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Calibration of Road Roughness Measuring Equipment,

Volume II: Calibration Procedures

Research, Development, and Technology
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FOREWORD

Road roughness data are among the primary inputs to pavement management systems. Reliable equipment as well as test and calibration procedures are essential for providing high quality road roughness data. Two distinct methods of measuring road roughness are in use. One method profiles the road surface in one or both wheel tracks. While this is the preferred method, it is currently not widely used because of cost and complexity. A widely used, simple and inexpensive method measures the response of an automobile or trailer to road roughness. Obviously, the response depends on vehicle characteristics and on the speed of testing. The operating principles of both measuring methods have been analyzed in the research reported in Volume I. Limitations and error sources were identified from the analysis and from field test results. The findings provided the basis for recommended calibration and field verification procedures for both test methods and equipment. These procedures are given in Volume II of this final report.

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NOTICE

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16. Abstract

A separate report (FHWA-RD-89-077, Calibration of Road Roughness Measuring Equipment, Volume I: Experimental Investigation) documents an extensive series of measurements of the performance of a commercial inertial road profiling system (IRPS) and a commercial response-type road roughness measurement (RTRRM) system. Based upon the results of these measurements and upon an analysis of the operation of such equipment, calibration and testing guides, given in the present report, were developed to assist users in assessment of IRPS and RTRRM functionality and operating performance.

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1. INTRODUCTION

Road roughness is a very old engineering problem. On the one hand, rough roads produce wear and tear on the vehicles, people, and materials transported over them. On the other hand, rough roads themselves wear out faster than smooth roads. Thus, the quantification of road roughness is an important civil engineering endeavor because it enables engineers to set criteria for when to resurface roads and how to evaluate the irregularities of newly finished roads.

Pavement irregularities, generally random in nature, are divided into three scales: roughness, macrotexture, and microtexture. The dividing lines between these regions are based upon functional considerations such as traffic safety and ride quality. Roughness is the largest scale, with characteristic wave lengths of 0.3 to 300 ft and amplitudes of 0.04 to 4 in – it is of interest with regard to ride comfort. Macro- and microtexture describe smaller scale pavement irregularities, generally related to tire-pavement traction characteristics.

Road roughness is measured by: (1) inertial road profiling systems (IRPS), which measure actual pavement profiles, and (2) response-type road roughness measurement (RTRRM) systems which measure vehicle response to roughness. Ideally, road profiling systems yield accurate, scaled reproductions of the pavement profile along the path of vehicle travel. In practice, the range and resolution of any IRPS are limited, but within the wavelength and amplitude limitations of the system, a profile measurement may be called "absolute," in the sense that it does not require comparison to any other system, except for the calibration of its several sensors and the associated electronics. A response-type method records some measure of the dynamic response of a particular mechanical system as it travels over the pavement. It is, therefore, a relative method whose result depends on the characteristics of the mechanical system and the speed of travel.

The advantages of a profiling system are evident. It provides pavement-profile information that can be evaluated according to specific needs. In an IRPS, the vertical displacement of the vehicle frame is obtained by double integration of the signals from accelerometers. The road profile is obtained from the algebraic sum of the vehicle displacement and the relative frame-to-road displacement. In a modern IRPS, noncontact sensors (usually optical, but sometimes acoustical) are used for measuring the frame-to-road displacement.

Although, as stated above, an IRPS is an "absolute" method, it is necessary to ascertain that the sensors (accelerometers, height sensors, distance encoder) and electronics are calibrated and that the computer and software are functioning properly.

RTRRM systems typically accumulate a measure of the vertical movements of the rear axle of a vehicle relative to the vehicle frame. This method of measurement is simpler and cheaper than profiling equipment. However, since the results obtained depend upon the dynamic characteristics of the vehicle and upon the mechanical behavior of the device itself, the data from RTRRM systems are critically dependent upon suitable test procedures.

In volume I of the present report, an extensive study of the performance of a specific IRPS is documented, along with a closely related study of the performance of a particular type of RTRRM system. Based on these studies as well as on prior work by others, recommended calibration and test procedures have been developed for both IRPSs and RTRRM systems; these procedures are given in the present volume.

Section 2 is a generic field calibration guide for inertial road profiling systems, providing an overview of the types of calibrations, tests, and checks that should be carried out to ascertain proper performance of an IRPS.

Section 3 provides more specific detailed procedures for testing and calibrating IRPSs. In section 4, these procedures are made specific to the K. J. Law Model 690DNC road profilometer (the type of road profilometer whose performance was examined and is reported in volume I of this report).

Section 5 is a field test procedure guide for RTRRM systems, with many of the tests procedures being useful to a variety of RTTRM systems, but being specific to the Mays Ride Meter where generic tests were not possible or practical.

2. FIELD CALIBRATION GUIDE FOR INERTIAL ROAD PROFILING SYSTEMS

The purpose of this guide is to provide a general framework from which procedures for verifying the adequacy of performance of an inertial road profiling system (IRPS) may be adapted. The scope of this guide is limited to those vehicles capable of operation at high speeds without significantly disrupting normal traffic flow; other profiling methods, such as the rod and level or "walker" type systems(1), are excluded. IRPS equipment for measuring road profiles produces a high-resolution record of variations in the height of a road along its length, filtering out larger variations such as grades. Because the customary end use of such profiles is as an accurate basis for computation of generally-accepted single-number ratings of highway condition, IRPSs include hardware and software for these computations. Four basic subsystems of an IRPS are:

- Accelerometer(s) for determination of the height of the vehicle relative to an inertial reference frame (i.e., a reference frame that does not depend on riding height or position of the vehicle along the road).
- Height sensor(s) for measurement of the instantaneous riding height of the vehicle relative to a location on the road below the sensor.
- Distance or speed sensor for measurement of the position of the vehicle along the length of the road (i.e., an odometer which indicates fractions of a foot rather than fractions of a mile).
- Computer hardware and software for computation of road profiles from the above sensor inputs.

Because failure of a basic subsystem of an IRPS can sometimes produce bad data that look good, it is necessary for this guide to describe functional tests that may be employed every day to make sure that each subsystem has not failed. More detailed, fitness-for-service tests should also be used, though less frequently, to check for subtle changes which might significantly reduce the quality of data produced by the overall system. In order to make this guide easy to use, the everyday functional tests for each of the four subsystems are discussed before the more detailed tests. The detailed tests of IRPS subsystems involve comparison of the results of a particular test with baseline data previously developed for the particular vehicle tested. The overall outcome of these comparisons is a decision as to whether the vehicle is fit for further field use or must be repaired and/or recalibrated before any further use.

The correctness of this decision depends so heavily on the validity of the baseline data that data for the exact vehicle tested, rather those for vehicles of the same general design, are almost always required. If no such data are available, then go/no-go evaluations of fitness for further field service must be deferred. In these circumstances, detailed tests of IRPS subsystems should be conducted during field work at appropriate intervals for development of baseline values.

Implementation of the procedures described in this guide requires development of both a baseline database and specific procedures for each type of IRPS. The goal of long-term efficiency will be well served if the latter are developed in close association with the personnel who will perform the field work.

On-board Computing Equipment

Daily Functional Tests

Because of its considerable complexity, the computing equipment in an IRPS is often its most troublesome subsystem. Fortunately, the results of most failures are painfully evident, so that these problems rarely cause the gathering of bad data. Assuming that the computer system is known to have worked perfectly the last time it was used, everyday checkout can safely be limited to exercising programs and devices that will be used that day. To avoid such disappointments as spending a day gathering data only to find that they cannot be processed because of disk drive problems, the key program and device to be used must be tested before **any** data-gathering begins for the day. Comprehensive checkout of the computer system should require no more than diligent effort and, with some systems, dummy data with which to exercise it. Consistent difficulties, obviously attributable to software, should be reported for correction rather than worked around by field personnel. Arrangements for factory repair of equipment known to be weak spots in the computer system should always be made before extended trips from home base. If the mode of use of the IRPS requires power sources other than the electrical system of the host vehicle, computer operation with these power sources should be checked. Failure of the alternative power source can result in significant loss of data.

Since repairs to on-board computing systems in general will not affect overall system calibration, extensive field service is more feasible for the computing system than for the other elements of the IRPS.

Fitness-For-Service Tests

Computer systems of the type employed in IRPSs are rarely subject to gradual change in performance caused by use or the passage of time, provided that they are properly maintained. Performance that is erratic or otherwise marginal is almost always the result of misapplication of either software to its task or of hardware to its physical environment. Problems of this sort are ordinarily discovered early in the service life of each IRPS and should be corrected before full-time use is begun. If this is done, debugging will not be a part of fitness-for-service testing.

Because errors in data storage and retrieval are rare and usually obvious, benchmark programs should be necessary only for those parts of the computer system used for real-time, high-speed data processing and control of the other elements of the IRPS. Depending on the difficulty engendered in troubleshooting these other elements, it may be expedient to use benchmark programs designed to substitute for suspected defective hardware, such as multiplexers or A/D converters, as a primary tool in fault diagnosis. Benchmark programs designed only to test the performance of the computer system itself are unnecessary in a well-designed computer system for IRPSs.

Vehicle Height Sensing System

Daily Functional Tests

The Vehicle Height Sensing System (VHSS), of which there may be several on a given vehicle, determines instant-by-instant values of its own riding height, and thus that of the vehicle frame, above the pavement. By means of often-elaborate signal processing, the VHSS signal is subtracted from a signal from the Inertial Profile Reference (IPR) system. Because the IPR signal represents the elevation of an imaginary plane fixed in space, the result of each subtraction is a value of the road's profile, or height relative to a fixed reference plane. The fact that subtraction is involved makes functional checkout easy, provided that the IRPS has a way of displaying computed "profile" while standing still. If it does not, the IRPS will certainly have a way of displaying VHSS output. The daily check of the VHSS may consist of nothing more than a quick sweep of a flat board of known thickness under each height sensor while watching the display; a square pulse of appropriate height will be seen if the VHSS is functional. If the display is set to show the computed profile, then the vehicle must be still during each sweep to avoid interference by IPR signals. If convenient, the daily test may involve a more elaborate procedure requiring gauge blocks, discussed below and also described in section 3. In the event of an apparent failure, only the simple remedies known not to affect sensor calibration should be attempted (e.g., cleaning a sensor window). Under no circumstances should a repair which affects calibration be followed by data gathering and then by performing "retroactive" calibration procedures; all corrective calibration work must be completed before the IRP system is returned to service.

Fitness-For-Service Tests

The need for and difficulty of performing quantitative tests of VHSS performance will vary widely with the type of system used. For example, ultrasonic systems are compact, highly unitized, and subject to few adjustments other than those related to repositioning a replaced unit. Optical designs are both mechanically and electronically complex and, while capable of greater resolution than simpler designs, are sensitive to both slight changes of the geometry of various components and to drift in the electronics. The schedule for VHSS fitness-for-service tests for a given IRP system should be greatly influenced by such details. Testing may also be required upon discovery of specific varieties of anomalous performance. The most basic and reliable field test is simple – a platform is aligned in position relative to the sensor, and a gauge block of accurately known thickness is placed under the sensor. Comparison of the indicated change in vehicle height with the known block thickness allows diagnosis of the sensor. With some designs, the use of multiple gauge blocks may be dictated by a need to check sensor linearity. Some optical systems require measurement of intercomponent angles and distances as a part of a full calibration of the sensor. Full calibrations of such systems are not considered feasible in the field, because of the complexity of the procedures and the need for special equipment. If the results of gauge block tests deviate from the limits established when the IRP system was commissioned, the physical cause must be found and corrected, and appropriate recalibration work done before returning the vehicle to service. Computer-stored parameters should be adjusted only when specifically authorized by established operating procedure; indiscriminate adjustment of such parameters can result in serious errors.

Inertial Profile Reference System (Accelerometers)

Daily Functional Tests

The Inertial Profile Reference (IPR) system, of which there may be more than one on a given vehicle, determines instant-by-instant values of its vertical position relative to an imaginary reference plane fixed in space. Thus, the motion of the vehicle itself, rather than its position relative to the road, determines IPR output. While exotic devices exist which can directly provide the required data, all inertial profilometers of modern design use accelerometers whose output can be processed electronically into a suitable form. While it can be established by purely electronic means that the servo accelerometers used in some IPR systems have a high probability of being in working order, it is worth remembering that no accelerometer can be **proven** to be working without moving the accelerometer or the vehicle to which it is attached.

Computer programs that purport to check accelerometers while they are motionless actually check the accelerometer electronics instead. Checking the performance of each IPR system on a vehicle is readily done by vertically shaking the vehicle and looking for changes in the IPR system's output signal. This procedure is best done by shaking the entire vehicle (the bounce test) or by having a person shift his weight while inside the vehicle. Tapping on the housing of the IPR system itself should not be done because tapping produces vibration of the wrong frequencies and might cause damage. If no means are provided for displaying accelerometer raw data, profile data may be used instead by temporarily defeating the VHSS sensor for the profile channel in use. If no means are provided for turning the VHSS off, it may be defeated by interposing an opaque material between the sensor and the pavement. Suitable materials include black velvet for optical sensors and fiberglass batts or blankets for ultrasonic sensors. If the bounce test indicates an erroneous result, it must be determined whether the accelerometer or its associated signal-processing equipment is faulty. Diagnostic computer programs or spare accelerometers should be tried, if available. Alternative IPR system operating modes should be employed only if specifically authorized by established operating procedure. Field installation of spare components should be done only if means for recalibration are established and available.

Fitness-For-Service Tests

Both the schedules and the methods of field fitness-for-service tests are primarily determined by the type of accelerometer used in the IPR system. Servo accelerometers can be quantitatively tested, and even calibrated, using only a voltmeter and a stable positioning fixture to turn the accelerometer upsidedown. Although this procedure is readily performed in the field, it is of only academic interest because the magnitude of drift typical of servo accelerometers is insignificant. The primary means of failure of servo accelerometers is fracture of an internal component; this is caused by excessive vibration and results in complete loss of output. Piezoelectric accelerometers, the other kind suitable for use in an IPR system, are much less susceptible to damage but are subject to significant drift in effective gain. Because piezoelectric accelerometers can be quantitatively tested only with the use of special equipment that is impractically complicated for field use, quantitative testing of an IPRS employing a piezoelectric accelerometer is limited to comparisons of on-the-road results obtained with swapped accelerometers. Quality assurance of IPR systems using piezoelectric accelerometers is probably best served by scheduled replacement with freshly calibrated accelerometers and adjustment of digitally-stored parameters.

Vehicle Travel Sensing System

Daily Functional Tests

Of the four basic subsystems of an inertial road profiling system, the Vehicle Travel Sensing System (VTSS) requires the least effort to verify its functionality. This check can be done by attempting to obtain a profile while driving around the block, because the scheme for computing profile would fail in the absence of the VTSS signal, provided the profile is being collected as a function of the traveled distance rather than time. Assuming that the other three IRPS elements have already been proven to be functioning, obtaining either a flatline profile or an error message signifies VTSS failure. The associated sensor always measures wheel revolutions (within a small fraction of one revolution) and is attached to a free rolling wheel to minimize errors due to slippage. Practical field service is limited to replacing the entire sensor; this does not necessitate recalibration, because overall accuracy is determined by tire diameter rather than sensor calibration. Due caution should be exercised when sensor replacement involves disturbing hub attachment hardware; frangible and prevailing-torque fasteners should not be reused.

Fitness-For-Service Tests

Initial calibration of VTSS equipment involves driving the vehicle a known distance and calculating the scale factor relating wheel encoder counts and distance traveled. Since current and proposed standards require the combined error in both measurement of the known distance and in measurement of vehicle travel (using the VTSS) to be less than 5 ft/mi (0.1 percent), the method used for initial calibrations may be impossible to duplicate in the field.(3,4) Field tests of the VTSS should be attempted only if the length of the measured course is known with the required certainty and if any necessary special triggering methods can be used safely without disrupting traffic. The need for trips to home base for VTSS recalibration can be minimized by repeating VTSS calibrations using several sets of new tires of the same type every time the vehicle is at home base. The spare tires thus "VTSS-calibrated" can be stored at home base, at inflation pressure recommended by the manufacturer for long-term storage, and shipped out as needed when the tire wear on the previous set has exceeded a certain limit. Tires used for this purpose must not be removed from their rims between calibration. Thus each tire must have its own rim. It should be noted that the current and proposed standards requiring 0.1 percent accuracies of VTSSs may be excessively tight for road roughness calibrations, such as the calibration of RTRRMs.

3. DETAILED PROCEDURES FOR TESTING AND CALIBRATING INERTIAL ROAD PROFILING SYSTEMS

The following procedures are recommended for calibrating and testing vehicles that directly produce road roughness profiles.

Power Up Procedure

A uniform procedure should be developed to power up the entire system before testing any part of it. The procedure may be fashioned into a check list.

Depending on the system, items to switch on may include the vehicle's engine, electronics for the accelerometers and road sensors, light sources, computers, and computer peripherals such as disk drives, tape drives, printers, and CRTs. The proper software should also be in place on disks or tapes.

Daily Functional Tests

Vehicle Height Sensing System

This procedure is a static test of the accuracy with which a known height can be measured by the road sensor. It is simple enough to be used on a daily basis but it can also be used as a quantitative test to monitor fitness-for-service. Like the accelerometer test, the procedure should test both the analog and digital components together as a system. If the reading is found to be in error by greater than a prescribed percentage, the source of the problem should be located.

Procedure:

1. Drive the vehicle to a level stretch of pavement in a quiet place.

2. The vehicle should remain as motionless as possible during this test (no moving around inside, no wind, etc.).

3. Place a calibration fixture under the road sensor. The calibration fixture should consist of a lower surface and an upper surface whose heights are probed by the road sensor. The calibration fixture should either be leveled on the pavement or it should be mechanically squared up to the vehicle to avoid potential leveling errors. The height difference between the upper and lower surfaces of the calibration fixture should be at least 1 in.

4. Measure the height of the lower surface with the road sensor, then measure the height of the upper surface. Make sure that the two surfaces are positioned accurately for this procedure.

5. The measured height should be within 1 percent of the actual height difference. If not, try to understand the source of the discrepancy. Check the road sensor components and examine the calibration fixture and redo the procedure, Steps 3-4.

6. If the equipment is found to be operating properly, recalculate the appropriate scale factor to give the correct value of upper to lower surface height difference.

7. Repeat the procedure, Steps 3-5.

8. Record the current scale factor and measured height on a control chart.

Bounce Tests

Observation of the road profile output as a function of time should be made while the vehicle is shaken manually, but otherwise motionless. The rolling, pitching, and yawing modes of excitation should be checked in turn. Excursions of the observation profile should be smaller than certain limits consistent with previous results.

Procedure:

1. Start the profile output of the vehicle so that a recording of the profile is taken.

2. Observe the profile output as a function of time for about 30 seconds in a quiet environment with no disturbances of the vehicle. This step establishes a noise and drift baseline for the other tests.

3. Shake the vehicle in a pitching mode for about 15 seconds. The drift in the profile output should be less than about 0.1 in.

4. Do the same for the yawing mode. The output drift should be less than about 0.05 in.

5. Do the same for the rolling mode. The output drift should be less than about 0.20 in.

Fitness-For-Service Tests

Inertial Profile Reference System (Accelerometer)

This is a static test of the inertial profile reference system to see whether it can accurately sense a simulated change in acceleration of 1 g. The procedure should test the entire computerized system for measuring the acceleration, including any amplification stages and the analog-to-digital conversion. If the reading is found to be in error by greater than a prescribed percentage, the source of the problem should be located.

Procedure:

Commercial servo-accelerometers are normally equipped with means for producing a signal that accurately represents a 1 g acceleration. The general procedure would therefore be as follows:

1. Drive the vehicle to a level stretch of pavement in a quiet place.

2. Turn off electronics and equipment that are not required to operate the accelerometer.

3. Make sure that the vehicle remains as motionless as possible during the test.

4. Measure the background signal from the accelerometer and then measure the signal under a simulated 1 g excitation.

5. The difference between these two signals should equal 1 g (32.17 ft/sec^2) to within certain limits, for example, 1 percent.

6. If the measured value falls outside the control limit, try to understand the source of the discrepancy. Experience with the system and the use of control charts will help to differentiate between genuine problems and acceptable variations.

7. If it can be conclusively shown that the change in the measured value results from a genuine change in the gain of some stage of the IPRS, recalculate the scale factor to produce a calibrated 1 g result and check its accuracy by performing Steps 4 and 5 again.

8. Record the measured value of g on a control chart that plots these factors versus time for long periods.

9. Turn on the equipment that was turned off in Step 2 to bring the vehicle back to full operation.

Static Test of Accelerometer Noise

Observation should be made of the accelerometer signal as a function of time with the van motionless and in a quiet environment to check the noise output of the accelerometers. The reading should remain within certain limits.

1. Drive the vehicle to a quiet place.

2. Turn off the engine and any equipment not required to operate the accelerometer.

3. Make sure that the vehicle remains as motionless as possible during the test.

4. Observe the output of the accelerometers as a function of time for about 30 seconds. If possible, record the results as a permanent record.

5. The output should remain within certain limits consistent with previous tests.

6. Turn on the equipment that was previously turned off in order to bring the vehicle back to full operation.

Static Test of Integrated Accelerometer Output Noise

Observation should be made of the doubly integrated accelerometer signal as a function of time with the vehicle motionless and in a quiet environment to check its noise output. The reading should remain within prescribed limits.

Procedure:

1. Drive the vehicle to a quiet place.

2. Turn off the engine and any equipment not required to operate the accelerometer.

3. Observe the profile output as a function of time with the VHSS turned off so that only the double integrated accelerometer signal is being shown. If possible, make a permanent record of the results.

4. The output should stay close to zero within certain limits consistent with previous tests.

5. Turn on the equipment that was previously turned off for this test.

Static Test of Vehicle Height Sensor Noise

Observation should be made of the VHSS signal as a function of time with the van motionless and in a quiet environment to check the noise output of the displacement sensor. The reading should remain within prescribed limits.

Procedure:

1. Drive the vehicle to a quiet place.

2. Turn off any equipment not required for operation of the road sensor.

3. Operate the sensor so that only the output from the road sensor is being observed. The accelerometer is either turned off or its output is bypassed.

4. Remain quiet and observe the road sensor output as a function of time.

5. The output should stay near zero within certain limits consistent with previous tests. If possible, make a permanent record of the results.

6. Turn on the equipment that was previously turned off to bring the vehicle back to full operation.

Encoder Test and Recalibration

A calibrated length of road should be measured for distance using the wheel encoder or other distance measuring device on the vehicle. If the result disagrees with the accepted value by more than certain limits, the digital scale factor may be changed or various subsystems may be checked.

Procedure:

1. Select a stretch of road at least 1500 ft in length whose length is known to an accuracy of 0.5 percent or better. The stretch of road should have clearly marked starting and ending points.
2. Operate the vehicle in a mode that permits you to measure the distance traveled.
3. Drive over the measured length of road at constant speed and start and stop the distance encoder precisely at the end markers. You should be able to start and stop with a precision of ±4 ft.
4. The measured road length should be within 1 percent of the accepted value.
5. Perform the test at least three times.
6. If the disagreement is greater than 1 percent, check the tire pressure and other possible causes of error.
7. If no causes of error are found, recalculate the encoder scale factor and record its value on a control chart. Then redo the test, Steps 2-4, at least twice.

Flat Plate Test

This is a dynamic test of the road profiling response at high frequency. The flat plate represents a sharp step on the road. The vehicle is driven over it at a speed of about 10-15 mph to test the profiling output for a square pulse input. The output as a function of time should be predictable from the vehicle specifications for high-pass and low-pass filtering and should be repeatable over the course of time.

Procedure:

1. If possible, set up the vehicle operation to record the profile as a normal run on a permanent storage medium, such as a magnetic tape, and on a hard-copy printout.
2. Select a quiet area such as a quiet parking lot about 400 ft in length.
3. Use a flat plate to represent the square pulse. See figure 18 in volume I of this report for a suggested design, made of aluminum with dimensions 18 by 24 by 5/8 in.
4. Lay the plate on the pavement with its long dimension along the direction of travel of the vehicle.
5. Drive the left wheel of the vehicle over the plate and record the profile as follows.

6. Start from rest and allow approximately 200 ft to pick up speed to about 10-15 mph before passing over the plate.

7. Once the vehicle is up to speed, start the run recording.

8. As the vehicle passes over the plate, the width of the plate should be centered on the recorded left wheel track.

9. Stop the run recording soon after the vehicle has passed completely over the plate.

10. Repeat Steps 5-9 for the right wheel track sensor.

11. The output profile should not show any high frequency disturbances except for the section where the road sensor scans the plate itself. That section should look like a rectangular step 5/8 in high, modified by the low-pass or high-pass filtering in the sensor system. A typical profile for two plates placed sequentially along the left wheeltrack is shown in figure 1.

Profiling Consistency Test

This is a dynamic test of profiling repeatability over a long period of time. The profile is taken for a section of road that has been profiled previously. A time history is kept of the recorded profiles to see whether the road profile is consistent with previous ones. If significant changes begin to occur, the previous tests should be carefully checked. If no problems are discovered, the road should be profiled by an alternative means such as another profilometer or a rod-and-level survey. Note that if an alternative means of profiling the road is used, the effects of sampling distance and filtering must be considered (see volume I of this report).

Procedure:

1. Choose a section of road that has been profiled before and that has a stable profile.

2. Set up the vehicle operation to record the profile on a permanent storage medium and on a hardcopy printout.

3. Start the vehicle about 400 ft before the beginning of the course and pick up speed to about 50 mph.

4. Start the profile recording at the beginning marker and stop at the ending marker of the course.

5. Perform Steps 2-4 at least three times and check the consistency of the profiles.

6. In addition, check the consistency of the measured profiles with those measured at previous times for the same stretch of road.

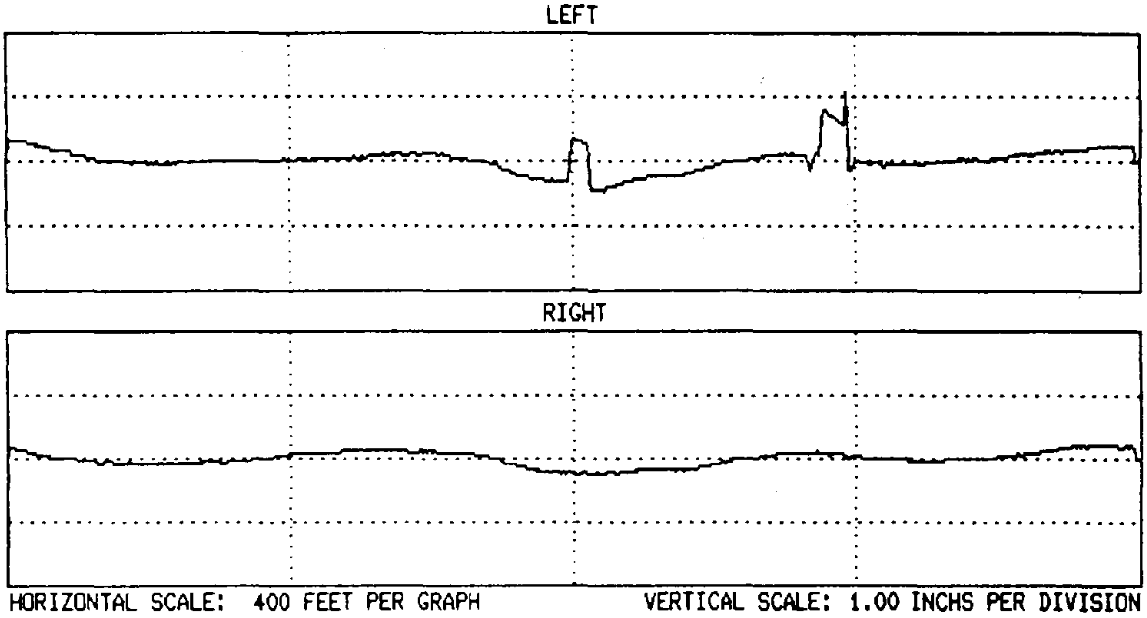

Figure 1. Road profiles obtained when two test plates are positioned along the left wheeltrack of the road profilometer.

Control Charts

Control charts should be kept of the digital scale factors and measured values for the accelerometers, the displacement sensors, and the distance encoders. The values as a function of time should not show trends nor should any value lie outside control limits of ±3 standard deviations centered about the mean value.

4. PROCEDURES FOR TESTING AND CALIBRATING THE K.J. LAW MODEL 690DNC ROAD PROFILOMETER

This section is an adaptation, to the K. J. Law Model 690DNC Road Profilometer, of the generic procedures in section 3.

Power Up Procedure

1. Turn the generator on.
2. Install the system disk in the upper disk drive (DU0:).
3. Install the profile disk in the lower disk drive (DU1:)
4. Turn on the micro PDP 11 computer.
5. Wait for the profilometer menu to appear on the CRT terminal.
6. Turn on the main (right hand) switch for the sensor electronics.
7. Turn on the sensors, sensor lamps, and event lamp.
8. Install a magnetic tape in the tape drive. The tape should have a write ring in place if data are to be recorded on it.
9. Load and put the tape on-line by pressing the LOAD REWIND and ON-LINE buttons. When the lights stop blinking, the tape is loaded and on-line.
10. If the tape is new, type INITIALIZE MS: at the terminal to initialize the tape for data recording.
11. Turn on the van engine to avoid having the sensor lamps drain the main battery.
12. Check the printer buttons to make sure that the printer is powered on and that it is on-line to the computer.
13. Turn on the driver encoder display on the dashboard.

Daily Functional Tests

Noncontact Displacement Sensor Test

1. Drive the van to a level stretch of pavement in a quiet place.
2. Note: The van should remain as motionless as possible during this test (no moving around inside, no wind, etc.).
3. Type RUN CAL on the CRT terminal.

4. When the CAL menu appears, type either R or L depending on whether you are testing the right or left sensor.

5. Place the calibration plate on the pavement and level it there as close as possible to the illuminated area under the sensor. Make sure that both the plate and the 1-in block are clean and free of grit.

6. Move the plate into the illuminated area and signal the program to take a height reading by typing Y as per instructions in the program.

7. Move the 1-inch block into the illuminated area. Then type Y again to instruct the program to take another height reading. Note that if grit gets trapped between the plate and the block, an incorrect height reading may result.

8. The measured height should be within 1 percent of 1-in, that is between 0.990 and 1.010 in. If not, then redo Steps 4-7. If the measured value still falls outside of the above limits, then locate the source of the problem.

9. If after thorough testing, the sensor is found to be operating properly, choose the appropriate option in the program to modify the scale factor to yield a measured value that is within the control limits. Then redo Steps 4-7.

10. Record the current scale factor and measured value for use in a control chart.

Bounce Tests

1. Type RUN TSTFIL on the CRT terminal.

2. Type various entries as per instructions in the TSTFIL program. You may choose to record these profiles on magnetic tape.

3. In turn, shake the van in the yawing, pitching, and rolling modes and observe the profile output on the CRT as a function of time.

4. Excursions from zero should be less than 0.1 in for the pitching, 0.05 in for yawing, and 0.2 in for vigorous rolling.

Fitness-For-Service Tests

Accelerometer Test

1. Drive the van to a level stretch of pavement in a quiet place.

2. You may turn off the engine, the sensor lamps, the sensor, and the event lamp since they are not needed for this test. The main (right hand) switch for the sensor electronics must remain on.

3. NOTE: The van should remain as motionless as possible during this test (no

moving around inside, little wind, etc.).

4. Type RUN CAL on the CRT terminal

5. When the CAL menu appears, press the A option for accelerometer calibration and wait for the results.

6. Both the right and left transducer values for the acceleration of gravity (g) should be within 1 percent of the accepted value of 32.17 ft/sec^2. If not, then redo Steps 3-6. If the measured value still shows a discrepancy, then locate the source of the error before proceeding further.

7. Record the current scale factor and measured g value for use in a control chart.

8. If you turned off the engine, sensor lamps, sensors, and event lamp in Step 2, remember to turn them back on again before proceeding to other tests.

Static Test of Accelerometer Noise

1. Drive the van to a quiet place.

2. Turn off the engine, sensor lamps, sensors, and event lamp.

3. Type RUN CAL on the CRT terminal.

4. When the CAL menu appears, type X to display the accelerometer outputs as a function of time.

5. The output should stay mostly between ±1/2 full scale with occasional larger spikes.

6. Exit the CAL program and turn on the engine, sensor lamps, sensors, and event lamp again.

Static Test of the Integrated Accelerometer Noise

1. Drive the van to a quiet place.

2. Turn off the engine, sensor lamps, and event lamp.

3. Type RUN TSTFIL on the CRT terminal.

4. Type various entries as per instructions in the TSTFIL program. See Profiling Consistency Test, below, for more information. In particular, you may choose to record these profiles on magnetic tape.

5. Start the simulated surface profile by pressing the operator pendant (large black button) and remain still. Since the noncontact sensor lamps are turned off, the graphic output is entirely due to the doubly integrated accelerometer signal.

6. Observe the profile for about 30 second. If the van is not moving, the signal should stay between ± 0.02 in.

7. Stop the profile by pressing the pendant again.

8. Exit the TSTFIL program and turn on the engine, sensor lamps, and event lamp again.

Encoder Test and Calibration

1. Type RUN CAL at the CRT terminal.

2. When the CAL menu appears, type W to start the encoder test program.

3. Type F to show distance units in feet on the driver's display.

4. Type option D which calls for driving a measured distance.

5. Drive over a predetermined length of road at least 1500 ft long with clear markers at each end. Press the event pendant (red button) to start and end the test at the markers.

6. The measured road length should be within 1 percent of the accepted value.

7. Perform this test at least three times. For each of the last two, exit from the program and begin the procedure again by typing RUN CAL. Otherwise, an inaccurate measurement will result.

8. If the disagreement is greater than 1 percent, check the tire pressure.

9. If the tire pressure is at the rated value and the velocity encoder seems to behave consistently, type the appropriate option to modify the encoder scale factor. Then redo Steps 1-6 at least twice.

Flat Plate Test

1. Type RUN TSTFIL at the CRT terminal.

2. Type various entries to set up the run as per instructions in the TSTFIL program. Choose the filter cutoff length to be 300 ft. In addition, you will likely choose to record these profiles on magnetic tape.

3. Drive to a quiet area about 400 ft in length such as a quiet parking lot.

4. Lay the flat plate on the pavement with its long dimension along the direction of travel of the van.

5. Drive the left wheel of the van over the plate and record the profile as follows.

6. Start from rest and allow approximately 200 ft before passing over the plate to pick up speed to about 10 mph. The outside edge of the plate

should correspond to the outside edge of the wheel track.

7. Once you are up to speed, start the run by pressing the operator pendant (large black button) before passing over the plate.
8. Stop the run with the same pendant after the van has passed completely over the plate.
9. Repeat Steps 5-8 for the right sensor.
10. Examine the profile at the highest resolution possible.
11. The output profile should not show any high frequency disturbances except for the section where the sensor itself scanned the plate. That section should look approximately like either of the pulses shown in figure 1.

Profiling Consistency Test

1. Choose a section of road that has been profiled before.
2. Type RUN PROFILE at the CRT terminal.
3. Type various entries to set up the run as per instructions in the PROFILE program. In particular:
4. Type "F" to display the measured distance in feet.
5. Type "Y" to record the data on magnetic tape.
6. Type a three-digit number, different from any others used that day, to identify the run on the magnetic tape.
7. Type a six-letter file name that is generally used to identify the date or the overall theme for the series of runs on the magnetic tape. Wait while the program searches for the end of the last file on the tape.
8. Type the run parameters as requested at the CRT terminal by the program. In particular, set the filter cutoff at the standard value of 300 ft.
9. Allow about 400 ft before the start of the course to pick up speed to about 30 mph.
10. At the beginning marker, press the operator pendant (large black button) to start the road profile.
11. At the ending marker, use the same pendant to end the profile.
12. Perform Steps 2-11 at least three times and check the consistency of the measured profiles for both left and right wheel tracks.
13. In addition, check the consistency of the measured profiles with those measured at previous times for the same stretch of road.

14. If significant differences begin to occur in the profiles, the vehicle should be carefully checked for developing sources of error. If no problems are discovered, the road should be profiled by an alternative means such as another profilometer or a rod-and-level survey. Note that if an alternative means of profiling the road is used, the effects of sampling distance and filtering must be considered (see volume I of this report).

Control Charts

See the instructions in section 3 on control charts.

5. FIELD TEST PROCEDURE GUIDE FOR MAYS RIDE METER

Background

The need for regular and controlled calibration of response-type road roughness measurement (RTRRM) systems has been well documented, and the consensus among users is that the systems should be calibrated using computer-simulated vehicle response to excitation imposed by the geometry of the longitudinal profile of the traveled wheeltracks.(2) A basis for such a calibration, by correlation with an inertial profilometer, is provided by ASTM E 1082-1985, Standard Test Method for Measurement of Vehicular Response to Traveled Surface Roughness.(3) The reference roughness for calibration sites may also be determined by any other method capable of measuring pavement profile and simulating the RTRRM system, as described in the ASTM draft entitled "Standard Practice for Calibration of Systems Used for Measuring Vehicular Response to Pavement Roughness".(4)

A summary of the calibration procedure is given in section 7.3 of ASTM Standard E 1082. The Field Test Procedure Guide for Mays Ride Meters presented in this section is based on ASTM Standard E 1082 and the ASTM Draft Procedure, supplemented by results obtained during evaluation and testing of profilometers and response-type measurement systems presented in volume I of this report.(3,4)

Apparatus

The test apparatus may consist of: (1) a sensor to measure relative vertical axle-to-frame displacement and a displacement accumulator, (2) a sensor for measuring the vertical body acceleration of the vehicle, (3) a sensor for measuring the vertical axle acceleration of the vehicle, (4) a distance-measuring system, and (5) a recording system mounted in a vehicle. The host vehicle may be a passenger automobile or a single-axle, two-wheel trailer towed by an appropriate vehicle. The vehicle should be of rear-drive design with solid rear axle, rear coil springs and four-link suspension, heavy duty shock absorbers, and dynamically balanced tires. In reference 1, it is recommended that (1) original equipment tires should always be used on RTRRM vehicles and (2) when possible, balancing should be performed on the test vehicle to include the tire, wheel, and brake drum. In addition, "the test vehicle and its attachments should comply with applicable state and Federal laws. Precautions imposed by law should be taken to ensure the safety of operating personnel and the public" (section B6 of reference 3). Cruise control and air conditioning are desirable, but optional, features. If a trailer is used it should be designed and equipped to house the appropriate transducers, meeting the requirements given in section 5.3 of ASTM E 1082 for test trailers.

Most roughness-related measurements have been made using such RTRRM systems as the Mays Ride Meter (MRM). The MRM displacement sensor consists of a transmitter located in the vehicle body and just over the center of the rear axle (differential housing). The movements of the axle relative to the body of the vehicle are conveyed by a rod connecting the transmitter and the differential housing. The transmitter sends electrical signals to the MRM chart recorder which processes the data from the transmitter, the odometer, and an event button, and records these data with three pen traces on chart paper. The transmitter signal controls the advancement of the chart paper and the position of the axle displacement pen. The displacement accumulator for this system is a stepper-motor driven chart which accumulates the total axle displacement. The total displacement is read from the chart by measuring the total length of paper advanced. The odometer signal comes from a cam that is mechanically linked to the vehicle's speedometer cable. Every 0.05 mile the cam opens or closes a microswitch that is connected to the recorder such that the odometer pen trace can be used to determine how many miles the vehicle traveled during a given test run.

If a RTRRM sensor is selected for measuring the vertical body acceleration of the host vehicle, it should be located as close to the vehicle roll axis as possible. This minimizes the influence of roll motions on the measurement. The accelerometer will record the total accelerations to which it is subjected, i.e., both vertical and roll motions if the latter are present due to road nonuniformities or wind effects. Similarly, a RTRRM sensor for measuring the vertical axle acceleration of the host vehicle should be mounted on the axle differential housing as close to the center of the vehicle as possible.

Instrumentation

The instrumentation should function accurately at ambient temperatures between 40 and 100 °F. All electronic and mechanical components of the system should be adequately designed to withstand adverse conditions such as dust, moisture, vibrations and shock. Shock isolation is essential for the protection of RTRRM sensors such as accelerometers mounted to an axle housing or on the host vehicle body. Servo accelerometers, which have many of the desirable features for use as RTRRM sensors, are particularly vulnerable to mechanical shock hazards and require special precautions in order to be adequately protected.

Displacement-measuring RTRRM sensors should be capable of measuring relative axle-to-frame displacements of 0.125 in or less in response to traveled surface roughness. The displacement accumulator should be capable of accumulating the output of the displacement measuring sensor in one or both directions and transmitting the output to the recording system. RTRRM sensors for measuring body and/or axle accelerations should have a frequency response which is flat from 0 to about 100 Hz, a resonance frequency of at least 500 Hz, a resolution of the order of 10^{-6} g (where g represents the gravitational constant), and low transverse or cross-axis sensitivity.

The measuring system should indicate distance by producing an output directly proportional to traveled distance that will actuate a high-speed counter capable of operating correctly at count rates corresponding to worst-case roads traversed at the highest possible test speed. The system should have the capability of measuring distance in either feet or miles (meters or kilometers). The recording system should provide an accumulative graphic, printed, or digital display of the displacement accumulator and distance measurement system outputs.

Calibration Test Sections

The test sections should be continuous sections of well-traveled roads of uniform age and composition that have been subjected to essentially uniform wear. Pavements with extensive patching, potholes, or cracking should not be used. The calibration sites should be representative of the roads routinely surveyed, and all pavement types to be surveyed should be represented in the calibration sites selected. Test sections should not include bridge structures or railroad crossings and, when possible, they should have roughness properties that are uniform over the length of the site, including a 150-ft lead-in. The calibration sites should be located on roads that will not be altered by maintenance during their period of use as calibration sites. Calibration sites may have to be clearly marked so that maintenance crews do not inadvertently repair them. If a calibration equation is desired for each pavement material, then a separate calibration test section is required for each pavement material considered. Alternatively, one calibration equation may be obtained covering both bituminous concrete and portland cement concrete pavements with an expected reduction in the stated precision of the RTRRM system. The following attributes for the calibration test sections are given in reference 4:

1. For a calibration to be valid, the calibration sites selected should cover the range of roughness normally encountered. Calibration is technically valid only over the range of roughness covered by the calibration sites. Extrapolation beyond this range is not considered to be meaningful.

2. The roughness of calibration sites should be uniform over their length, and each calibration site should have an approach at least 150 ft (46 m) in length which has a roughness similar to the roughness of the site. Avoidance of abrupt changes in roughness during entry to the test section is necessary to ensure that the RTRRM system is not subjected to transient excitations. Such excitations should be minimized, insofar as possible.

3. Calibration sites should be on straight sections of road which do not include bridges, railroad crossings, or intersections. There should be no noticeable change in grade on or immediately before the site.

4. In order to minimize calibration error, the roughness of the calibration sites selected should be well distributed within the range of roughness covered by the calibration sites. A guideline for selecting sites to achieve this objective is given in reference 4.

5. In reference 4, it is proposed that at least 14 calibration sites be used for the minimum site length of 0.2 mi, at least 10 sites for a length of 0.3 mi, or at least 8 sites for the maximum site length of 1.0 mi. All calibration sites which are selected should be the same length.

6. Sites should be clearly marked. An earlier ASTM procedure suggested that "The beginning and ending should be marked with bright colored highway paint across the lane. The beginning and ending points of each site should also be marked by a permanent marker such as an iron bar or stake driven into the ground off the road so that the boundaries of the site can be re-established in the event the paint is worn off by weather or traffic." The

latest Draft Standard simply specifies that the calibration sites be marked clearly so they can be easily identified.(4)

Determining the Reference Roughness of Calibration Sites

If an inertial profilometer is used to measure pavement profile, the reference roughness for each calibration site is determined by averaging the simulated roughness values obtained from the required number of replicate profile measurements. To reduce the effect of random operator error in the measurement, at least five replicate measurements should be made, with more replicates recommended for the shortest test site lengths.(4)

The wheeltrack(s) should be identified for each calibration site and should be traversed by the profiling device whenever the longitudinal profile of a calibration site is measured. Testing should be accomplished with the test vehicle's tires centered in the normal traffic wheelpaths.(3)

Lateral positioning of a test vehicle may be facilitated by means of alignment marks on a pavement surface. It may also be useful to have observers stationed adjacent to the site during preliminary tests to determine whether vehicle operators need to make adjustments to maintain wheelpath alignment before actual measurements are made.

Reference roughness values should be reestablished for each calibration site at least every 12 months. Use of a test site should be discontinued if the site is altered by maintenance or repairs. A reduction in the correlation coefficient computed during recalibration of MRM vehicles might be an indication that the standard Mays index of one or more of the selected test sites has changed.(5) A calibration site should not continue to be used if the reference roughness value has changed by more than a value commensurate with existing specifications. For example, the ASTM Draft Standard recommends a maximum value of 5 percent for acceptable change in the reference roughness value.(4) Some pavements exhibit seasonal changes in roughness in which case profiling should be done more frequently. In such cases, the use of control charts is recommended in order to assist in the determination of how frequently the profiling is required.

RTRRM System Calibration

General Considerations

All road meters should meet the requirements of ASTM Method E 1082.(3) Prior to calibration, all electronic and mechanical equipment should be checked to ensure proper operation in accordance with the manufacturer's recommended procedures and requirements. For the MRM, for example, it is necessary to check out the operation of the drive cable, odometer and landmark functions and the profile pen/chart feed. The drive cable should be inspected to make sure that it is not slack, to prevent possible slippage of the drive pulley. Procedures for removing any slack are given in the operation manual for the MRM. The words "TOP" and "BOTTOM" should be correctly oriented. The odometer circuit may be checked by driving the vehicle to ensure that the mileage pen stops at 0 and 0.05 miles. The landmark circuit is checked by operating the push button on the recorder housing. It is necessary to drive or bounce the rear of the vehicle to check the proper operation of the profile pen and chart feed. If any of the MRM system components do not operate properly, use should be made of the troubleshooting guide in the operation manual. The transmitter lamp focus, relative to the slit for the encoder program film, should be checked periodically, since this focus is critical to the correct operation of the MRM system. If RTRRM sensors are employed to measure body and/or axle vertical acceleration, their functionality is easily determined by checking the sensor output voltage on an oscilloscope or chart recorder as the vehicle is bounced.

The test vehicle should also meet the requirements of the ASTM standard.(3) When a RTRRM is mounted in a trailer, the same towing vehicle should always be used between calibrations; if a vehicle is replaced, the RTRRM requires recalibration. In order to obtain the best reproducibility and lowest measurement uncertainty, the RTRRM system test vehicle should be equipped with very stiff shock absorbers. Another reason for routinely bouncing the rear of an RTRRM test vehicle prior to calibration is to ensure that no significant degradation in the suspension system has occurred.

Several criteria have been recommended for acceptable variability caused by mechanical problems such as weak suspension, leaking shocks, tire unbalance and roundness, or worn wheelbearings. In reference 7, it is recommended that if the single-number roughness ratings have a variability of 10 percent or more, the system should be corrected prior to any calibration. In the ASTM Draft Standard, it is proposed that if the roughness indices from an RTRRM system are more than 20 percent greater on the average than the reference roughness values on moderately rough calibration test sections, then the shock absorbers should be replaced prior to calibration.(4) The reason for such precautions is that any system with extreme variability cannot be calibrated with sufficient accuracy. Calibration of an RTRRM system is always necessary whenever shock absorbers are replaced, since they have a major influence on the response characteristics of the test vehicles.

Distance Calibration

The RTRRM system's distance measuring system should be calibrated at different speeds. In the ASTM Draft Standard, it is recommended that the system be calibrated at three speeds by determining the distance recorded after traversing a level (±0.1 percent) and straight section of pavement at least 1 mile in length at a constant indicated speed. At least three test runs are recommended at each speed. The average distance indicated by the distance measuring equipment for the test runs should be within 1.0 percent of the distance actually traversed.(4)

Obtaining RTRRM System Roughness Values

The basis for the proposed calibration of RTRRM systems is the determination of the calibration equation from a regression analysis of all paired reference roughness values and RTRRM system roughness values (referred to as Response-Type System Number, RTSN, in reference 4). The roughness for each calibration site is found by averaging the required number of RTRRM system replicate measurements. The RTRRM system roughness value, or RTSN, for each site is determined by averaging the repeat system roughness values. The minimum number of replications recommended for sites of different length is given in reference 4.

In reference 4, the following terms are defined and subsequently employed to obtain a RTRRM system calibration:

1. International Roughness Index (IRI) - An index resulting from a mathematical simulation of vehicular response to the longitudinal profile of a pavement using the quarter-car simulation model described in ASTM Standard E1170 and a traveling speed of 50 mph (80 km/h). Units are in inches per mile or meters per kilometer (63.36 in/mi = 1.0 m/km).

2. Half-Car Roughness Index (HRI) - An index resulting from a mathematical simulation of vehicular response to the longitudinal profile of a pavement using the half-car simulation model described in ASTM Standard E1170 and a traveling speed of 50 mph (80 km/h). Units are in inches per mile or meters per kilometer (63.36 in/mi = 1.0 m/km).

3. Response Type System Number (RTSN) - The raw measured output from a response type system being calibrated. Units are arbitrary, being whatever the road meter in the response type system measures.

As noted in reference 8, the IRI is a standardized roughness measurement related to those obtained by response-type road roughness measurement systems, e.g. the Mays Ride Meter, with recommended units: meter per kilometer (m/km). The measure obtained from a RTRRM system is called either by its technical name of average rectified slope (ARS), or more commonly, by the units used (m/km, in/mi, etc.). The ARS measure is a ratio of the accumulated suspension motion of a vehicle, divided by the distance travelled by the vehicle during the test.

Obtaining a RTRRM System's Calibration Equation

From a linear regression analysis of all paired reference values and RTRRM system roughness values, the coefficients and the standard error for a regression equation should be determined. The form of this equation in the ASTM Draft Standard is:

$$SRI = A + B \times RTSN_X$$

where: SRI = standard roughness index (International Roughness Index, IRI, Half-Car Roughness Index, HRI, or the average of the IRI in the right wheelpath and the IRI in the left wheelpath).

$RTSN_X$ = response-type system number obtained at a selected test speed of x mi/h.

Note that this standard is under development so that this equation is subject to change.

Calibration Acceptance

A calibration may be considered valid if the standard error of estimate for the regression expressed as a percent of the average of all reference roughness values is consistent with specified criteria. Reference 4 gives an example of acceptable least-squares regression and error estimation procedures, but notes it is up to the user or a specifying agency to establish maximum system error limits.

RTRRM System Calibration Verification

The calibrations are valid only if no changes occur or are made in the test apparatus. In the ASTM Draft Standard, it is recommended that a RTRRM system be verified, by remeasurement over a calibrated section of road, at least monthly when the system is in use, or after every 2,000 mi of operation. Detailed nonmandatory information regarding the RTRRM system calibration verification procedure is given in reference 4.

Repeatability

Individual repeated determinations of the RTSN for the same test section by the same operator with the same equipment on the same day should agree with the average of the determinations of RTSN within limits commensurate with recommended practices. For example, the repeatability recommended in ASTM E 1082 is ± 10 percent.(3) In reference 4, it is specified that (1) at least 10 RTSN's be obtained per site on at least two test sites, and (2) the test sites should be selected having a length equivalent to the smallest test section to be surveyed by the RTRRM system.

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