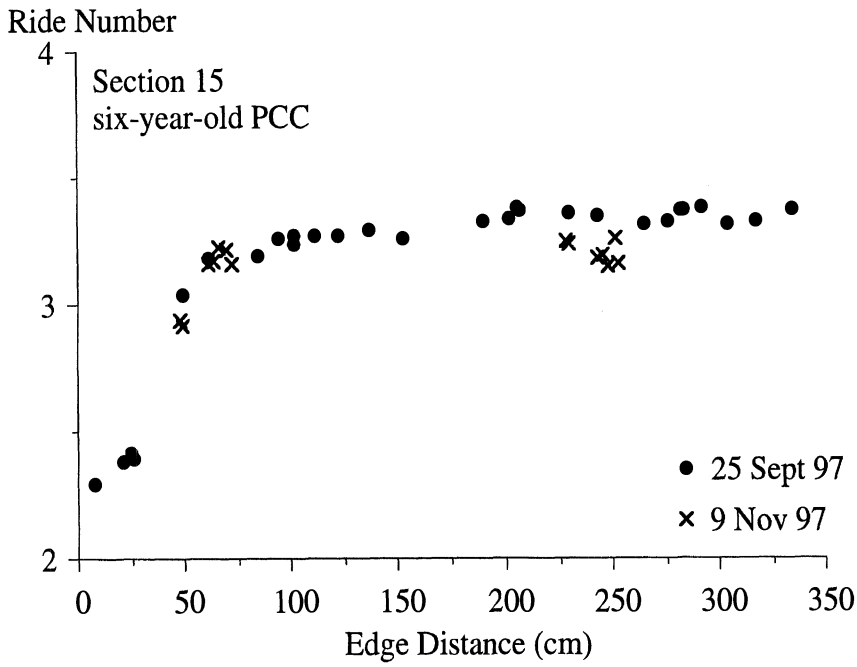

Figure D-15. Transverse variations in RN of section 15.