Concrete Pavement Surface Characteristics:

Key Findings and Guide Specifications

National Concrete Pavement Technology Center

Tech Center

Final Summary Report
July 2012

Sponsored through
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The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

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16. Abstract

In 2004, the Federal Highway Administration, Iowa State University, American Concrete Pavement Association, and the International Grooving and Grinding Association initiated a five-year Concrete Pavement Surface Characteristics Program (CPSCP). This program was administered through the National Concrete Pavement Technology Center located at Iowa State University. The purpose was to determine the interrelationship among noise, friction, smoothness, and texture properties of concrete pavements. It was envisioned at that time to consist of the following parts:

- Part 1: Portland Cement Concrete Pavement Surface Characteristics (referred to as Project 15 of FHWA/ISU Cooperative Agreement No. DTFH61-01X-0042)
- Part 2: 2005-2006 Field Data Collection of Current Surface Characteristics Practices
- Part 3: 2006-2012 Data Analysis and Innovative Surface Characteristics Solutions, Transportation Pooled Fund TPF-5(139)

Part 1 included the development of a long-term Strategic Plan as well as documentation on all concrete pavement noise reduction trials with a specific focus on European and U.S. methods. The report compiled information on design, bidding, construction, quality control, maintenance, and field evaluations. Part 2 consisted of the collection, measurement, presentation, and preliminary analysis of noise, skid, texture, and smoothness data for conventional texturing variations and grinding techniques on pavements. Part 3 investigated innovative texturing techniques with potential to reduce noise, while not degrading the other surface characteristics (smoothness, friction, drainage, etc.) of the pavement. Part 3 concluded with an extensive outreach effort including the development of guide specifications, a how-to guide for constructing concrete pavement textures, several technical briefs, and a day-long training workshop.

The CPSCP has led to better practices for designing and constructing quieter concrete pavements. The implementation of these guidelines has begun, and several early adopters have already been reported.

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CONCRETE PAVEMENT SURFACE CHARACTERISTICS: KEY FINDINGS AND GUIDE SPECIFICATIONS

Final SummaryReport
July 2012

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- New York
- Texas
- Washington
- Wisconsin

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- American Concrete Pavement Association (ACPA)
- International Grooving and Grinding Association (IGGA)

BACKGROUND

A pavement surface characteristic (PSC) is a way to describe a pavement surface that directly or indirectly connects to a human response or societal need. It includes things such as smoothness, friction, noise, splash and spray, surface drainage, and rolling resistance. Other characteristics include tire wear, vehicle wear, and reflectivity, and illuminance.

Numerous pavement properties affecting these surface characteristics, with the most important being surface texture. These "bumps and dips" in the road range in size from long rolling undulations to asperities that cannot be seen with the naked eye. Other important pavement properties include the degree of permeability and porosity, cross-slope, and mechanical impedance (stiffness). Even the color of the surface will also affect some surface characteristics both directly and indirectly.

Concrete pavements are, of course, a subset of all pavements in use today. To understand their surface characteristics requires an understanding of how texture is imparted into the fresh or hardened concrete. There are unique challenges with concrete pavements; namely that – unlike asphalt pavements – the resulting texture is anisotropic. In other words, its geometry is a function of its direction (transverse versus longitudinal).

These intricacies illustrate the complexity that is inherent with concrete pavement surface characteristics. Modeling is a part of developing this understanding; there must be some basic capability to predict PSC as a function of practical and meaningful parameters (e.g., texture). However, while modeling is an important prerequisite, the ultimate goal must be to link PSC to pavement design and construction. Only in this way can practical guidance be developed for the concrete pavement industry.

To accomplish this goal, a multidisciplinary and coordinated approach was necessary.

In 2004, the Federal Highway Administration, Iowa State University, American Concrete Pavement Association, and the International Grooving and Grinding Association initiated a five-year Concrete Pavement Surface Characteristics Program (CPSCP). This program was administered through the National Concrete Pavement Technology Center located at Iowa State University. The purpose was to determine the interrelationship among noise, friction, smoothness, and texture properties of concrete pavements. It was envisioned at that time to consist of the following parts:

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- Part 2: 2005-2006 Field Data Collection of Current Surface Characteristics Practices
- Part 3: 2006-2012 Data Analysis and Innovative Surface Characteristics Solutions, Transportation Pooled Fund TPF-5(139)

Part 1 was completed in September 2006. It included the development of a long-term Strategic Plan under Task 1. Task 2 called for the development of a comprehensive documentation on all concrete pavement noise reduction trials with a specific focus on European and U.S. methods. This investigation included interviews with many of the innovators that have worked with these techniques firsthand. The report compiled information on design, bidding, construction, quality control, maintenance, and field evaluations.

Part 2 consisted of the collection, measurement, presentation, and preliminary analysis of noise, skid, texture, and smoothness data for conventional texturing variations and grinding techniques on pavements. This work began in the summer of 2005 and concluded in the summer of 2007. Several hundred test sections were identified in Part 2, and numerous test protocols were developed. A first set of guidance for the concrete paving industry was also issued at the conclusion of Part 2.

Part 3 has just been concluded. In this project, the CPSCP team investigated innovative texturing techniques with potential to reduce noise, while not degrading the other surface characteristics (smoothness, friction, drainage, etc.) of the pavement. There was also further evaluation of the numerous test sections identified in Part 2, as well as new sections that were added to fill remaining gaps. Part 3 concluded with an extensive outreach effort including the development of guide specifications, a how-to guide for constructing concrete pavement textures, several technical briefs, and a day-long training workshop.

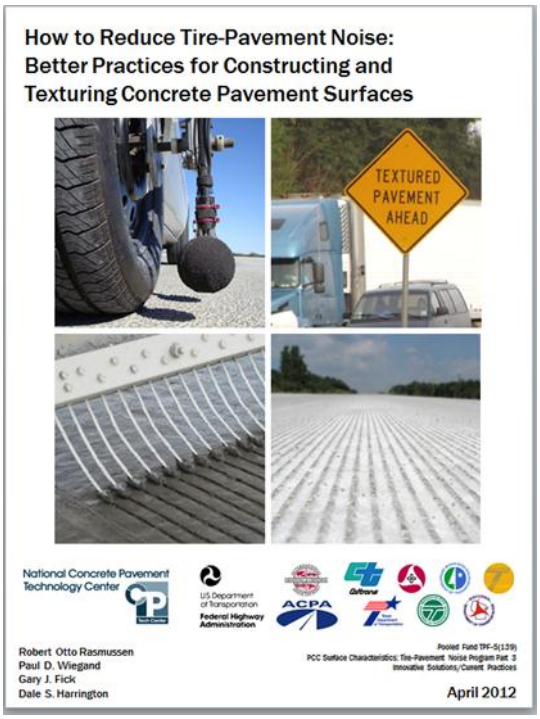
A lot has been learned in the eight years since the CPSCP began. What began as a detailed investigation and catalog of concrete pavement surface characteristics nationwide has since led to better practices for designing and constructing quieter concrete pavements. The implementation of these guidelines has begun, and several early adopters have already been reported.

SUMMARY OF ACCOMPLISHMENTS

Concrete pavements can be designed and constructed to be as quiet as any other conventional pavement type in use today. Furthermore, they can routinely be constructed with high friction and excellent ride quality. To accomplish all of these objectives, along with the additional requirement of durability, often requires nothing more than an attention to detail.

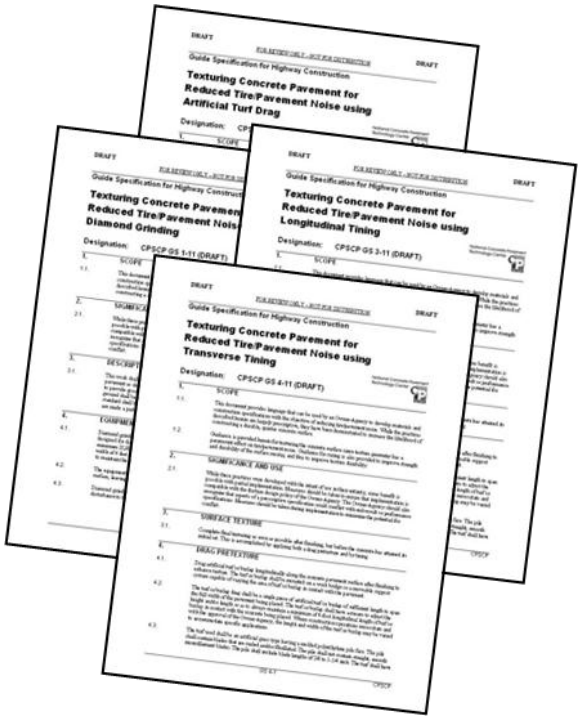
Under the CPSCP, numerous products have been developed to assist the practitioner in designing and constructing concrete pavements with improved surface characteristics. In support of each of the products is a large database of concrete pavement surface characteristics data. Among the major deliverables from this effort are two flagship products.

How to Reduce Tire-Pavement Noise: Better Practices for Constructing and Texturing Concrete Pavement Surfaces



The first principal product from this program is a guide that describes better practices for design and construction of concrete pavement surfaces from the perspective of reducing variability and tire-pavement noise. An interim version of this guidance was published in 2008, which has since been distributed and referenced worldwide. Also since that time, more has been learned about the variety of concrete pavement surfaces, along with the most up-to-date guidance on how to design and construct them. The final version of the guidance was published in 2012.

Guide Specifications for Controlling Tire-Pavement Noise



This second principal product is a set of generic (guide) specifications that can be used – in whole or in part – to improve the probability that a quieter concrete pavement will be constructed. Two approaches have been employed in the development of this product. The first is the development of an end-result specification that identifies tire-pavement noise measurements found to be reasonable in terms of their constructability. The second approach includes means and methods specifications that address the nuances of the most commonly used concrete pavement textures.

The guide specifications are available as standalone documents from the National CP Tech Center at www.cptechcenter.org.

In addition, numerous Technical Briefs were developed as part of this effort, including the following.

Diamond Grinding to Reduce Tire-Pavement Noise in Concrete Pavements

This technical brief was done in conjunction with Pooled Fund TPF-5(185), CP Road Map Operations and Support Group. It introduced the process of diamond grinding of concrete pavements as a means to reduce tire-pavement noise. It has been found from all of the data collected thus far that diamond grinding yields the highest probably of success for a quieter surface. To further improve these chances, better practices can be followed, which are summarized herein.

"Moving Advancements into Practice"

MAP Brief 4-1:

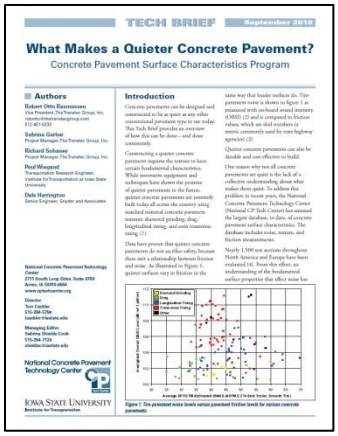
Diamond Grinding to Reduce Tire-Pavement Noise in Concrete Pavements

What Is Diamond Grinding?

How Does Diamond Grinding Affect Friction and Noise?

What Makes a Quieter Concrete Pavement?

The fundamentals of what results in a quieter pavement are described in this technical brief. The concept of optimizing texture for not only noise, but also friction, durability, and cost, is also described. Finally, relevant results from the study that describe the various nominal concrete pavement textures and better practices to construct more uniform surfaces is described.



TECH BRIEF September 2010

What Makes a Quieter Concrete Pavement?

Concrete Pavement Surface Characteristics Program

Authors

Introduction

The Language of Noise and Quieter Pavements

With each of the products developed under this program delving into a new vocabulary, a technical note like this is important. The idea of this tech brief was to provide a standalone document that can serve as both a handy reference as well as a quick tutorial in the language inherent with tire-pavement noise.

TECH BRIEF October 2010

The Language of Noise and Quieter Pavements

Concrete Pavement Surface Characteristics Program

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Introduction

Over the last few years, the National Concrete Pavement Technology Center has helped the transportation industry identify concrete pavement options that are quiet while still being safe, durable, and cost-effective.

The multi-year Concrete Pavement Surface Characteristics Program (CPSCP) was initiated in 2004, from which several products are emerging. Among these are better practices for design and construction, a set of construction specifications, and guidance on how to select the right texture for a given project.

As part of this program, the world's largest database of noise data for concrete pavements has also been collected and analyzed. While care has been taken to develop products that are readily implementable by the concrete paving industry, there remain the challenges of introducing aspects of a whole new discipline to our industry—that of acoustics and noise control.

This document serves as both a brief tutorial and a handy reference for those wishing to understand the findings from the CPSCP and other projects that address tire-pavement noise or quieter pavements. It provides an introduction to the language that is commonly used in the acoustics world, and explains how this language is applied to pavements.

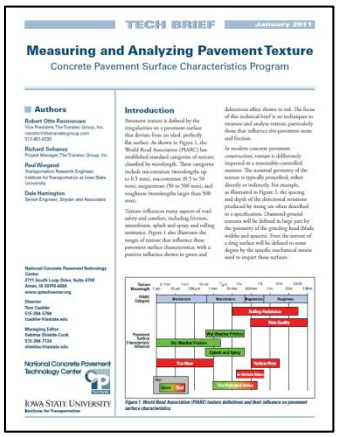
What is sound?

Sound is small but fast changes in air pressure. Sound can be caused by mechanical vibrations, such as the tapping of a drum. Sound can also be aerodynamic, such as the sound from a person whistling. And, in some cases, sound is even caused by thermal changes, such as thunder from lightening.

Longitudinal grooving and turf drag tool section from the Concrete Pavement Surface Characteristics Program

Measuring and Analyzing Pavement Texture

Instrumental to this effort has been the use of a robotic-based texture measurement system termed RoboTex. The system allows for three-dimensional measurements of pavement surfaces, which are particularly important for concrete pavement surfaces since the texture is often oriented in a principal direction. Just as important as measuring the texture in a relevant way, is calculating the texture parameters that are meaningful to predicting tire-pavement noise, friction, etc. This technical note summarizes all of the above.



TECH BRIEF January 2011

Measuring and Analyzing Pavement Texture

Concrete Pavement Surface Characteristics Program

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Introduction

Pavement texture is defined by the irregularities on a pavement surface that deviate from an ideal, perfectly flat surface. As shown in Figure 1, the World Road Association (PIARC) has established standard categories of texture, classified by wavelength. These categories include microtexture (wavelengths up to 0.5 mm), macrotexture (0.5 to 50 mm), megatexture (50 to 500 mm), and roughness (wavelengths larger than 500 mm).

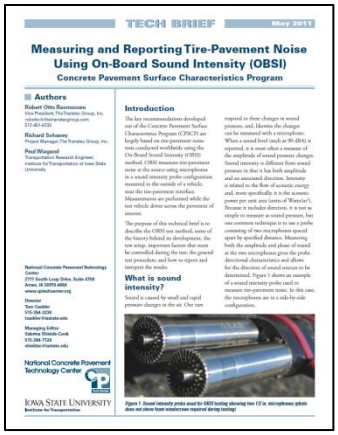
Texture influences many aspects of road safety and comfort, including friction, smoothness, splash and spray, and rolling resistance. Figure 1 also illustrates the ranges of texture that influence these pavement surface characteristics, with a positive influence shown in green and deleterious effect shown in red. The focus of this technical brief is on techniques to measure and analyze texture, particularly those that influence tire-pavement noise and friction.

In modern concrete pavement construction, texture is deliberately imparted in a reasonably-controlled manner. The nominal geometry of the texture is typically prescribed, either directly or indirectly. For example, as illustrated in Figure 2, the spacing and depth of the directional striations produced by tining are often described in a specification. Diamond-ground textures will be defined in large part by the geometry of the grinding head (blade width and spacer). Even the texture of a drag surface will be defined to some degree by the specific mechanical means used to impart these surfaces.

Figure 1. World Road Association (PIARC) texture definitions and their influence on pavement surface characteristics

Measuring and Reporting Tire-Pavement Noise using On-Board Sound Intensity (OBSI)

The control of tire-pavement noise has been a central focus of this study. However, the measurement of noise can be difficult to decipher. The AASHTO TP 76 standard for measuring tire-pavement noise using on-board sound intensity (OBSI) is highlighted here, along with information about analyzing and reporting data in a meaningful way.



TECH BRIEF May 2011

Measuring and Reporting Tire-Pavement Noise Using On-Board Sound Intensity (OBSI)

Concrete Pavement Surface Characteristics Program

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Introduction

The key recommendations developed out of the Concrete Pavement Surface Characteristics Program (CPSCP) are largely based on tire-pavement noise tests conducted worldwide using the On-Board Sound Intensity (OBSI) method. OBSI measures tire-pavement noise at the source using microphones in a sound intensity probe configuration mounted to the outside of a vehicle, near the tire-pavement interface. Measurements are performed while the test vehicle drives across the pavement of interest.

The purpose of this technical brief is to describe the OBSI test method, some of the history behind its development, the test setup, important factors that must be controlled during the test, the general test procedure, and how to report and interpret the results.

What is sound intensity?

Sound is caused by small and rapid pressure changes in the air. Our ears respond to these changes in sound pressure, and, likewise the changes can be measured with a microphone. When a sound level (such as 90 dBA) is reported, it is most often a measure of the amplitude of sound pressure changes. Sound intensity is different from sound pressure in that it has both amplitude and an associated direction. Intensity is related to the flow of acoustic energy and, more specifically, it is the acoustic power per unit area (units of Watts/m²). Because it includes direction, it is not as simple to measure as sound pressure, but one common technique is to use a probe consisting of two microphones spaced apart by specified distance. Measuring both the amplitude and phase of sound at the two microphones gives the probe directional characteristics and allows for the direction of sound sources to be determined. Figure 1 shows an example of a sound intensity probe used to measure tire-pavement noise. In this case, the microphones are in a side-by-side configuration.

Figure 1. Sound intensity probe used for OBSI testing showing two 1/2 in. microphones (photo does not show foam windscreen required during testing)

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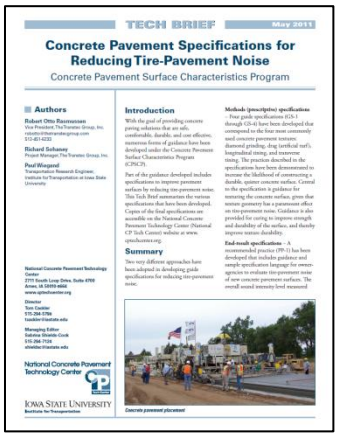
Concrete Pavement Specifications for Reducing Tire-Pavement Noise

One of the key products from this study is the development of guide specifications that are intended to control pavement surfaces in such a way that reduces tire-pavement noise. In this technical note, these specifications are summarized.



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Introduction

With the goal of providing concrete paving solutions that are safe, comfortable, durable, and cost effective, numerous forms of guidance have been developed under the Concrete Pavement Surface Characteristics Program (CPSCP).

Part of the guidance developed includes specifications to improve pavement surfaces by reducing tire-pavement noise. This Tech Brief summarizes the various specifications that have been developed. Copies of the final specifications are accessible on the National Concrete Pavement Technology Center (National CP Tech Center) website at www.cptechcenter.org.

Summary

Two very different approaches have been adopted in developing guide specifications for reducing tire-pavement noise.

Methods (prescriptive) specifications – Four guide specifications (GS-1 through GS-4) have been developed that correspond to the four most commonly used concrete pavement textures: diamond grinding, drag (artificial turf), longitudinal tining, and transverse tining. The practices described in the specifications have been demonstrated to increase the likelihood of constructing a durable, quieter concrete surface. Central to the specification is guidance for texturing the concrete surface, given that texture geometry has a paramount effect on tire-pavement noise. Guidance is also provided for curing to improve strength and durability of the surface, and thereby improve texture durability.

End-result specifications – A recommended practice (PP-1) has been developed that includes guidance and sample specification language for owner-agencies to evaluate tire-pavement noise of new concrete pavement surfaces. The overall sound intensity level measured

Concrete pavement placement

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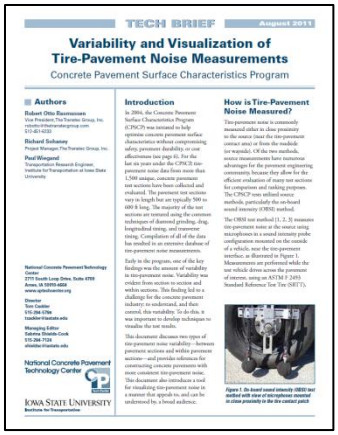
Variability and Visualization of Tire-Pavement Noise Measurements

Driving the need for design and construction guidance is the variability that has been observed in the field with respect to how loud or quiet concrete pavements can be. Much of this variability has the possibility of being controlled, but just as important is to understand the sources of variability. This technical note summarizes these concepts.



TECH BRIEF August 2011

Variability and Visualization of Tire-Pavement Noise Measurements

Concrete Pavement Surface Characteristics Program

Authors

Introduction

How is Tire-Pavement Noise Measured?

A workshop program has also been developed under this program. Effective technology transfer is a key objective of the overall program, and with a number of important products, an effective workshop is needed to facilitate their implementation. The workshop has been developed in a format that facilitates both a webinar and face-to-face format. The agenda includes a “101” module that describes the fundamentals of both noise and texture. Building off this, the major products from this study are described with ample examples of how an owner/agency can readily integrate the results within their current practices. The generic agenda is as follows:

- Welcome and introduction
- Setting the stage
  - Pavement performance and surface characteristics (noise, friction, etc.)
  - Need and objectives of the Concrete Pavement Surface Characteristics Program (CPSCP)
- Noise and Texture 101
  - Noise and texture fundamentals
  - Traffic noise
  - Tire-pavement noise
  - Measurement techniques (noise, texture, friction, etc.)

- Fundamentals for Improved Pavement Surface Characteristics
  - Texture
  - Uniformity
- Concrete Pavement Surface Characteristics Program database
  - Trends
  - Variability
- Guidance for design and construction
- Guide specifications for noise and texture
  - Performance (end-result)
  - Means and methods
- How to select the right texture for the project
- Ongoing Activities
- Technical Challenges and Policy Considerations

To make the most of the successes from this program, a series of technology transfer and implementation activities has been executed under this effort. The objective was to facilitate the integration of these products into the practices of various state DOTs nationwide. Each state DOT that participated had different needs. For some, the training of the fundamentals from this program was important. For other states, there was already recognized demand for the products from this study, and assistance was needed for their proper implementation.

GUIDE SPECIFICATIONS

With the goal of concrete paving solutions that are safe, comfortable, durable, and cost effective, guide specifications have been developed that seek to improve pavement surfaces by reducing tire-pavement noise. The various specifications that have been developed are summarized in this chapter. Copies of the standards are available from the National CP Tech Center at www.cptechcenter.org.

Two very different approaches have been adopted in developing guide specifications for reducing tire-pavement noise:

- **Methods (prescriptive) specifications** – Four guide specifications (GS-1 through GS-4) have been developed that correspond to the four most commonly used concrete pavement textures: diamond grinding, drag (artificial turf), longitudinal tining, and transverse tining. The practices described in the specifications have been demonstrated to increase the likelihood of constructing a durable, quieter concrete surface. Central to the specification is guidance for texturing the concrete surface, since texture geometry has a paramount effect on tire-pavement noise. Guidance is also provided for curing to improve strength and durability of the surface, and thus to improve texture durability.

- **End-result specifications** – A recommended practice (PP-1) has been developed that includes guidance and example specification language for owner-agencies to evaluate tire-pavement noise of new concrete pavement surfaces. The overall sound intensity level measured with on-board sound intensity (OBSI) is designated as the quality characteristic.

While these practices were developed with the intent of use in their entirety, some benefit is possible with partial implementation. Measures should be taken to ensure that implementation is compatible with the friction design policy of the owner-agency. It should also be recognized that these two types of specifications cannot both be implemented at the same time on the same project. Many aspects of prescriptive specifications conflict with end-result or performance specifications. As such, measures should be taken during implementation to minimize the potential for these conflicts.

CPSCP Specification GS-1 – Diamond Grinding

Diamond grinding has been identified as one of the best options for achieving a quieter concrete pavement. It can be used to texture newly constructed concrete, or alternatively to reduce the tire-pavement noise level of an existing concrete pavement surface.

To increase the probability of achieving a quieter surface, the grinding equipment must be a minimum of 35,000 pounds, provide a minimum grinding width of 4 feet, and have a positive means of vacuuming grinding residue. The equipment must also be capable of performing the intended work without causing spalling, raveling, aggregate fractures, or excessive disturbance to the joints, cracks, and other locations. In addition to the equipment being in proper working order, a particular emphasis is given to the runout (roundness) of the match and depth control wheels. Even small deviations in these wheels can introduce unwanted texture in the pavement surface that can lead to an increase in tire-pavement noise.

The construction specifications describe a final pavement surface that must be true to grade and uniform in appearance as a longitudinal type texture. Successive passes of the grinder must not lead to excessive height differentials, overlap, or holidays (gaps of unground texture). A 12-foot straightedge is used to control the surface, and corrective work is specified if the tolerances are exceeded.

When texturing newly constructed concrete pavement, diamond grinding is specified so as not to begin until the concrete has attained sufficient strength to be opened to all types of traffic. Curing compound must be re-applied after grinding if within three days of placement. When diamond grinding an existing concrete pavement, it is specified that concrete pavement preservation activities, except for joint sealing, be completed prior to any diamond grinding.

Regarding the management of grinding residue, Best Management Practices are available from the International Grooving and Grinding Association.

Diamond grinding should produce a neat, uniform finished surface; the peaks of the lands should be approximately 1/8 inch higher than the bottoms of the grooves, and the grooves evenly spaced. The width of the lands will be determined by the width of the spacers used between the sawblades. The most appropriate combination of sawblade and spacer types and thicknesses

should be based on experience; guidance is provided for typical parameters. When diamond grinding newly constructed concrete pavement, a minimum of 98 percent of the pavement surface must be textured; existing pavements should have a specified minimum of 95 percent.

It is recommended that an AASHTO Standard Practice R 54-10, "Accepting Pavement Ride Quality When Measured Using Inertial Profiling Systems," be considered with a maximum International Roughness Index (IRI) of 65 inches/mile. If an inertial profiler is specified for measurement, a line laser (or other wide footprint sensor) should be used for the height sensor. A single point laser should not be used because it can introduce measurement artifacts (error).

CPSCP Specification GS-2 – Artificial Turf Drag

Drag textures using artificial turf represent another alternative with an excellent probability of achieving a quieter concrete pavement. To achieve this, final texturing should be completed as soon as possible after finishing, but before the concrete has attained its initial set.

In order to assure uniformity, the turf must be mounted on a work bridge or a moveable support system that allows for adjustment of the area of turf in contact with the pavement. A single piece of turf spanning the full width of the pavement must be used. To achieve the desired texture, a minimum length of 5 ft. of turf must be in contact with the concrete at all times.

Turf is artificial grass, which comes in many types. For this specification, the material must be a strong, durable, and not subject to rot. It must have a molded polyethylene pile face with 0.6- to 1.3-in. long curled and/or fibrillated blades (no straight, smooth monofilament blades). The minimum weight of the turf material is 60 oz/sy.

Turf dragging operations should be delayed if there is excessive bleed water. Furthermore, measures must be taken to prevent the turf from getting plugged with grout or dragging larger aggregates through the pavement surface. It should be cleaned or replaced as necessary in order to ensure a surface of uniform appearance and free from deep striations.

To assure that adequate texture has been achieved, either Mean Texture Depth (MTD) per ASTM E 965 or the Estimated Texture Depth (ETD) calculated from the Mean Profile Depth (MPD) per ASTM E 1845 can be used. Verification testing is conducted after the concrete has

hardened sufficiently at points located in the outside wheel path. Excessive curing compound may affect the results, and thus the surface can be brushed prior to testing. In the current specification, it is recommended that the running average of three sequential test results result in a texture depth of no less than 0.03 in.

CPSCP Specification GS-3 and GS-4 – Longitudinal and Transverse Tining

Both longitudinal and transverse tining are routinely used by owner-agencies, particularly for high-speed facilities. Achieving a quieter concrete surface is possible, but requires additional control, particularly for transverse tining which is often associated with some of the loudest concrete pavements.

When specifying both longitudinal and transverse tining, texturing should be applied as soon as possible after finishing, but before the concrete has attained its initial set. This is accomplished by applying both a drag pretexture and subsequently by tining.

Drag Pretexture

To create needed texture on the lands (areas between the tined grooves), artificial turf or burlap must be dragged longitudinally along the concrete pavement surface after finishing. The turf or burlap must be mounted on a work bridge or a moveable support system that allows the area of turf or burlap in contact with the pavement to be modified.

A single piece of turf or burlap drag is used that spans the full width of the pavement. A minimum of 4 ft. of drag material must be in contact with the concrete being placed. It should be noted that this is slightly less than the requirement for the drag texture described in GS-2, because the tining process will provide additional texture in this instance.

If a turf material is used for the drag, the material should meet the same standards as described previously in GS-2. If burlap is used instead, is must meet the Class 3 or Class 4 requirements of AASHTO M 182, "Standard Specification for Burlap Cloth Made from Jute or Kenaf." In this case too, the trailing end of the burlap that is in contact with the concrete surface must be frayed by removing yarns perpendicular to the direction of paving. The resulting burlap frays must be 2 to 6 inches in length, and uniform in length across the width of the pavement.

If there is excessive bleed water, turf or burlap dragging operations should be delayed. Measures must be taken to assure that the drag material does not get plugged with grout or begin to drag larger aggregates. The drag pretexture should result in a uniform surface that is free from deep striations.

Tining

When using tined textures, grooves are imparted in the surface of a pavement while the concrete is plastic. This can be done either longitudinally (as specified in CPSCP GS-3), or transversely (CPSCP GS-4). Tining must be done with a mechanical device such as a wire comb with a single row of tines, each nominally 5/64 to 1/8 in. wide. For longitudinal tining, the nominal spacing of the tines is 3/4 inch. For transverse tining, a nominal spacing of 1/2 inch is specified. The nominal depth of the tined grooves in the plastic concrete is 1/8 inch.

Longitudinal tining must use equipment that has automated horizontal and vertical controls to ensure straight tined grooves with a uniform depth. For transverse tining, the texture must be uniform across the width of the comb, and between successive passes of the comb. Furthermore, successive passes of the comb must only be overlapped by the minimum necessary to achieve a continuously textured surface.

The timing of the tining operation is important. Tining must be performed such that the intended surface texture geometry is imparted, it must minimize displacement of the larger aggregate particles, and of course be conducted before the surface permanently sets.

Tines should be thoroughly cleaned at the end of each day's use, and damaged or worn tines replaced as necessary.

Curing Specifications

For both drag (CPSCP GS-2) and tined textures (GS-3 and GS-4), the protection of the concrete surface is of paramount importance. Unless proper methods of curing are adopted, the texture can deteriorate prematurely under the influence of traffic and climate.

To control this, curing should begin immediately following the texture operation by spraying the concrete surface uniformly with two coats of membrane curing compound at an individual application rate not to exceed 180 sf/gal. If the evaporation rate during paving operations does not exceed 0.1 lb/sf/hr, then only one coat of membrane curing compound at an individual application rate not to exceed 180 sf/gal is allowed.

It is important not to allow the concrete surface to dry before the curing compound is applied. Standing pools of bleed water that are present on the surface should be removed before applying the curing compound. The first coat of curing compound must be applied within 10 minutes after completing texturing operations, and if applicable, the second coat applied within 30 minutes.

The evaporation rates cited in the specification should be evaluated using the Menzel nomograph or its underlying equations. For more information, refer to the "Guide to Curing Concrete," 308R 01, ACI International, http://www.concrete.org.

It is important that the curing materials be properly maintained, and any damage promptly repaired. This should be done for at least three curing days, or until the pavement is open to the traveling public, whichever occurs first.

CPSCP Recommended Practice PP-1 – Accepting New Concrete Pavement Surfaces for Tire/Pavement Noise

A recommended practice was developed that is intended to facilitate the adoption of an end-result specification for tire-pavement noise, if one is believed necessary. The trend to use end-result type specifications is recognized. However, it is important to note that by simply adopting better practices, there is a high likelihood that a quieter concrete pavement will be constructed. The methods specifications highlighted herein can be used to encourage adoption of these better practices, which make an end-result specification unnecessary.

That said, if this practice is to be adopted, a critical first step is to minimize (or eliminate) the used of prescriptive language that would describe how the surface texture is to be imparted. This language could be in direct conflict with the intent of the end-result specification to encourage innovation and an emphasis on quality control.

At the core of this practice is the evaluation of tire-pavement noise, with the overall sound intensity level designated as the quality characteristic used for pay adjustment. A quality assurance model has been adopted, based in part on the recently adopted AASHTO R 54-10, "Accepting Pavement Ride Quality When Measured Using Inertial Profiler Systems."

Measurement Method

Overall sound intensity level is measured using *on-board sound intensity* (OBSI), in general conformance with AASHTO TP 76. Prior to testing, the concrete surface should be cleaned, and the contractor permitted to operate construction traffic on the surface in order to further condition the surface.

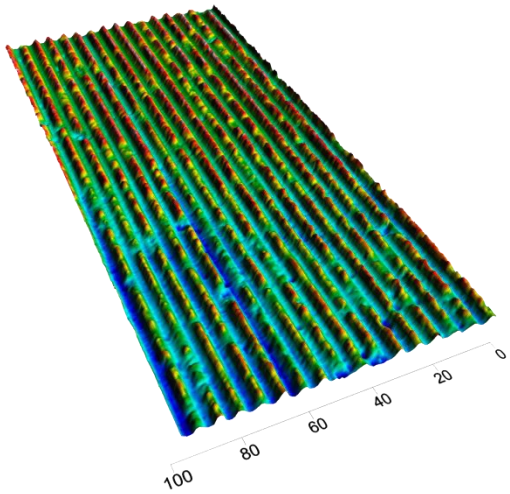
Because OBSI measurements are still a relatively new test, quality controls for both equipment and operators are described in the recommended practice. For example, systems should be demonstrated through comparative testing as sanctioned by the Tire/Pavement Noise Research Consortium, TPF-5(135), or the Tire/Pavement Noise Technical Working Group, sponsored by the Federal Highway Administration Office of Pavement Technology. Qualified operators must also participate in these activities, and furthermore meet the education and experience requirements for becoming a full member of the Institute of Noise Control Engineering (INCE) of the USA.

The recommended practice recommends 528-ft test segments; however, owner-agencies can adopt other lengths that are more compatible with their existing standards and practices. Gaps between test segments are permitted to avoid structures, manhole covers, utility covers, and areas of pavement that do not comply with the criteria for valid testing per AASHTO TP 76 (e.g., steep grades).

Quality Assurance Process

The recommended practice includes four types of testing:

- Quality Control (QC) Testing
- Acceptance Testing
- Verification Testing
- Independent Assurance (IA) Testing



Quality Control Testing is conducted by the contractor per an approved QC plan. Testing can be conducted using OBSI measurements, or alternatively via pavement texture measurements using a relationship that is provided demonstrating a proven relationship between texture and tire-pavement noise evaluated using OBSI. The correlation must be developed and documented from data measured on concrete pavements of the same nominal texture type (e.g., diamond grinding, longitudinal tining). The as-predicted OBSI level (using texture measurements) versus the as-measured OBSI level must have a standard error of no greater than 1.2 dBA.

Acceptance Testing is also conducted by the contractor, but it is necessary in this case to use the OBSI method. Testing is conducted on the surface of the completed project, or at the completion of a major stage of construction. Ideally, a standard test speed of 60 mph should be used, but other speeds are permissible. Given the sensitivity of OBSI level versus speed, pay factors and other limiting values must be selected to correspond with the test speed that is used.

Verification Testing can be conducted by the owner-agency as desired. If the verification testing demonstrates an overall sound intensity level greater than 3.0 dBA different from Acceptance Testing, then the differences should be resolved to a mutual satisfaction.

Independent Assurance (IA) Testing is specified if these differences cannot be resolved. This testing is conducted by an operator with a higher order of qualifications. Comparisons are made to both the Acceptance and Verification Test results in order to determine the validity of each. If the overall sound intensity level is within 1.5 dBA of the IA testing, then those test results are confirmed valid.

Pay Adjustments

While not a required feature, a pay adjustment schedule is provided in the recommended practice. A target set of OBSI sound intensity level limits is provided, for which a corresponding pay adjustment can be determined. Incentive is offered for constructing quieter sections, and disincentive for louder sections. Table 1 shows just one possible example of a pay adjustment

schedule. In this table, overall sound intensity level limits and pay adjustment factors should be selected based on the specific project requirements, and the specific test speed that is used on the project. The final pay factor is determined by taking the values in column (2) and multiplying them by column (3). The results are shown in column (4), which are then summed and divided by 100 to obtain the Final Pay Factor (incentive or disincentive).

Table 1. Example pay adjustment schedule with sample results and final pay factor calculated.

Overall Sound Intensity Level Limit for Testing at 60 mph (dB(A)) (1)	Pay Adjustment Factor (2)	Percent of Test Segments within Overall Sound Intensity Level Limit (%) (3)	Pay Adjustment (4)
< 102.0	1.##	#.#	##.#
102.0 – 103.9	1.00	#.#	##.#
104.0 – 106.0	0.##	#.#	##.#
> 106.0	0.##	#.#	##.#
	Final Pay Factor (PF) = Sum of Column (4)/100 =		#.### or 0.###

The pay adjustment schedule is flexible and can be modified in a variety of ways. The number of OBSI limit steps and their ranges are adjustable column (1), as well as the scale of the pay adjustment factors column (2). This allows flexibility in targeting specific noise ranges that may vary by agency, region, and road design. It allows flexibility in setting the priority of noise performance for the specific project.

Deficiencies and Corrective Action

For test segments designated as defective segments, corrective actions can be recommended. A plan should be developed that identifies the methodology to identify and correct defective segments. Corrective action should be done with the purpose of correcting the pavement surface in order to decrease tire-pavement noise level to acceptable limits. Diamond grinding is an example of a commonly accepted methodology.

Recommendations for Implementation

In order to implement the practices summarized herein, it is further recommended that a stepwise sequence be employed:

- Phase 1A: Develop a "shadow" specification—Specific language should be developed for a specification that is compatible with existing specifications and standard practices of the owner-agency. As such, a review of existing concrete pavement texture specifications is warranted. Regardless of which type of specification is being considered for adoption, it should be noted that prescriptive language will likely conflict with an end-result specification, and thus measures should be taken to modify or eliminate existing language as appropriate. As a best management practice (BMP), a shadow specification (and any requisite changes to existing standards) should be developed through a cooperative effort

with the owner-agency and industry stakeholders, such as local representatives of the American Concrete Pavement Association. If the end-result approach is adopted, another BMP is to begin implementation with relatively small deviations from a pay factor of 1.0; for example, extreme pay factors could initially be established at 1.05 and 0.95, respectively.

- Phase 1B: Field trial the "shadow" specification—A field trial of the shadow specification should include use on a job that would be typical for more widespread implementation. All aspects of the specification should be in force except for any relevant provisions of independent assurance, pay adjustments, and/or corrective action. From this field trial, a report should be prepared by the owner-agency that documents the test methods and test results. If relevant, and while not in force, instances that could have required independent assurance should be documented, as well as the pay adjustments and/or corrective actions that would have been applied.

- Phase 2: Special provision—Based on the outcome of the shadow specification field trial, revisions should be made as appropriate to the specification language. A special provision should be developed that is gradually implemented on projects that are typical for more widespread implementation. Early projects should be closely monitored, and additional revisions to the special provisions made as necessary to reflect the lessons learned. If relevant, specific changes could include modifications to the pay adjustment schedule.

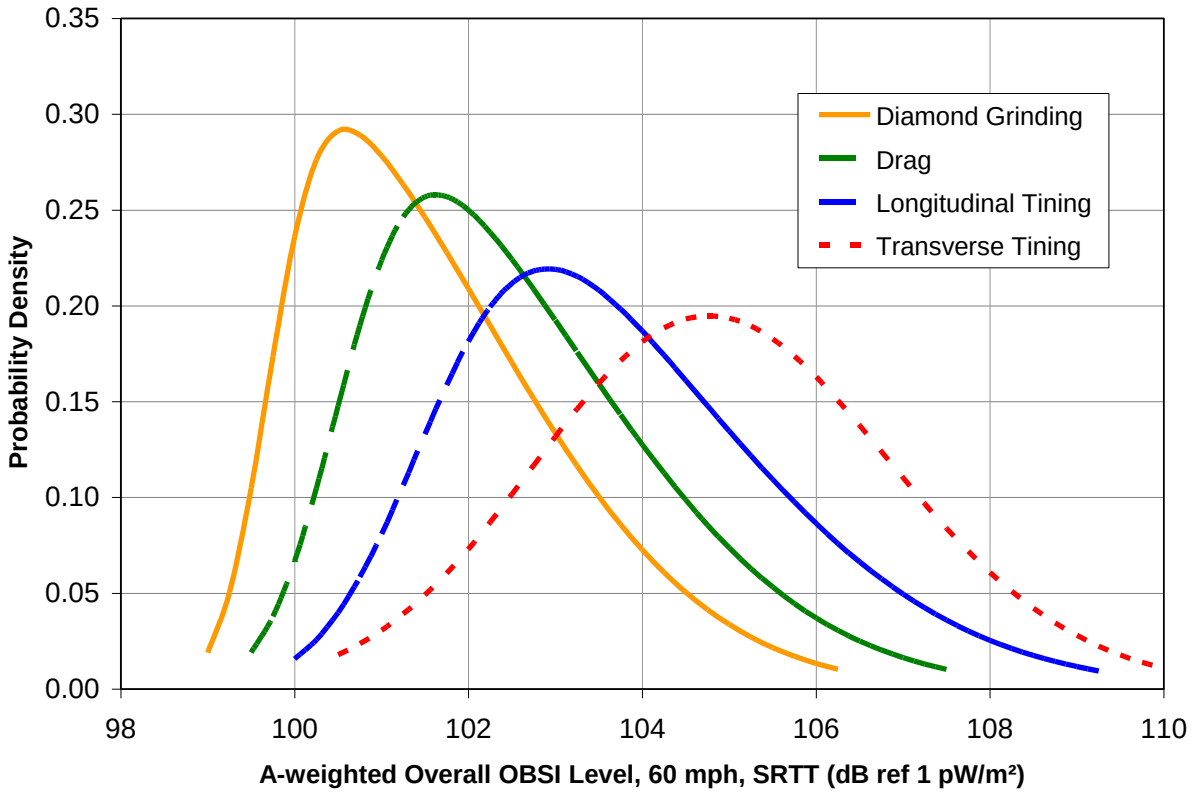
- Phase 3: Standard practice—As the specification matures during subsequent field trials, it can subsequently be adopted as a standard practice, along with requisite changes to other aspects of the concrete pavement texturing standards to ensure compatibility.

SUMMARY OF SURFACE CHARACTERISTICS DATA

Over the past eight years, the CPSCP has amassed a large database of concrete pavement surface characteristics data, including measurements of noise, texture, and friction. Nearly 1,600 test sections throughout North America and Europe have been evaluated.

From this, relationships have been derived that link surface properties such as texture with key PSC, including noise. As part of the evaluation of the concrete pavement textures measured to date, both the "best" and the "worst" of virtually every nominal concrete pavement texture in use today has been catalogued. With so many measurements, distributions have emerged showing what noise characteristics are possible for each nominal texture type. Like in other ways that a pavement would be judged—smoothness, cracking, faulting—pavements throughout the world vary in their quality. Noise is no different. The distribution that has been found is due to differences in design, construction, age, climate, and traffic, among many other factors.

With respect to tire-pavement noise, the following figure illustrates the range of levels that have been measured under the CPSCP.



Normalized distributions of OBSI noise levels for conventional concrete pavement textures

The pavements are broken down by nominal texture type and shown as normalized distributions of the noise levels evaluated using OBSI (per AASHTO TP 76). It should be noted that the pavements measured under the CPSCP do have a bias towards those earlier in life since one of the program goals is to link the measurements to construction factors that are generally only available for younger sections.

Based on these data, an A-weighted tire-pavement noise level of approximately 101 to 102 dB (ref 1pW/m^2), measured using OBSI at 96.6 km/h (60 mph), appears to be a reasonable target threshold for new concrete pavements. With this in mind, the following can be concluded:

- A majority of conventionally diamond ground surfaces that were measured meet this goal.
- About a third of drag textures also meet this goal
- About a quarter of the longitudinally tined surfaces that were evaluated meet this goal
- A small but important fraction of transversely tined surfaces meets this goal; for those that did, the nominal tine spacings are all at or less than 12.5 mm (0.5 in.)

From these data, it can be concluded that virtually all conventional nominal textures have the potential to be constructed as quieter concrete surfaces, although some have a higher probability than others do. While selection of the nominal texture would be the first logical step toward achieving the goal of a quieter pavement, this was not the sole intent of this study. Instead, better practices are necessary to help owner-agencies and/or contractors achieve the quietest surface within any given nominal texture. Developing the better practices, however, requires tapping into the combined experience of both concrete paving contractors and paving equipment manufacturers.

TECHNOLOGY TRANSFER AND IMPLEMENTATION ACTIVITIES

The following implementation activities were conducted during the course of Part 3 of the CPSCP:

1. **Workshops**
   - Jan 2008: TRB Annual Meeting 2008 – "How to Design and Build Quieter Pavements"
   - Feb 2011: Wisconsin Department of Transportation, Appleton
   - Feb 2011: Iowa Department of Transportation, Des Moines
   - Dec 2011: Delaware Department of Transportation, Dover
   - Dec 2011: California Department of Transportation, HQ Executive Workshop, Sacramento
   - Dec 2011: California Department of Transportation, District 7, Los Angeles
   - Jan 2012: Washington State Department of Transportation, Olympia

2. **Webinars**
   - Jun 2007: FHWA Highways for LIFE / LLCP Scan Implementation - Two-lift Construction.
   - Apr 2009: ACPA Webinar
   - Mar 2011: Part 1 – Concrete Pavement Surface Characteristics 101
   - Apr 2011: Part 2 – Concrete Pavement Surface Characteristics 101
   - Aug 2011: TRB Principles and Practices of Quieter Pavements

3. **Presentations and Outreach**
   - Jun 2007: ASTM E 17
   - Jul 2007: TRB ADC40 Summer Meeting
   - Jul 2007: FHWA Noise ETG
   - Jul 2007: ACPA Mid-Year Meeting
   - Aug 2007: TRB Annual Meeting 2008
   - Aug 2007: OK/AR ACPA Presentation
   - Oct 2007: ISO WG 33 Meeting
   - Oct 2007: Noise-Con 2007
   - Nov 2007: ACPA Annual Meeting
   - Dec 2007: ASTM E 17
   - Jan 2008: TRB Annual Meeting
   - Feb 2008: CO/WY ACPA Annual Meeting
   - Feb 2008: ICPA
   - Mar 2008: ACPA Technical Task Force Meetings
   - Apr 2008: Tire-Pavement Noise Pooled Fund, TFP-5(135)
   - Apr 2008: SC Track Meeting
   - Jul 2008: TRB ADC40 Summer Meeting
   - Jul 2008: Noise-Con 2008
   - Jul 2008: ACPA Mid-Year Meeting
   - Sep 2008: Washington State SR 520 Expert Review Panel

- Oct 2008: Two-lift concrete paving open house
- Oct 2008: InterNoise 2008
- Oct 2008: RPUG
- Nov 2008: IGGA leadership
- Dec 2008: ACPA Annual Meeting
- Jan 2009: TRB Annual Meeting
- Jan 2009: Tire-Pavement Noise ETG
- Feb 2009: Mid-Atlantic QA Workshop
- Apr 2009: National Concrete Consortium
- Jun 2009: IGGA Meeting
- Jun 2009: Harris County Toll Authority
- Jul 2009: TRB ADC40 Summer Meeting
- Aug 2009: InterNoise 2009
- Aug 2009: Mid-Continent Transportation Symposium
- Jan 2010: TRB Annual Meeting
- Feb 2010: ICPA Annual Meeting
- Feb 2010: Meeting with Austrian Concrete Pavement industry
- Apr 2010: NCC
- May 2010: ACPA Chapter-States
- Jul 2010: TRB ADC40 Summer Meeting
- Sep 2010: NCC
- Sep 2010: International Conference on Sustainable Pavements
- Oct 2010: National Pavement Evaluation Conference
- Oct 2010: International Concrete Pavement Symposium
- Dec 2010: TxDOT-CCT Workshop
- Jan 2011: TRB Annual Meeting
- Feb 2011: WCPA Annual Meeting
- Feb 2011: ICPA Annual Meeting
- Mar 2011: CO-WY ACPA Annual Meeting
- Mar 2011: CPAM Annual Meeting
- May 2011: ACPA Chapter-States
- Jul 2011: TRB ADC40 Summer Meeting and Noise-Con 2011
- Aug 2011: Mid-Continent Transportation Symposium
- Sep 2011: InterNoise 2011
- Dec 2011: ASTM E 17 Symposium
- Jul 2012: 10th International Conference on Concrete Pavements
- Jul 2012: TRB ADC40 Summer Meeting

4. **Publications**
   - Apr 2007: Abbas, A., et al. "Three-Dimensional Surface Texture Characterization of Portland Cement Concrete Pavements", Computer-Aided Civil and Infrastructure Engineering, Vol. 22 Iss. 3, pp. 197-209.

- Oct 2007: Rasmussen, R.O., et al., "Using On-Board Sound Intensity within the Concrete Pavement Surface Characteristics Program", Proceedings of the 2007 Noise-Con, Reno, Nevada.
- Nov 2007: Roads & Bridges
- Jan 2008: Rasmussen, R.O., et al. "Identifying Quieter Concrete Pavements using On-Board Sound Intensity", presented at the 87th Annual Meeting of the Transportation Research Board, Washington.
- Jul 2008: FHWA CPTP Program Article
- Jul 2008: Rasmussen, R.O., et al. "NITE II: Noise Intensity Testing in Europe, the sequel", Proceedings of the 2008 Noise-Con, Dearborn, Michigan.
- Oct 2008: Rasmussen, R.O., et al., "Comparative Measurements of Tire/Pavement Noise in Europe and the United States: NITE II", Proceedings of Inter-Noise 2008, Shanghai, China.
- Jan 2009: Roads & Bridges
- May 2009: Concrete Producer magazine
- Jun 2009: Rasmussen, R.O. "Measuring and Modeling Tire-Pavement Noise on Various Concrete Pavement Textures", Noise Control Engineering Journal, Special Ed. on Tire-Pavement Noise, Vol. 57, No. 2, pp. 139-147.
- Aug 2009: Rasmussen, R.O., et al., "Improving Functional Performance of Highways in the USA using Quieter Pavement Techniques", Proceedings of the PIARC International Seminar on Maintenance Techniques to Improve Pavement Performance, Cancun, Mexico.
- Aug 2009: Rasmussen, R.O., et al., "Modeling source and wayside sound levels as affected by pavement and bridge joint impulse noise", Proceedings of Inter-Noise 2009, Ottawa, Canada.
- Nov/Dec 2009: Rasmussen, R.O., et al., "Pavimentos silenciosos para el mejoramiento de las carreteras" (silent pavements for road improvement), Vial, No. 70, pp. 82-85.
- Dec 2009: Rasmussen, R.O. and P.R. Donavan, "What causes road noise?", Physics Today, Vol. 62, No. 12, pp. 66-67.
- Apr 2010: Rasmussen, R.O., et al. "Quiet Concrete Pavement Surfaces," Proceedings of the 2010 Noise-Con, Baltimore.
- Sep 2010: Rasmussen, R.O., et al., "Use of Exposed Aggregate Concrete Surfaces as a Sustainable Practice," Proceedings of the International Conference on Sustainable Concrete Pavements: Practices, Challenges and Directions, Sacramento.
- Oct 2010: Rasmussen, R.O., et al., "Exposed Aggregate Concrete Pavement Design, Construction, and Functional Performance: A Comparison of European and US Experiences," Proceedings of the 11th International Symposium on Concrete Roads, Sevilla.
- Oct 2010: Rasmussen, R.O., et al., "Quiet Concrete Pavement Surfaces," Acoustical Society of America, Proceedings of Meetings on Acoustics (POMA), Volume 9, pp. 040008.
- Nov 2010: Rasmussen, R.O., et al., "What Causes Road Noise?", Parity, Vol. 25 No. 11.
- Jul 2011: Rasmussen, R.O. and R.C. Sohaney, "Variability and Visualization of Tire-Pavement Noise Measurements," Proceedings of the 2011 Noise-Con, Portland.

- Sep 2011: Rasmussen, R.O. and R.C. Sohaney, “Development and Implementation of Concrete Pavement Construction Specifications to Control Tire-Pavement Noise,” Proceedings of Internoise 2011, Osaka.

KEY FINDINGS

To build a quieter concrete pavement, one must do the following:

1. **Recognize** which properties of a pavement surface make it quiet (and which make it loud)
2. **Design** the pavement surface in such a way as to avoid those adverse properties
3. **Construct** the pavement surface to avoid those adverse properties, but also in a manner that is both consistent and cost effective

The first item has been addressed in large part under the CPSCP, and through the results of numerous other studies (Ferragut 2007; FEHRL 2006; Sandberg 2002). The following figure summarizes some of the key relationships, and can serve as a reference for those seeking to better understand the link from the design and construction to the most relevant as-constructed properties affecting tire-pavement noise.

Surface texture (bumps and dips)

- Avoid (flatten) texture that repeats itself at intervals of 1 in. or larger.
- Avoid extremely smooth (e.g., floated or polished) surfaces; instead, some fine texture (that is on the scale of 1/8 to 1/4 in.) should be provided.
- Texture should be “negatively oriented", meaning that any “deep” texture should point down (e.g., grooves) rather than up (e.g., fins).
- Striations or “grooves” should, if possible, be oriented in the longitudinal direction, as opposed to the transverse direction.
- If grooves are oriented in the transverse direction, they should be closely spaced and randomized whenever possible. The depth of the grooves can be important in some cases, particularly if material that is displaced is re-deposited on the lands (areas between the grooves).

Concrete properties

- The mortar (at least, near the surface) should be consistently strong, durable, and wear-resistant. Mix design is a key factor, but so are proper placement techniques, including finishing and especially curing.
- Siliceous sands should be used whenever possible in order to improve texture durability and friction.
- For diamond ground pavements, the makeup of the concrete is exposed at the surface. Because the majority of the concrete used in paving consists of coarse aggregate (rock), the nature of this constituent will significantly affect the ability of the surface to retain the texture necessary for both a quiet and safe surface. As with any pavement related decision, careful consideration should be given to friction. With respect to diamond grinding, selection of projects and grinding patterns should be based on experience and/or a careful evaluation of the concrete material, and more specifically, the coarse aggregate type.
- For tined textures, there should be an adequate and consistent depth of mortar near the surface to hold the intended geometry.

Joints

- If joints are present, they can contribute to not only overall noise level, but also annoyance.
- Narrow, single-cut joints are preferred over widened (reservoir) cuts.
- Faulted joints should be avoided by providing adequate load transfer.
- Excess joint sealant should be avoided, especially if it protrudes above pavement surface.
- Spalled joints should be prevented through proper design, materials selection, and construction.

Concrete pavement surface properties that affect tire-pavement noise

Better practices to improve surface properties and thus tire-pavement noise are really about establishing a higher order of control over the texture and other surface properties. Innovation can be helpful in achieving this goal, particularly with feedback systems that are relevant to how the texture is imparted (either in fresh concrete or through diamond grinding). This feedback could, at the very least, instill a renewed awareness of the impact that some of the subtle operational characteristics can have on the texture as constructed.

Predictable tire-pavement noise levels are not about how the texture is imparted as much as they are about the recognition and management of the sources of variability. Regarding the concrete, noise levels have to do with the fact that the contractors are imparting texture into a material with inherent variability in both stiffness and plasticity. Concrete changes from batch-to-batch, and it changes within a batch. The wind and the sun play a major role, as does the timing of the concrete mixing, transport, placement, and the texturing and curing (the latter being important for acoustical durability). Because of these ever-changing parameters, equipment innovations, such as vibration and motion monitoring and continuous texture measurements, are being developed.

The figure on the next page summarizes better practices to reduce tire-pavement noise on concrete pavements. This too can serve as a helpful reference for understanding the numerous issues at play that affect tire-pavement noise.

These are, of course, just a few of the better practices that could be adopted if reducing tire-pavement noise is of concern. Many of these better practices, along with those listed in more detail herein, will also improve smoothness, durability, and, in some cases, reduce costs.

For today, we can promote better practices that focus attention on what we should be doing better during concrete paving. For tomorrow, the solution will likely be automation of the texturing operation. Over the years, slipform concrete paving operations have become increasingly automated. Automatic grade control, for example, is now a standard feature for most slipform pavers. Monitoring vibrator functionality and frequency is also common. Because of its importance, monitoring of the texture operation in plastic concrete will certainly become a reality in the near future. This, as part of an Intelligent Construction System and Technology (Torres et al. 2012)

To meet the demands for predictable low-noise surfaces, automation will allow the paver, texture cart, and grinding operators to monitor the texture being produced and to make adjustments on the fly. Ultimately, this approach may be the best way to achieve a specified target texture on concrete pavements. For now, we can make significant improvements by simply adopting better practices.

Concrete Materials Selection and Proportioning

- Aggregate gradation—for tining and drag surfaces, having adequate mortar concentration near the surface is a critical variable. Ideally, this could be achieved with a consistent, dense mixture. While it is important to have a nominally ideal mixture, consistency of the mixture as batched and placed is paramount.
- Aggregate selection—selection of fine aggregate should be made with friction in mind; thus siliceous sands are preferred over calcareous sands. Coarse aggregate type is of consequence if the aggregates are expected to become exposed, through either surface wear or diamond grinding. The selection of a hard and durable aggregate is therefore preferred.
- Mortar quality—a high-strength, low-permeability, wear-resistant mortar fraction will help maintain the intended texture over time. Measures to lower the w/cm through the use of SCM and/or chemical admixtures should be used when possible. Although they may promote bond for concrete overlays, sticky mortars should be avoided, as they may not hold the texture as intended, and instead deform under action of tining. Mortars that are too fluid could lead to grooves that slump or close up. Both extremes in mix consistency may lead to unintended or undesirable texture.

Paving Equipment

- Minimize vibrations—to minimize texture in the pavement surface that repeats itself on the order of 1 in. or longer, vibrations in the paver should be avoided—at least, vibrations that could potentially be imparted into the slab surface at the profile pan.
- Uniform paver motion—ideally, the paver should move as smoothly and consistently as possible. In addition to “obvious” problems with sudden starts and stops, even the impact of poorly maintained paving tracks can potentially impart undesirable texture features, as can small but rapid adjustments of the paver resulting from improper elevation and lateral control systems (e.g., stringline).
- Uniform extraction—heavy paving equipment would be preferred as a means to control variations in the pavement surface. Maintaining a constant head of uniform concrete at the proper level is also important.
- Equipment maintenance—equipment maintenance activities may be overlooked as a potential source of jerk or vibration that can manifest itself as texture variations in the pavement surface.

Texture/Cure Equipment

- Minimize vibrations—especially important for tined surfaces where vibrations of the tining rake can potentially impart undesirable texture.
- Cleanliness—for drag and tined surfaces, the texturing medium will always be contaminated to some degree with latent mortar. Care should be taken that the buildup of latency is not so significant as to depart from the intended texture.
- Consistent tracking—texture equipment should have a stable and consistent footing and minimize lateral wander. Track-driven equipment may inadvertently introduce small, repeating texture irregularities, as can wheeled devices due to wheel hop or imperfections. Wheeled devices have a disadvantage in their ability to maintain constant traction.
- Heavy duty curing—curing is paramount to the durability of the pavement surface. While often done immediately after texturing on the same cart, this process cannot be compromised in terms of the timing or application rate. Multiple pass (or higher concentration) curing application is recommended whenever possible.
- Equipment maintenance—like with the paver, proper and routine maintenance could improve the working condition of the texture/cure equipment, potentially preventing unwanted jerk or vibrations.

Grinding Equipment

- Grinding head—there does not appear to be an optimum size and spacing of blades and spacers to reduce tire-pavement noise as there is for improving friction (as a function of aggregate type). In conventional practice, these components are selected based on the specific concrete being ground in order to optimize production rate and the durability of the surface from subsequent wear under traffic and maintenance. This practice is still recommended to better ensure that safety, cost, and durability are not compromised for the sake of decreased noise.
- Size—larger, heavier grinding equipment is more likely to have the control necessary to consistently impart the texture at the intended depth and lateral coverage.
- Holidays and overlap—care should be taken that the match line between passes of the grinder does not coincide with the wheel path, as this can be a source of irregular grinding patterns. Wider grinding heads (e.g., 4 ft) will minimize the number of match lines, keep them out of the wheel path, and potentially impart better control.
- Bogie wheels—any imperfections in the bogie wheels that support the grinding head can manifest as texture variations in the as-ground surface. Care should be taken to ensure that the wheels are true (round).
- Fins—measures should be taken to minimize the variability in the height of the remaining fins of concrete. While some fin wear can be expected under traffic and from winter maintenance activities, excess fin height should be avoided by configuring the grinding head with the appropriate spacers (primarily a function of coarse aggregate type).
- Vibrations—while inevitable due to the nature of grinding, excess vibration should be avoided. If unchecked, these vibrations can impart themselves as undesirable texture in the pavement that can increase noise levels, especially in texture that repeats itself on the order of 1 in. or longer.

Summary of better practices to reduce tire-pavement noise

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), "Standard Method of Test for Measurement of Tire/Pavement Noise using the On-Board Sound Intensity (OBSI) Method", AASHTO Specification TP 76-11 (2011).

Cackler, E.T., et al., *Concrete Pavement Surface Characteristics: Evaluation of Current Methods for Controlling Tire-Pavement Noise*, Final Report of FHWA Cooperative Agreement DTFH61-01-X-00042, Project 15 (2006).

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Ferragut, T., Rasmussen, R.O., Wiegand, P., Mun, E., and E.T. Cackler, *ISU-FHWA-ACPA Concrete Pavement Surface Characteristics Program Part 2: Preliminary Field Data Collection*, National Concrete Pavement Technology Center Report DTFH61-01-X-00042, Project 15, Part 2 (2007).

Rasmussen, R.O., et al., *The Little Book of Quieter Pavements*, Report FHWA-IF-08-004 (2007).

Sandberg, Ulf and J. Ejsmont, *Tyre/Road Noise Reference Book*, Informex, Handelsbolag, Sweden (2002).

Scofield, Larry, *Development and Implementation of the Next Generation Concrete Surface*, American Concrete Pavement Association (2011).

Taylor, P.C., et al., *Integrated Materials and Construction Practices for Concrete Pavement, A State-of-the-Practice Manual*, Report FHWA-HIF-07-004 (2006).

Torres, Helga, et al., *Intelligent Construction Systems and Technologies Roadmap*, Federal Highway Administration Contract DTFH61-08-D-00019 (2012).

APPENDIX. FOR MORE INFORMATION

The following reports and websites provide practical information that was not included herein for the sake of brevity.

Reports

To better understand tire-pavement noise…

- FHWA, *The Little Book of Quieter Pavements* (Rasmussen 2007)

To better understand good practices for concrete paving…

- CP Tech Center, *Integrated Materials and Construction Practices for Concrete Pavement* (Taylor 2006)

Websites

National Concrete Pavement Technology Center

- http://www.CPTechCenter.org

Concrete Pavement Surface Characteristics Program

- http://www.SurfaceCharacteristics.com

American Concrete Pavement Association

- http://www.ACPA.org

International Grooving & Grinding Association

- http://www.IGGA.net