CENTER FOR
PORTLAND CEMENT CONCRETE
PAVEMENT TECHNOLOGY

Developing Smooth, Quiet, Safe Portland Cement Concrete Pavements

Final Report
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Department of Civil, Construction and Environmental Engineering
IOWA STATE UNIVERSITY

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The Center for Portland Cement Concrete Pavement Technology (PCC Center) is housed and administered at the Center for Transportation Research and Education (CTRE), Iowa State University.

The mission of the PCC Center is to advance the state of the art of portland cement concrete pavement technology. The center focuses on improving design, materials science, construction, and maintenance in order to produce a durable, cost-effective, sustainable pavement.

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16. Abstract

The concrete paving industry has spent large amounts of time working to provide safe, quiet, and smooth pavements for the traveling public as their needs and driving habits have changed since the advent of the automobile. During that time, the efforts of research, design, and construction were directed at one of the problems at a time. Current public surveys indicate that the traveling public wishes to have safe, quiet, and smooth pavements.

This report identifies the problems remaining in the areas of developing smooth, quiet, and safe portland cement concrete pavement in each pavement we build. It develops the research framework that can be used to bring the existing information together with additional research in each area. The resulting answers can be used in each pavement design for a quiet, safe, and smooth pavement that is also long lasting.

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DEVELOPING SMOOTH, QUIET, SAFE PORTLAND CEMENT CONCRETE PAVEMENTS

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INTRODUCTION

Our goal of providing smooth, quiet, and safe pavement requires us to deliver a surface with the correct balance of low roughness, low noise, high friction, and minimal splash and spray. In theoretical terms, researchers have often organized these objectives in terms of the range of characteristic lengths along the profile that affect each aspect of performance. This is usually expressed as a range of "wavelengths." Figure 1 shows the sensitivity of various vehicle performance aspects to profile features over a range of wavelengths from 0.001 mm to 100 m (Ayton 1991). The figure shows that building smooth, quiet, and safe pavement involves a balance between these objectives. The goal of the research suggested in this document is to find methods of providing each of these desirable qualities without sacrificing any of the others.

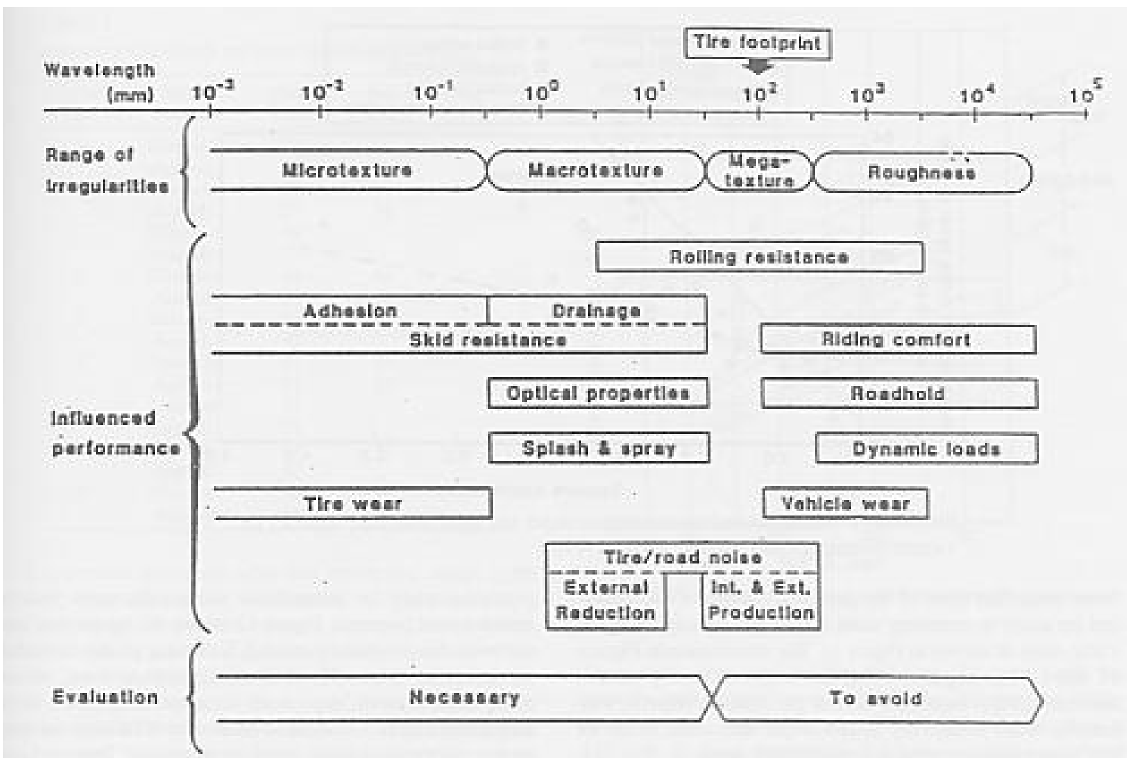

Figure 1. Influence of surface characteristics on vehicle performance.

Figure 1 breaks pavement surface profile characteristics into four ranges: (1) roughness, (2) megatexture, (3) macrotexture, and (4) microtexture. The figure states that megatexture and roughness are to be avoided, and macrotexture and mircotexture are necessary. The figure also shows that the wavelength range of interest for smoothness, skid resistance, and noise interact with each other. For example, avoiding roughness helps enhance riding quality, but also increases road-holding ability, which may boost safety. While megatexture is known to increase noise, macrotexture is thought to help decrease it. On the other hand, macrotexture helps provide drainage for increased safety. Further, microtexture is desirable because it provides adhesion, which is necessary for skid resistance. Although it is not shown in the figure, excessive adhesion may also increase noise.

The trade-off between noise and friction, implied in Figure 1, is a major focus of the suggested research described in this document. Of course, quiet pavement should never be provided at the expense of safety. As such, the challenge is to provide quiet pavement with sufficient drainage and without any reduction in friction. This will require a systematic study of the precise manner in which pavement textural features affect each of these qualities. In particular, a better understanding of how texture direction (i.e., longitudinal versus transverse), shape (i.e., texturing patterns), and depth affect noise and safety will help define the problem beyond the definition of wavelength ranges. Once we understand precisely what aspects of microtexture and macrotexture affect noise, friction, and water drainage, we may begin to build pavements with the most desirable surface characteristics.

Of course, defining desirable pavement surface characteristics is only of interest if they can be specified by the owner agency, built by the paving industry, and verified through quality assurance. For this reason, it is anticipated that the greatest contributions to the state of the art will have two important features. First, they will require the cooperation of the pavement owner agency, the paving contractor, and the researcher. This will be critical if the results of the research are expected to have an immediate and positive impact on current practice. No research will be deemed a success unless it produces cost effective recommendations that have been proven in the field. Second, the research must leverage the most modern measurement equipment. Smoothness, pavement noise, and friction have been studied for generations. Many of the contributions that can still be made to the subject exist because they require measurements that had not been practical in previous efforts.

Recommendations for smooth, quiet, and safe pavement research will fall into the following categories:

- What is needed to best serve the public?

  Although smooth pavement is known to reduce user cost, and is thought to last longer, there is a point of diminishing marginal return. Our research must provide the industry with the best target smoothness level, such that a dollar spent on making the pavement smoother always contributes to a dollar saved by the public, or an extra dollar’s worth of contribution to the pavement life cycle.

  Friction must not be compromised to improve noise. On the other hand, it is likely that some limit exists where additional texture does not improve safety, but does exacerbate noise. We should seek to find this limit. It is also well known that beneath some threshold value, tire/road noise is overshadowed by other sources.

- What are the most desirable pavement surface properties?

As described above, a systematic understanding of the affect each aspect of pavement surface shape has on safety, noise, and smoothness is required to help optimize the pavement surface. Concisely stated, we must learn to build a smoothest, quietest surface possible and preserve superior safety. Most of the background material in this report and the majority of the research suggestions are devoted to this category.

- How are these properties measured?

The effect of any surface characteristics on pavement behavior can only be studied properly if the pavement shape and the resulting performance can be measured with a repeatable and reproducible system. Further, the economic viability of innovations can only be evaluated if the benefits are grounded on the absolute scale. (In other words, the change from marginal to good performance is much more compelling than “a little better.”)

A robust measurement system will also help to specify pavement surface characteristics directly. Alternatively, a reproducible system for measuring smoothness, noise, and wet pavement friction will permit performance-based specifications that may lead to meaningful innovation by the industry.

- How can we help the industry build it?

The paving industry has a long history of innovating to improve their product as cost effectively as possible. All of the research conducted in this program should have the final goal of demonstrating a cost-effective process for providing desirable surface characteristics.

TEXTURE AND TRAFFIC NOISE

Noise Basics

NCHRP Synthesis 268 provides an excellent overview of the relationship between pavement surface texture and highway traffic noise (Wayson 1998). Most of the material in this section is paraphrased from the Synthesis.

Noise is directly quantified by the root-mean-square of sound pressure fluctuations traveling through the air. However, this quantity is rarely used to describe noise level. Instead, noise level is reported as sound pressure level in decibels (dB). This is done by normalizing the mean square pressure level by a reference value and computing the logarithm of the result. The dB scale is very convenient, because it is anchored at a value of 0 for the typical threshold of human detection. Unlike direct measurements of sound pressure fluctuations, it does not span several orders of magnitude.

Note that the dB scale is not additive, such that a doubling of the sound energy increases the noise by 3 dB. On this scale, a value of 35 dB is typical of a quiet library, while a value 130 dB is at the threshold of pain. Although this scale is meant to reflect a human's reaction to sound, different people react to sound differently. It is generally accepted that a difference of 3 dB is at the threshold of human detection indoors, and 3-5 dB is the threshold of detection for a human outdoors.

Raw measurements of sound pressure level do not reflect typical human reactions to sound. The human ear can detect frequencies from 20 Hz to about 20,000 Hz, and are most sensitive to the range from 250 Hz through about 10,000 Hz. To account for this, standard frequency weightings are applied to sound pressure measurements before they are summarized by a dB value. For moderate sound levels, a standard frequency weighting, called the "A" weighting, is applied before the final sound pressure level is calculated. The resulting value is expressed as dB(A). This is the most common scale for reporting traffic noise.

On the dB(A) scale, noise may be reported in several ways. All of these values are given the symbol L to distinguish them from direct measurements of sound pressure fluctuation:

L_{eq}: This is the equivalent sound pressure level. It represents a single sound level that would be needed to equal the average influence of a varying sound level over a given period of time.

L_{10}: This is a statistical description of sound level. It is the threshold sound level that was exceeded for 10 percent of the overall time of the measurement. L_{10} is the most common descriptor of peak traffic noise levels. Of course, other percentiles have been used.

L_{max}: This is the maximum noise level observed for a very short period of time over a given measurement interval.

For residential areas, U.S. noise regulations specify values of 67 dB(A) for L_{eq} and 70 dB(A) for L_{10} as thresholds for consideration of noise abatement (FHWA 1995).

Traffic Noise Mechanisms

Two major sources contribute to noise observed at the roadside: power train noise and coast-by noise. Power train noise is attributed primarily to engine noise and exhaust emissions. Coast-by noise is attributed primarily to the interaction of the tire and pavement, but also includes vehicle vibration and aerodynamic noise. The noise caused by the interaction of tire and pavement is considered dominant at high speed, but it is overshadowed by the engine and exhaust at low speed. The cross-over speed between these two sources depends on the type of vehicle, pavement texture, traffic conditions, and several other factors (Hibbs 1996). As such, there is not complete agreement in the literature about the speed at which tire noise becomes the dominant source. However, there is agreement that at highway speed tire noise is dominant (Sandberg 2002).

For dry pavement, Sandberg (2002) attributes tire noise to three fundamental mechanisms: (1) tire radial vibrations, (2) tire tangential vibrations, and (3) air pumping. Radial vibrations happen when the tread impacts the road, which causes side wall vibrations. This mechanism is exacerbated by road roughness. Tangential vibrations are caused by sliding motion within the tire contact patch, or by the vibration that results from the tread sticking to the pavement, then being quickly released. Air pumping causes shock waves that propagate as sound when the air that is trapped in between the tire and the road makes rapid transitions from compression to expansion.

Each of the three noise mechanisms described above are caused by surface texture in a distinct range of wavelengths (Nilsson 1980). As such, they cause noise in a distinct frequency range. Of course, this relationship is very sensitive to vehicle speed. Macrotexture and mircotexture cause vibrations within the tread of a tire. Macrotexture also decreases pavement noise, because it mitigates the air pumping effect by helping to prevent air from getting trapped. Megatexture causes tire vibration beyond the contact patch, such as vibrations of the side wall. These complicated relationships between pavement surface characteristics and noise have thus far prevented the direct specification of pavement surface texture. However, some relationship between texture power spectra and sound power spectra have been reported (Eberhardt 1985). Further, a recent study sponsored by the Wisconsin Department of Transportation has produced the data needed to investigate this relationship further (Kuemmel 2000). Of course, in some cases, this relationship may be irrelevant because noise abatement should not be achieved at the expense of safety.

Tire tread design is thought to have much less influence on traffic noise than the road itself. In terms of tire vibration effects, the functional aspects of tire design prevent tires from having much diversity in tread or side wall stiffness that may lead to major changes in the potential for producing noise. On the other hand, tire tread design affects the air pumping mechanism significantly (Ejsmont 1984; Willett 1975). A “good” tread design is one that allows air to escape as the tread makes contact with the road. This mechanism is responsible for the findings of some studies in which the relative noise levels on various pavement types did not produce the same rankings for different tire tread designs (NBS 1970).

Traffic Noise Measurement

Traditionally, traffic noise has been measured at the roadside as a random sampling of vehicles passes by. Pavement surfaces are usually compared using this method, and the FHWA has made an effort to standardize it (Lee 1996). Occasionally, a variation on this method is used in which a known vehicle (with known tires) passes a fixed microphone that is placed a standard distance from the vehicle path in a “controlled passby”. Efforts are still underway to standardize this method of measurement (Sandberg 1996). This method provides a direct estimate of the sound level that has propagated to the roadside because of a given vehicle or traffic mix. The passby method captures the sound produced at the tire/road interface and the effects of the pavement surface on sound propagation. However, the sound level measured using the passby method includes the noise from all sources, including power train noise. Thus, although the passby method provides an estimate of the annoyance that traffic noise may cause to nearby residents, it requires careful control of multiple variables (microphone placement, air temperature, ambient noise, etc.) when it is used to compare vehicle and road surface combinations.

An alternative means of noise measurement that has become more common in recent years is the close-proximity method (ISO 1997). In the close-proximity method, a microphone is mounted to a vehicle near the contact patch. This method seeks to isolate the noise at the contact patch from other sources. For this reason, it may provide a more direct comparison of the effect of tire type and road surface texture on noise generation. Although it isolates the noise caused by tire and pavement contact from other sources, it ignores the effects of noise propagation (Donovan 2003). Thus, the close-proximity method does not provide a complete assessment of pavement type. Nevertheless, close-proximity measurements of noise have become a very useful research tool.

Since the passby method and close-proximity method do not measure the same set of noise sources, there is no direct relationship between them. Indeed, recent studies have found that these methods may rank the noise level of a given set of pavement differently with each method (LaForce 2001; MinnDOT 1987; ND DOT 1994; McNerney 2000).

Either method, like any measurement, has inherent pitfalls. Many of the research studies that have been done on traffic noise in the past three decades have reported on the sensitivity of noise measurement to different variables. Each of these must be controlled carefully if measurements from different studies are to be compared directly. For example, von Meier (1990) observed a difference of up to 6 dB(A) between different tire types on the same roads at a standard speed. Perhaps more importantly, the quietest road was not the same for each tire. Vehicle speed, vehicle type, pavement surface temperature, and air temperature also strongly affect traffic noise. In addition, the manner in which the measurement is made is very important. Efforts are underway by the International Organization for Standardization to standardize every aspect of the close-proximity and passby methods.

Pavement Comparisons

Hundreds of studies have been conducted worldwide that compared the noise level of a group of surface types and texturing alternatives. Most of these studies used one method of noise measurement, and were limited to a few standard vehicles and tires. The most common outcome has been a list of pavements described by their surface type and specified texture and ranked by their relative noise level. These studies have been extremely useful, in that they have each provided some new understanding of the way tires and road surfaces interact to produce noise. Indeed, the detailed fundamental understanding of the mechanisms involved was developed incrementally in studies of this type. Further, these studies have often provided their sponsors with a basis for selecting texturing alternatives in their jurisdiction.

Unfortunately, it is not valid to compare the absolute, or even relative, noise levels reported in these studies to each other (Wayson 1998). This is because each study has approached the task of controlling the other variables involved in noise generation and propagation differently. Often, the expected influence of these effects on noise is greater then the difference that is reported between pavement surfaces. To make matters more complicated, pavement surface textures are typically underspecified. For example, transverse tining is typically identified by the longitudinal spacing of the tines, but the width and (actual) depth of trough is rarely identified or is known to be different than the intended value (Kuemmel 2000). As such, different studies have ranked certain groups of texturing specifications differently, and no clear ranking has been established between common surface texturing alternatives. Nevertheless, consensus has been reached on some findings:

- Transverse tining usually causes more noise than longitudinal or random textures.
- When transverse tining is specified with a constant spacing, the resulting pure tone appears to be more annoying than the tone of other pavements of the same noise level. This phenomenon has been given the nickname “whine” (Kuemmel 1997).
- A change in speed, vehicle type, tire tread design, or measurement method (passby versus close-proximity) may change the rank order of a set of pavements.
- For tined pavements, texture depth and groove width are important parameters in noise generation (Hoerner 2003).

Suggested Research

The following are suggestions for research that would help enhance the state of paving practice and assist the paving industry in delivering an even better product. In particular, the first recommendation seeks to define the performance level that is required to properly serve the public. Most of the following research efforts pursue the needed performance through advances in pavement design and in the construction process.

The recommendations here only cover the issue of noise measurement inasmuch as a reproducible system is needed to successfully carry out other aspects of the research. Standardization of interior, near field, and far field noise measurement is a very important pursuit, but research in this area will only improve paving practice indirectly. Further, it is recommended that those efforts be coordinated through the International Organization for Standardization, as the future international regulatory environment will require a high level of cooperation and coordination.

How Quiet is Quiet Enough?

Purpose: The purpose of this research is to define goals for tire/pavement noise levels that are needed to sufficiently satisfy the public.

Research Gap: Noise regulations are not necessarily uniform from one agency to the next. Further, intervention for noise abatement is often the result of politics, rather than objective measurements and procedures. Research is needed to identify public goals in pass-by noise, potential for interior noise, and noise generated at the tire. (Note that noise generated at the tire may be considered the least relevant, because it is not a direct measurement of what a person may hear. On the other hand, it may have strong relevance to both interior and pass-by noise.) Close proximity noise also includes a shorter list of mechanisms. It may, therefore, constitute a good benchmark and help systematic study.

Methods: This study may involve a survey of the roadside noise and occupational health literature, a limited focus group, and a study of existing noise abatement thresholds and procedures.

Threshold noise levels will be defined in light of the public's perception of noise at the roadside, as well as the noise caused by other mechanisms that may overshadow tire/pavement noise. It is expected that separate threshold values of roadside noise may be established for each class of surrounding land usage. Further, the level of noise generated at a tire that may be tolerated for a single vehicle may depend on the expected traffic density for a given road segment.

Products: This study will recommend context-sensitive goals for interior, close-proximity, and passby noise levels.

These target values will serve as the basis for weighing the potential benefits of improving a pavement's noise characteristics against the cost, and will help ground the work that is done to eliminate noise in an absolute scale.

A Reproducible Noise Evaluation System

Purpose: The purpose of this research is to assess the repeatability and reproducibility of standard close proximity and passby noise measurements.

Research Gap: Often, noise comparison studies report differences between pavements of 3 dB(A) as very significant. The reported noise levels are often the average of several measurements, but the level of scatter is rarely listed. Before policy is written that is based on these results, the noise differences should be considered in light of the level of repeatability of the measurement.

A tremendous database of pavement surface comparisons has been reported through decades of research. However, the reported noise values can not be cast onto a common scale. Although a large number of noise comparison studies have been carried out with similar methods, the environmental variables that may confound the measurement process are not always recorded. Further, the noise measurement systems, while similar, have not been completely standardized. The consequence is that results from noise comparison studies may only be treated as relative to some baseline pavement, and that no two studies may be merged. Worse yet, a given pavement owner-agency may not be able to count the absolute level of noise performance reported by another, unless they share a measurement system.

Methods: The goal of this project is to establish a method of close-proximity noise measurement that may be reproduced between different studies, or simultaneous measurement efforts in the same study. This will be done by evaluating the repeatability of multiple close-proximity measurement systems, and by comparing them to each other under the same conditions.

One system will be operated in several different ways to study its sensitivity to various aspects of the set-up and environmental conditions. As a minimum, position and orientation of the microphone shall be studied, as well as the choice of vehicle (and hence, suspension) and tire.

This research will also quantify the probable impact of variables that can not be controlled, such as air and pavement surface temperature.

Products: This research will seek to produce a reproducible standard for close-proximity noise measurement, and recommend the most typical or relevant choices for variables that can be controlled, such as tire type and speed.

Comparison of Profile and Acoustic Traces

Purpose: The purpose of this study is to develop a relationship between pavement profile and noise measurements.

Research Gap: Very few studies have been done that directly relate the texture power spectrum to the noise power spectrum (Eberhardt 1985). This is partly because detailed measurements of texture profile were previously difficult to obtain. This omission in the understanding if the relationship between texture and noise may hinder the development of new concepts for delivering quiet pavement with high friction. Further, defining the relationship between short-duration rough features (i.e., faults, opened joints) and acoustic traces may help improve the consistency of noise measurements.

Methods: Recent advances in profile measurement technology, as well as improvements in close-proximity noise measurement, provide a unique opportunity to study this relationship in a cost effective manner. If the texture is random in nature, or transverse, a single instrumented vehicle may be adapted to collect synchronized measurements of sound pressure, texture profile, and road roughness without traffic control. For longitudinal textures, the measurements would not be simultaneous and would require traffic control. For this reason, a pilot study may pursue this relationship for transverse and random textures only.

With these measurements, texture spectra can be related to sound spectra directly. If measurements are made of diverse enough pavements, statistical methods can be used to systematically relate the level and type of macrotexture, megatexture, and roughness to sound generation. The study may also help to standardize noise measurement by revealing the level and type of roughness that can exist without contaminating noise measurements.

On concrete pavement, the presence of transverse joints is known to affect noise level. This study would provide an opportunity to quantify the level of noise that may be expected at joints of various widths. If these data are collected under the proper conditions, the diurnal changes in noise level that are caused by curling (and joint movement) may be quantified.

Products: The main product of this study will be a detailed explanation of the relationship of each waveband to tire/pavement noise and the way this relationship interacts with other variables.

A Parametric Study of Texturing and Noise

Purpose: The goal of this project is to develop a systematic understanding of the relationship between noise and the way texturing is specified and placed.

Research Gap: Significant research has been done to demonstrate the sensitivity of tire/road noise to texture in various wavelength ranges and to explain the fundamental mechanisms involved. However, very little systematic information exists to explain the sensitivity of noise to the specific dimensions of each type of texture, including directionality, and items such as channel width and depth or aggregate size. This is needed in order to build a quiet pavement without compromising safety.

Methods: The study will attempt to break the process of texturing down into characteristic dimensions. For example, tining would be studied using following parameters: direction, tine spacing, groove width, and groove depth. Other textures would be defined by specific aspects of the surface shape, rather than overall texture level.

Before a complete parametric study is conducted, a pilot study is suggested in which a few aspects (i.e., tine spacing and groove depth or width) of prevalent texturing alternatives are studied.

The study will require careful measurements of the texture profile, so that the actual shape of the textural features can be properly obtained. The detailed measurements would also permit a statistical evaluation of the relationship between the specified texture and the texture that was actually achieved.

It is recommended that the study include several representative tire types since the texturing dimensions are expected to interact with tire tread design. Friction measurements must be done in conjunction with the noise measurements to prevent a negative trade-off between friction and noise.

This study must be done in conjunction with a parametric study of friction and noise.

Products: The results of this study will help write a texturing specification that will deliver the expected noise reduction with high friction.

The study may also explain some of the differences in the reported performance of tined pavements in past studies.

The Impact of Mix Design on Noise Generation and Propagation

Purpose: The purpose of this study is to quantify the impact of mix design on noise generation and noise propagation.

Research Gap: The mechanisms of noise generation at the tire/road interface are well understood, and their relative influence on roadside noise has been studied very carefully. Although the mechanisms that affect the propagation of noise to the roadside are also well defined, their influence appears as uncontrolled external variables in most studies. Little information is available about the effect of mix design, aggregates, and surface texture on noise propagation. In part, this is because these effects are masked by the influence of direct tire/road contact in passby noise measurements. Further, access to pavements with similar surface texture but controlled changes in mix design and aggregate type are very rare.

No systematic relationship has been established within the literature between close proximity and passby noise measurements. This is a direct consequence of the confounding variables that affect noise propagation. If the aspects of the pavement that affect noise propagation are to be optimized, systematic measurements of their influence are needed.

Methods: In this study, close proximity and controlled passby measurements must be made on pavements with equivalent surface texture but well-known and diverse mix design and aggregate selection. In the best case, these measurements could be performed on existing pavements that offer these properties. (An LTPP SPS-2 site may provide a useful site.) However, a much richer and well-targeted study is possible with the cooperation of the state DOT on a new paving project.

Measurements are needed at all of the test sites to verify that the type and level of surface texture are equivalent.

Products: Two important products should result from this research.

First, the study should help explain the lack of a systematic relationship that has been observed between close proximity and controlled passby noise measurements. This is expected to help explain the differences in the way each method has ranked the noise performance of different pavements in the past. In addition, this knowledge would help establish guidelines for selecting the most appropriate measurement system and interpreting their output in standard noise studies.

Second, the study will provide road designers with knowledge of the consequences to noise that various choices of mix, aggregate, or texture depth may have. It is not anticipated that mix design or aggregate selection will be made on the basis of noise performance. However, road designers can establish guidelines for the level of noise mitigation that is appropriate for a given design. In addition, mixes and aggregates that are known to cause very high levels of noise propagation may be avoided near noise-sensitive land.

Time Stability of Noise Properties

Purpose: The purpose of this study is to observe and explain the changes in noise level on selected pavements with time over the long term.

Research Gap: Only a small number of studies have been done that measured the changes in noise on pavements with age. One study observed a decrease in noise on concrete pavements over the first seven years, then an increase afterward (Chalupnik 1992). Another study found an increase in noise on porous asphalt of 2.9 dB(A) over seven years (Poelmans 1994). Changes in the noise characteristics of open-graded asphalt have also been observed in instances where dirt accumulates (Steven 1990).

The limited amount of information on the effect of pavement wear on noise shows that it may be significant. Further, the changes in noise level reported with time are as large as the differences in noise level that are often used to justify selecting one surfacing or texturing alternative over another.

Methods: This study would proceed in the same manner as typical studies that compare noise generated on different pavements, with the exception that measurements would be made at regular intervals over several years. Detailed texture profiles should supplement the noise measurements, so that observed changes in noise generation may be linked to changes in texture. (In part, this is a study of the change in texture with time.) Traffic must also be estimated for each pavement. In addition, pavement roughness may appear as a confounding factor in the study. As such, periodic road profile measurements are needed.

If close-proximity measurements are used in this study, great care must be taken to ensure the time-stability of the measurements. Pottinger (1981) reported significant changes in the force and moment properties of unused tires with time, including properties that relate to the way the tread deforms and dissipates energy.

The group of pavements selected for this study should include a range of surfacing techniques, and a range of mix and aggregate designs. To compress the schedule of the project, pavements may be selected that sustain heavy traffic volumes.

It is recommended that a mix of texturing methods in this study coincide with some of the methods covered in other recent studies. This way, the first year of measurements may be used to test the efficacy of recent findings of other studies.

This study should proceed in conjunction with a study of change in friction with time.

Products: This project will produce improved specifications for new pavement noise properties that account for the likely changes with time. The results of the study may also help road designers specify surface types and texturing methods with desirable noise characteristics that last.

PAVEMENT FRICTION

Friction Basics

The amount of retarding force that a tire can develop at the pavement interface is directly related to the level of slip. During braking, slip is defined as the difference, in percent, between the vehicle forward velocity and the velocity implied by the tire rotation. Thus,

$$\text{Slip} = 100 \bullet (V_x - R \bullet \omega)/V_x$$

Where V_x is the vehicle forward velocity, R is the tire-rolling radius, and ω is the rate of tire rotation (van Eldik Thieme 1971). During free rolling, the value of slip is zero. When the brakes are applied the wheel rotational speed will decrease more rapidly than the vehicle velocity, and slip will take on a positive value. If the wheel is locked (i.e., not rotating) the tire is sliding, and the value of slip is 100.

The longitudinal force that is developed at the interface between the pavement and the tire depends very heavily on the level of slip. Figure 2 shows a sample measurement of the longitudinal force on a rolling truck tire versus slip for wet and dry pavement (Ervin 1981). The longitudinal force is normalized by vertical load to help estimate the level of deceleration that can be achieved at each level of slip. The values on the vertical axis are usually interpreted as a dynamic coefficient of friction.

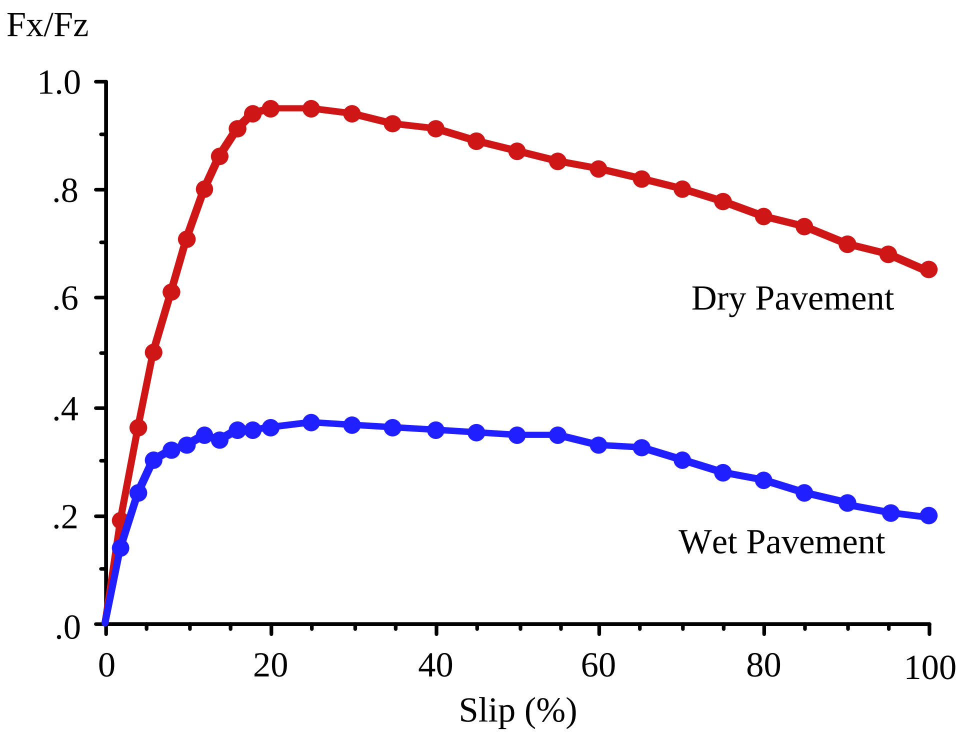

Figure 2. Longitudinal force versus slip.

Figure 2 provides an example of several important aspects of the way vehicles use pavement friction. First, the peak level of friction for operation on both wet and dry pavements occurs for a slip of about 20 percent. For most tire and pavement combinations, the peak will occur between 5 and 30 percent (Kummer 1966). Second, the coefficient of friction is reduced significantly when the wheel is locked up (at 100 percent slip). This is the sliding friction value (Meyer 1962). The reduction in friction for the locked-wheel case is also common. This is the motivation behind anti-lock braking systems, which attempt to maintain a level of slip near 10 percent to optimize the friction level. Third, the friction level on wet pavement is much lower than that of dry pavements, regardless of the wheel slip (Dijks 1974). For this reason, wet pavement friction is considered paramount to pavement safety. In fact, surveys of friction for the purposes of evaluating pavement sufficiency rarely consider dry pavement friction and have assigned the term “skid resistance” to the level of wet pavement friction at 100 percent slip.

Note that Figure 2 shows the friction level for a tire that is not cornering. When a tire is also providing lateral force to a vehicle, the maximum level of longitudinal force that it can provide is reduced. When a tire is operating near its lateral force (handling) limit, it can provide almost no longitudinal force (braking) (Bernard 1977).

At a low level of slip, most of the longitudinal force is transmitted to the tire by adhesion to the pavement surface. Potential for adhesion is provided primarily by microtexture. At a high slip speed, sufficient macrotexture also becomes important. This is because the tire tread elements will deform as they pass over coarse macrotexture. This mechanism dissipates energy. Macrotexture is also needed for drainage (Sabey 1965).

Friction Measurement

Henry (2000) reported that four basic types of in-situ friction measuring devices are in common use: (1) locked wheel, (2) fixed slip, (3) variable slip, and (4) side force. In a survey, Henry found that the majority of U.S. highway agencies were using an ASTM E-274 trailer to measure friction, which is a locked wheel friction-measuring device.

Locked wheel friction devices measure wet pavement friction at 100 percent slip. As in ASTM E-274, they are typically mounted on a trailer. The trailer supplies a small film of water, and the longitudinal force is measured over a short duration while the wheel is locked. This type of trailer is commonly used with one of the two standard test tires: (1) ribbed, or (2) smooth. Unfortunately, these two tires may rank the skid resistance of roads differently. This is because the ribbed tire provides large channels for the water film to escape, whereas the smooth tire does not. This makes the ribbed tire insensitive to macrotexture (which is usually needed to provide the drainage) (Henry 1983a). Although the ribbed tire provides a good estimate of the sufficiency of pavement microtexture, it may report a skid resistance value that is artificially high on a pavement with insufficient drainage. The net effect, therefore, of using a ribbed tire to survey a pavement network is to put pavements with good drainage at a disadvantage.

Fixed slip friction testers operate at a constant slip in an attempt to measure the peak wet friction level. This value usually falls between 10 and 20 percent. As in locked wheel testers, fixed slip testers are usually mounted on a trailer that supplies a film of water to the tire and measures the longitudinal force during an event in which the required level of slip is induced. Variable slip devices are very similar to fixed slip devices, except that they sweep through a range of slip values. Variable slip testers provide an entire friction versus slip characteristic, as shown in Figure 2. Many of the locked wheel testers in operation around the U.S. have the ability to operate in a variable slip mode but are usually used as locked-wheel testers to comply with ASTM E-274.

Side force friction testers are not common in the U.S. They measure the cornering force that exists while the tire is held at a fixed yaw angle, but allowed to roll freely. Because of their configuration, side force testers generally measure friction at a low slip condition.

International Friction Index

The locked-wheel skid resistance measurement described above has become a common aspect of road network monitoring in the U.S. (Henry 2000). However, locked-wheel measurements are most sensitive to pavement microtexture, particularly if a ribbed tire is used. As such, they are able to verify that a pavement has adequate adhesion, but ignore the contribution macrotexture may make to drainage. Recent efforts by PIARC have sought to remedy this situation through the development of the International Friction Index (IFI) (PIARC 1995). The IFI is a composite index that captures the influence of microtexture and macrotexture into a single value.

The contribution of microtexture may be measured using a trailer-mounted friction tester, as described above, or a device called a Dynamic Friction Tester (DFT). The DFT is a small device that is placed on a pavement and observes the ability of a pavement to slow a spinning flywheel through wet contact with small rubber feet.

The contribution of macrotexture is included through direct measurement of the texture level. This is usually done using the Circular Track (CT) Meter (Henry et al. 2000). The CT Meter measures the profile of the pavement in a circle that is 10 inches in diameter. The measurement is used to calculate Mean Profile Depth. Several other methods, such as the sand patch test, have also been used to estimate macrotexture.

After completing a rather ambitious testing program and performing detailed statistical correlation, PIARC was able to harmonize estimates of pavement friction from common measurement schemes. The result of this work is a method of combining the contribution of microtexture and macrotexture to form the IFI, regardless of the measurement source. Since the original experiment in 1992, an ongoing effort exists to maintain a database of correlations between friction measurements through the annual friction workshop in Wallops Island, Virginia.

Research Needs

The topic of pavement friction has been under intense study around the world for two generations. As a result, no fundamental work is still required. However, some work is needed with direct relevance to the concrete industry.

Feasibility of the IFI for Specification of Concrete Friction

Purpose: The purpose of this study is to evaluate the potential benefits of replacing ASTM E-274 skid resistance measurements with the International Friction Index (IFI).

Research Gap: The ASTM E-274 method for skid resistance measurement may be applied with a smooth or ribbed tire. Although the ribbed tire is much more prevalent, it is not adequate for testing the drainage provided by macrotexture and is only sensitive to the adhesion provided by microtexture. The smooth tire, on the other hand, is sensitive to a balance of both. The IFI supplements ASTM E-274 with concurrent measurements of texture to help include the contribution of drainage to safety.

Since the IFI harmonizes measurements from both types of tire, no equipment changes are needed, and historical databases may be maintained.

The IFI includes separate measurements for adhesion and drainage. If the relative role of each in providing safe pavement is ascertained, the IFI can be further refined to set minimum thresholds for both qualities.

Methods: The IFI should be measured using several methods, including multiple types of objective macrotexture measurements, in-situ skid resistance, and direct friction measurements. Of particular interest in this study is the change in relative friction level that may occur if the overall measurement strategy properly accounts for the influence of macrotexture on drainage. This will permit a more valid texturing specification to be written and a more equitable comparison of common tining methods to each other and the alternatives to be done.

Laboratory tire testing and on-road vehicle testing may be needed to determine what level of microtexture and level (and type) of macrotexture are needed for a safe pavement surface. This testing should also search for cases in which the index fails because an unnecessarily high level of one quality compensated for a deficiency in the other.

Products: This project will produce standards for friction measurement that simultaneously include adhesion and drainage. One standard will be customized for network level friction measurement, and another will be more detailed for project level and research purposes.

Time Stability of Pavement Friction

Purpose: The purpose of this study is to quantify the seasonal changes in friction level on pavement with common texture specifications and changes over the long term.

Research Gap: Pavement friction is generally known to decrease with pavement age because of polishing and aging of aggregates. However, expected changes in friction with age or traffic have rarely been associated with common surfacing and surface texturing alternatives. This may be due in part to the potential liability.

Seasonal variations in friction that were caused by increases in microtexture during the winter have also been observed (Henry and Saito 1983b). Few agencies that perform network friction measurements correct the values for seasonal variations, in part because few measurements of the seasonal variation in friction exist. Further, seasonal conditions that include a lot of rain may wash away contaminants that reduce friction.

Methods: This study would proceed in the same manner as typical studies that compare friction of different pavements, with the exception that measurements would be made seasonally and at regular intervals over several years. Detailed texture profiles should supplement the friction measurements, so that observed changes in friction may be linked to changes in texture. (In part, this is a study of the change in texture with time.) Traffic must also be estimated for each pavement. In addition, pavement roughness may appear as a confounding factor in the study. As such, periodic road profile measurements are needed.

The group of pavements selected for this study should include a range of surfacing techniques. To compress the schedule of the project, pavements may be selected that sustain heavy traffic volumes.

This study should proceed in conjunction with a study of change in pavement noise with time.

Products: This project will produce improved specifications for new pavement texture that account for the likely changes with time. In addition, the project will produce guidelines for the timing of friction measurements and correction factors for measurements that occur in various seasons.

A Parametric Study of Texturing and Friction

Purpose: The goal of this project is to develop a systematic understanding of the relationship between friction and the way texturing is specified and placed.

Research Gap: Significant research has been done to demonstrate the sensitivity of friction to texture in various wavelength ranges and to explain the fundamental mechanisms involved. However, very little systematic information exists to explain the sensitivity of friction to the specific dimensions of each type of texture, including directionality and such items as channel width and depth, or aggregate size. This information is needed in order to make sure a pavement has sufficient adhesion and drainage, which would help provide a quiet pavement surface.

Methods: The study will attempt to break the process of texturing down into characteristic dimensions. For example, tining would be studied using following parameters: direction, tine spacing, groove width, and groove depth. Other textures would be defined by specific aspects of the surface shape, rather than by overall texture level.

Before a complete parametric study is conducted, a pilot study is suggested in which a few aspects (i.e., tine spacing and groove depth or width) of prevalent texturing alternatives are studied.

The study will require careful measurements of the texture profile, so that the actual shape of the textural features is properly quantified. The detailed measurements would also permit a statistical evaluation of the relationship between the specified texture and the texture that was actually achieved. Further, the study will require measurements by the Dynamic Friction Tester as well as ASTM E-274 measurements with both the smooth and ribbed tire.

The study should primarily include traditional wet pavement friction measurements. However, an additional study of icy pavement is needed. This research should seek to define the desirable qualities in the pavement surface that (1) provide the proper drainage to prevent icing, and (2) minimize the penalty to friction caused by ice.

This study must be done in conjunction with a parametric study of texturing and noise.

Products: The results of this study will help write a texturing specification that will deliver the expected safety with low noise.

The study may also explain some of the differences in the reported performance of tined pavements in past studies.

PAVEMENT SMOOTHNESS

Smoothness Background

Strong evidence exists that pavements that are smooth when they are built remain smooth longer than pavements that are initially rough (Perera 1998). To help provide smooth pavements, most state departments of transportation have implemented smoothness specifications, in which incentive payments are available for very smooth pavements and penalties are imposed for unacceptably rough pavements.

Most of the states with smoothness incentive programs originally used the profilograph for measuring smoothness. A profilograph is a rigid frame with support wheels at both ends and a center wheel. The support wheels at the ends establish a datum from which the deviations of the center wheel can be compared. The movement of the center wheel is recorded, and the trace is reduced to a single value that serves as an estimate of smoothness. The smoothness value is called the Profilograph Index (PI). The PI is the sum of the heights of all of the *scallops* that appear in the profilograph's trace. A scallop is defined as a protrusion of the profilograph's trace beyond a given limit. Each time this limit is violated, a contribution to PI is added that equals the height of the protrusion. Typically, the threshold limit is 0.1 inches in either direction (i.e., a 0.2 inch blanking band) (Scofield 1992; Kulakowski 1989). If a pavement feature produced a very large scallop, corrective action was required.

Note that, with a threshold level on profilograph response of +/- 0.1 inches, it was common to produce a pavement with no scallops. This led to anecdotes in which pavement with roughness that was annoying to the public achieved a perfect smoothness score. This was possible because low-amplitude roughness with quick reversals could still be annoying because it would cause axle hop in vehicles (Gillespie 1992b). This type of feature has the nickname "chatter" and prompted the elimination of the threshold value (i.e., a zero band). Without the threshold value, every dump and dip is considered a scallop, with some rules applied for eliminating insignificant features. Even with this "improvement," profilographs have little direct relevance to vehicle response. First, they are very sensitive to features that are the same length as the wheelbase of the device (Gillespie 1992a). The most common type of profilograph, the California Profilograph, has a wheelbase of 25 ft. Second, the method of counting scallops creates a system in which a pavement that is simultaneously wavy and contains chatter would be rated better than a pavement with chatter only (Karamihas 2004b).

Weaknesses in the profilograph and the pervasiveness of inertial profilers for use in network pavement management have prompted a move to the International Roughness Index (IRI) for construction quality control. The IRI is calculated from a longitudinal profile measurement, typically from an inertial profiler. For measurement of new construction, lightweight profilers are most commonly used, which are inertial profilers mounted to a small all-terrain vehicle.

An IRI was developed in the 1980s when the World Bank initiated a correlation experiment in Brazil to establish a correlation and a calibration standard for existing roughness measurement devices (Sayers et al. 1986). These devices measured road roughness through direct measurements of their host vehicle response, but were mounted to a diverse group of host vehicles. The IRI, on the other hand, was calculated from a measurement of profile, and therefore had a consistent meaning. Thus, if the profile were measured properly, it could serve as a correlation standard for other roughness measurement schemes (Gillespie 1980). It was also "tuned" to be as relevant as possible to as many vehicles as possible (Sayers 1998). It has since been shown to provide good information about several aspects of vehicle response, including general pavement condition, truck dynamic loading, automobile ride quality, and truck ride quality (Gillespie 1992a).

Since its development, the IRI has become the standard roughness index for network pavement management. The FHWA has required the States to report roughness of their Highway Performance Monitoring System (HPMS) sections in IRI. Most States are also using IRI as the parameter for monitoring the roughness of their highway network. As profilers begin to replace profilographs for measuring new pavement smoothness, it appears that the IRI will eventually become the dominant measure of new pavement smoothness.

Readers who need more background on inertial profilers and the IRI are referred to *The Little Book of Profiling* (Sayers 1998).

AASHTO Smoothness Specifications

Four American Association of State Highway and Transportation Officials (AASHTO) provisional standards exist for implementing pavement smoothness specifications:

AASHTO MP 11-03: Standard Specification for an Inertial Profiler

AASHTO PP 49-03: Standard Practice for Certification of Inertial Profiling Systems

AASHTO PP 50-03: Standard Practice for Operating Inertial Profilers and Evaluating Pavement Profiles

AASHTO PP 51-03: Standard Practice for Pavement Ride Quality Specification when using Inertial Profiling Systems

Together, these standards provide the framework for a smoothness quality assurance program. The standards recommend the use of inertial profilers for measurement of pavement smoothness and base incentive and disincentive payments for smoothness on the IRI.

The standards cover most of the elements needed to implement in a smoothness quality assurance program. Standard MP 11-03 specifies all of the components needed in an inertial profiler, including hardware, software, and operational requirements. It is meant to assist an agency or contractor in the development of the equipment procurement specification. Standard PP 49-03 defines a profiler certification program. The standard recommends that an inertial profiler be certified before it is used within a quality assurance program. Certification is obtained by demonstrating that profile and IRI measurements are repeatable and agree with reference measurements on a limited number of sites. PP 50-03 describes the way a profiler should be operated, calibrated, and periodically subjected to “sanity checks.” The standard also suggests a file format for road profiles. PP 51-03 defines an incentive and disincentive program that is based on the IRI. It proposes bonus and penalty schedules, sets limits for corrective action, and provides a method for detection of localized roughness.

The purpose and makeup of the standards have been very carefully considered. The methods they recommend are the best that were available when the standards were written. In addition, the numerical values and thresholds set for many of the engineering aspects of the standards are based on the best information that was available. Some parts of the standards specify performance and leave the methods up to the practitioner, and others specify the method for obtaining the desired performance. As the field becomes more advanced, the specifications will evolve to require performance only.

These standards provide an excellent resource for implementing a smoothness quality assurance program, but they should be under constant review as more is learned about the measurement and interpretation of pavement smoothness. All of the methods and settings that appear within the specifications have real consequences in the field. It is up to the research community to develop an understanding of how each part of these specifications affects their end goal – smooth pavement. Each aspect of the standards should help promote pavement smoothness in some way. Further, each method and setting must be the result of rational science and engineering that can be defended by quality research and must be demonstrated to be realistic and practical for use in the field.

Research is needed in three aspects of pavement smoothness so that these specifications can help deliver smooth pavement as efficiently as possible:

1. Profile Measurement: Profile measurements must be repeatable and reproducible, so that the estimates of smoothness that are made from them have consistent meaning. The measurement strategy (e.g., sensor footprint) must also help ensure that estimates of smoothness are relevant to vehicle occupants.
2. Profile Interpretation for Quality Assurance: These issues pertain to the way information is extracted from profiles and used to rate smoothness. The interpretation methods must provide relevant, understandable output and minimize the sensitivity of the process to measurement errors. Further, a strong link must exist between the index used for smoothness and user satisfaction and expected gain (or loss) of service life.
3. Profile Interpretation for Quality Control: These issues pertain to the way contractors measure smoothness in an effort to improve their performance. A system of smoothness measurement used by a contractor must provide the same information that is used for quality assurance by the owner agency. The measurements must also be repeatable and reproducible. More importantly, they must provide information in a timely fashion and in a clear format.

The first two aspects of pavement smoothness have seen considerable research effort and are currently under study in several projects by the FHWA and the concrete industry. They are discussed below. These studies are very important, and future studies should not be planned until the results take shape. Profile interpretation for quality control, on the other hand, is only just beginning to get the attention of the research community. Further, the constant advancement in sensing technology has led to some innovation by the industry that may be leveraged for improved quality control. As such, many of the research suggestions below focus on field technologies for smoothness quality control.

Profile Measurement

Accurate and repeatable measurement of profile is essential to the success of a smoothness incentive program. No matter what index is used to rate smoothness, including the IRI, simulated PI, or some index that has not yet been proposed, the ability of the construction industry to minimize it depends on the quality of profiler output. Measurement problems currently hinder this effort (GAO 1999; Karamihas 2003; Karamihas 2004a). Initiatives are underway to improve the state of the art in four important aspects of smoothness measurement.

1. Profiler Component Performance

AASHTO Specification MP 11-03 spells out the components that must be included in an inertial profiler. The standard describes the needed elements of an inertial profiler, including sensors, signal conditioning capability, software, and operational capability. It also specifies the performance of each element that is required to ensure that the overall system works properly. In the best case, this would not be necessary. A profiler that demonstrates satisfactory performance and certified using the procedure in PP 49-03, could include any set of components as long as the end product provides the right type of output. Then the industry would be free to innovate. This is not currently the case.

Several studies have been conducted recently that address high-speed profiler component performance (Karamihas 1999; Lu 1994; McGhee 1992; Pong 1992; Perera 1996). While these studies have focused on high-speed profilers, much of the knowledge they have produced will also raise the state of the art in lightweight profiling. Further, some very recent studies of lightweight profiler accelerometer performance have been conducted (Gagarin 2003a; Gagarin 2003b) and the interaction of height sensors with coarse surface texture (Karamihas 2004a).

Most of the studies mentioned above evaluate profiler component performance in light of a given reference measurement with an established method of comparison to it. As discussed below, both of these aspects of profiler performance testing are under intense study. It is recommended that the performance of specific profiler components follow improvements in the way reference measurements are made and the way candidate profilers’ measurements are compared to them.

2. Surface Type

Specification PP 49-03 calls for certification of profilers on smooth and medium smooth pavement sections. For many applications, these turn out to be wise choices because repeatability and accuracy are most difficult to achieve on smooth pavement. The net result of this practice in Texas has been the improvement of profile measurement capability to account for the problems that can be discovered under these conditions (Fernando 2000).

Unfortunately, many profile measurement errors have not gotten proper attention because the surface types that cause them are not included in most profiler certification programs. For example, coarse textured pavement is especially challenging to profilers if the pavement is very smooth (Karamihas 2002). This is because the depth of texture, introduced by tining and joints on new pavement, for example, is of the same scale as the height of longer wavelength features that affect a roughness index.

Researchers have already acknowledged the impact of texture and roughness characteristics on the quality of profile measurements. Nearly 20 years ago, the Ann Arbor Road Profilometer Experiment cited transverse roughness variations, aliasing errors caused by texture, and the increased sensor accuracy requirements on smooth pavements as problems that needed attention in the near future (Sayers 1986b). Since then, various profiler comparison studies have repeated these needs and motivated some improvements. The 1993 and 1994 Road Profiler Users Group experiment showed that few profilers performed well on pavement with a coarse seal coat (Perera 1994; Perera 1995). This finding helped eliminate ultrasonic height sensors, which were highly prone to errors on coarse-textured pavement.

Further improvement of profilers requires that they are certified under the same conditions that they will encounter in the field. This will help reveal measurement problems that have not gotten proper attention so far. Hopefully, capturing these problems in profiler certification programs would lead to long-standing solutions in the near future, and a constant effort to include all combinations of roughness and texture will not be needed indefinitely.

The concrete industry and the FHWA are pursuing solutions to this problem. The concrete industry is working on a strategic initiative to motivate improvement in profiler technology. This has resulted in the development and testing of an enhanced lightweight profiler by Ames Engineering (ACPA 2004). This profiler showed excellent repeatability on transversely tined and turf dragged pavement and vastly improved repeatability on longitudinally tined pavement. LMI Selcom is also developing a sensor with a footprint in the shape of a line–100 mm long–that may be integrated by profiler manufacturer to improve performance on coarse-textured pavement.

The FHWA has sponsored a large profiler round-up that will help quantify the effect of coarse texture on just about every type of profiler operating in North America. The project also calls for development of a sensor footprint shape and a tire envelopment and bridging filter. This will help minimize sensitivity to coarse texture and improve the relevance of profile measurements to vehicle response.

3. Profile Comparison Method

The profile comparison method in specification PP 49-03 is currently based on ASTM Standard E-950 (ASTM 1999). This standard specifies a composite level of precision in repeat elevation measurements and a composite level of bias (or the lack thereof) in elevation compared to a reference measurement. The main weakness of this approach is the emphasis on long-wavelength features that results from comparison of elevation values within a profile.

In most road profiles, the amplitude of elevation is roughly proportional to wavelength. That means that short-wavelength features will have very low amplitude compared to long-wavelength features. This is how "chatter" is able to hide beneath the blanking band of profilograph measurements. Comparison of elevation values directly makes the long-wavelength features seem very important because they contribute most to the overall elevation value. (Short-wavelength features may not add much to overall elevation, but they can cause quick reversals in elevation that are very important to vehicle response.) The end result is that short-wavelength errors are not detected. The emphasis on long-wavelength content also places a premium on the specific characteristics of the high-pass filter used in the profile computation. In other words, the current method of comparing profiles emphasizes parts of the profile that are not very important and ignores parts of the profile that are very important. The consequence of this is that good performance under ASTM E-950 does not ensure accurate measurement of IRI or other road qualities that are relevant to vehicle response (Karamihas 2002; Li 2003).

An objective method of comparing profiles is needed that emphasizes the important aspects of the profile, such as the features that affect the overall IRI, rating of localized roughness, or other aspects of the profile that may be needed for future uses. When the method is used to judge the measurement of IRI or any other index, the rating that it provides must have a direct link to the error level that is expected under the same conditions in future measurements. This will eliminate situations in which two profilers that obtain certification for construction quality assurance provide output that implies a different level of incentive pay for the same pavement. Such a method is under development by the FHWA. The theoretical portion of the development is complete (Sayers and Karamihas 1996; Karamihas 2002). A large profiler round-up is planned for April of 2004 to provide the experimental basis needed to finalize the method.

4. Reference Measurement

Certification of profiler performance requires that a measurement of the "truth" is available. Profiles and index values from candidate profilers are compared to the "reference" profile, which is considered to be correct.

In the past, the most common method of obtaining a reference profile measurement was to perform a rod and level survey. Rod and level measurements are rarely performed at a short enough sample interval to serve as a complete reference measurement because they take so long. The large rigid footprint under the rod also complicates the interpretation of the resulting profile. Each reading may be the true elevation of some point under the footprint of the rod, but the collective set of readings may not make up the complete signal that is needed for profiler verification.

Most profiler certification programs get reference measurements from devices that use an inclinometer and operate at walking speed or slower (Fernando 2000; Perera 1995). Both the Texas DOT and the Pennsylvania DOT profiler certification programs use the ARRB Walking Profiler, which is inclinometer based and can measure a tenth mile in about 40 minutes. In Texas, the absolute elevation values are adjusted using long-interval rod and level measurements. When this strategy is used in conjunction with ASTM E-950 and for comparison of overall IRI value on pavement without coarse texture, it is successful. However, the sample interval is too long for measurement of IRI on coarse-textured pavement or pavement with short-wavelength chatter. Any move to a more relevant method of profile comparison will require improvement of this measurement method.

No matter what reference device is chosen, its physical configuration affects the meaning of its measurements. This is true because the way the device is supported (its footprint) and the sensor technology it uses determines the way it averages out texture and the way it bridges over short narrow troughs. Choosing a specific device for reference measurements causes you to inherit these aspects of its operation as "truth." If the footprint of the device does not match the likely effect on a common vehicle tire, it may not be a good choice.

The issue has been identified as the top priority of a large FHWA pooled fund study initiated in 2003. The pooled fund study has hired the University of Michigan to help define the requirements for a proper profile reference measurement. Further, the 2004 profiler round-up will provide a rich experimental database to assist in these efforts. Once the requirements for a reference measurement device are defined, the FHWA pooled fund study plans to procure such a device. Hopefully, the study will address this issue in full.

Profile Interpretation for Quality Assurance

Profile interpretation is a mature subject, and a full complement of analysis methods has been developed for extracting information from road profiles (Sayers 1996; Sayers 1998). However, most of these methods were not developed specifically for quality assurance of new construction. Three important aspects of profile interpretation require research for successful implementation of smoothness specifications:

1. A link must be established between the IRI and ride quality and truck dynamic loading for very smooth pavement.
2. Incentive and penalty schedules must reflect the "cost" of decreased smoothness to ride quality and truck dynamic loading.
3. A localized roughness detection method is needed to replace the profilograph bump template.

Fortunately, the FHWA has sponsored ongoing research in all three of these aspects of profile interpretation. With the exception of smoothness limits, it is recommended that research is not performed until these efforts are concluded.

1. Roughness Scale

Although the relevance of the IRI scale is well established, insufficient information exists to relate small changes in the IRI value to user and agency "cost". Smoothness incentive pay schedules are often set on the basis of what it takes to motivate contractors to include smoothness among their priorities. A more systematic approach would require that the benefits of additional smoothness are quantified in terms of extra pavement service life and additional value (ride quality) provided to the user. Incentive schedules could then directly reflect the benefits of smoother pavements. Contractors could then make decisions on when it is appropriate to invest in process of equipment improvements that increase smoothness.

The FHWA is addressing this through the research project in the Concrete Pavement Technology Program called "Task 16: Smoothness Criteria for Concrete Pavements." This project is expected to produce information about the cost of various rough features that may appear in new concrete and help define the level of smoothness that is needed to best serve the public. In particular, the project seeks to answer the question: "How Smooth is Smooth Enough?" Although the project is sure to provide valuable information to help address this question, it is too large and complex a topic for a single research study. Research suggestions are therefore provided below to help supplement the work planned for that study.

2. Localized Roughness

With a profilograph, localized roughness was detected using a bump template. The bump template is a tool for finding excessive response of the profilograph within a short distance. This was a successful way to look for localized roughness when the overall smoothness was also rated with a profilograph. However, when the IRI used to rate overall smoothness, the profilograph-based bump template is a poor choice (Swan 2003). This is because features that affect profilograph response most are not necessarily those that contribute most to the IRI.

As an interim step, AASHTO PP 50-03 recommends that localized roughness be identified by applying a high-pass filter to measured profile with a cutoff wavelength of 25 ft. Deviations in the resulting trace greater than 0.15 inch are considered candidates for correction. This method has been shown to find artificial bumps placed on test pavements (Fernando 2002). This strategy has advantages: (1) it is similar to the response of a profilograph, so the industry may transition to it easily; (2) it places a high weighting on features that can be corrected with a grinder; (3) it does not place unwarranted emphasis on features that are 25 ft long, like the profilograph. However, it still does not have a direct relationship to the IRI.

An FHWA pooled fund project, "Improving the Quality of Pavement Profiler Measurement," has set out to procure a new localized roughness detection method. This method is based on U.S. Patent 6,682,261. The method is customized for profile-based roughness indexes, such as the IRI. In the method, short sections of pavement are identified that contribute most to the overall roughness. Simulation is then used to predict the potential benefits of grinding, and the best starting and ending points for application of a grinder are derived.

It is expected that this method will be available by the beginning of 2005, and it will be integrated into the FHWA ProVAL software for free distribution to interested states. When that is complete, it is recommended that the method be considered for demonstration on pavement rehabilitation projects.

Profile Interpretation for Quality Control

The increased emphasis on new pavement smoothness and the move toward inertial profilers and the IRI for smoothness measurement has prompted a great deal of innovation in the pavement construction industry. For example, profiling equipment has recently been developed that has the potential to provide feedback to a paving crew in real time. This tool, if it is implemented properly, has the potential to warn contractor of problems when there is still time to make corrections. An even more power outcome of real-time smoothness measurement would be the potential for recognizing the source of smoothness problems so that a paving crew can be trained to build smooth pavement without corrections.

Issues related to profile measurement and quality assurance are under active study by the FHWA in multiple research projects. However, innovations such as real-time profiling often require more time than necessary to implement because of the risk and investment that must be made to demonstrate them. It is highly recommended that some research effort is devoted to demonstration and implementation of innovative methods of building smooth pavement.

How Smooth is Smooth Enough?

Purpose: The purpose of this project is to identify the new pavement smoothness level needed to (1) satisfy the public and (2) sufficiently reduce truck dynamic loading.

Research Gap:

User Perception: The IRI has served as the most common general pavement ride quality indicator for two decades. Although it has well-established relevance to vehicle dynamic response, it was developed on roads that were extremely rough. The ability of the IRI scale to distinguish between subtle differences in smooth road, therefore, has never been established.

Poister (2003) performed a study of the public's perception of road quality. This study concluded that public perception was affected strongly by the class of roadway, and that expectations were highest for interstate roads. The study reported the relationship between IRI value and percent satisfaction for four roadway classes. Shafizadeh (2002) performed a similar study for urban highway, and concluded that the IRI was a good indicator of the public's perception of a road.

Neither of these studies sought to explain scatter in the relationship between the IRI and user perception using detailed analysis of profile features or other profile-based indexes. These studies should be repeated (in part, because they were so important) with a focus on newly built or rehabilitated roads.

Truck Dynamic Loading: The relationship between truck dynamic loading and road roughness for rougher roads has been well documented (Ervin 1983; Sweatman 1983; Gillespie 1993; Cebon 1993). However, little information has been reported about the dynamic loading imposed by trucks on very smooth pavement. Frictional behavior of truck suspension springs causes them to appear stiffer when the deflections are small (Sayers 1982; Fancher 1980). This means that as the road gets smoother, the severity of truck dynamic loading will diminish more and more slowly. The point of diminishing marginal returns has never been reported–in part, because it has never been investigated, and in part, because of disagreement in the most appropriate way to translate truck dynamic loading into usage of pavement life (Cebon 1989).

Methods:

User Perception: It is recommended that further surveys of user perception of ride quality be conducted. These surveys should seek to establish threshold for user satisfaction with new roads. The study should focus on setting IRI thresholds. However, the data collection must include longitudinal profile. At some level of smoothness, the IRI will no longer explain the differences in user perception of a road. The profiles will be needed to discover what aspects of the pavement surface shape contribute to user perception beyond the IRI. Further, selection of pavements for the study must include some groups of roads that have the same overall IRI level, but have (1) long-wavelength content, (2) chatter, and (3) localized features as their primary sources of roughness.

Differences in noise level between pavements within the study are expected to confound the results. It is therefore suggested that standard noise measurements be made on all test pavements.

Truck Dynamic Loading: An initial simulation phase of this study is recommended. Truck dynamic loading by a population of common vehicles should be simulated over progressively smoother roads. The change in pavement life should be estimated with the most common pavement damage laws. It is expected that this exercise will reveal the point of diminishing marginal returns for smoothness. The effect of variations in the pavement damage criteria on the results should be investigated.

Products: The project should produce the basis for smoothness targets that will ensure user satisfaction and mitigation of truck dynamics loading. It is likely that the targets will be expressed in terms of cost functions, rather than as hard limits. However, this may still serve as the justification for progressive smoothness incentive schedules.

Early, Frequent, Detailed Measurements for Jointed Concrete Performance Studies

Purpose: The purpose of this project is to study the effect of early-age behavior on the long-term performance of jointed concrete.

Methods: This project will be mostly experimental. Detailed measurements of maturity, temperature profile, weather, joint behavior, and surface profile will be collected on selected pavement projects. It is recommended that these measurements are performed frequently. For example, measurements could be done with the frequency of one per hour for a day or two, four times per day for a week, etc. As the results reveal the pace of changes in smoothness or joint behavior, the measurements can be scheduled (less frequently) to capture the relevant behavior. However, diurnal and seasonal changes are anticipated. The appearance of cracks at the joints is of particular interest, and an important observation may be the long-term performance of the joints that produce a crack before the others around it.

If the paving projects are carefully selected, this measurement effort can serve as a platform for studying critical design and construction variables. Of course, the results may only have regional implications.

Products: This project will produce a link between early-age pavement behavior and long-term performance. It is expected that the knowledge from this project may produce a methodology for optimizing concrete curing methods without the need for long-term observations.

Stringless Paving

Purpose: The purpose of this project is to develop and demonstrate the use of stringless paving for the achievement of smoothness.

Methods: Ideally, the paver would have the capability to measure its own position in three dimensions and the approximate elevation of the base layer. The control system would be required to ensure a minimum pavement thickness, a maximum layer thickness, and a smooth transition toward the planned geometry from the existing position. This project will require the cooperation of a paving contractor, the DOT, and the GPS (or total station) and control system experts. A feasibility study may be needed to test the control system in light of the maximum accuracy of the required measurements and the limits of paver height control.

Product: This project should produce a demonstration of a stringless paving operation and its potential benefits.

Field Validation of Stringline Impacts

Purpose: The purpose of this project is to study the impact of stringline spacing, stringline sag, and stringline survey error on smoothness.

Research Gaps: Rasmussen (2004) reported theoretical predictions of stringline impacts on smoothness. Rasmussen predicted the potential negative impacts of stringline sag, stringline survey error, and the cord effect on the resulting IRI. These predictions were carried out for values of stringline spacing from 25 ft through 50 ft.

The predictions concluded that 25 ft spacing did a better job of protecting against stringline errors than did 50 ft spacing. However, these conclusions depended on the voracity of various assumptions made as input to the theoretical calculations. As such, the research needs to be supplemented with field observations.

Methods: In this project, the predictions made by Rasmussen would be repeated using more realistic "input" values for survey error and stringline sag. (These values would be obtained by observing real stringline set-ups.) The modeling would be further refined by assessing the degree to which a paver is able to reflect the shape of a stringline.

Once a more realistic model is established, the predictions will be carried into the realm of establishing a cost-benefit relationship between stringline spacing alternatives. It is hoped that other aspects of the process that are under a contractor's control may be studied as well (e.g., survey methods, stringline materials and tension, etc.).

Products: This project should establish written best practices for stringline set-up. The project should also produce rules of thumb for the cost of smoothness resulting from various types of stringline error (e.g., the penalty to IRI in in/mi caused by survey error in hundredths of an inch).

Real-Time Smoothness Field Trails

(This project is already underway.)

Purpose: The goal of this project is to demonstrate the use of real-time profiling technology in the paving process.

Methods: This research will evaluate equipment and methods to measure profile being produced. This evaluation should be done at the slipform paver and by each of the various pieces of paving equipment and processes used from the deposit of the pavement concrete to the completion of the curing operation.

The project will demonstrate commercial real-time profilers on active paving projects. The demonstration should include the following: (1) a comparison of the existing commercial systems to each other, (2) an assessment of the accuracy of the measured profiles, (3) documentation of roughness detected in real time that may have assisted the paving crew, (4) measurement of smoothness at various stages of the process, and (5) assessment of the feasibility of using an expert system to convert profile data into warnings to the paving crew in English.

Products: This project will produce multiple products. First, the project will produce estimates of the consequences to smoothness of various stages of the paving process. Second, the project will provide an assessment of the accuracy and relevance of the measurements provided by commercial real-time smoothness measurement devices. Third, the project will provide recommendations for the most useful method of reporting smoothness as feedback to a paving crew.

Impacts of Texturing on Actual and Measured Smoothness

Purpose: The goal of this project is to quantify the impact of various concrete pavement texturing methods on smoothness.

Research Gap: A recent experiment in Minnesota has shown a significant (~20 in/mi) difference in the IRI of a pavement with burlap drag texturing and the same pavement over a segment with no artificial texture. This difference has been attributed entirely to profile measurement errors that lead to an upward bias in IRI. In reality, the upward bias in IRI was caused by a combination of profile measurement error and a genuine degradation in ride quality induced by the texturing method.

Methods: This project would use detailed pavement surface characterization (i.e., close interval profiles or, preferably, 3-dimensional scans) to estimate the negative impact of various texturing methods on ride. Measurements are required before and after the application of texturing. These data should be analyzed using standard profile analysis procedures and detailed tire modeling. The analysis should yield the following results:

- an estimate of the overall change in measured smoothness caused by a given texturing method,
- an estimate of the portion of that change that is caused by inappropriate profile sampling procedures and that should be treated as upward bias, and
- an estimate of the roughness that is induced by the texturing procedure and may actually be felt within a vehicle.

It is recommended that these measurements be conducted on multiple types of texture. Note that 3-D scan will be necessary (instead of close-interval profiles) on any longitudinal textures.

Products: This project will provide estimates of any “texturing” penalty that may exist. The project will also help motivate improvements, as needed, in profile sampling techniques or texture placement procedures.

RECOMMENDATIONS

The goal of this work was the identification of research necessary to assist highway agencies in the development of portland cement concrete pavements that provide for smooth, quiet, and safe pavements. It has identified the following key research elements in each of the three areas.

Texture and Traffic Noise

- Noise Research Element Gaps
  1. How Quiet is Quiet Enough?
  2. A Reproducible Noise Evaluation System
  3. Comparison of Profile and Acoustic Traces
  4. A Parametric Study of Texturing and Noise
  5. The Impact of Mix Design on Noise Generation and Propagation
  6. Time Stability of Noise Properties

Friction

- Friction Research Element Gaps
  1. Feasibility of an International Friction Index for Specification of Concrete Friction
  2. Time Stability of Pavement Friction
  3. A Parametric Study of Texturing and Friction

Smoothness

- Profile measurement repeatability and reproducibility
  1. Profiler component performance
  2. Surface type
  3. Profile comparison methods
  4. Reference measurements
- Profile data interpretation for quality assurance
  1. Linkage of IRI, ride quality, and truck dynamics into a smoothness statistic
  2. Incentive and disincentive schedules for deficiencies in ride and truck dynamic loadings
  3. Development of a localized roughness detection method to detect bumps
- Profile data interpretation for quality control

- Missing Smoothness Research Elements
    1. How smooth is smooth enough?
    2. Early Frequent, Detailed Measurements for Jointed Concrete Performance Studies
    3. Stringless Paving
    4. Field Validation of Stringless Impact
    5. Real-Time Smoothness Field Trials
    6. Impacts of Texturing on Actual and Measured Smoothness

This research sets the stage for a system approach to solving the problems of surface noise/texture, friction, and smoothness. It provides an integrated network of individual research projects that can result in the elements that must be included in the design and construction of the pavement surface to create a long lasting, smooth, quiet, and safe driving surface.

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