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PAVEMENT SURFACE SPECIFICATION FOR ROAD LOAD MEASUREMENT

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16. Abstract

This report proposes a framework for specifying coast-down test surfaces that will produce relevant, reproducible road load measurements. The proposed specification includes grade, roughness, megatexture, and macrotexture. Specification using standard scales in use by the pavement monitoring community is recommended for roughness (International Roughness Index), megatexture ("megatexture level" from ISO 13473-5), and macrotexture (Mean Profile Depth). These scales are well understood, and have demonstrated relevance to various type of vehicle response to the pavement. However, they may be replaced over the long term when other scales are developed with a specific emphasis on fuel consumption. The report also reviews commercially available equipment of measuring grade, roughness, megatexture, and macrotexture.

This report presents a detailed survey of roughness values found on the public road system using data obtained from the Federal Highway Administration's Highway Performance Monitoring System. The report also includes a tutorial presentation of road surface textures and some pavement design specifications that affect surface texture.

17. Key Word road load, coast-down testing, road roughness, pavement macrotexture, pavement megatexture, rolling resistance, International Roughness Index	18. Distribution Statement

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Table of Contents

List of Figures

List of Figures (cont)

List of Tables

List of Acronyms

AADT – Annual Average Daily Traffic

CTM – Circular Texture Meter

DOF – Degree of Freedom

DOT – Department of Transportation

FE – Full Extent

FHWA – Federal Highway Administration

HPMS – Highway Performance Monitoring System

IRI – International Roughness Index

ISO – International Organization for Standardization

MAS – Maximum Aggregate Size

MPD – Mean Profile Depth

MSD – Mean Segment Depth

MTD – Mean Texture Depth

NHS – National Highway System

NMAS – Nominal Maximum Aggregate Size

SAE – Society of Automotive Engineers

SMA – Stone Matrix Asphalt

SP – Sample Panel

VFA – Void Filled with Asphalt

VMA – Voids in Mineral Aggregate

VMT – Vehicle Miles Traveled

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Pavement Surface Specification for Road Load Measurement

Introduction

SAE J1263 specifies road surfaces for road load testing as follows:

> *"Roads must be dry, clean, smooth, and must not exceed 0.5% grade. In addition, the grade should be constant and the road should be straight since variations in grade or straightness can significantly affect results. (The road surface should be concrete or rolled asphalt (or equivalent) in good condition since rough roads can significantly affect rolling resistance.)"*

SAE J2263 specifies road surfaces as follows:

> *"The test road must be dry, clean, straight, smooth, be hard surfaced, not have excessive crown, and have a constant grade of no more than 0.5%."*

Although J1263 acknowledges the potential influence of roughness on rolling resistance, neither document recommends a quantitative limit on roughness or texture of the test surface. This is due in part to the lack of information about the influence of roughness and texture on measured road load and in part to a lack of information about the roughness and texture that exists on the road system.

Since a high level of variation in roughness and texture of coast-down test surfaces is possible, there is no guarantee that measured road load will be reproduced at different tracks for the same vehicle. In practical terms, coast-down testing is either performed on a sufficiently long multipurpose test track surface or a dedicated surface that may have been built for that specific purpose. It is possible to build a test track that is compliant with the SAE standard, is much smoother than the roads encountered on the public road system, and yields unrealistically low measured road load. While this may be justifiable under the technical requirements and limitations of the standard, it could affect the credibility of the fuel economy results presented to the consumer, as it could be a contributor to the known inaccuracies of the current fuel economy measurement process.

This report proposes a framework for specifying coast-down test surfaces that will produce relevant, reproducible road load measurements. The proposed specification addresses the following questions:

What are the qualities of a road load test track that must be specified?

How should those qualities be specified (i.e., on what scales)?

How should those qualities be monitored (i.e. with what equipment and procedures)?

What does the road load test track pavement represent?

A practical constraint on the specification is the selection of a single road surface. This constraint exists because of the cost that would be required to maintain multiple surfaces of sufficient length and to perform the testing on all of them. Since a very diverse range of road roughness and texture exists in practice, no single pavement surface can represent a typical driving experience. However, the specification should require pavement surface properties that are realistic and, to the extent possible, common. With this in mind, the report provides the results of a survey of existing pavement surface properties for the U.S. road system.

The survey of existing pavement surface properties used existing data from past research studies and public databases. The information presented in the survey is available for three important purposes. First, it provides the justification for selecting realistic pavement surface properties for the proposed specification. Second, it provides a way to evaluate whether existing road load test surfaces have a counterpart on the actual road system. Third, it may provide a basis for extrapolating from testing done on a single pavement surface to a typical driving experience once the sensitivity of measured road load to pavement surface properties is known.

The report is organized to address the four questions above. The following section defines the pavement surface characteristics to be specified. The Quantifying Surface Characteristics section describes the engineering scales used in practice to measure road surface characteristics. The Measurement Options section lists existing technology that is available for measuring road surface characteristics. The Survey of Pavement Roughness section presents the survey, and the Pavement Surface Texture section presents a typical pavement design and common pavement textures. Finally, the Conclusions section proposes a format for the specification and describes the work needed to justify the engineering values defined within it.

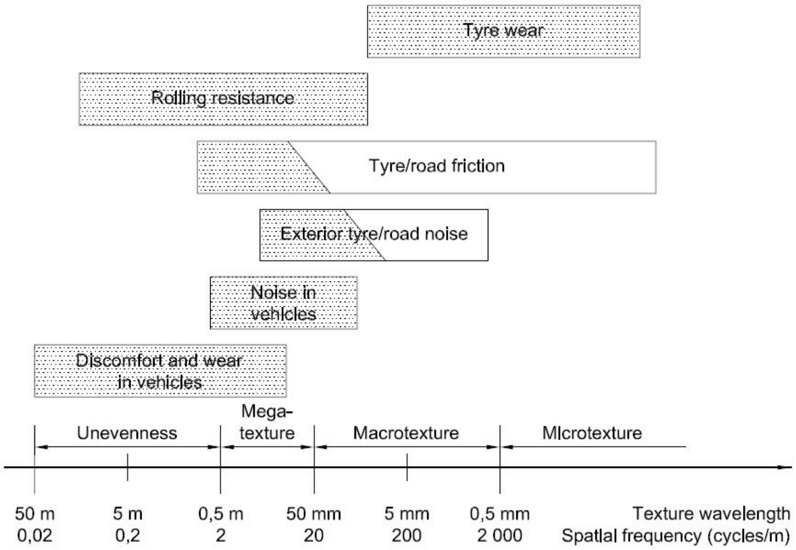
Pavement Surface Properties

The road-monitoring community has defined four categories of road surface irregularity that affect free-rolling vehicles, as shown in Figure 1. (ISO 13473-2, 2002) The figure defines a range of wavelengths within a profile for each category of irregularity, and for each type of influence that road irregularities have on vehicles. Although it is not identified in the figure, the “grade” experienced by passing vehicles is determined by changes in road elevation and vertical alignment that correspond to wavelengths greater than 50 meters.

A specification designed to ensure reproducible measured road load must place requirements on grade, unevenness, megatexture, and macrotexture.

Grade affects coast-down testing because mechanical work is required to change the relative height of a vehicle as it travels up or down hill. In simpler terms, vehicles that travel on roads with an overall slope will experience a net force in the downhill direction as part of the forces that react against gravity.

Roughness, which is the common term used for unevenness in North America, degrades ride quality, and is caused by construction defects, pavement wear, and occasionally exists as part of the roadway design. Roughness affects coast-down testing primarily by exciting rigid-body motion in vehicles that exercise suspension components. In turn, energy is lost through damping effects in shock absorbers, suspension component mounts, and in some cases friction that resists suspension motion. (Gillespie, 1992; McLean and Foley, 1998)



NOTE A lighter shade means a favourable effect of texture over this range, while a darker shade means an unfavourable effect.

Figure 1. Road surface irregularities by wavelength. (ISO 13473-2: 2002)[1]

Megatexture is typically associated with construction defects and pavement distress. Megatexure affects coast-down testing by exciting high-frequency suspension motion, such as axle hop, tread band vibrations within the tire, and flexure of the tire sidewall (Pottinger, 1986; Sandberg, 1990; Bendtsen, 2004). Megatexture also increases localized flexure of the tire tread band within the contact patch during rolling (Descornet, 1990).

Macrotexture is often present on the road by design, to help drain water away from the tire and improve tire-pavement friction through hysteretic dissipation in tire tread elements (Kummer, 1966; Henry, 2000). Macrotexture causes energy loss in passing vehicles primarily through deformation of tire tread elements (Sandberg, 1990; McLean and Foley, 1998). Microtexture is a property of the road surface that makes it feel gritty. Microtexture increases energy dissipation through the same mechanisms that cause tire wear (e.g., scrubbing during localized sliding between the tire and road).

For travel on public roads over an interval equal to that of a coast-down test, the influence of grade is likely to trump roughness and texture. However, grade is well controlled on surfaces designated for coast-down testing, its effects are easy to predict, and compensation is possible at modest levels of grade by testing in both directions.

Experimental studies of rolling resistance have not produced a consensus rank order of importance for roughness, megatexture, and macrotexture. (See the review by McLean and Foley, 1998.) It is also difficult to distinguish the effects of each range, since the

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[1] This excerpt is taken from ISO 13473-2:2002, Figure 2 on page 4, with the permission of ANSI on behalf of ISO. (c) ISO 2013 - All rights reserved.

level of irregularity that appears in each range is often correlated. (Sandberg, 1990; Holbrook, 1973) In many studies, roughness and megatexture show a stronger influence on rolling resistance than macrotexture. Some recent work has confirmed this, but also concludes that a new measurement scale for macrotexture may be needed for studying rolling resistance that takes localized gaps between tire treads and low points within the texture profile. (Ejsmont, et al., 2012; Sohaney and Rasmussen, 2013)

Collectively, past studies that have appeared in the literature have demonstrated a high enough sensitivity of rolling resistance to roughness, megatexture, and macrotexture to justify their specification and measurement as part of the coast-down testing process. No compelling evidence was found in the literature that would support the need to specify the microtexture of a surface used for coast-down testing.

Quantifying Surface Characteristics

This section describes standard scales for quantifying roughness, megatexture, and macrotexture of pavement surfaces. These scales are recommended for quantifying the irregularities of existing coast-down test surfaces. They were selected because they are standard within the pavement community. As such, an engineer who describes pavements on these scales inherits a large body of past experimental work that relates pavement properties to rolling resistance and other pertinent vehicle (and tire) dynamic responses. Further, quantifying irregularities of test track surfaces on these scales provides a way to compare them to existing road surfaces, because a large body of past measurements of public roads are available that use these scales (particularly roughness). Lastly, commercial measurement systems already exist for measuring these quantities.

Although they can be readily implemented in a specification, none of the scales recommended were developed specifically to estimate the pavement's contribution to rolling resistance or fuel consumption. Further, since they are summary indices, two pavements that rate equally on a given scale may have different spectral content within their profile, and may in turn contribute to road load differently.

Roughness

The International Roughness Index (IRI) is a standard indicator of road roughness in the United States and elsewhere around the world. Early work for the U.S. National Cooperative Highway Research Program in the 1970s produced an early version of the IRI (Gillespie et al., 1980). At the time, the underlying profile measurements were expensive, and it was developed as a correlation standard for casting roughness measurements that were based on direct measurement of vehicle response onto a reproducible, time-stable scale. The IRI was further developed and standardized under funding from the World Bank as a standard scale for comparing the roughness of road networks in developing countries (Sayers et al., 1986).

Since its development, the IRI has become the most widely used scale for rating the roughness of roads worldwide. In the U.S., most state and federal road authorities have used the IRI to help monitor the status of their pavement networks for at least two decades (Gramling, 1994; TRDF 1995). In addition, the Federal Highway Administration

(FHWA) requires states to report the roughness of all roads on the National Highway System, which includes the entire Interstate System, biannually (HPMS, 2010).

The IRI is a general pavement roughness indicator designed to estimate the relative level of vehicle vibration caused by the unevenness of the road (Sayers and Karamihas, 1998). The index is based on a simulation of a broadly representative vehicle's response to the profile of the road surface (Sayers et al., 1986). The IRI is expressed in units of slope, typically in inches per mile or meters per kilometer. The IRI scale starts at 0 for a perfectly smooth and even road and increases with roughness of the road, with no limit at the upper end of the scale. The Survey of Road Characteristics provided with this report shows the range of IRI values that occur on the U.S. public road system.

The core of the IRI calculation procedure is the Golden Car simulation. (See Figure 2.) The Golden Car model is a linear, two-DOF quarter car model with standardized mechanical properties. To obtain the IRI, the simulation produces a prediction of suspension stroke of the Golden Car traveling at 80 km/hr as a function of distance along the road. Over a given segment of roadway, the IRI is the accumulated suspension stroke divided by the distance traveled. In practice, this is equivalent to averaging the spatial rate of suspension stroke over a given segment of road. In fact, that is what the standard source code for calculating the IRI is actually doing (Sayers, 1995; ASTM, 2008).

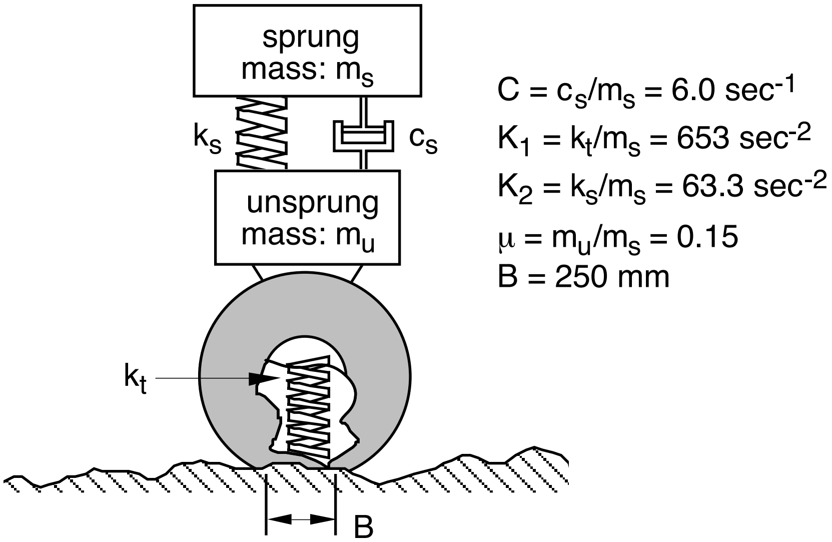

Figure 2. The Golden Car model (after Sayers, 1995).

The IRI was not developed specifically for estimating the contribution of road roughness to rolling resistance or energy consumption. However, since the index is based on a simulation of the rate of suspension stroke in a representative vehicle, it is likely to have some relationship to energy dissipated in passenger vehicle suspensions. Recent literature reviews have identified several experimental studies that demonstrate the increase in fuel consumption of vehicles as the IRI increases (Chatti, 2012; Tan et al., 2012).

Megatexture

Summary index values that quantify pavement megatexture appear in the literature sparsely compared to roughness and macrotexture. At the time this report was written, no U.S. road authorities were explicitly measuring megatexture as part of their efforts to manage their pavement networks, nor were they specifying the megatexture of newly paved or newly resurfaced pavements. However, a standardized algorithm exists for quantifying megatexture from measured profile (ISO 13473-5, 2009), and two studies demonstrate a link between the megatexture index and rolling resistance (Sandberg, 1990; Sohaney and Rasmussen 2013).

The ISO megatexture index, called "megatexture level," is:

$$L_{Me} = 20 \log\left(\frac{a_{Me}}{10^{-6}}\right)$$

where a_{Me} is calculated from the profile spectrum in one-third octave bands. It is the root-mean-squared variation in elevation in meters in bands with center frequencies ranging from 63 mm to 500 mm. (This makes the effective wavelength range of interest 56 mm to 561 mm.) The index is expressed in decibels relative to the reference value 10^{-6} meters.

The ISO standard provides requirements for ensuring that the profile is measured with sufficient waveband, the profile is preprocessed to eliminate invalid readings, and that the megatexture within a pavement segment is sufficiently uniform.

Macrotexture

Historically, pavement texture depth has been measured using the volumetric ("sand") patch technique and reported as a mean texture depth (MTD). The sand patch test involves carefully spreading a known volume of small glass beads of standard size into a circle on the pavement surface; the MTD is the volume of beads divided by the area of the circle.

As laser-based profilers became widely available, mean profile depth (MPD) was developed as a means to estimate the MTD. MPD is formally defined in ISO 13473-1:1997. As shown in Figure 2, calculating MPD involves dividing a 100-mm texture profile segment into two 50-mm segment halves. A peak profile point in each segment half is determined, then averaged, and then the mean profile elevation (in this case, zero) is subtracted. The result in this example is 0.69 mm. The currently proposed revision to the ISO 13473-1 specification refers to the calculation within a 100-mm sample as a mean segment depth (MSD); the MPD is then an average of a minimum of five MSD values.

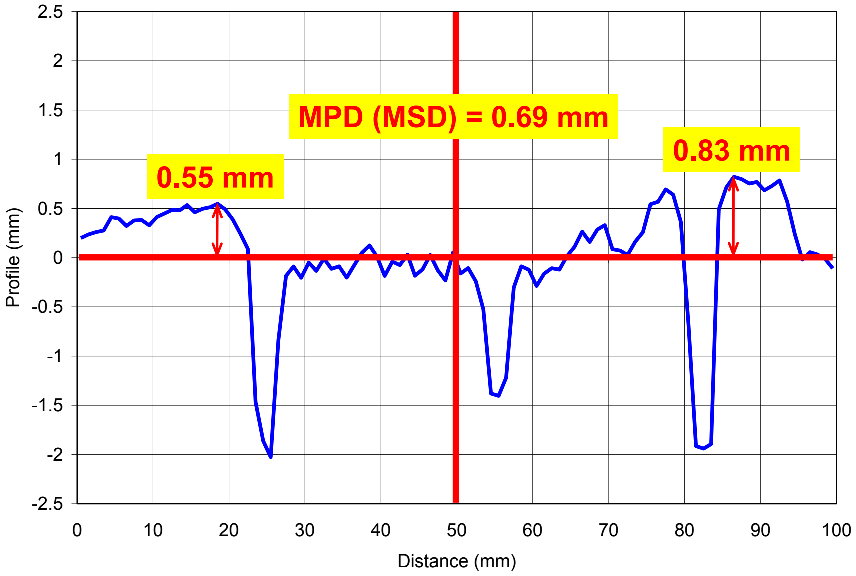

Figure 3. Calculation of Mean Profile Depth.

MPD is the most common index for characterizing pavement macrotexture, and measurement equipment is readily available for measuring it. However, it is not very reproducible when it is measured using the different types of equipment. (Sezen, et al., 2008) Several factors contribute to this:

- Specifications for laser performance (footprint, detection angle, sampling rate) have been established recently, and have not been fully adopted in practice.
- Some devices measure texture while passing over the pavement at a very high speed, which degrades their performance relative to slow or stationary devices.
- Each device samples the road differently, and each device provides a different level of coverage along the wheel path. Some devices measure the road at selected locations over a small circular path or a small area. Other devices move along a wheel path of interest, and sense the profile over a narrow (~ 1 mm) line along the direction of travel or a wider (> 100 mm) swatch along the direction of travel.

This complicates the use of MPD as a scale for specifying test track macrotexture, because measurements of MPD on in-service pavements can only be readily compared to other measurements made by the same equipment type.

Two recent studies found that other indices may relate more closely to rolling resistance than MPD if they accounted for tire envelopment (Ejsmont, et al., 2012; Sohaney and Rasmussen, 2013). For this purpose, a next generation macrotexture scale for estimating rolling resistance may be needed that incorporated tire envelopment algorithms used for measurement of ride quality (Karamihas, 2005) and tire-pavement noise (Rasmussen, 2009).

MPD is only recommended as a temporary scale for characterizing the macrotexture of coast-down test tracks until a more suitable alternative is developed.

Measurement Devices

This section describes some of the devices available for measuring grade, roughness, megatexture, and macrotexture. A large variety of equipment exists that is capable of measuring at least one of these qualities of the road surface. However, many of the devices in use by pavement engineers provide a summary index without measuring and reporting an underlying trace, and several others produce a trace that is distorted because of the device's hardware configuration. Only the devices that capture and record profile as part of the measurement process are considered here.

Measuring and storing profile offers several advantages. First, it facilitates data quality control. Second, it provides the underlying data for diagnosing the source of irregularities that contribute to calculated summary index values (e.g., for seeking periodic content and localized events). Third, it provides the data needed for defining a next generation of summary indices that are optimized for predicting the effect of pavement irregularities on rolling resistance and coast-down testing.

Table 1 provides a summary of the devices that are discussed in this section. All of the devices were originally created to measure in-service road or airfield pavements. As such, many of them have evolved to meet requirements placed on them by the road-monitoring community, which differ from the job of obtaining detailed measurements on specialized test track pavement. For example, many of the devices are configured to offer a high rate of production, and to operate safely within a live traffic stream or minimize the duration of a road closure. They typically operate in a "network management" mode, and provide a statistical sampling of the roughness or macrotexture over long stretches of road or entire road networks. For measurement of a specialized test track, efficiency is useful, but not at the cost of relevance, detail, or accuracy. Closure of the track to operate a slow-moving device or operation of a vehicle-mounted device at low speed is feasible.

Each of the commercially available devices listed in Table 1 was originally developed with measurement of only one type of road irregularity (e.g., grade, roughness or macrotexture) in mind, and none of them were developed expressly for megatexture. With upgrades to components and performance specifications, some of the commercial roughness or macrotexture measurement devices could be adapted to incorporate measurement of megatexture. Measurement of a test track pavement using as few devices as possible may offer some advantages. Extending the capability of an existing device for measurement of roughness, megatexture, and macrotexture will require a specialized combination of components, careful consideration of design requirements, and some effort to verify the validity of the measurements.

Operating existing and (particularly) enhanced versions of these profiling devices for verification of specialized test track surface properties requires a high level of operational proficiency and training in data quality control. The recommended road surface specification presumes that the operator of each track can designate such a person.

Applications: Table 1 classifies the output of each device as "reference level," "project level," and "network level." These are terms used by the road monitoring community to classify measurement systems by application. Reference level implies that the measurements can be used to verify the validity of measurements from other devices.

Project level implies that the measurements have sufficient quality for use in forensic applications or for optimizing maintenance treatments and corrective strategies. Network level implies that, although the measurements are based on profile, the calculated index values are used only for a statistical snapshot of the health of a system of pavements. For this discussion, research level, project level, and network level can be thought of as providing accuracy and reproducibility of a summary index on the order of 2 percent, 5 percent, and 10-15 percent, respectively.

Waveband: Table 1 also lists the waveband that is typically measured by each device. These are estimates, since each model of a given type of device performs differently. Note that the waveband of some of the devices extends to infinity, because they were designed to measure road grade. The table lists the typical waveband for inertial profilers used in pavement monitoring applications. However, specifying a custom system with a faster sampling rate, careful selection of hardware, and signal conditioning can extend their waveband to include macrotexture. For many of the devices that measure megatexture and macrotexture, there is a dearth of experimental evidence for verifying their valid waveband.

Availability: All but two of the devices listed in Table 1 are available for purchase by a test track operator. The two "one of a kind" devices are listed because they offer a level of detail that is not provided by the devices that are available for purchase. Preliminary work to implement a new road surface specification may show that a higher level of detail than commercially available devices offer is required to properly estimate the rolling resistance of test track surfaces. In that instance, the non-commercial devices may be needed, or the commercial sector may come forward with more measurement options if the necessary specifications are presented to them.

Operation: Table 1 identifies which devices cover the pavement with a high rate of production, and which do not. "Slow" indicates that the pavement is covered at walking speed or faster, but below 10 mph. "Fast" indicates 15 mph or faster. When Table 1 lists "closure required," it means that the operators are on foot or riding in a slow-moving vehicle such as a golf cart. In these instances, safe operation is only possible with no road vehicle traffic on the test pavement.

Table 1. Measurement Devices.

Device	Grade	Roughness	Megatexure	Macrotexture	Waveband	Commercially Available?	Operation	Notes
Rod and Level	●				> 1 m[†]	Yes	Very slow, closure required	Measurements only needed once
Benchmark Profiler	●	●	●	●	> 10 mm[†]	No	Very slow, closure required	Used for verification of other devices only
Inclinometer-Based Profilers	●	◑			> 0.6 m[†]	Yes	Slow, closure required	Walking speed, portable
Inertial Profiler, Portable		◑	○		0.3 - 90 m[††]	Yes	Fast, no closure required	Portable, requires a local host vehicle with a proper hitch
Inertial Profiler, High Speed		◑	○		0.3 - 90 m[††]	Yes	Fast, no closure required	Permanently mounted to a van, pick-up or SUV
Inertial Profiler, Lightweight		◑	◑		0.2 - 60 m[††]	Yes	Fast, closure required	Somewhat portable, adaptable to macrotexture
Vehicle-mounted Point Laser			○	○	unknown	Yes	Fast, no closure required	2-D only
Vehicle-mounted Scanning Laser			○	◑	unknown	Yes	Slow, no closure required	3-D, limited experience in practice
Robotex			◑	●	2 mm - 3 m	No	Slow, closure required	3-D, comparison to library possible
Circular Texture Meter				◑	2 - 50 mm	Yes	Slow, closure required	2-D, configured for MPD only, collects discrete samples
Texture Scanners				◑	1 - 50 mm	Yes	Slow, closure required	3-D, configured for MPD, collects discrete samples

● — Reference level ◑ — Project level ○ — Network Level

[†] Waveband extends to absolute grade.

[††] If they are built with custom specifications not common to pavement management applications, the waveband of these devices can often be extended cover wavelengths as low as 50 mm measured with network-level quality.

Rod and Level

Figure 4 shows a crew measuring the roughness of a road using a rod and level. Before the introduction of more efficient methods, a surveyor's rod and level was often used to measure the profile of roads for studying their roughness. Each elevation measurement is obtained by reading the depth along a vertical rod of the road below a leveled reference established from a tripod. Compared to modern devices, the rod and level is exceptionally slow. In a recent study that sought to verify vehicle-based roughness measurement systems, a two-person crew (shown in the figure) spent more than 10 hours measuring a test section 160.9 m long using a sample spacing on 76.2 mm (Karamihas and Gillespie, 2003).

The rod and level typically provides an excellent measurement of road grade. However, a recent experiment showed that when it was used to collect a profile with a sample spacing of 0.15 m, it was not able to collect valid profile for wavelengths below 1 m, which disqualified it for measurement of roughness (Karamihas, 2011). Figure 5 shows an automated version of the rod and level that operates at walking speed. It collected valid measurement of grade, but it was not able to collect valid profile for wavelengths below 2 m in the aforementioned experiment.

Figure 4. Rod and level.

Figure 5. Auto rod and level.

Benchmark Profiler

The FHWA Benchmark Profiler is a custom device built to verify measurements from "reference" devices that measure profile for roughness. It senses its vertical position and attitude by detecting a stable plane established using a spinning laser. (See Figure 6.) It senses the elevation of the road beneath its chassis using a scanning laser that measures a swatch of pavement 100 mm wide. The device pilots along a segment of road automatically by sensing and reading a nylon-coated steel tape. This device is capable of exceptional measurement quality over a very large waveband, but it is impractically slow and labor intensive for production measurements. However, it may be needed to verify devices that are selected or developed for specialized test track measurement.

Figure 6. FHWA benchmark profiler.

Inclinometer-Based Devices

Figure 7 shows some examples of inclinometer-based profilers. These devices use a precision inclinometer that measures the difference in height between the two supports, usually spaced 250 mm apart. Two of the devices shown in the figure roll along the pavement, and the slope readings are determined by the relative height of the supporting wheels. These devices operate at slightly slower than walking speed, and sense the road by contact over a fixed wheelbase. The wheelbase filtering effect places a physical limitation on the devices' ability to sense short wavelength content within the profile (Perera and Kohn, 2005). These devices have demonstrated the ability to collect high quality measurements of grade and roughness (Karamihas, 2011, Perera and Kohn, 2007).

Figure 7. Inclinometer-based devices.

Inertial Profilers

The inertial profiler was invented at General Motors for monitoring the roughness of test track pavements (Spangler and Kelly, 1964). It was designed to provide an efficient way to measure the profile of a test surface using a vehicle-based platform. Since inertial profilers are able to efficiently measure the roughness of in-service roads without impeding traffic, they are now in use worldwide for monitoring the ride quality of road networks.

Inertial profilers sense variations in height of the road compared to a reference point on the vehicle using a non-contacting sensor. (The sensor is typically a laser.) Since the host vehicle vibrates in response to the roughness of the road, the reference point does not maintain a consistent vertical position. The vertical acceleration of the reference point is measured and integrated twice. The resulting signal provides a vertical reference height, which changes as the profiler moves along the road. A non-contacting sensor measures the difference between the reference height and the road surface. When this difference is subtracted from the reference height, only the height of the road remains.

In theory, the inertial compensation provides a valid profile of the road surface that includes grade. In practice, very long wavelength variations in the road cause very low levels of acceleration in inertial profilers, and their measurement is contaminated by system noise and host vehicle misalignment (Karamihas, et al., 1999). As a result, inertial profilers typically filter out information for wavelengths greater than 91 m. In addition, typical inertial profilers apply sampling and filtering practices that prevent them from obtaining valid measurements of road irregularities for wavelengths below 200-300 mm, depending on the configuration.

Inertial profilers are available in several configurations. High-speed inertial profilers are typically permanently mounted to a van or SUV, with sensors mounted in front of the front bumper and data recording hardware inside the passenger compartment. (See Figure 8.) These are most often built for monitoring the roughness of in-service roads.

Figure 9 shows a lightweight inertial profiler. These operate using the same measurement concept as high-speed inertial profilers, but the hardware is mounted to a small utility vehicle. These profilers were developed to obtain the profile of newly paved concrete for construction quality control. The lightweight vehicle allows engineers to measure Portland cement concrete before it has strengthened enough to support automobile traffic. Since they operate at low speed, lightweight profilers offer a safe alternative to high-speed profilers on busy construction sites.

“Portable” inertial profilers are also available that are not permanently mounted to a host vehicle. (See Figure 10.) These are designed so that they can be shipped easily, and typically mount to any vehicle with a trailer hitch of the correct size. A well-trained technician is required to make sure the profiler is mounted with the correct standoff height and connect the rotational encoder to one of the vehicle wheels.

Figure 8. High-speed inertial profiler.

Figure 9. Lightweight inertial profiler.

Figure 10. Portable road profiler.[2]

Vehicle Mounted Texture Measurement

In an effort to augment their pavement roughness surveys, several state highway agencies have attempted to use lasers with a high sampling rate to measure pavement texture at highway speed. Vehicle-based scanning technology has also progressed to the point where the community is exploring ways to estimate texture from detailed transverse profiles, which are measured at highway speed for monitoring the rutting of road networks. The most common scanning laser used for measurement of road surface characteristics is the RoLine, which is manufactured by LMI/Selcom. The RoLine 1130 senses the pavement 3000 times per second using a line of laser light 110 mm wide. (Each line is carved into about 150 "columns.") When the laser line is positioned transversely, it covers about 1 mm in the longitudinal direction. With this combination of sampling rate and beam footprint, the sensor must travel along the surface at a speed no greater than 6.7 mph.

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[2] Photos courtesy of Rohan W. Perera, SME, Inc.

Robotex

Robotex is a pavement texture profiler that uses a line laser. Figure 11 shows it with a RoLine. The device operates at walking speed, and covers a continuous strip of pavement about 100 mm wide.

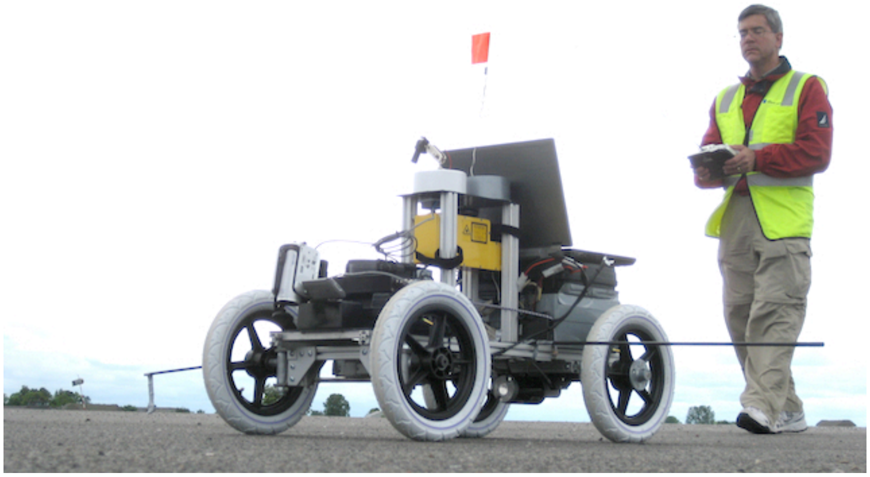

Figure 11. Robotex.

Circular Texture Meter

The Circular Texture Meter (CTM) records the profiler along the circumference of a circle with a diameter of 284 mm. (See Figure 12.) MPD is calculated from the profile using eight equally-sized, equally-distributed segments of profile that represent an arc length of about 112 mm. Coverage of a circular area provides a way to characterize anisotropy in the texture pattern.

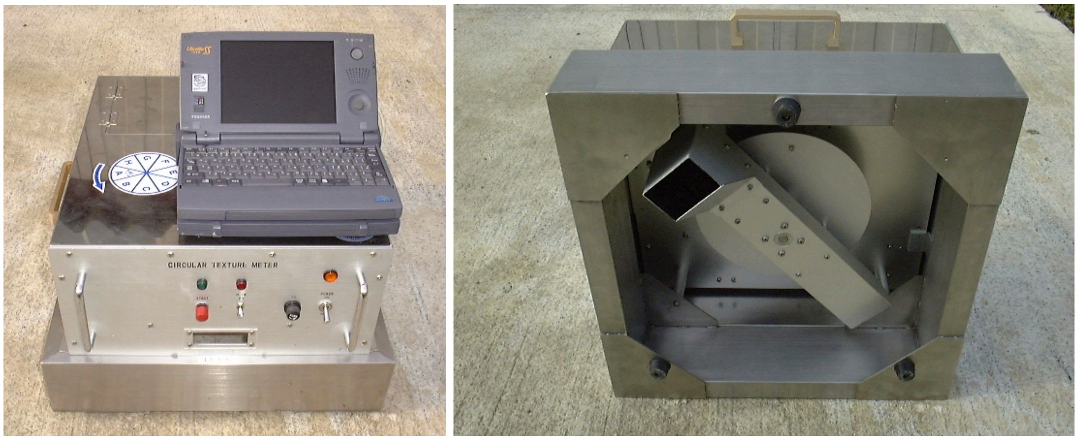

Figure 12. Circular texture meter.[3]

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[3] Photos courtesy of the FHWA.

Texture Scanners

Figure 13 shows a texture scanner that measures a very detailed 3-D profile over an area of the pavement surface 100 mm long and up to 75 mm wide. Like the CTM, the device in the figure provides a way to account for anisotropic textures. Both devices were designed with measurement of MPD in mind. They provide a sampling of the pavement texture, inasmuch as full coverage of the wheel path is not practical.

Figure 13. Ames Engineering Texture Scanner.

Survey of Pavement Roughness

This portion of the project analyzed the 2011 Highway Performance Monitoring System (HPMS) database to summarize surface roughness (IRI) measured by the on the national road system. Background and exploratory on the 2011 HPMS data, analysis plan, and results are presented below.

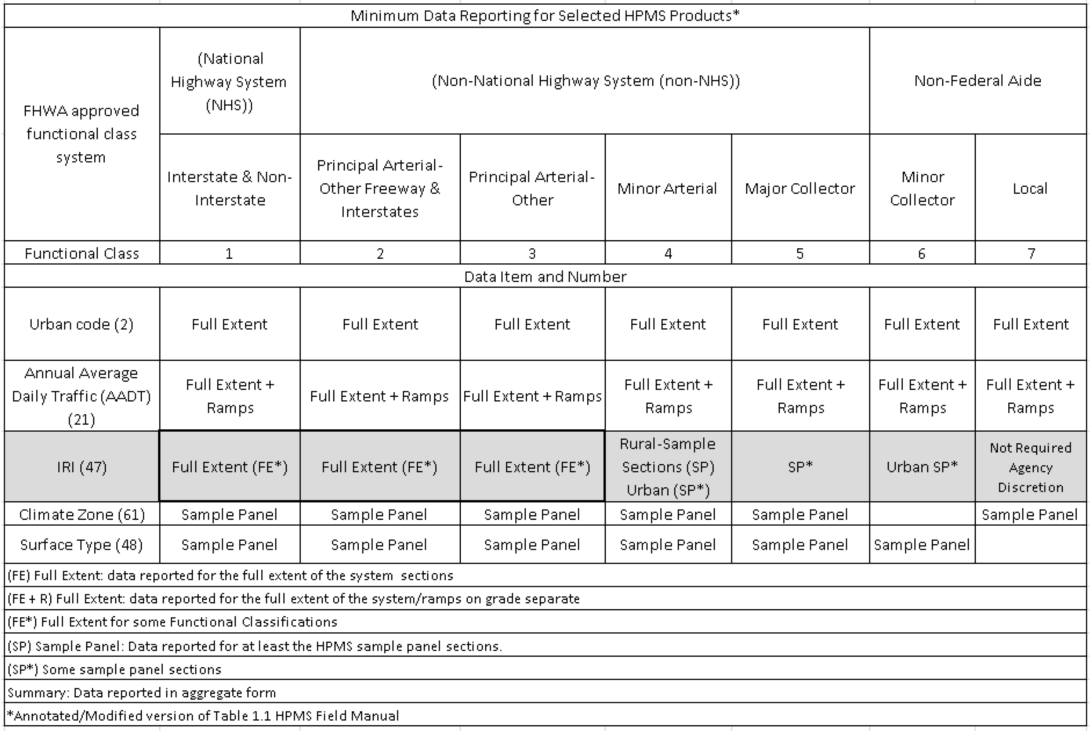
Background - HPMS

"The Highway Performance Monitoring System (HPMS) is the official Federal government source of data, extent, condition, performance, use and operating characteristics of the nation's highways." (HPMS, 2010) The HPMS data is collected annually by all states and territories then submitted to the FHWA Office of Highway Policy Information and is used by the Department of Transportation (DOT), FHWA, and Congress to make data-driven decisions regarding road network condition, performance and allocation of funding. HPMS was chosen as it provides the most accessible and complete set of national IRI data that is generated in compliance with federally established standards, equipment, data collection and analysis techniques for a significant portion of the paved national system.

The 2011 national public road miles total 4,094,447, which include federal parklands, tribal and unpaved roads. Of the 2011 total public road mileage, 2,605,331 are paved or

65% of the total system.[4] The 2011 HPMS database represents 4,077,756 miles of which some 1.1 million miles have section-level data collected. The balance of the HPMS mileage is reported by the states as aggregated totals by functional class. Data collection for up to 68 HPMS data fields is hierarchical and driven by functional class (road type). Table 2 is an annotated/modified version of the HPMS Field Manual "Table 1.1 Minimum Data Reporting for Selected HPMS Products" and summarizes the data collection requirements by functional class and federal system categories. As shown in the Table 2 Full Extent (FE*) and Sample Panel (SP*), collection depends on functional class for IRI and other road data. Only functional classes 1- 3 require IRI data for all road sections. IRI data collected on functional classes 4-7 is based on a sampling scheme based primarily on volume groups and urban/rural designation. IRI data collected on functional classes 4-7 is sampled based on volume groups and urban/rural designation. IRI data collection is not required on local roads and is collected at the discretion of the jurisdictional agency. If a road section is not a sample panel or IRI data is unavailable, agencies code IRI as zero or null. Therefore, the IRI collected under the SP* requirement covers only a small percentage of the total system. Unless otherwise stated, the analysis was completed on those segments with IRI values greater than zero.

Table 2. Minimum Data Reporting for Selected HPMS Products.



Minimum Data Reporting for Selected HPMS Products*							
FHWA approved functional class system	(National Highway System (NHS))	(Non-National Highway System (non-NHS))				Non-Federal Aide	
	Interstate & Non-Interstate	Principal Arterial-Other Freeway & Interstates	Principal Arterial-Other	Minor Arterial	Major Collector	Minor Collector	Local
Functional Class	1	2	3	4	5	6	7
Data Item and Number							
Urban code (2)	Full Extent	Full Extent	Full Extent	Full Extent	Full Extent	Full Extent	Full Extent
Annual Average Daily Traffic (AADT) (21)	Full Extent + Ramps	Full Extent + Ramps	Full Extent + Ramps	Full Extent + Ramps	Full Extent + Ramps	Full Extent + Ramps	Full Extent + Ramps
IRI (47)	Full Extent (FE*)	Full Extent (FE*)	Full Extent (FE*)	Rural-Sample Sections (SP) Urban (SP*)	SP*	Urban SP*	Not Required Agency Discretion
Climate Zone (61)	Sample Panel	Sample Panel	Sample Panel	Sample Panel	Sample Panel		Sample Panel
Surface Type (48)	Sample Panel	Sample Panel	Sample Panel	Sample Panel	Sample Panel	Sample Panel	
(FE) Full Extent: data reported for the full extent of the system sections							
(FE + R) Full Extent: data reported for the full extent of the system/ramps on grade separate							
(FE*) Full Extent for some Functional Classifications							
(SP) Sample Panel: Data reported for at least the HPMS sample panel sections.							
(SP*) Some sample panel sections							
Summary: Data reported in aggregate form							
*Annotated/Modified version of Table 1.1 HPMS Field Manual							

Figure 14 displays the percent total miles for each functional class. Clearly, functional classes 1-3 have the most system miles of IRI data coverage with 93%+ of system miles for classes 1-3.

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[4] Bureau of Transportation Statistics, 2011.

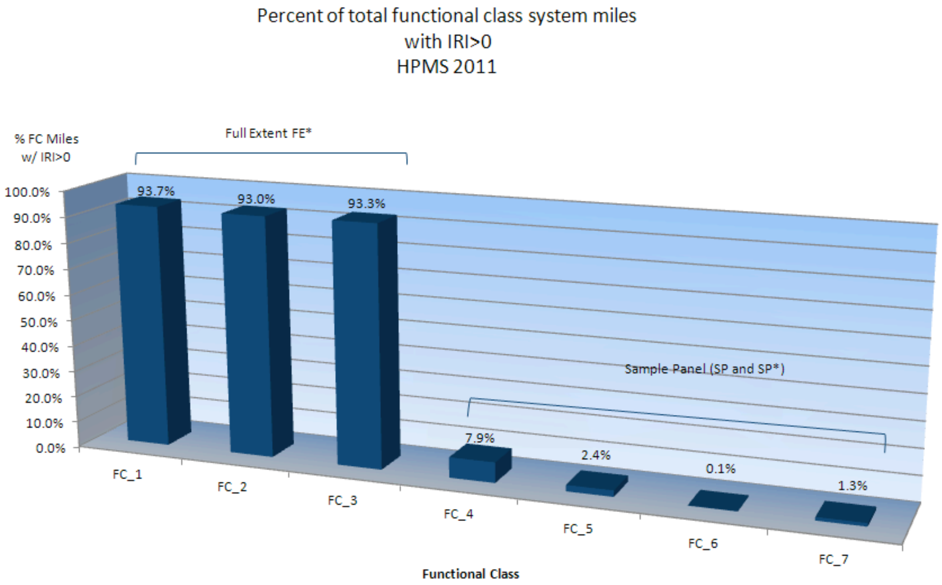

Figure 14. IRI data coverage by functional class system.

Figure 15 shows the percent distribution of vehicle miles traveled (VMT) with IRI>0 by functional class. Functional classes 1-3 have a significant portion (98.2%) of the total VMT. While functional classes 1-3 total only 218,941 of the 1.1 million miles in HPMS, these classes are where IRI data collection is required. The project considered including the sampled IRI data (SP and SP*) for functional classes 4-6 and surface type data for functional classes 1-3. However, the project was not able to acquire surface type data in time, and using SP data requires that the data be expanded "up to" a statistical representation of functional class system miles.

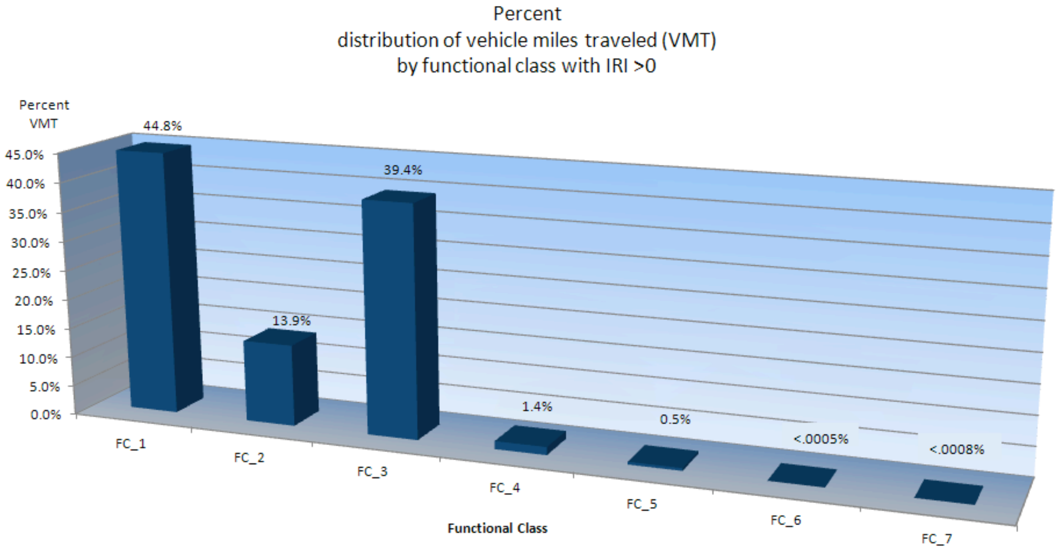

Figure 15. Vehicle miles traveled by functional class.

The Bureau of Transportation Statistics broadly classifies pavement surface types as bituminous (i.e. asphalt concrete), concrete (Portland cement concrete), or composite (asphalt concrete over Portland cement concrete). Figure 16 shows the mileage associated with each surface type for functional classes 1-6[5] for which data is required. Bituminous is the most prevalent surface type for all 6 functional classes.

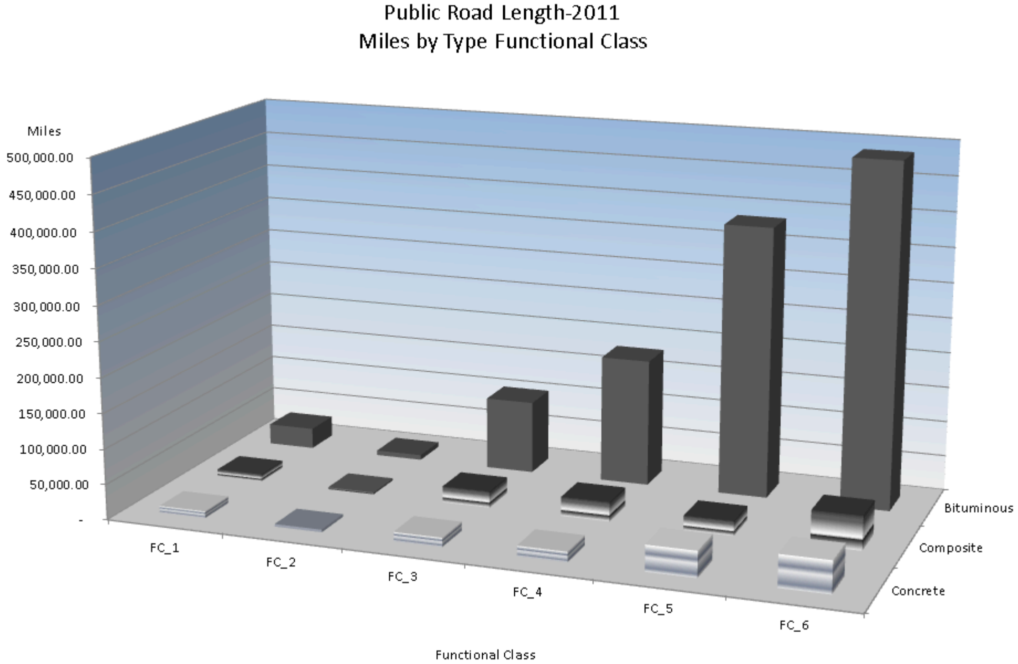

Figure 16. Surface type based on functional class.

In addition, functional classes 1-3 are the classes on which road roughness data was originally developed and have more temporal consistency. Therefore, IRI data *coverage* was the primary criterion for determining which portion of the road network would be investigated. While IRI data is central to the analysis, the volume of traffic is important. Therefore, the data universe or HPMS data subsets were based on the following criteria: what type of road (functional class), on what surface (IRI), and how much traffic (VMT). The analysis plan for the chosen 2011 HPMS data sets is presented in the next section.

HPMS Analysis Plan

In order to determine the prevalent surface roughness using IRI data; an analysis plan was developed based on three research questions and selected HPMS data listed in Table 3. The questions are the result of reviewing in detail the HPMS data collection requirements discussed above. This analysis approach is designed to drill down to that portion of the national system that has both the most extensive IRI data and the most miles driven (VMT) relative to land use (urban/rural) and climate zone (weather). Therefore, functional classes 1-3 were chosen to “represent” the most pervasive portion of measured surface roughness as measured by the IRI. The exception was the removal of some routes that represent 20,335,988 vehicle miles traveled within functional class 1 and

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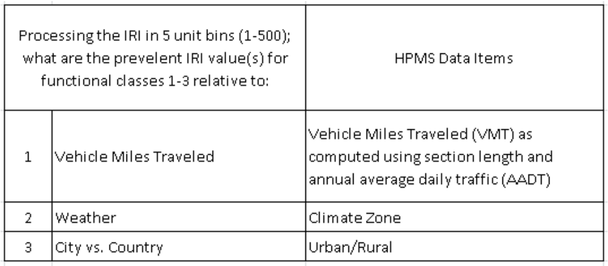
[5] Bureau of Transportation Statistics, 2011.

2. These data were removed because it was confirmed that the IRI values were placeholders, rather than actual measurements.

In summary, the analysis plan was designed to determine: what type of road (FC/functional class), on what surface (IRI), and how much traffic (VMT).

Table 3. Surface Characteristics Research Questions.



Processing the IRI in 5 unit bins (1-500); what are the prevelent IRI value(s) for functional classes 1-3 relative to:		HPMS Data Items
1	Vehicle Miles Traveled	Vehicle Miles Traveled (VMT) as computed using section length and annual average daily traffic (AADT)
2	Weather	Climate Zone
3	City vs. Country	Urban/Rural

Table 4 lists the VMT for the HPMS system. The IRI data was processed into probability distributions for IRI values from 1 to 500 in/mile in increments of 5 in/mile. Table 4 also includes the VMT for this IRI data range by functional classes 1-3.

Table 4. 2011 HPMS Vehicle Miles Traveled.

Vehicle Miles Traveled (all functional classes)[6]				1,316,037,458,771
IRI Range	FC1	FC2	FC3	Totals
1-500 in/mile	1,878,411,557	596,654,012	1,661,396,197	4,136,461,767

The HPMS data items chosen for analysis are either FE or FE* and include: IRI, traffic volume, and urban/rural code. Climate zone is the exception and requires only sample panel (SP) collection. However, the project was able to assign a climate zone value to all functional class 1-3 road sections using spatial integration. Vehicle miles traveled (VMT) was computed by multiplying the HPMS section length (miles) by the annual average daily traffic (AADT) data item.

What follows are the results of the analysis plan for each of the three research questions listed in Table 3.

Research Question 1 - IRI and Vehicle Miles Traveled (Functional Class 1-3)

Figure 17 shows the distribution of vehicle miles traveled for functional classes 1-7 on roads for which the IRI was reported. Functional classes 1-3 have the greatest number of miles driven, because HPMS requires full coverage of those roads. Table 5 provides the average IRI values weighted by VMT and weighted by segment length for functional classes 1-3. (The values weighted by VMT correspond to the distributions in Figure 17.) The table also identifies the increment within the distribution with the highest proportion of the travel by VMT for each functional class. The IRI/VMT data slice reveals that the "average" road in each functional class does not necessarily represent the highest proportion of VMT.

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[6] 2011 Highway Statistics Table VM 2M.

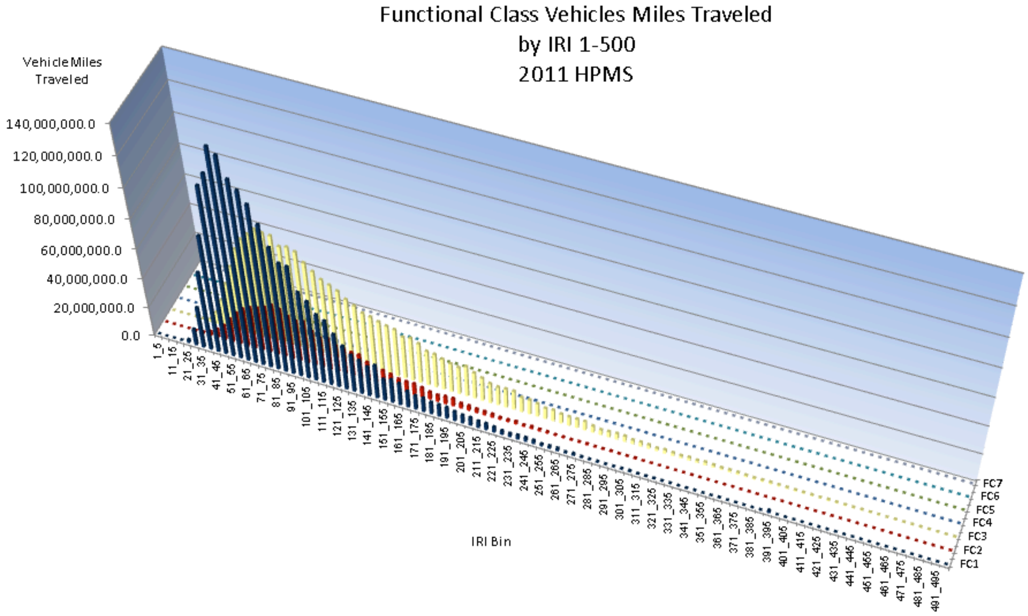


Figure 17. VMT for functional classes 1-7 by IRI Bin.

Table 5. Summary IRI Values, Functional Class 1-3.

	Average IRI (in/mile)		IRI range with the most travel	
Functional class	weighted by VMT	weighted by segment length	increment (in/mile)	percentage of VMT
1	88	80	56-60	7.4
2	105	95	76-80	5.9
3	123	108	66-70	4.5

Figure 18 and Table 6 emphasize the portion of the data that represents the most travel. Figure 18 shows the percent distribution of VMT for functional class 1-3 within IRI bins ranging from between 31 and 215 in/mile. As illustrated in Figure 17, the bins between 1-30 and 226-500 account for less than 1% of the VMT. Table 6 lists the smallest continuous range of IRI needed to account for at least half of the VMT for each functional class. Figure 19 shows a graphical example of the calculation for functional class 1. The 8 increments within the distribution identified in the figure account for exactly 50% of the VMT.

Table 6. Range of IRI that Accounts for Half of the VMT, Functional Class 1-3.

Functional class	IRI Range (in/mile)	Percentage of VMT
1	46-85	50.0
2	41-95	49.4
3	46-110	49.5

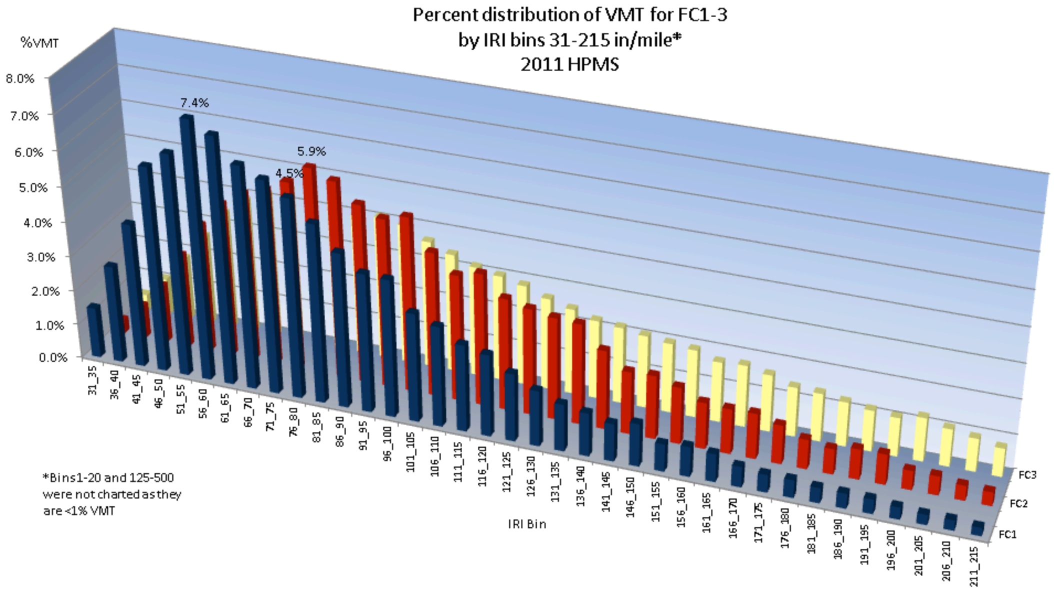


Figure 18. Percent distribution of VMT for FC 1-3 by IRI Bins 31-215 in/mile.

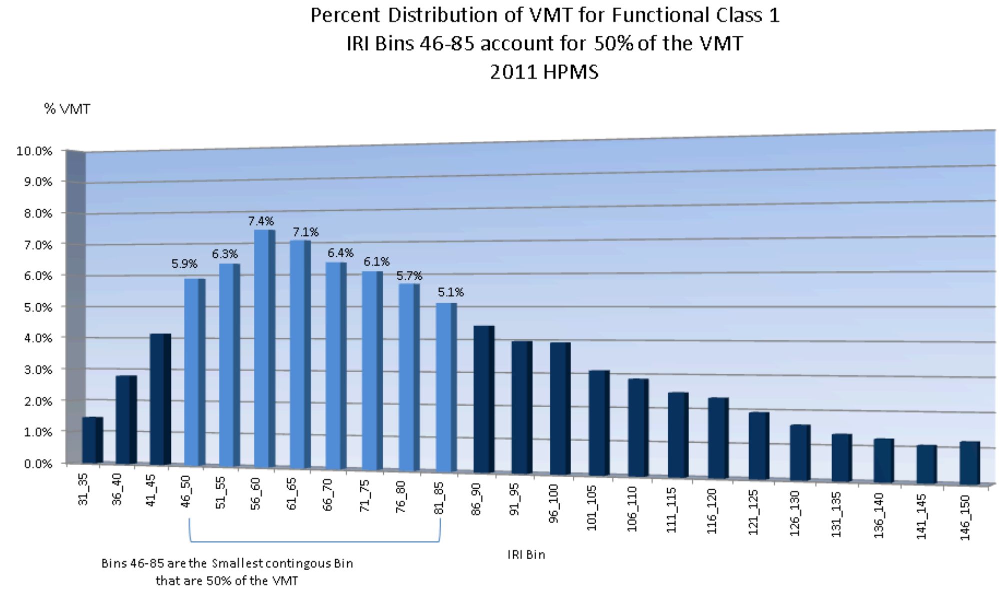
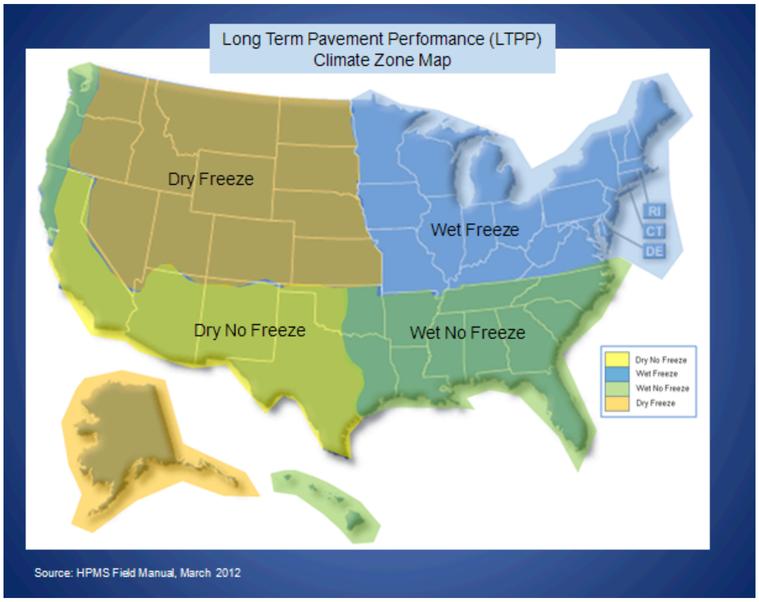


Figure 19 IRI bins – 50% VMT for functional class 1.

Research Question 2 - IRI and Climate Zone (Functional Classes 1-3)

The second research question investigated was VMT (functional classes 1-3) relative to climate zone. This HPMS data item is central to the development of pavement design and monitoring across the country. Variations in climate indicate the temperature extremes and precipitation that can have a significant impact on pavement surface characteristics and life cycle. Table 7 lists the climate zone coding definitions. Figure 20 depicts the climate zones for the country.



Source: HPMS Field Manual, March 2012

Figure 20. HPMS/LTPP climate zones.

Table 7. Climate Code Definitions.

HPMS Code	Climate Zone Description
1	Wet-Freeze
2	Wet-NonFreeze
3	Dry-Freeze
4	Dry-NonFreeze

Figure 21 (below) charts the VMT (FC 1-3) in climate zones 1-4 by IRI bins 1-500. Climate zones 1-2 clearly account for the highest proportion of VMT.

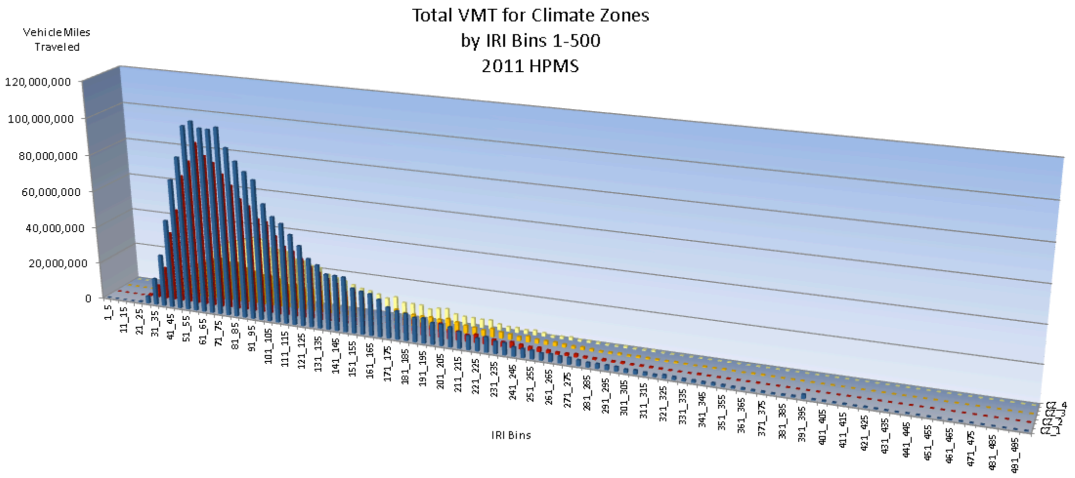


Figure 21. Total VMT for functional classes 1-3 by climate zone.

Only bins 31 through 165 in/mile have a percent distribution of VMT greater than 1%. To emphasize this portion bins 31-165 are shown in Figure 22. Table 8 below lists the increment with the highest proportion of VMT for each climate zone as well as the IRI weighted by VMT.

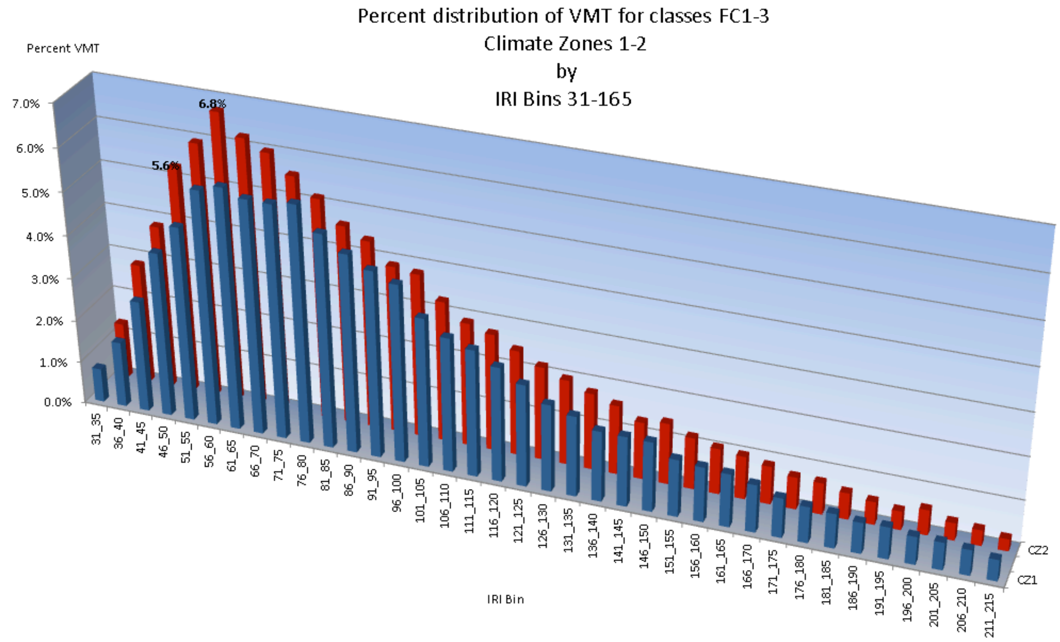


Figure 22. Percent distribution of VMT for functional classes 1-3 by climate zone.

Table 8. Summary IRI Values by Climate Zone.

Climate Zone	Average IRI (in/mile)	IRI range with the most travel	
	weighted by VMT	increment (in/mile)	percentage of VMT
1	106	61-65	5.60%
2	94	56-60	6.70%
3	119	61-65	4.90%
4	111	81-85	5.20%

Research Question 3 - IRI and Urban/Rural Designation (Functional Classes 1-3)

Urban or rural designation, like climate zone, is central to pavement design and maintenance and can have significant impacts on surface roughness. Figure 23 charts the VMT for urban and rural designations by IRI Bin. As expected, the urban system has a greater number of miles compared to the rural system. However, the urban/rural data slice has a more distinctive spread over the same range of IRI data bins when compared to VMT mileage distribution by functional class and climate zone. Urban/rural designations "shared" fewer IRI bins than VMT and climate zone.

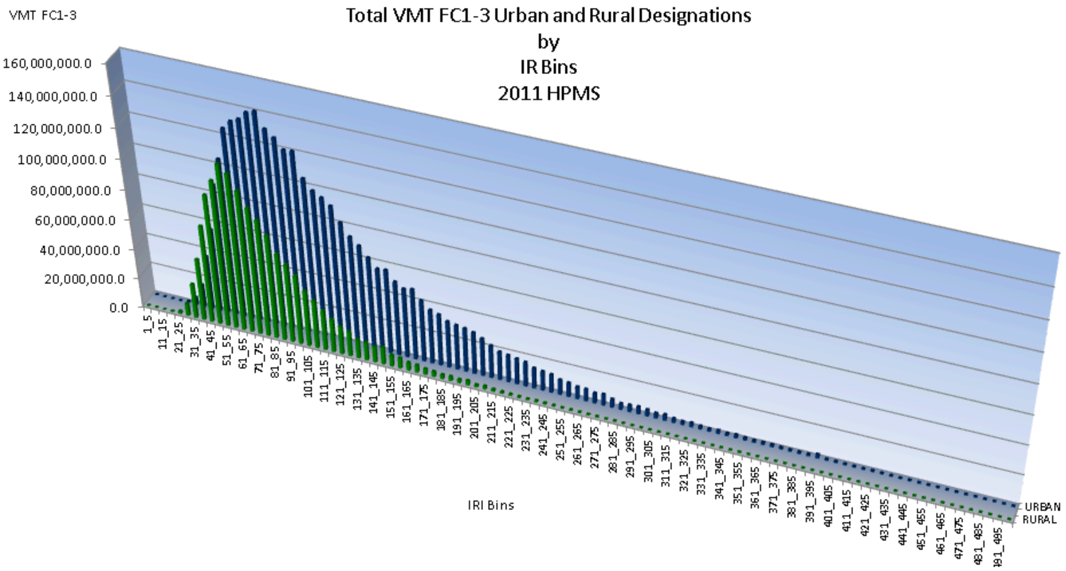


Figure 23. Total VMT for functional classes 1-3 by urban/rural designation.

To further narrow urban/rural designations relative to IRI values, only those bins corresponding to a percent distribution of VMT >1% were charted and provided as Figure 24.

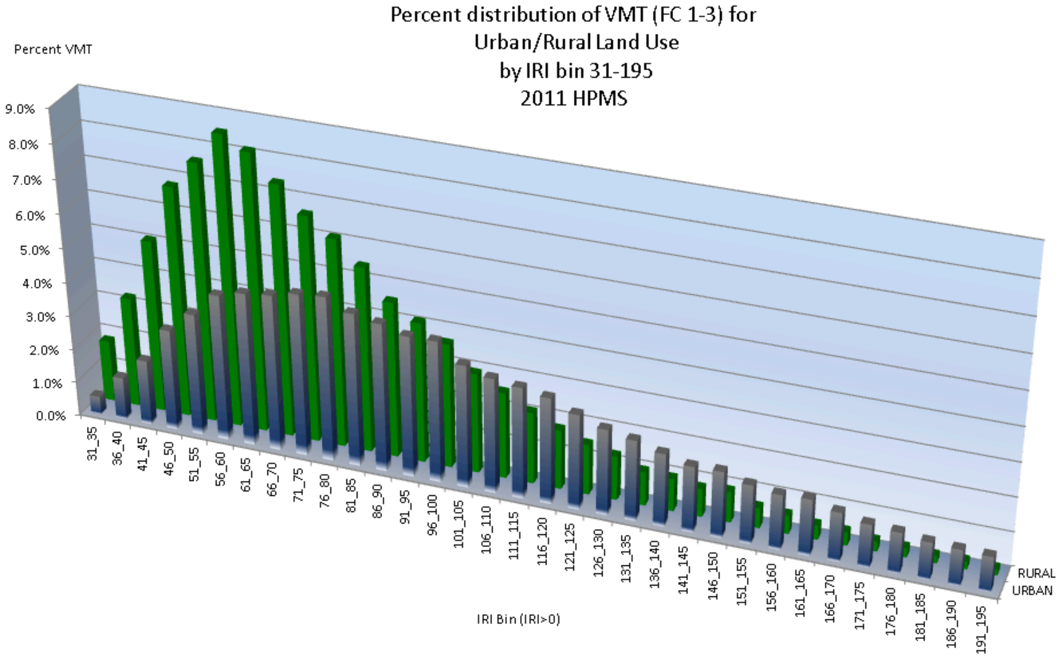


Figure 24. VMT for functional classes 1-3 by urban/rural designation, IRI 31-195.

The results of the VMT (FC1-3) urban/rural data slice are summarized in Table 9. The highest percentage of VMT is 8.5% and designated as rural with IRI values between 56 and 60 in/mile. The corresponding weighted IRI by VMT is 79 and is also reflected in Table 9.

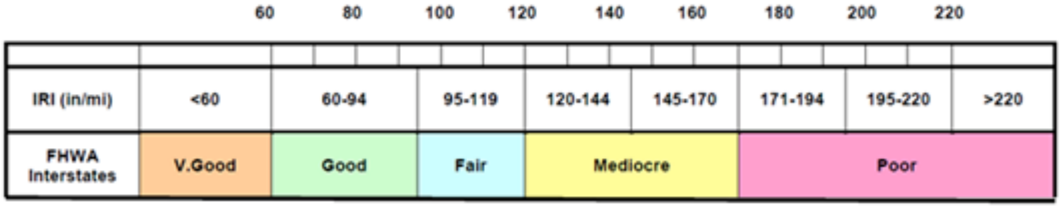
Table 9. Summary IRI Values by Land Use.

Land Use	Average IRI (in/mile)	IRI range with the most travel	
	weighted by VMT	increment (in/mile)	percentage of VMT
Urban	115	76-80	4.80%
Rural	79	56-60	8.50%

FHWA Classifications

Selection of a roughness level for coast-down testing should also consider the target IRI values for in-service roads established by the FHWA. Table 10 shows "IRI Ranges Defined by FHWA Highway Statistics Publications." [7] The FHWA classifies interstate pavements with IRI below 60 in/mile as "very good" and pavements with IRI between 60 and 95 in/mile as "Good." One of the FHWA's goals is to continuously increase the share of travel by the public on the NHS on roads classified as good or better. In addition, most state DOTs apply quality assurance provisions to paving contracts based on roughness, and rarely accept new pavement surfaces with IRI above 95 in/mile without applying a negating pay adjustment or requiring corrective action. FHWA's range of IRI values for designating roads as "Good" overlaps or includes many of the most prevalent IRI ranges identified above.

Table 10. IRI Ranges as Defined by FHWA Highway Statistics.



IRI (in/mi)	<60	60-94	95-119	120-144	145-170	171-194	195-220	>220
FHWA Interstates	V.Good	Good	Fair	Mediocre		Poor		

Summary Results

Functional class, land classification (urban versus rural), climate zone, and consideration of traffic volume all affect the distribution of IRI observed on a given subset of the road network. This diversity in roughness, and the diversity in the underlying road imperfections that contribute to it, makes the selection of a single representative roughness level very difficult. The skewed roughness distributions shown above also necessitate a compromise between the most prevalent roughness and an average roughness level.

The most prevalent roughness level in any classification is much smoother than the average, and may underrepresent the negative effect of road roughness on fuel efficiency of an in-service vehicle. An average roughness level may seem more representative.

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[7] Pavement Condition Assessment NYSDOT Network Level, Figure 1, redacted to include Interstate pavements only.

However, building a test surface with the additional roughness needed to reach an average IRI level would require the placement of artificial roughness with characteristics that may differ from natural road specimens. Further, natural roads at an average roughness level do not represent an amalgamation of the roughness on very smooth roads, which often include primarily long wavelength content, and very rough roads, which often include severe distress such as potholes.

Characterizing Typical Pavement Surface Textures

Introduction

Road surface properties (e.g., texture) for newly constructed roads and their future performance are highly influenced by several factors, including:

- The volume of traffic that the road supports: number of vehicles per day per lane.
- The type of traffic: heavy loads including trucks and busses versus light loads including passenger cars.
- Climatic regions: roadway performance for dry non-freeze regions (Arizona) is significantly different from wet hard-freeze regions (Michigan).
- Construction materials and construction method: aggregate sources used in both asphalt and concrete mixtures significantly vary from state to state across the United States. In turn, these differences in mixture lead to differences in relevant material properties such as texture, durability, acoustical absorption, etc.

Characterizing Pavement Variability

In order to begin to pinpoint "typical" roadways in the United States, the first step is to characterize the variety of pavements found on public highways. No single database exists that characterizes roadways in this manner, and thus strategic sampling is required.

To begin this process, the project team evaluated standard materials and construction specifications for select State DOTs). To sample which states to investigate as part of this project, the project team began with the 2013 Highway Statistics data published annually by the FHWA Office of Highway Policy Information. Within these data, individual states are ranked by the total VMT. Since these data are collected and reported annually, trends of the change in VMT could also be developed. A summary of the VMT by state and by year is shown in Figure 25.

From these data, it can be observed that the top ten states by VMT include:

1. California
2. Texas
3. Florida
4. New York
5. Ohio
6. Georgia
7. North Carolina
8. Illinois
9. Pennsylvania
10. Michigan

The rationale for using VMT as a first screening tool is based on a reasonable assumption that total fuel consumption is proportional to this metric.

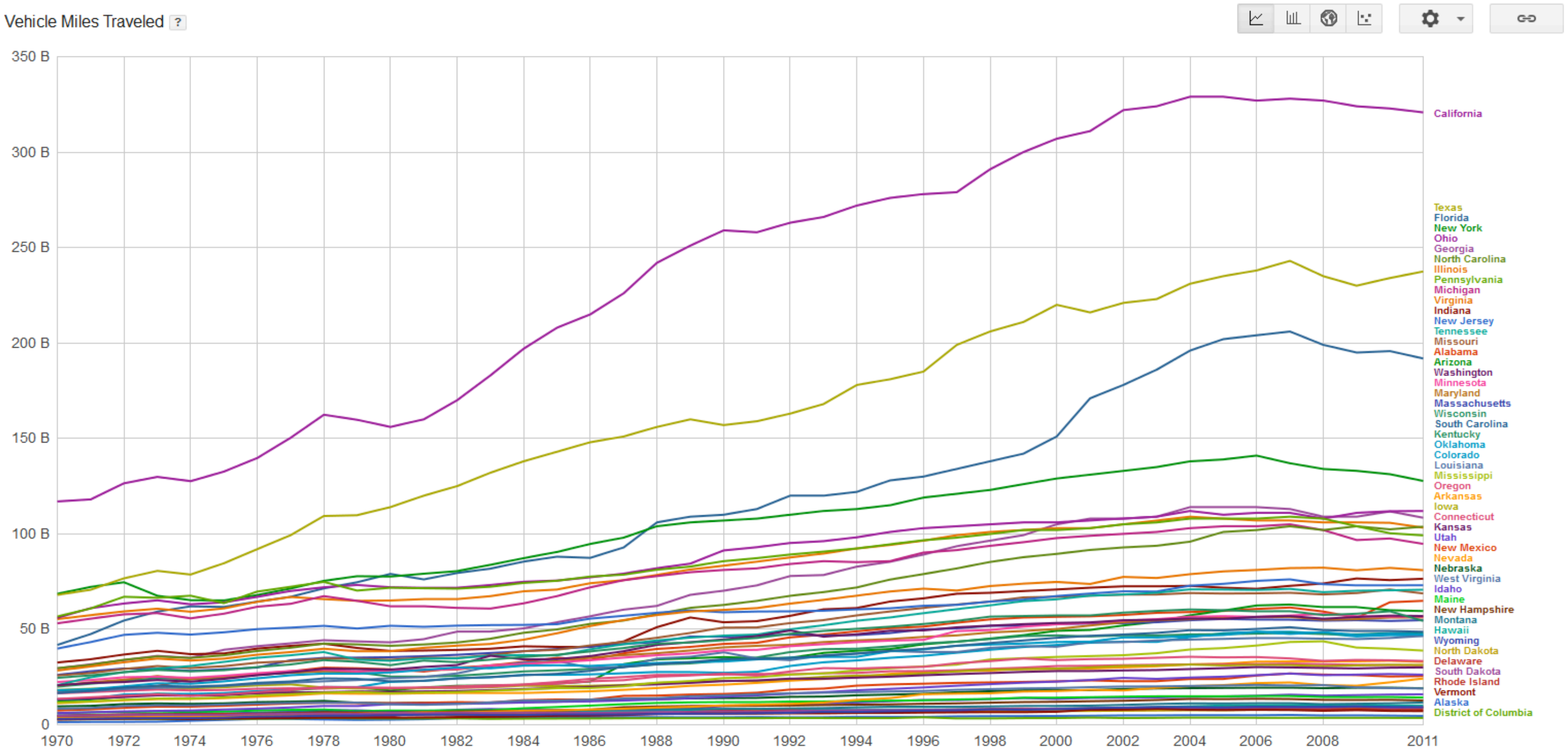


Figure 25. State DOTs ranked by total vehicle miles traveled.

The list of ten states that emerged successfully passes a second screening measure, which is to select states representing a variety of geography and climate. This is particularly important since both initial construction methods and maintenance techniques are a function of these factors. Since adjacent states typically adhere to similar practices, this sample of ten states is representative of the majority of the country.

Finally, the top ten states include Michigan, Texas, Ohio, North Carolina, and Florida. These states collectively contain most of the automotive and tire proving grounds and test tracks in the United States. While more exacting, the basis for the design and construction of most proving ground pavements are local state DOT standards. These pavements are often constructed by contractors that build to these DOT standards, and thus know the requisite techniques and locally available materials.

Key Materials and Construction Parameters

With the list of states selected, Standard Construction Specifications for the states were thoroughly reviewed. Relevant data was summarized into a database, and includes material and construction parameters that are known to influence surface texture and smoothness.

For asphalt (flexible) pavements, key parameters include aggregate gradation, voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), air voids, and density of the asphalt after compaction.

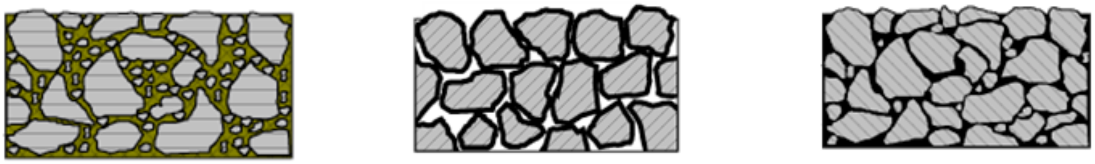
For concrete (rigid) pavements, key parameters include nominal surface texture type and dimensions.

Specifications for texture depth and smoothness were also sought.

In the following sections, these parameters are discussed, along with the potential relevance to rolling resistance by way of their effect on the final surface texture.

Aggregate Gradation

Aggregate gradation is the “recipe” of aggregates that are present in an asphalt mixture. Aggregates range in size from the Maximum Aggregate Size to the finest material that is often termed “Mineral Filler”. The proportions of the various sizes in between the maximum and minimum describe the nominal type of mixture. The three most common mixture types are dense-graded asphalt, open-graded asphalt, and gap-graded asphalt, as illustrated in Figure 26.



Dense-graded (Superpave)

Open-graded (Permeable Friction Course)

Gap-graded (Stone Matrix Asphalt, SMA)

Figure 26. Typical hot mix asphalt mixture types.

Dense-graded asphalt mix is by far the most common type of asphalt mixture in use today. These mixtures are produced with continuously graded aggregates of all sizes (see Figure 27). Because of the gradation and the angularity of the materials, the larger particles tend to "float" in a matrix of asphalt binder and finer aggregates. In the 1990s, "Superpave" was introduced to the industry as a means to properly engineer dense-graded mixtures.

Figure 27. Dense-graded asphalt wearing course.

Open-graded asphalt mixes are also used, particularly for the surface mixture of some pavements. These mixtures are produced with near-uniform-sized aggregate, and are typically absent of medium sized particles (Figure 28). Open-graded mixes are permeable to air and water, and a modified binder (using polymers, rubber, or fibers) is commonly used to minimize drain-down of surface water into the mix. Because of their porosity and high-quality stone, "friction course" is often used to describe these mixtures.

Gap-graded asphalt mixtures are designed with a gradation ranging from coarse to fine, but have little intermediate-sized materials (see Figure 29). If engineered properly, this type of mix forms a stone "skeleton" that is commonly more durable and less permeable than open-graded mixtures. Stone Matrix Asphalt (SMA) is a common type of gap-graded mixture.

Figure 28. Open-graded asphalt wearing course.

Figure 29. Gap-graded asphalt wearing course.

Mixtures are also labeled with their maximum aggregate size (MAS), which is defined as the smallest size of the opening of a square mesh (sieve) that all the material will pass. More commonly used is a Nominal Maximum Aggregate Size (NMAS), which is the smallest sieve size that allows more than 90% of the material to pass.

Aggregate gradations for mixtures are usually defined by control points that describe the maximum and minimum percent of the total weight of aggregate that can pass a variety of sieves. An example of control points for a standard Ohio DOT mixture is illustrated in Figure 30. This 12.5 mm NMAS mixture is dense graded, and a common wearing course surface for heavily trafficked roadways.

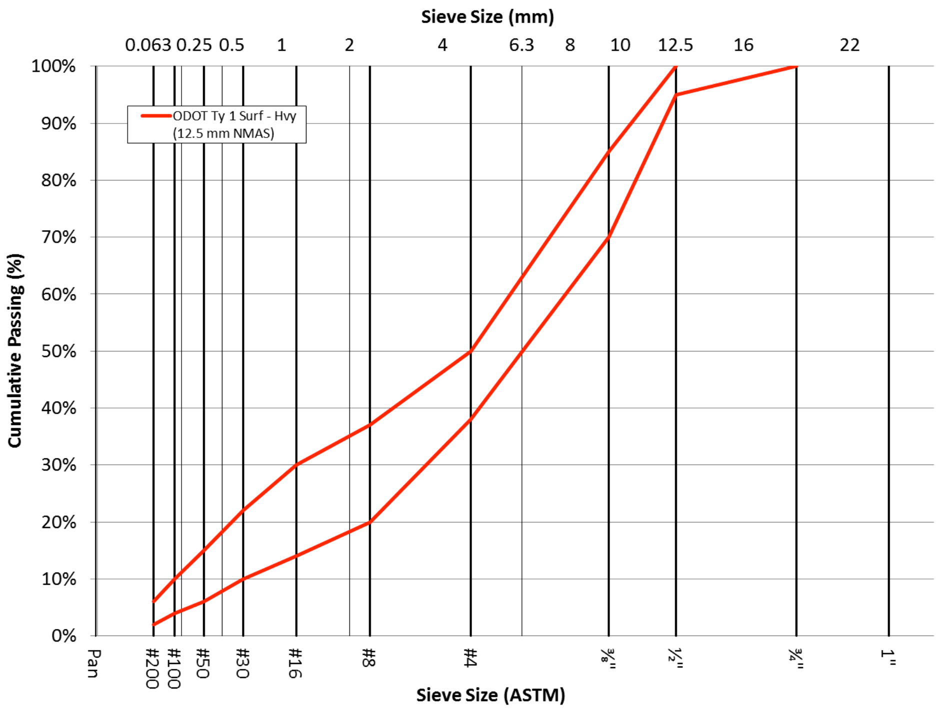


Figure 30. Aggregate gradation controls for a dense-graded HMA.

Voids in Mineral Aggregate (VMA)

Voids in the Mineral Aggregate (VMA) are an asphalt mixture property that can have a significant impact on both constructability and long-term durability. VMA is a measurement of the space within a compacted asphalt mixture (see Figure 31). It is a function of several mixture properties including aggregate gradation, aggregate shape and texture, and binder content and type (which affects the compactive effort).

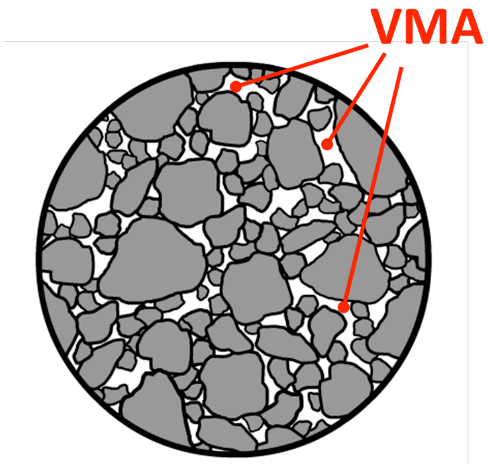


Figure 31. Illustration of VMA due to voids within compacted aggregate structure.

VMA is important because it is the “space” available to be filled by the asphalt binder. The remaining space is air voids. Minimum values of VMA are typically set for individual mix type and gradations.

VMA can affect the “openness” of an asphalt mixture, which has an impact on the texture and thus possible rolling resistance.

Air Voids and Density

Compaction of an asphalt mixture is typically expressed in terms of density, which is mathematically related to the quantity of air voids. In its simplest definition, these properties can be complementary; for example, 5% air voids for a mixture at 95% density with a sum of 100%. In this instance, the reference (100%) density is the maximum theoretical density for the asphalt mixture with no (0%) air voids. In practice, there will nearly always be some air in the mixture.

Poorly compacted mixes with high air voids can deteriorate prematurely due to both climatic and traffic effects. Conversely, asphalt mixes that are over-compacted can also be problematic. Since air voids can affect performance so significantly, it is usually carefully controlled in the field during construction. Nearly all owner-agencies have density or in-place air void specifications, but other mixture controls are necessary so that the contractor does not modify the mixture to artificially achieve a higher density by potentially compromising pavement performance in another way.

Figure 32 illustrates density differences in an asphalt core. As illustrated here, there can be zones of varying density in the same pavement, whereas most state DOT specifications will only control the “average” of the density through the depth.

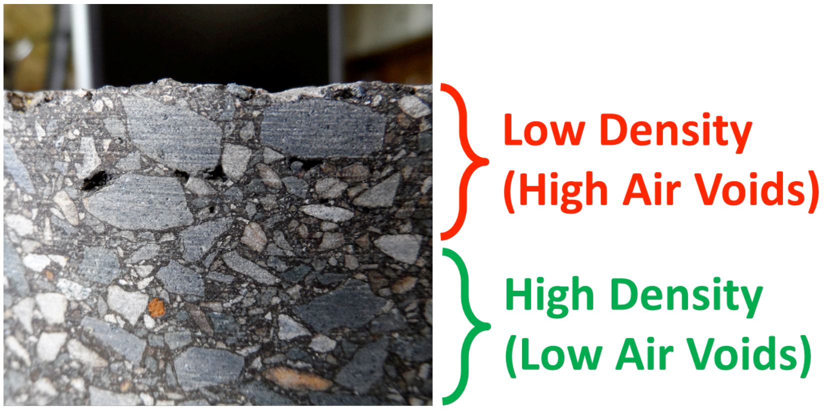


Figure 32. Asphalt density as it varies with thickness.

Concrete Pavement Texture

Concrete pavements are commonly textured as part of the final stage of construction. Texturing may consist of longitudinal or transverse tining (Figures 33 and 34), or dragging the fresh concrete surface with a broom, artificial turf, or burlap (Figure 35). Techniques to texture hardened concrete are also sometimes used, including both diamond grinding (Figure 36) and grooving (Figure 37).

Figure 33. Texturing concrete pavement with longitudinal tining.

Figure 34. Texturing concrete pavement with transverse tining.

Figure 35. Texturing concrete pavement by artificial turf drag.

Figure 36. Texturing concrete pavement by diamond grinding.

Figure 37. Texturing concrete pavement by grooving.

Concrete pavement texture defines much of the final surface geometry that is relevant to rolling resistance. Selection of the nominal texture will have an effect, but so do the techniques used to impart the texture, and also the properties of the concrete mixture being textured. Climatic conditions during texturing will also have an effect since this will affect both the fluidity of the mortar at the surface during construction, and the durability of the mortar at the surface for the years to follow.

Summary of State DOT Practices

From the review of the ten State DOT standards, materials and construction practices were tabulated for ready comparison. Table 11 includes an overview of the key parameters.

From Table 11, it is evident that there are numerous common specifications among the ten strategically selected states. For asphalt paving, all ten states commonly use dense-graded mixtures for wearing courses, with six of the 10 as the material of choice. Two states use gap-graded (SMA) mixtures for the majority of their high-type surfacing, and two states use open-graded mixtures. It should be noted that those states that use open-graded mixtures for wearing courses do so to help mitigate splash & spray and/or noise. All states commonly use 12.5 mm (1/2”) mixtures for their most heavily traveled roadways, and eight of the 10 use 9.5 mm mixtures as well.

For concrete pavement textures, half of the states are using longitudinal tining, which includes most of the states known to construct many of these types of pavements (recognizing that some states prefer asphalt over concrete, due to economics of available materials and local preferences). Many states also use transversely tined textures, but this number is decreasing as states migrate to longitudinal textures due to highway noise complaints.

Specifications to control pavement smoothness are mostly using IRI, particularly for asphalt pavements. For many states that are currently using the profilograph, there are institutional pressures to migrate to IRI. Texture is rarely measured and controlled on highway projects, although a few states occasionally evaluate mean texture depth (using the "sand" patch method).

Table 11. Summary of Key Pavement Surface Materials and Construction Practices.

DOT	HMA Surface Mixes	HMA NMAS (mm)	VMA (typical range for min.)	Density (% Max. Theoretical)	Concrete Texture	Smoothness/Texture Specifications
California	DG, GG, OG	9.5-12.5	13%-17%	91 - 97%	Longitudinal Tining	IRI Friction spec < 0.3
Texas	GG, DG, OG	9.5-12.5	14% -16% 17.5%-19% (SMA)	92 - 96%	Transverse Tining (migrating to Longitudinal Tining)	IRI MTD > 1.0 mm (special provision)
Florida	OG, DG	9.5-12.5	14% -16%	92 - 97%	Diamond Grinding	IRI (asphalt)
New York	DG	9.5-12.5	14%-15%	92 - 97%	Longitudinal Tining	IRI (asphalt) Profilograph & IRI (concrete)
Ohio	DG, GG	12.5	13%-16% SMA=16%-19%	93 - 97%	Longitudinal Tining	IRI
Georgia	OG, DG	9.5-12.5	15%-16%	93 - 95%	Transverse Tining	IRI (asphalt) Profilograph (concrete)
North Carolina	DG, OG	9.5-12.5	14.5%-16%	92% +	Diamond Grinding	IRI Target MTD > 0.8mm
Illinois	GG, DG	9.5-12.5	14%-15%	92 - 96%	Transverse Tining	Profilograph
Pennsylvania	DG	9.5-12.5	14%-15%	91 - 98%	Transverse Tining	IRI
Michigan	DG, GG	12.5	12%-15%	92% +	Longitudinal Tining	IRI MTD = .04" to 0.1"

DG – Dense graded GG – Gap graded OG – Open graded

Defining the "Typical" Pavement

From the data collected during this effort, it is possible to identify a "typical" pavement wearing course for the United States. by bracketing known material and construction practices. The parameters for this pavement are as listed in Table 12. (Alternatively, a concrete pavement can be used, with a longitudinally tined texture, with a nominal tined groove spacing of 19 mm.)

Table 12. Material and Construction Practices for a Common Pavement.

Mixture Type	NMAS	Minimum VMA	Density (% Maximum Theoretical)	Smoothness Specification
Dense-Graded HMA	9.5 mm or 12.5 mm	14%	93 – 97%	IRI

The material and construction specifications suggested can be used to produce a facsimile of a common in-service pavement surface, so long as the construction process itself is managed with quality control for texture and texture durability in mind.

These specifications do not provide a scale that can be used to measure whether existing tracks provide realistic pavement texture, or to compare them with each other. Because of its prevalence, the MPD scale is the only available tool for doing so. Unfortunately, pavements with the same nominal specifications vary significantly in their measured MPD.

In the experience of the authors of this report, a value of 0.5 mm is a reasonable (albeit crude) estimate of MPD for a new pavement surface with a “fine” highway mixture like the one defined in Table 12. As the pavement ages, the MPD may increase to 0.7 mm or as high as 1.0 mm if the pavement begins to ravel. Very smooth surfaces on new pavements have been observed with MPD as low as 0.3 mm. MPD values of 0.2 mm to 0.25 mm have been observed on test track surfaces, but they are not common on in-service highways.

Recommendations

This report recommends specification of roughness, megatexture, and macrotexture of road surfaces for automobile coast-down testing to ensure reproducible measurement of road load. The specification may either appear as an augmentation to testing standards, such as SAE J1263 and SAE J2263, or as a stand-alone document like ISO 10844, which specifies test tracks for measuring noise emitted by vehicles. (ISO 10844, 2011)

The International Roughness Index (IRI), a “megatexture level” defined by the ISO, and Mean Profile Depth (MPD) are the recommended scales for roughness, megatexture, and macrotexture, respectively. None of these scales were developed explicitly for estimating the contribution of roads to fuel consumption, and the literature suggests that MPD is not a sufficiently relevant scale to use for this purpose over the long term. However, all three of these scales are in use within the pavement community, the scales are well understood, and equipment is available for measuring each index and the underlying profiles.

For a given vehicle, coast-down testing is typically performed on just one road surface. No single road surface can represent the diverse pavement surface characteristics experienced by in-service vehicle. In lieu of a "representative" surface, the specification should define conditions that are realistic, and to the extent possible, prevalent.

The specification should include the following:

Grade: a constant grade no greater than 0.5%.

> This is the existing specification.

Roughness: a target value of IRI with an associated tolerance (e.g., "surfaces shall have a measured IRI value in each wheel path of XX in/mi +/- YY in/mi).

> The report shows that IRI values of 50-100 in/mi are common on the U.S. National Highway System when travel patterns are considered. Based on a statistical analysis of IRI values in U.S. interstate and principal arterial roads, a target (XX) value of 70-75 in/mi is a reasonable choice. This is at the high end of the roughness commonly expected of paving contractors to avoid a negative pay adjustment for placement of new pavement surfaces. Other choices of a target value, such as an "average" IRI value for public roads, can be justified. However, building a pavement with a higher IRI may require the addition of roughness with characteristics that are not natural.

Megatexture: a maximum value of the ISO "megatexture level" (e.g., "surfaces shall have megatexture level no greater than XX dB").

> A maximum level is recommended here, because megatexture is typically associated with construction defects and pavement structural distress.

Macrotexture: a target value of MPD with an associated tolerance (e.g., "surfaces shall have a measured MPD value in each wheel path of XX mm +/- YY mm")

> MPD is used as a placeholder to facilitate an interest in texture measurement and comparison of test tracks over the short term. Values from 0.3-1.0 mm are commonly observed in practice. MPD of 0.5 mm is a reasonable target value.

Measurement: Measure the grade of test surfaces each time major resurfacing is performed. Measure the roughness, megatexture, and macrotexture in the left and right wheel path of test surfaces once at the start of the testing season and again at the end of the testing season, or after resurfacing is performed.

> The grade, IRI, megatexture level, and MPD should be included with the metadata that appear in road loads test reports. Further, the test procedure should include storage of the underlying profiles for diagnostic purposes. Lastly, measurement of macrotexture should include as much coverage along the longitudinal distance covered by the testing as possible, and include measurements along the transverse axis over a width as close to a tire contact footprint as possible.

Establishing target values for the specification will require a compromise. The cooperation of practitioners will require the selection of values that are represented as broadly as possible on in-service roads, disqualify as few existing tracks as possible, and are not costly to maintain.

Introduction of the specifications should begin with an effort to measure and compare the properties of existing coast-down test surfaces. It is unlikely that the prevailing set of coast-down test surfaces will have roughness, megatexture, and macrotexture that are similar to each other or to common in-service roads. As a result, short-term implementation of a surface specification may require an effort to “normalize” the results from each test surface to that of a target surface. This is not ideal, and it would require a robust experiment to establish the sensitivity of road load measurement to road surface properties.

The credibility of the specification requires a direct experimental demonstration using road load and pavement surface characteristics measurements at multiple coast-down facilities and on a diverse set of pavements. The experiment must establish the sensitivity of road load to each quality of the pavement on the recommended scales for setting tolerances and estimating the bias associated with each test track. Detailed measurements of the road surface are needed to develop a replacement for MPD with direct relevance to coast-down test results, and verify the relevance of the megatexture and roughness scales for this purpose. This will require detailed measurement of pavement surface characteristics using instrumentation on-board coast-down test vehicles, and a more diverse set of test track pavements than exists among existing coast-down test facilities.

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