National Cooperative Highway Research Program

RESEARCH RESULTS DIGEST

November 1999—Number 244

Subject Areas: IA Planning and Administration; IB Energy and Environment; IIB Pavement Design, Management, and Performance; IIIB Materials and Construction; IIIC Maintenance; IVA Highway Operations, Capacity, and Traffic Control; and V Aviation.

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Operational Guidelines for Longitudinal Pavement Profile Measurement

This is an NCHRP digest of NCHRP Project 10-47, "Guidelines for Longitudinal Pavement Profile Measurement." The project resulted in recommended guidelines for measuring a longitudinal pavement profile to use in computing that pavement's International Roughness Index (IRI) and/or Ride Number (RN). These operational guidelines are based on the determination of factors that affect roughness measurements, the quantification of the effect of these factors on repeatability and accuracy, and the determination of how and when these factors can be controlled. This digest presents the project findings in the form of guidelines for "best practices"; more technical presentations of the research findings are contained in the companion publication, NCHRP Report 434, "Guidelines for Longitudinal Pavement Profile Measurement." The University of Michigan Transportation Research Institute personnel under the direction of Dr. Thomas D. Gillespie drafted this digest.

INTRODUCTION

This digest provides road profiler operators, their supervisors, the users of road profiler output, and interested engineers and administrators practical details about the workings and operation of various road profilers. It differentiates between the data requirements for computing the International Roughness Index (IRI) and the Ride Number (RN). It addresses the several areas that can affect proper data collection: the equipment, the shape of the surface being measured, the measurement environment, the profiler operations, and the profiler operator skill requirements.

A road profile is a measure of the road elevation in the wheeltracks encountered by motor vehicles. In its coarsest form, it is equivalent to a depiction of the road's elevation contours, but measured at close interval and with sufficient resolution, it captures the roughness features that affect vehicle vibration and consequently affect the road users' perceptions of acceptability or serviceability. Profiles can be measured by a number of methods, each with different attributes and shortcomings. The accepted reference for measuring the road profile is the precision rod and level method, conducted in accordance with ASTM Method E1364. Other devices, such as the Dipstick, mechanize the process somewhat, but are still slow and labor intensive.

In the 1960s, technology became available allowing profiles to be measured at high speed using an instrumented vehicle. The original concept was developed at the General Motors Research laboratory. The resulting vehicle became known as the GMR Profilometer. The concept and the name "Profilometer" are now owned and commercialized by K. J. Law Engineers, Inc. In the past decade, high-speed profiling systems (called "profilers" in lieu of the trademarked name "profilometer") have become available to most state highway department and transportation agencies for measuring road roughness. The profilers are used in a number of applications, including network surveys, project monitoring, and research testing.

A profiler, like any device, has limitations on its accuracy and potential sources of error. With such broad usage, it has become apparent that the user community could benefit from a systematic understanding of these limitations. This document is intended to provide such information in the form of guidelines for "best practices" in the use of high-speed profilers. These *Guide-*

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lines may be viewed as complementary to the National Highway Institute Short Course, "Measuring and Analyzing Road Profiles," offered annually in cooperation with the Road Profiler Users Group (RPUG). The Short Course is intended to offer an in-depth understanding of the theory employed (i.e., the technical details of how the profiler measures, processes, and displays roughness information). The material presented in this course is included in the document, "Little Book of Profiling." The *Guidelines* focus on operating procedures and how the equipment and environment impact the error or variance of the final measure, the roughness metric. To make the *Guidelines* more usable by practitioners, technical discussion is avoided. The reader can refer to *NCHRP Report 434* if technical questions arise.

The *Guidelines* were developed from a series of analyses and experiments with profilers. The experiments included participation by personnel and equipment from state highway departments from which some of the very practical problems with profiling were identified—for example, the problem of maintaining speed and lane position in traffic during network surveys. Thus, some of the guidelines were derived from anecdotal reference to the problems of profiling, while others were developed from examinations of the subtle sources of variations, such as deviations in lane position.

This NCHRP project did not allow for a broad examination of in-use sources of variation. Thus, these guidelines should be viewed as a starting point for building an ongoing and expanding set of guidelines as additional problems are identified. Users should become familiar with the suggestions made here and then contribute their own insights as other sources of problems in use are identified. It is suggested that an organization like the Federal Highway Administration (FHWA), together with RPUG, assume responsibility for accumulating additional guidelines to be published on a periodic basis.

How the Guidelines Were Developed

The guidelines were primarily developed from the results of actual field measurements of several profilers, from data collected during previous RPUG meetings, profiles collected for the FHWA Long Term Pavement Performance (LTPP) program, and the experimental data collected during the project. This combination of experimentation and analytical study of past data provided a vast amount of information for identifying sources of variation. The field studies were designed to fill the gaps in the previous data sets. Experiments focused on driver variability and the longitudinal variability of the profile.

In the course of the field measurements and analytic studies, several desirable profiler features were identified through the experience of operating the PRORUT vehicle and observations of state personnel using other profiling systems. The features for an ideal profiling system are described in a separate section at the end of this digest.

Equipment Characteristics

The individual components that comprise the profiler system all have individual measurement accuracies. However, it is rarely the individual components' ability to measure that affects the equipment's ability to collect valid and accurate roughness data. Rather, it is how the components act in unison and the procedures used that affect the measurement. In many cases, there is an interaction of one or more of the factors studied. Where possible, individual factors have been isolated. If interaction with another variable is considered to have a major affect on a measurement, it will be so noted.

How to Interpret Error Estimates

Because the factors affecting the measurement of road profiles are numerous and most of the time confounding, it is not always possible to isolate a given factor and determine its effect on the measurement. In addition, the reality that there are an infinite number of possible profiles on a road surface clouds the determination of measurement error. This ambiguity precludes the design of a statistically robust experiment to test for measurement error, or at least makes it cost prohibitive to do so. Therefore, the research team selected the data and experiments for this study to represent the state-of-the-practice in collecting profile data.

When dealing with measurements, the terms error, precision, bias, accuracy, and variance have specific meaning. However, there are times when colloquial phrases are used that cause misinterpretation of these terms. The error measures summarized in this digest should be interpreted as mean errors under good operating conditions and procedures. Severe departures from the average have not been investigated in this study. The terms error and variance should be interpreted as meaning the same. That is, when a factor is found to have an impact on the resulting roughness index, this report will provide an estimate of the error or expected variance related to the factor. When possible, commentary on the precision, bias, and accuracy of a device has been provided in the traditional definition of these terms.

The wording used in the *Guidelines* is generally advisory in nature, with occasional use of the word "must." Those guidelines that are advisory in nature are provided to assist in achieving good practices, and in some cases simply to suggest a rule that will improve consistency in practices among profiler users. For example, high pass filtering at 91 m (300 ft) is recommended simply to improve the comparability of profiles measured by different machines. In actuality, the filter length can be set much longer without compromising the ability to measure roughness indices accurately; however, the appearance of the profiles measured by different systems will be visually much different. When observance of a guideline is essential to obtain comparable performance among profilers, the wording will be much more restrictive, generally implying that a certain guideline

"must" be observed to achieve comparable performance among systems.

These *Guidelines* are written with the drivers and operators in mind. However, some of the recommendations may go beyond the scope of what can be controlled by drivers and operators (e.g., the choice of profiler sensors). Nevertheless, these recommendations are included in the *Guidelines* so that drivers and operators are aware of the issues; managers can note these advisories.

EQUIPMENT

Sample Interval and Recording Interval

Sample interval is the longitudinal distance between points that are digitized for computation of profile. Recording interval is the interval at which a profiler stores the computed elevation values. For some profilers, the recording interval is the same as the sample interval. On profilers for which the recording interval is longer than the sample interval, the height values are averaged before recording. Guidelines for sample and recording intervals follow:

- For computation of IRI, the sample interval must be 167 mm or less, and the recording interval must be 250 mm or less.
- For computation of RN, the sample interval must be 25 mm or less.
- The height sensor and accelerometer signals must pass through anti-alias filters with a cutoff wavelength equal to twice the sample interval.

Profile Computation Algorithm

The profile computation algorithm is the procedure that is used to compute the profile from the signals that are obtained from the height sensor, accelerometer, and the distance measuring system. Guidelines for the profile computation algorithm follow:

- The high-pass filters on profilers should be set to 91 m or longer.
- The programs for computation of profile and roughness indices should be verified by processing standard data sets. (It is expected that this validation would normally be conducted by a manufacturer, and the system thus certified. A typical standard data set for computation of RN is contained within the ASTM Standard E1489-96, "Standard Practice for Computing Ride Number of Roads from Longitudinal Profile Measurements Made by an Inertial Profile Measuring Device.")
- For network-level data collection, it is acceptable to employ computation of profiles and indices "on-the-run" (i.e., concurrent with measurement) even though some longitudinal shifting of roughness features will occur.
- For project-level data collection in which the location of roughness features is important, the profile must be computed after measurement using a bi-directional processing method to cancel the phase shift of long wavelength features associated with digital filters.

Height Sensors

Height sensor refers to the transducer that is used to measure the distance from the vehicle chassis to the road surface. The types of height sensors that are commonly used in profilers are laser, optical, infrared, and ultrasonic. Guidelines for height sensors follow:

General

- Height sensors must have a resolution of at least 0.5 mm.
- Bumper mounted height sensors should have a measurement range of at least 250 mm.
- Height sensors mounted between the axles of a vehicle should have a measurement range of at least 125 mm.
- Suspension spring and shock absorber maintenance is very important for bumper mounted systems, as well as maintenance of the connections of the hardware to the vehicle chassis in order to minimize vibrations and the overall vertical motion of the height sensors.
- Height sensors must be mounted so that they are in the center of their measurement range when the vehicle is at rest.

All Height Sensor Types

- The height sensors must be calibrated using the procedures described by the profiler manufacturer. Guidance regarding the time interval between calibrations should be obtained from the profiler manufacturer.
- It is recommended that the profiler software be capable of performing a calibration check on the height sensors. The calibration check is performed by putting a block of known height below the sensor and checking to ensure that the system will accurately measure the height of the block within a specified tolerance. Power should be supplied to the system to allow sufficient time for it to warm up prior to performing this test. Guidance regarding the time necessary to warm up the system should be obtained from the profiler manufacturer.
- Prior to profile data collection, power should be supplied to the system to allow sufficient time for the electronic components to warm up. Guidance regarding the time necessary to warm up the system should be obtained from the manufacturer.
- The height sensors should be wiped clean prior to profile data collection. The sensor may need more frequent cleaning during the day depending on environmental conditions (e.g., water splashing on the sensor).
- It is recommended that the output of the height sensor be displayed on the screen of the computer when data is

collected, preferably in a graphical format for easier tracking. This display can be used for a quick visual check that the height sensor is working properly during measurements.

- It is recommended that the profiler issue an audible beep when height sensor readings are outside the valid range.
- Whenever repairs are performed on the suspension system or the bumper of the host vehicle, the height sensors should be positioned so that they are in the center of their measurement range when the vehicle is at rest. The mounting position should also be checked whenever tires are replaced or rotated, or when wheel alignments are performed.
- The height sensor should be calibrated after any repairs are performed on the suspension system or the bumper of the vehicle if the sensors are mounted on the front bumper. The height sensors should also be calibrated whenever tires are replaced or rotated, or when wheel alignments are performed.
- Potential invalid points in height sensor measurements should be flagged during data collection. This can be accomplished using an algorithm that will look at differences between two consecutive height sensor measurements. If the differences are high enough to indicate a possible measurement error, these locations should be flagged in the data file.
- Some height sensors are equipped with covers to protect them when profile data are not being collected. The software should prohibit data collection while the covers are in place.
- Do not operate the profiler in temperatures outside of the range listed by the height sensor manufacturer.

Ultrasonic Sensors

- Ride Number (RN) cannot be measured by ultrasonic profilers.
- Ultrasonic profilers cannot collect accurate profile data on surfaces that have coarse macrotexture, particularly chip seals. They should not be used to measure IRI.
- Do not collect data using ultrasonic profilers in winds exceeding 65 kph.
- Do not use ultrasonic height sensors without calibrating them for the specific temperature conditions under which they will operate.

Laser Sensors

- The laser beam emitted by the sensor can cause serious eye injury. The operator should exercise caution when working with the sensors.

Infrared Sensors

- The beam emitted by the sensor may cause serious eye injury. The operator should exercise caution when working with the sensors.

Optical Sensors (visible light spectrum)

- Optical profilers have a shroud to enclose the sensors so that sunlight will not interfere with data collection. This shroud should be maintained in good condition, because even a small amount of sunlight intruding under the shroud can contaminate the data.
- When the optical sensor runs over a white pavement marking, it produces a large spike in the height signal. This introduces an artificial roughness to the profile. Care should be taken to eliminate these spikes before computing roughness values.
- Optical profilers sometimes have difficulty in obtaining measurements on dark pavement surfaces. Such conditions generally occur on new asphalt concrete (AC) overlays. Profiles taken on such surfaces may only contain the accelerometer signal. The operator should examine the height sensor signal closely during data collection on such surfaces to ensure that valid data are being collected.

Accelerometers

The accelerometers in a profiler are (should be) placed on top of the height sensor to measure vertical acceleration. The signal from the accelerometer is combined with those from the height sensor and the distance measuring system to compute the profile. Specific accelerometer guidelines follow:

- An accelerometer should be provided for each height sensor used to measure profile.
- The accelerometers should have a range of at least ±5 g and a bandwidth up to at least 150 Hz.
- The accelerometers must be calibrated using the procedures described by the manufacturer. Guidance regarding the time interval between calibrations should be obtained from the manufacturer.
- It is recommended that the profiler software be equipped with the capability of performing a check on the accelerometer function. This check should be performed on the accelerometer to verify that it is in proper working condition prior to data collection. A recommended method is the "bounce" test, wherein a motion is introduced to the profiler while it sits stationary on a flat surface and the resulting profile is recorded. This motion can be induced by rocking the profiler sideways or along the longitudinal direction of the vehicle. The resulting profile should be flat (i.e., the system output should be less than 1 percent of vehicle bounce amplitude). Prior to conducting this test, power should be supplied to the system to allow adequate warm-up. Guidance regarding the time necessary to warm up the system should be obtained from the manufacturer.
- It is recommended that the output of the accelerometer be displayed on the screen of the computer when data is

collected, preferably in a graphical format. By knowing the valid range of an accelerometer signal, the operator should be able to tell if the accelerometers are functioning properly.

- It is recommended that the profiler issue an audible beep when accelerometer readings are outside the valid range.
- Prior to collecting profile data, power should be supplied to the accelerometers to give them sufficient time to warm up. Guidance regarding the time necessary to warm up the system should be obtained from the manufacturer.

Distance Measuring System

The distance measuring system refers to the instrumentation that is used to measure the longitudinal distance along the road when the profile measurements are being made. Guidelines for the distance measuring system follow:

- The distance measuring system should be calibrated at intervals recommended by the manufacturer. Calibration involves laying out a section of known distance and running the profiler over this section. The section should be laid out using a steel tape or an electronic distance measuring system accurate to at least 0.05 percent. The system should be calibrated at a typical operating speed used during profile measurements with a photocell (or other automated triggering system) being used to detect the beginning and the end of the section.
- Prior to calibrating the distance measuring system, the cold tire pressure should be checked to ensure that it equals the recommended tire pressure. The vehicle should be driven for 20 to 30 min at highway speeds to warm up the tires prior to calibration.
- The distance measuring system must be calibrated after any repairs are performed on the suspension system or tires. The system should also be calibrated whenever tires are replaced or rotated, or when wheel alignments are performed.
- When operating temperatures fluctuate more than 28°C in a day, tire pressure should be checked and the effect on the distance measurement determined. Spot checking mileage should be performed when these temperature conditions exist.
- A profiling system should be capable of adding an event mark to the data record at the option of the operator.

Number of Sensors

The number of sensors refers to the number of accelerometers and height sensors that are used to collect profile data. Most profilers have height sensors and accelerometers located along the two wheeltracks to measure profile. Most profilers also have a height sensor (without an accelerometer) that is located at the center of the vehicle. Data obtained from this sensor is used with the height sensor data from the wheeltracks to compute rut depth. Guidelines for sensors follow:

- It is recommended that an accelerometer be installed at every location on the profiler where profile measurement is being performed. This means that individual accelerometers should be installed above the height sensors in each wheeltrack. Following this advice on systems that measure height at the center of the vehicle for rut depth determination provides some redundancy in the system that allows further checks on data validity.
- It is recommended that profile data be collected, as a minimum, along both wheeltracks. The roughness index for a section that is computed using the data from the two wheeltracks will give a better indication of the overall roughness of the road.
- On most roads, the difference between the left and the right wheeltrack IRI values is within 0.3 m/km. It is recommended that the left and right wheeltrack IRI values be computed and routinely compared. Locations where the differences in IRI consistently exceed 0.3 m/km may alert operators to problems with one of the sensors. Such locations should be examined more closely to verify that the data are valid.

Lateral Sensor Spacing

Lateral sensor spacing refers to the lateral separation between the profiles measured along two wheeltracks. Guidelines for lateral sensor spacing follow:

- It is recommended that the lateral spacing between the profiles be 170 to 180 cm. Such a spacing will ensure that the profile data can be collected in commonly traveled wheeltracks and that the spacing will satisfy the requirements needed to compute the rut depth.
- Most profilers use the data from the two sensors located in the wheeltracks along with a center sensor to determine rut depths. Therefore, the lateral sensor spacing in such cases will be governed by the distance that is needed to accurately compute a rut depth.

Repeatability of Profilers

The repeatability of a profiler refers to its ability to obtain the same profile or roughness value in more than one measurement of a given segment of roadway. The repeatability of the profiler will be influenced by factors other than the profiling equipment, such as lateral wander and pavement distress. These issues are discussed in subsequent sections. Guidelines for profiler repeatability follow:

- For project-level data collection and for profiling of new construction, it is recommended that a minimum of five profiler runs be conducted to obtain a statistical quantification of variability.

- In evaluating the ability of the profiler to obtain repeatable IRI values over a pavement section, it is recommended that the standard deviation of IRI be used as the parameter. The use of coefficient of variation (COV) of IRI for evaluating the repeatability is not recommended. On some rough pavements, the profilers are capable of measuring profiles such that the standard deviation in IRI has the same magnitude as that obtained on very smooth pavements. This results in a lower COV on rough sections when compared to smooth sections, and incorrectly implies that the profilers are more repeatable on rough sections than on smooth sections.
- In evaluating the ability of the profiler to obtain repeatable RN values over a pavement section, it is recommended that the standard deviation of RN be used as the parameter. The use of coefficient of variation (COV) of RN for evaluating the repeatability is not recommended. Usually pavements with higher RN have low standard deviation in RN, while pavements with lower RN have high standard deviation in RN. For the same standard deviation of RN, the use of COV will result in the smooth section having a lower COV than the rough section, incorrectly indicating that the profiler is more repeatable on the smooth surface.

SURFACE SHAPE

Pavement Distress

Distresses that are present on the pavement are a major contributor to transverse variability in profile data. For a profiler, the roughness values that are obtained for a specific pavement section can vary from run to run. In addition, pavement distresses interact with the sample interval of the profiler. Profilers that use a shorter sample interval have a higher probability of picking up more features on the pavement surface than profilers with a longer sample interval. In some pavements, only a specific distress is present (e.g., transverse cracking in AC pavements or faulting on portland concrete cement [PCC] pavements). However, usually a pavement will include several types of distresses that make it difficult to quantify the effect of each distress (e.g., PCC pavements can have faulting, spalling and transverse cracking; AC pavements can have rutting, alligator cracking, and transverse cracking). General guidelines regarding the variability in roughness values that are expected for different distress types are presented below for each distress type. When a current roughness value for a pavement section is compared with the previous year's roughness value, the magnitude of the difference between the values will be influenced by the types of distress that are present in the pavement. Guidelines for pavement distress follow:

- Alligator cracking on AC pavement can have a large influence on transverse variability. If a series of repeat runs are made by the same profiler on a pavement section that has alligator cracking, the difference between the maximum and the minimum IRI that is obtained can vary from 0.20 to 0.50 m/km. For the RN, this difference can vary from 0.1 to 0.3 on a scale of 0 to 5 for present serviceability. Ultrasonic profilers will give the lowest difference when compared to other profilers, because of the large footprint size and their inability to detect short wavelengths.
- Transverse cracking on AC pavements can cause variation of roughness indices between repeat runs. A major contributor to this variability is whether a crack is picked up or missed between the runs. The difference between the maximum and minimum IRI has been observed to range from 0.10 to 0.20 m/km. The difference for RN can vary from 0.1 to 0.2 on a scale of 0 to 5 for present serviceability. PCC pavements that have transverse cracking can also cause similar variations in IRI.
- Faulting as a predominant feature on PCC pavements will not have a large effect on variability in roughness indices between repeat runs. Usually the difference between maximum and minimum IRI from a series of repeat runs will be less than 0.10 m/km. The difference for RN will be about 0.1 on a scale of 0 to 5 for present serviceability. Lateral variations in the profiled path will not have a major effect on the magnitude of the fault that is picked up, because the faulting at locations adjacent to each wheeltrack will be fairly constant.
- Spalling on PCC pavements can have a large influence on lateral variability. The depth of a spall will vary both along its length (direction of travel) and width (transverse to direction of travel). If a series of repeat profiler runs are made on a pavement that has spalling, the difference between the maximum and minimum IRI values can range from 0.10 to 0.20 m/km. The difference in RN can range from 0.1 to 0.2 on a scale of 0 to 5 for present serviceability.

Surface Texture

This section covers the effect of surface texture on profile data collection. Specific guidelines follow:

- Ultrasonic profilers should not be used to collect data on AC pavements that have coarse texture because large errors can occur. For example, on smooth chip sealed surfaces (IRI between 1.0 and 1.5 m/km), the data collected by ultrasonic profilers can give IRI values that overestimate the correct IRI value by as much as 100 percent.
- Available data indicates that chip sealed surfaces do not affect the data collection capabilities of laser, infrared, and optical sensors.
- Laser sensors (small footprints) may experience signal dropout on coarse texture surfaces. Error checking procedures should be used on the signal from laser sensors to guard against errors from this source.

Transverse Profile Variations

Transverse variation in roughness can be significant. Variations observed across pavement sections during the experiments in this project ranged as high as 1 m/km. Deviation in RN was found to be even more significant. A change in RN of more than 1 was observed on an older AC pavement when the profiler lateral position only shifted 30 cm. Guidelines for transverse profile variations follow:

- Operators must drive in the wheeltrack of the pavement being tested. A monitor system or windshield target should be used to aid in positioning the vehicle.
- Variation in roughness up to 50 percent has been observed across pavement sections.
- Normal wander in a wheeltrack (typically 30 cm) will commonly produce variation in the roughness index on the order of 5 to 10 percent.
- For project-level measurements, repeat measurements should be made to quantify the magnitude of this influence.
- For rutted pavements, the profiles should be measured in the ruts.
- Driving far to the right of center will generally cause an increase in the measured roughness.

Daily Profile Variations

The shape of a jointed PCC pavement surface changes with environmental conditions, particularly daily temperature cycles. On days where the air temperature changes significantly throughout a 24-hour cycle, variations in temperature in the PCC slab can give rise to a slab curling effect. This will cause a variation in the profile over the course of the day. Daily profile variations normally only occur in jointed PCC pavements. Guidelines for daily profile variations follow:

- Changes in roughness values caused by daily variations in profile will be more noticeable on plain jointed concrete pavements, which have a joint spacing that is less than 6 m. On days where the air temperature changes significantly, the highest roughness will occur during the early morning hours. The magnitude of the difference in the roughness index between morning and afternoon will depend on the time at which the pavement is profiled in the morning. Measurements taken early in the morning before the sun comes out can be different from the measurements that will be taken later in the morning after the sun has come out. Generally, the difference in IRI between morning and afternoon will be less than 0.10 m/km. However, differences up to 0.3 m/km may occur if the measurement is made very early in the morning (e.g., before 6:00 a.m.) or when the PCC slab is exposed to large temperature cycles.
- The magnitude of the change in roughness index will depend on the shape the PCC slab takes after construction and the slab thickness. Some slabs will take a shape after construction where the mid-slab will be at a higher elevation than the joints. In such a pavement, the variations in roughness caused by the temperature effects will be small.
- For project-level profiling, repeat runs over different times of day would be necessary.

Seasonal Profile Variations

Variations in surface roughness may be linked to seasonal conditions. The largest verifiable changes have been observed in the AC seasonal LTPP sites in January and February. Guidelines for seasonal profile variations follow:

- Analysis of data from AC seasonal monitoring sites has indicated that on average the IRI values at a site vary by 0.2 m/km within a year. Differences as high as 0.4 m/km have been observed at some sites.
- For PCC pavements, seasonal variations will also be confounded by daily variations in profile. Sufficient information was not available to assess the seasonal variability that can be expected on a PCC pavement. The changes observed were not as large as those seen on AC pavements.
- When it is important to track the progression of surface roughness on an annual basis, the profile measurements should always be conducted in the same season.
- Profilers often measure higher roughness in cold months in the northern regions, most likely due to frost heave effects. If measurements at these times are necessary, they should be viewed with caution.
- Network-level profiling should be performed in the same month from year to year. In a wet freeze environment, freezing months should be avoided. In addition, it may be beneficial to track the seasonal changes. Roadways which experience the maximum change in roughness may deteriorate faster.

Subgrade Conditions

Volume changes that occur in the subgrade can cause changes in the profile of a pavement. Changes in subgrade volume can occur due to swelling or shrinkage of the subgrade, or frost heave. Specific guidelines follow:

- To be consistent when collecting profile data, measurements in a region should be conducted in the same time frame each year; this will minimize variations in roughness from year to year that are due to subgrade conditions.
- In areas that have subgrade materials with a high shrink-swell potential, it should be noted that significant variations in the profile may occur between the seasons. This effect is expected to be small for PCC pavements, but it may have a significant effect on AC pavements.

- If profile data are collected during freezing periods, the profiles may contain frost heave effects.

Cross Slope, Curves, and Banking

Operation on cross slopes, curves, and banking can affect the accelerometer output, causing variations in the measured profile. Specific guidelines follow:

- Errors in roughness indices due to cross slopes, curves, and banking are not significant until lateral accelerations go beyond the 0.15 g range. This will not be a common problem on major highways with reasonable driving practices.
- Care should be exercised in driving the profiler to ensure that transitions into curves are smooth.

Hills and Grades

Traversing hills and grades can affect the accelerometer measurement, causing variations in the measured profile. Guidelines for traversing hills and grades follow:

- When grades are in the range of 3 to 6 percent, no problems are expected. The error introduced into the accelerometer in these ranges is not sufficient to cause an error in IRI or RN.
- Changes in grade which cause accelerations of 0.15 g can affect the profile. The effect on IRI will be minimal, but the visual changes in the profile can be large.

MEASUREMENT ENVIRONMENT

Wind

Heavy wind may affect profile measurements when debris pass under the height sensors. Wind conditions may affect ultrasonic height sensor readings due to noise. Guidelines for wind conditions follow:

- All Profilers: Do not operate in severe wind if sand, snow, or other surface contaminants pass under the profiler, or when wind conditions are such that it is difficult to maintain proper lateral position in a lane.
- Ultrasonic Height Sensors: Do not operate in winds exceeding 65 kph (40 mph).

Temperature

Extreme air and surface temperatures can cause errors in height sensor measurements. Guidelines for temperature conditions follow:

- Laser, Optical, and Infrared: Do not operate the profiler in temperatures outside of the range listed by the height sensor manufacturer.
- Ultrasonic: Do not use ultrasonic profilers without calibrating them for the specific temperature conditions under which they will operate.

Humidity

Profiling in humid conditions can contaminate data that is collected if water condenses on height sensor transducers, receivers, lenses, and mirrors. Guidelines for humid conditions follow:

- All Profilers: Do not operate the profiler when the humidity level in the atmosphere is above the value listed by the manufacturer. When operating in high humidity, extra care should be taken to ensure that the transmission path of the height sensor beam is free of condensed water. This includes emitters, pick-ups, lenses, and mirrors. When checking these surfaces, no power should be supplied to sensors, because laser light can cause serious eye injuries.

Surface Moisture

Moisture on the pavement surface may interfere with height sensor readings. Guidelines for surface moisture follow:

- Profiling should not be performed on pavements that have standing water or on pavements where passing vehicles cause the surface water to splash and spray.
- Profiling should not be performed on pavements that have snow or ice.
- Profiling should not be performed when the pavement texture is submerged in water.

Pavement Contaminants

Surface contaminants that are commonly encountered on roadways include sand or gravel that has fallen on to the roadway from passing trucks, and leaves that are blowing across the highway (especially during the fall). These may add artificial roughness to measured profiles. Specific guidelines follow:

- Pavement profiling should not be performed on pavements that have noticeable surface contaminants.
- Leaves present on the roadway or blowing across the roadway can create spikes in the profile data. If such conditions are encountered, they should be noted and the profile should be examined closely to determine if the conditions caused spikes in the data.
- When profiling new pavements, care should be taken to ensure that the surface is clean prior to measurement. The surface should be completely clear of loose gravel particles or any other objects.
- If debris are unavoidable, the data file should be so marked.

Pavement Markings

Stripes and other markings on pavements that cause a contrasting color change may cause spikes in optical height sensor measurements. Specific guidelines follow:

- Profilers with laser, ultrasonic, or infrared height sensors are not affected by white pavement markings.
- White pavement markings will introduce a spike in a profile that is collected by optical height sensors. When a white pavement marking is covered by a profiler with optical height sensors, the data file should be so marked.

Ambient Light

Ambient light may contaminate optical height sensor readings. Specific guidelines follow:

- Laser, ultrasonic, and infrared height sensors are not affected by changes in ambient light.
- Optical height sensors are affected by sunlight. These sensors must be enclosed by a shroud to prevent sunlight from contaminating the measurement. The shroud should be kept in good repair. Particular care should be taken when profiling during the evening when the sun angle is low, because such conditions may allow sunlight to illuminate the surface under the shroud and contaminate the data.

PROFILER OPERATIONS

Lateral Positioning

Roughness varies significantly across the lanes of most pavements. Consistent lateral positioning of a profiler is essential to obtaining repeatable measurements, particularly on pavements with significant surface distress. Guidelines for lateral positioning follow:

- Attempt to drive as straight as possible.
- Drive in the center of the lane or the center of the ruts.
- Windshield or camera targeting systems can be used as a guide in training a driver to maintain a consistent lateral position.
- Profiler operators should perform repeatability tests on pre-established courses prior to initiation of field surveys as a means of developing consistent lateral positioning.

Longitudinal Positioning/Triggering

The start of data collection during profiling can be performed by either manual or automated methods. In the manual method, data recording is initiated by pressing a pendant or a specific key on the computer. In the automated method, a photocell in the profiler is used to detect a mark that is placed on the pavement surface or a reflective tape attached to a cone that is placed on the shoulder of the pavement. Guidelines for data collection follow:

- Most profilers need some lead-in distance after the system is turned on for the filters (used in profile computation) to stabilize. Therefore, the profile data collection system should be in operation before the beginning of the segment that is to be measured. In this phase of operation, data is collected but not recorded. Details regarding the lead-in that is needed before the valid data can be collected should be obtained from the profiler manufacturer. This error is more serious for project-level measurements than for network-level measurements. If the data recording is initiated without a sufficient lead-in prior to the test section, the data that is collected at the beginning of the section can be erroneous.
- For network-level data collection, manual triggering is sufficient to initiate data collection.
- For project-level data collection, especially for profiling new pavements to identify specific roughness locations, an automated method should be used to initiate data collection (i.e., a photocell). This will ensure that pavement features are correctly located within the section.
- For all studies that are performed to assess the repeatability of a profiler, the automated method must be used to ensure that the starting location of all repeat profile runs is the same.

Operating Speed

There is a minimum speed as well as a maximum speed within which valid profile data can be collected. Operating speed guidelines follow:

- The speed range over which valid profile data can be collected is specified by the profiler manufacturer. Operators should adhere to the speed limits set for the profiler by the manufacturer.
- Any measurements outside the recommended speed range for a profiler should be marked as potentially unreliable. Roughness values should not be computed from data that have been collected outside the speed range of the profiler.
- The profiler should mark data files appropriately during intervals when operating speed is outside of the recommended range.

Speed Changes

A profiler that is operated within the permissible speed range may experience measurement errors if the change in

speed is too rapid within a run. The following recommendations are targeted at measuring IRI and RN. These rules can be followed and variations in the profile may still exist; however, their influence on the computed IRI and RN will be minimal. Guidelines for speed changes follow:

- Moderate acceleration and deceleration of 0.15g (about 5 kph per second) and below can be tolerated in network-level profile measurement. These conditions are achieved as long as only moderate applications of brake or throttle are applied during data collection.
- Acceleration and deceleration should be held under 0.1g (about 3.5 kph per second) at all times in construction acceptance or project-level applications of profilers. Unless profiling with a limited lead-in or lead-out distance must be done, nearly constant speed operation is preferable.
- When measuring from a dead stop, the first 150 m of the profile should be ignored. A shorter distance is permissible if a profiler has special provisions for initializing profile computation from low speed.
- If a profiler makes a stop during data collection (e.g., at a stop sign) and resumes right away, the 50 m of profile ahead of the stop and the 150 m after the stop is invalid.
- Discard any data collected below the minimum operating speed.

Segment Length

A different picture of the roughness characteristics of a section can be presented depending on the segment length over which the roughness index is calculated. IRI values can be averaged when they are taken over any interval. RN values cannot be averaged. Guidelines for segment length follow:

- For network-level surveys, reporting IRI at 150 m intervals should provide an overall view of the condition of the roadway. For pavement management, these 150 m sections can be averaged. If a more detailed analysis of a specific roadway segment is required, segment lengths between 25 and 50 m can be used to get a closer look at specific locations that have high roughness.
- For project-level applications, localized rough spots can be identified by using a segment length that is as short as 10 m. A segment length such as 150 m can initially be used to get an overall view of the roughness characteristics along the roadway. Then, to investigate specific characteristics of a shorter length in that roadway, a segment length of 10 m can be used. This will identify the localized areas that have a large contribution to the overall roughness of the section.
- RN values measured over adjacent pavement segments can not validly be combined by averaging. To combine RN values from adjacent sections of equal length, you must compute the root-mean-square of the Profile Index values from each section. The RN is computed from the result.

Frequency of Data Collection

Frequency is the number of times per year a section should be measured to be monitored successfully. It is directly tied to the issues of seasonal variations in profile and pavement deterioration rate. Studies have shown that seasonal variability is a factor that can affect the roughness of a pavement. However, this is a very complicated issue because variations in roughness will depend on a variety of factors. Guidelines for frequency follow:

- For network-level profiling, the frequency of data collection will be related to the resources that are available to the agency. For a specific agency, the frequency of data collection can vary depending on the type of the highway system that is being profiled (e.g., interstate vs. secondary). The interstate system may be profiled at a more frequent interval when compared with the secondary road system.
- For studies that involve obtaining an overall assessment of variability in roughness throughout the year on AC pavements, profile measurements should be obtained four times a year. The section should be profiled in the middle of each season (spring, summer, fall, and winter). For PCC pavements, variations in roughness can occur throughout a day due to temperature effects. For studies involving an overall assessment of variability in roughness over the year on PCC pavements, a procedure similar to the one recommended for AC pavements should be followed. However, each PCC section should be profiled three times during the day (morning, noon, and afternoon) each time it is profiled.
- In order to keep track of the condition of the pavements within a network, an annual or biennial data collection frequency is recommended. The data collection for a specific region should be performed during the same time frame each year to minimize the impact of seasonal variations in profile data.

Tire Inflation Pressure

Tire inflation pressure affects the accuracy of longitudinal distance measurement directly through a change in the effective rolling circumference of the tire. Guidelines for tire inflation pressure follow:

- Use radial-ply tires on high speed profilers.
- Set the tire pressure at the recommended cold inflation pressure. This should be done daily prior to collecting profile data and also before the calibration of the distance measurement system.
- Warm up the tires before the calibration of the distance measuring system by driving the profiler 20 to 30 min at highway speed.

Construction Acceptance

Caution should be used when an inertial profiling device is used in construction acceptance applications. Specifically, on-the-run processing or poor filtering can cause a phase shift in the computed profile. Guidelines for construction acceptance follow:

- In construction applications, profile should not be calculated on-the-run. Use bi-directional processing to avoid phase shifts. Errors of up to 0.5 m can be encountered if the profile is computed on-the-run. Thus, using profile data for locating must-grind areas can inadvertently add to roughness rather than remove it.
- The anti-aliasing filters should have a cut-off wavelength equal to twice the sample interval.
- Distance measuring equipment should be calibrated daily when used in construction applications.
- A sufficient lead-in should be allowed prior to the beginning of the test section for the filters to stabilize. The profiler manufacturer should be contacted in order to determine the lead-in that is required.
- Repeat runs of each section should be obtained, with the start of data collection being initiated by an automated triggering system.

PROFILER OPERATOR

Training

A road profiler is a complex piece of equipment. Operators need training beyond the simple operating practices to ensure data quality. Guidelines for training follow:

- The profiler operator should be trained to identify when valid and accurate data are being collected.
- The operator should be familiar with all operations that are involved in the calibration of the height sensors, accelerometers, and the distance measuring system.
- The operator should be familiar with the daily checks that need to be performed on the equipment prior to data collection to ensure that the height sensors and the accelerometers are working properly.
- The operator should be trained to recognize valid ranges for height sensor measurements and accelerometer measurements. The operator should be able to review the data that is being collected by the height sensor and the accelerometer and be able to spot any problems with the data acquisition systems.
- The operator should have an understanding of roughness indices and the ride quality that is associated with each roughness index. Some profilers have the ability to display or print out the roughness indices at specified intervals (e.g., 150 m). The operator can review the roughness index and see if it is in agreement with subjective judgment of the road condition.
- It is recommended that a set of guidelines be developed by the agency that details calibration, daily calibration checks, and other procedures to be followed during data collection. This will make it easier for the operator to follow and adhere to these procedures.

Driving Skills

Driving practices can have an influence on the roughness measurements. Guidelines for driving practices follow:

- The driver of the profiler should be trained to correctly follow the wheeltrack. The driver should be made aware of the variations that can occur in roughness indices when an incorrect wheeltrack is being profiled.
- The driver should be trained to anticipate traffic conditions so that conflicts do not arise to disrupt the collection process. The following behaviors can aid in better data collection: anticipating conditions at merging ramps so that the driver is not forced to change lanes, avoiding sudden heavy braking that can drop the speed of the profiler below the minimum recommended speed, and avoiding heavy acceleration or deceleration.

Daily Operating Procedure

The daily operating practices executed by the profiler driver and operator can have significant impact on the quality of the roughness measurement program. Guidelines for daily operating procedures follow:

- The sensors should be checked to see if there is any visible damage, such as chipped or broken glass. Sensors should also be checked for dirt. The power to the sensors should be off while the sensors are being checked, because laser sensors can cause eye injury.
- The tire pressure should be checked to verify that it is at the recommended value.
- The electronic equipment within the vehicle should not be turned on until the vehicle interior has been brought within the operating temperature range of the components. Generally, 10 to 15 min are sufficient for all components to equalize. However, during extremes in temperature, warm-up may take up to 30 to 40 min.
- Daily checks should be performed on the height sensors and the accelerometers prior to data collection. The procedures for performing the daily checks can vary depending on the equipment. It is recommended that the profiler software be capable of performing a calibration check on the height sensors. In this procedure, a gauge block of known height is placed below the height sensor and the change in height is computed. This height should agree with the height of the gauge block within a specified tolerance. It is recommended that the profiler software be capable of performing a "bounce test." In this test, a swaying or a pitching motion is induced on the vehicle while it is stationary and the profile data is

collected. The collected profile should show an amplitude that is less than 1 percent of the motion that is induced. The electronic equipment should be turned on and given time to warm-up before performing either of these.

- Maintain a checklist on the tasks that have to be done daily prior to data collection.

Calibration

Three components in the profiler require calibration: the height sensor, the accelerometer, and the distance measuring system. If any of these systems are operated without calibration, the profile data that is obtained is questionable. Guidelines for calibration follow:

- The calibration of the height sensor and the accelerometer should be performed according to the procedures that are provided by the manufacturer. Calibration should be performed at the time intervals that are recommended by the manufacturer. Keeping track of the calibration parameters when the systems are calibrated will provide an indication of the relative stability of these components between calibration periods.
- The distance measuring system is calibrated by driving the vehicle over a known distance. The length of the calibration section should be known accurately within 0.05 percent. The calibration section should be laid out with an electronic distance measuring system or a steel tape using standard surveying procedures.
- The distance measuring system should ideally be calibrated at the measuring speed that is usually used during data collection. The cold tire inflation pressure should be set at the recommended value, and the vehicle should be driven for 20 to 30 minutes to warm up the tires prior to the calibration.
- A record of the calibration factors that are obtained, together with the vehicle mileage corresponding to the time when the calibration is performed, should be maintained to track the stability of the distance measuring system.
- The calibration of all three components should be performed whenever repairs are performed on the suspension system or the wheels are aligned. The calibration should also be performed whenever tires are replaced or rotated.
- As a further check on the profiler, calibration sites should be established at convenient locations to verify that the equipment is working properly. These sites can be established close to the office, and should be profiled immediately after the profiler has been calibrated. These sites can again be profiled after the profiler returns from a network-level survey. A minimum of two calibration sites is recommended: a smooth section (IRI less than 1.2 m/km), and a fairly rough section (IRI between 2.3 and 3.0 m/km).

Adherence to Guidelines

One of the most effective means to ensure that quality data are being obtained is to develop and adhere to a set of guidelines for profiler operation. Specifics follow:

- Adherence to a standard set of guidelines is essential to collect consistent profile data. Each agency should develop a standard set of guidelines that should be followed for data collection at the network and project level. These guidelines will ensure that the same procedures will be followed, because staff turnover can result in different personnel being assigned to operate or drive the profiler over time.

IDEAL PROFILER

During the research that supported these guidelines, several features were identified that are essential to profiler performance. Most of these have been noted previously in these *Guidelines*. The intent of this section is to highlight the elements that should be considered when purchasing or developing a profiler.

The main elements of a profiler are the height sensors and accelerometers. As previously stated, the sensitivity of most commercial accelerometers is adequate for use on these devices. However, height sensors have been shown to vary widely in design and performance. Optical, infrared, and laser height sensors are all adequate for use in network-level and project-level applications. Optical and infrared sensors have the benefit of a large footprint on the pavement surface. The older optical sensors appear to be more accurate; unfortunately, these older sensors are mechanical devices subject to break down that can be very costly and are prone to error due to ambient light and surface color changes. The newer infrared devices offer the benefit of a larger footprint and better performance without the mechanical complexity of an optical sensor.

The other measurement component of the profiler is the distance measuring system. The wheel hub mounted units appear to run smoothly and stay in calibration. However, recent tests have shown that tires can have a great impact on the performance of the system. In the recent LTPP profiler calibration study, four identical systems were used. The systems employing cheaper tires were found to fall out of calibration due to tire pressure changes. Although the changes were small, the difference in performance was large. High quality tires should be used on profilers.

On-board processing of data varies considerably among manufacturers. The following is a list of highly desirable profiler requirements:

- The profiler should display the raw data for height and accelerometer signals.
- The roughness index should be calculated and displayed on a continuous basis. A short segment analysis of 25 to 50 m is recommended.

- A spike warning feature should be included in the software to identify potentially erroneous data. Warning flags should be placed in the data file when the signals for the height sensors or accelerometers are potentially in error.
- Speed changes should be monitored to detect accelerations greater than the 0.15 g limit.
- A cutoff filter for wavelengths greater than 91 m should be employed.
- For reporting indices or profile, the date, time, and temperature should be stored with the measurements.
- Keyboard entry of symbols or numbers to flag events or locations should be provided in the profiler software.

ACKNOWLEDGMENTS

This project was sponsored by NCHRP as Project 10-47, "Guidelines for Longitudinal Pavement Profile Measurement." It was guided by NCHRP Project Panel 10-47, chaired by Mr. Gaylord Cumberledge, with members Kent Hansen, Sonya Hill, Khaled Ksaibati, Blair Lunde, Harry Schmerl, Larry A. Scofield, Steven L. Tritsch, and James C. Wambold. The contract was undertaken by The University of Michigan Transportation Research Institute, T. D. Gillespie and S. M. Karamihas, in cooperation with S. D. Kohn and R. W. Perera of Soil and Materials Engineers, Inc.

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