CONCRETE PAVEMENT TEXTURING

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INTRODUCTION

Pavement surface texture plays important roles in roadway safety and noise issues. More than 32,000 deaths and 2.3 million injuries occurred in more than 6 million vehicle crashes in the U.S. in 2014 (NHTSA 2016) and about 16 percent of those crashes took place on wet pavement (FHWA 2016). The two main causes of wet weather crashes are: 1) hydroplaning (loss of contact between tires and the pavement surface due to a film of water) and 2) poor visibility due to splash and spray. Inadequate friction also contributes to many dry-weather accidents, particularly in work zone and intersections where braking and unusual vehicle movements are common.

There are many sources of sound in the highway environment, including vehicle sounds (e.g., engine and exhaust noise, etc.), sound due to the passage of air around the and through the vehicle, and the interaction of vehicle tires and the pavement surface. Tire-pavement interaction is generally the predominant source of sound for cars and trucks at vehicle speeds greater than 20 mi/h (32 km/h) and 30 mi/h (48 km/h), respectively. When other factors are held constant, traffic noise levels vary mainly with the characteristics of the pavement surface, e.g., the porosity and texture (ACPA 2006).

The selection, design and construction of concrete pavement surface texture requires the consideration of both noise and safety concerns, as well as durability and cost – often competing factors! This Tech Brief complements FHWA Technical Advisory T 5040.36 (FHWA 2005) by: 1) providing additional details concerning how pavement texture affects roadway noise and safety; 2) describing current concrete pavement surface texturing methods and their impacts on roadway noise and safety; and 3) providing guidance concerning best practices for concrete pavement texture selection, specification and construction.

CHARACTERIZING SURFACE TEXTURE

Surface Texture Definitions and Their Impacts on Noise and Safety

Overall pavement surface texture is comprised of the contributions of aggregate texture and gradation, pavement finishing techniques, pavement wear, and more. The resulting surface texture can be characterized in terms of texture depth and feature length or wavelength. Different combinations of texture depth and wavelength have different effects on tire-pavement interactions, such as noise and friction.

The Permanent International Association of Road Congresses (PIARC) has proposed the following four categories of pavement surface characteristics based on measurements of depth (or amplitude) and wavelength: microtexture, macrotexture, megatexture and unevenness (roughness) (PIARC 1987). These four categories and their impacts on tire-pavement interaction are presented graphically in figure 1 (after Rasmussen et al. 2004) and are described below.

Microtexture

Microtexture is defined as having wavelengths of 0.0004 to 0.02 inches (1μm to 0.5 mm) and depth of less than 0.008 inches (0.2 mm) (PIARC 1987). In concrete pavements, microtexture is typically provided by the fine aggregate (sand) in the concrete mixture.

Good microtexture is typically sufficient for adequate friction on dry concrete pavements at normal operating speeds and on wet (but not flooded) concrete pavements at vehicle speeds under 50 mi/h (80 km/h). At higher operating speeds on wet concrete pavements, good macrotexture is also required (Hibbs and Larson 1996). Microtexture is usually not considered to significantly impact the generation of pavement noise or splash and spray.

Macrotexture

Macrotexture is defined as having wavelengths of 0.02 to 2 inches (0.5 to 50 mm) and depth of 0.004 to 0.8 inches (0.1 to 20 mm) (PIARC 1987). In concrete pavements, macrotexture is typically provided by small surface channels and grooves that are intentionally formed in the plastic concrete or cut in the hardened concrete (e.g., from tining, grooving, exposed aggregate, turf drag, etc.)

Macrotexture plays a major role in the wet weather friction characteristics of pavement surfaces, especially at higher vehicle speeds, as it helps to prevent hydroplaning by allowing water to escape from beneath the vehicle tires. Macrotexture is not intended to address surface drainage problems, which are addressed mainly through pavement cross-slope.

Macrotexture is also the pavement surface characteristic with the strongest impacts on tire-pavement noise and splash and spray (see figure 1 after Rasmussen et al. 2004). The impacts on noise are strongly influenced by both the type of texture (e.g., tining, exposed aggregate, turf drag, etc.) and the details of the texture design and construction (e.g., width, depth and spacing of grooves; randomness of the pattern; orientation of the texture; etc.) (Wu and Nagi 1995).

Megatexture

Megatexture is defined as having wavelengths of 2 to 20 inches (50 to 500 mm) and depth of 0.004 to 2 inches (0.1 to 50 mm) (PIARC 1987). This type of texture typically results from poor construction practices, localized settlements or surface deterioration. (Wu and Nagi 1995)

Megatexture has little impact on pavement friction but can cause some external noise and may result in some in-vehicle noise. It also typically reduces ride quality and increases wear on some components of vehicle suspensions (e.g., tires, shock absorbers and struts).

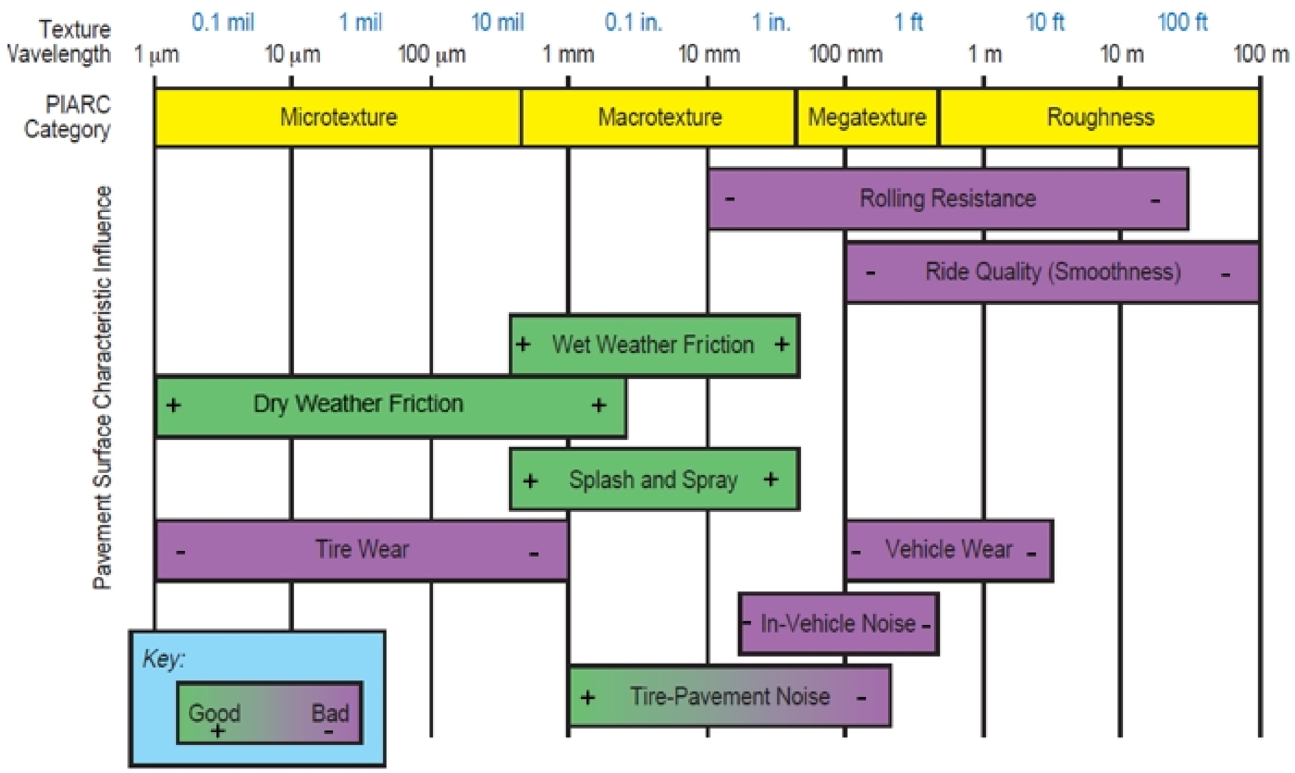

Figure 1. Illustration of PIARC pavement surface characteristic classifications and their impacts on pavement performance measures.

Unevenness or Roughness

Pavement unevenness or roughness is defined as pavement surface irregularities with wavelengths greater than 20 inches (500 mm). Wavelengths in this range have little impact on tire-pavement noise or surface friction, but often affect ride quality and surface drainage. In concrete pavements, unevenness is generally attributed to environmental effects (e.g., slab curl and warping), construction practices and localized settlements.

Measurement of Surface Texture

There are several methods for measuring and quantifying pavement surface texture and the results of these measures are often difficult to compare directly. One of the most common measures is “mean texture depth” (MTD), which is determined volumetrically using ASTM E 965 (the “sand patch” test – figure 2). Acceptable levels of MTD vary widely among agencies for various pavement applications (ACPA 2006); FHWA’s Technical Working Group recommended that concrete surfaces have an average MTD of no less than 0.03 inches (0.8 mm) with no individual test result less than 0.02 inches (0.5 mm) (Hibbs and Larson 1996).

Source: FHWA

Figure 2. Sand patch test.

Laser-based texture scanners (figure 3) are also available to quickly, accurately, and automatically estimate MTD and other texture-related parameters. One such hand-held device uses a line laser to scan a 4-inch (100 mm) square area of the pavement surface and produces data that are immediately available for viewing and analysis.

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Figure 3. Laser texture scanner.

Another common measure of surface texture is “mean profile depth” (MPD), which is determined by analyzing laser-based profile data (e.g., profile data from the Road Surface Analyzer – RoSAn) in accordance with ASTM E-1845. It can also be determined using the Circular Texture Meter (CT Meter), a small portable device (figure 4). Additional information on these measurement techniques and others, as well as on correlations between the various measures, is available in the literature (ACPA 2006; Hall et al. 2009a; Hall et al. 2009b).

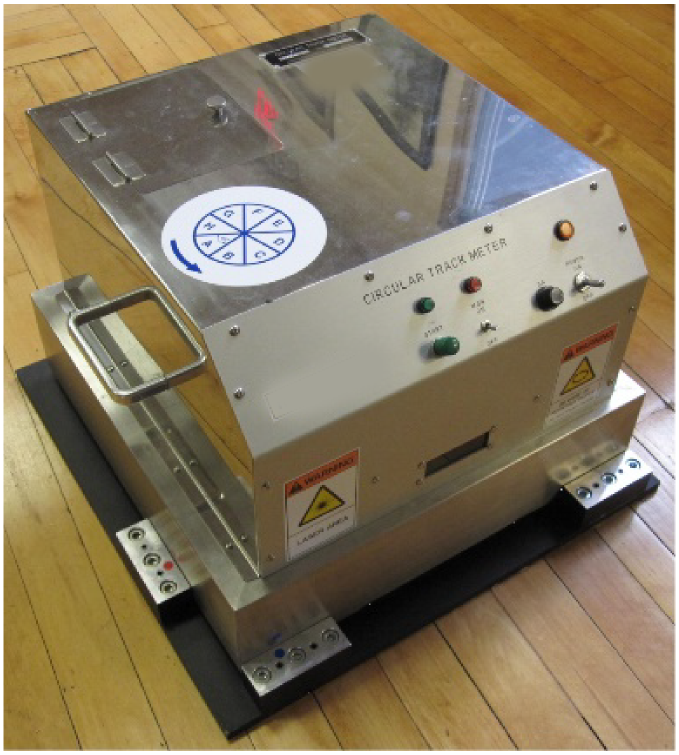

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Figure 4. CT Meter.

PAVEMENT TEXTURE AND SAFETY

Introduction – The Effects of Pavement Texture on Pavement Safety

Pavement surface friction (or "skid resistance") is the force developed at the tire-pavement interface to resist tire slippage. Adequate friction for vehicle operations often exists on dry pavement surfaces, but even thin films of water on the pavement surface reduce tire-pavement contact and result in a loss of friction. Tires can completely lose contact with the pavement surface if the water film is sufficiently thick and the vehicle speed is sufficiently high (hydroplaning) (Dahir and Gramling 1990). Water on the pavement also contributes to splash and spray problems when it is picked up by vehicle tires and becomes airborne, reducing visibility for drivers following or adjacent to the vehicle creating the splash and spray.

Larson, Scofield, and Sorenson (2005) suggest that up to 70 percent of wet weather crashes can be prevented with improved tire-pavement friction. Improved surface friction would also significantly reduce dry pavement accident rates and severity by reducing dry weather stopping distances (ACPA 2006). The most dramatic potential for reducing accident rates comes from providing both microtexture and macrotexture, as is shown in figure 5 (Viner, Sinhai, and Parry 2004).

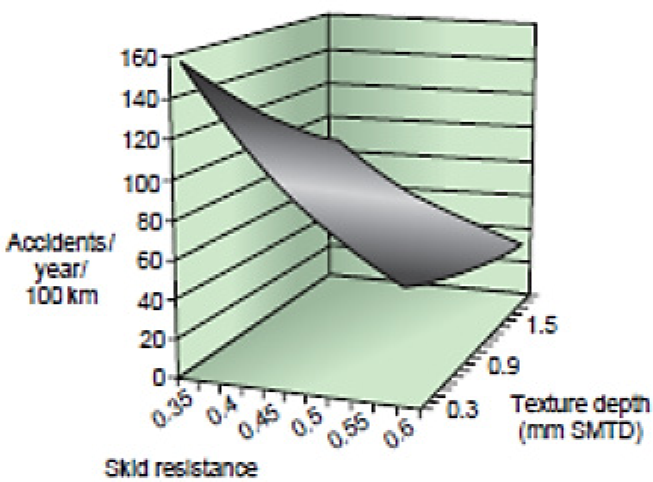

Figure 5. Accident model for skid resistance texture depth on selected U.K. roadways.

Factors That Affect Pavement Friction and Safety

There are many factors that affect pavement friction and safety, including tire design (e.g., rubber compounds used, tread pattern and wear, etc.), environmental conditions (e.g., tire and surface temperature, surface moisture, etc.), pavement microtexture and macrotexture, and the relative speed between the tire and pavement surface ("slip speed").

Effects of Pavement Texture on Surface Friction

As noted previously, microtexture is sufficient for most dry weather traffic operations, but rapidly loses effectiveness in providing tire-pavement friction as water film thickness increases. Macrotexture offers the potential to dissipate water pressure under tires on wet and flooded surfaces, thereby improving wet weather tire-pavement friction and (in combination with reduced vehicle speed) reducing the potential for hydroplaning. Increased macrotexture also generally reduces the potential for splash and spray (ACPA 2006).

Studies have shown that increased macrotexture reduces accident rates under both wet and dry conditions, particularly at intersections, as well as at lower speeds. One of these studies suggests that the lower limit of satisfactory surface texture is 0.015 to 0.02 inches (0.4 to 0.5 mm), with crash risks nearly doubled when average macrotexture dropped below these values. (Roe, Parry, and Viner 1998; Caimey and Styles 2005).

Effects of Pavement Surface Texture on Hydroplaning

When a rolling tire encounters a film or layer of water on the roadway, the water is channeled through the tire tread and the pavement surface texture. Hydroplaning occurs when the channeling or drainage capacity of the tire tread/pavement surface texture system is exceeded by some combination of water film thickness and vehicle speed, resulting in the build-up of a wedge of water in front of the tire that is capable of lifting the tire off the pavement surface. Hydroplaning potential increases with increasing water depth and vehicle speed, and decreases with increased tire pressure, tread depth and pavement macrotexture.

Pavement Age and Temperature Effects on Friction

Pavement friction usually decreases with pavement age due to: 1) polishing of exposed aggregate particles (both coarse and fine) by traffic, which decreases microtexture; and 2) surface wear under traffic, which reduces macrotexture.

Measurement of Pavement Friction

Friction Number/Skid Number

The most common approach for measuring pavement surface friction in the U.S. is the use of a locked-wheel trailer (ASTM E 274 - see figure 6) using either an ASTM E 501 standard ribbed (longitudinally grooved tread) or an ASTM E 524 "blank" (smooth) tire. The test involves towing the trailer at a specified speed (typically 40 mi/h [64 km/h]) and while applying a specified amount of water to dry pavement in front of the trailer wheels. When the trailer brake is applied and the wheels are locked, the increased towing force is measured and the friction number (FN) or skid number (SN) is computed as 100 times the force required to slide the locked wheels over the pavement surface divided by the effective wheel loads.

Figure 6. Locked-wheel skid trailer.

Friction numbers are reported as the letters FN or SN (for friction number or skid number) followed by the test speed in mi/h (or km/h if in parentheses), and the letter R or S (for ribbed or smooth tire). For example, a test result conducted at 40 mi/h (64 km/h) using a smooth tire would be reported as FN40S (or FN(64)S for the metric version).

FHWA (2005) recommends the use of smooth tires for highway friction tests because they produce test results that correlate much better with wet weather accident rates than do ribbed tires, which are somewhat insensitive to macrotexture and measure mainly the effects of microtexture.

It should be noted that pavement friction test results can be significantly influenced by road conditions (e.g., accumulations of dust and oil that mix with or repel the test water) as well as environmental conditions and events (e.g., rainfalls that wash away dust and oil, temperature conditions that impact tire rubber hardness, and winter maintenance operations that increase surface microtexture). Some agencies apply seasonal corrections to their friction test values to account for these mechanisms (ACPA 2006; Henry 2000).

International Friction Index (IFI)

The IFI is a measure of tire-pavement friction that standardizes how the dependency of friction on tire sliding speed is reported and is comprised of two numbers: F(60) and S_p, the IFI friction number and speed number, respectively. Details concerning the computation of IFI from friction and surface texture test data are presented in ASTM E1960 and Hall et al. (2009b).

Sideways-force Coefficient Routine Investigation Machine (SCRIM)

The SCRIM originated in the United Kingdom and averages sideways force measurements from two wheels that are toed out at an angle of 7.5 degrees (see figure 7). Some SCRIMs are also fitted with laser macrotexture measurement systems to provide a more complete indication of pavement surface characteristics. The SCRIM can continuously measure friction, macrotexture, and other pavement surface characteristics while being driven up to 50 mile per hour (FHWA 2018).

Source: FHWA

Figure 7. Photos of SCRIM.

The SCRIM is commonly used for measuring pavement surface friction in the U.K., Australia and many European countries (ACPA 2006). The SCRIM is also one of the tools FHWA is currently using to advance its Pavement Friction Management (PFM) Support Program to reduce highway crashes and fatalities in the U.S. It has been used to test pavement in several states and the results are being correlated with data from conventional locked-wheel skid testers, crash histories and other data to develop pavement friction management criteria and programs (FHWA 2018).

Policy

The FHWA pavement policy (23 Code of Federal Regulations [CFR] 626.3) states: “Pavement shall be designed to accommodate current and predicted traffic needs in a safe, durable, and cost-effective manner.” FHWA (2005) notes that adequate wet pavement friction at both low and high speeds should be provided in the form of both microtexture and macrotexture to ensure a safe pavement. AASHTO (2008) provides guidance on the development of agency policies concerning project-level friction design, as well additional information concerning friction mechanisms, measurement and management.

PAVEMENT TEXTURE AND ROADWAY NOISE

Sources of Roadway Noise

Noise (unwanted sound) from vehicles and their interaction with the pavement can be attributed to many sources, including the engine, intake system, exhaust system, powertrain, tire-pavement interaction, air turbulence and other sources. Figure 8 shows the relative contributions of each of these categories to overall noise for a typical passenger car emitting a combined effect of 74 decibels (other vehicles and mixed traffic produce different distributions). It can be seen that tire-road noise is a major contributor to overall sound levels, particularly at high vehicle speeds (ACPA 2006).

It must be noted that both automotive technology and ISO 362 measurement methods have changed significantly since the 1996 study presented in figure 8. The contribution of tire/road interaction to overall noise levels is much higher today (Schumacher, Sandberg, and Moore 2019).

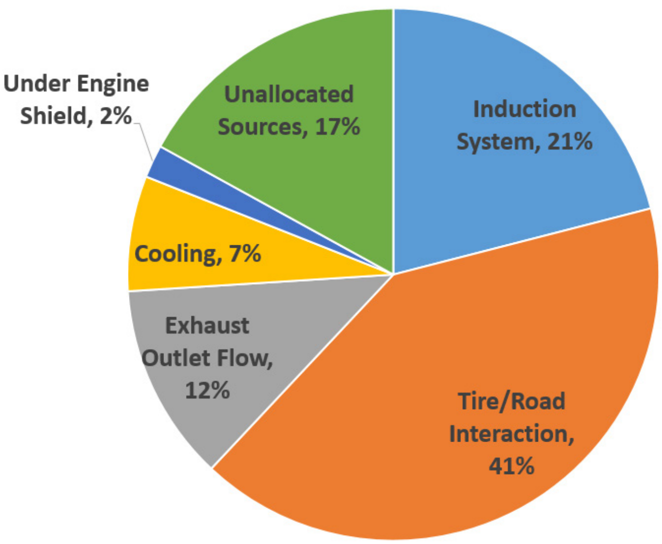

Figure 8. Typical source contributions to overall noise levels for a specific type of American car in 1996 testing using ISO 362.

Many factors influence the generation of tire-pavement noise, including vehicle speed, tire load and inflation pressure, torque/acceleration on the wheel, tire type/design, tread design/depth, use of tire studs, road condition (wet vs dry), temperature, and pavement surface texture. The most objectionable tire-pavement noise is associated mainly with megatexture and the higher wavelengths of macrotexture. This texture range is also important in pavement safety considerations, such as wet weather friction and the generation of splash and spray.

The sound emission characteristics of pavement surfaces are also functions of acoustic absorption, which is a measure of how much sound energy is absorbed (rather than reflected) by a material. Acoustic absorption is closely related to surface porosity, which reduces both the generation of noise at the tire-pavement interface and the reflection of noise off of the pavement.

Additional information concerning the generation of tire-pavement noise, as well as the mechanisms by which this noise is amplified, reflected, directed and absorbed, can be found in ACPA (2006) and Sandberg and Ejsmont (2002).

Factors Affecting Perception of Noise

Roadway noise that is generated by tire-pavement interaction is heard by people inside of vehicles as well as outside the vehicle. The factors that influence the perception of sounds at these two locations are very different.

Many studies have identified interior sound pressure peaks as much as 10 decibels above general sound levels at frequencies around 1000 Hz and have found that these peaks are perceived by humans as irritating pure tones – either a relatively high-pitched whine or a lower-pitched rumble (Sandberg and Ejsmont 2002; Hibbs and Larson 1996; Hoerner and Smith 2002; and Kuemmel et al. 2000). These tonal qualities are often more important in the perception of objectionable interior noise than is overall noise level. Different texturing techniques produce different tonal qualities and can be perceived as producing very different levels of noise, even when the total sound pressure or volume (in decibels) is identical. The key to reducing the most objectionable interior vehicle noise is to eliminate the high sound pressure peaks in the range of frequencies that are most irritating – typically between 500 and 1500 Hz, as shown in figure 9 (after Kuemmel et al. 2000; ACPA 2009). Interior noise levels are also affected by vehicle-specific factors, such as structural, suspension and insulation characteristics.

The perception of exterior noise varies with the level of sound produced at the source, but is also highly dependent on the distance from the source to the receptor (listener), the presence of barriers to the sound (e.g., sound walls, berms, vegetation, etc.), and environmental factors (e.g., wind, temperature and humidity). While significant reductions in perceived noise can be achieved through distance and the construction of sound barriers, consideration must also be given to the design and construction of pavement textures that reduce the emission of tire-pavement noise.

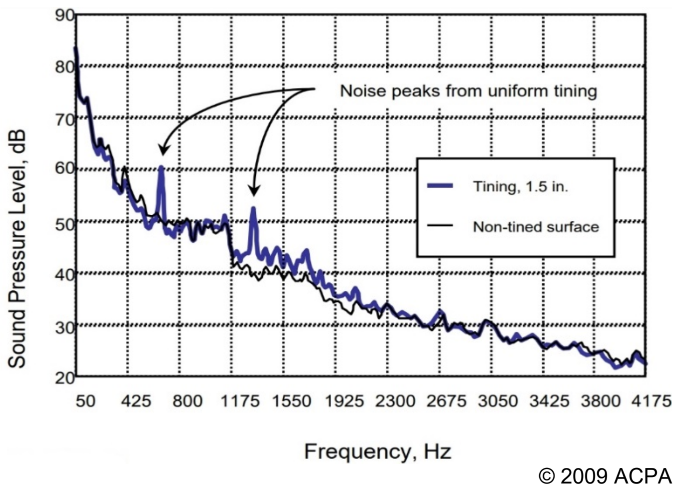

Figure 9. Inside-vehicle spectral sound frequency graph showing prominent peaks that produce objectionable noise.

Specifics concerning the mechanisms and magnitudes of the various factors affecting the generation and perception of tire-pavement noise, both inside and outside of the vehicle, are detailed in Sandberg and Ejsmont (2002) and summarized for concrete pavements in ACPA (2006).

Measurement of Sound in the Highway Environment

Interior vehicle sound is typical measured using one or more microphones, typically mounted near the driver's seat at ear-level, and an acoustic analyzer using procedures described in SAE J1477 ("Recommended Practice for Measurement of Interior Sound Levels of Light Vehicles"). While this type of measurement is typically performed only by vehicle manufacturers, Kuemmel et al. (2000) developed an in-vehicle noise measuring system and fast Fourier transform-based analysis method based on the SAE J1477 practice that can be used to identify pavement textures that generate objectionable tonal qualities.

Exterior sounds in the highway environment are typically measured using far-field techniques (which attempt to measure sound pressures at standardized receptor positions) or near-field techniques (which measure sound pressures, and sometimes directionality) very near the tire-pavement interface. Far-field measurements are sometimes favored because they can account for sound contributions from many sources (e.g., tire-pavement interaction, engine, exhaust, etc.) as well as the effects of wind, temperature, traffic mix, vehicle speed, etc.), but they are often time-consuming and expensive and difficult to perform in dense urban areas or when sound reflectors (e.g., sound walls, safety barriers, etc.) are located nearby. Near-field measurement systems are able to isolate tire-pavement interaction sounds from other sounds in the highway environment and they can be performed much more rapidly than can typical far-field measurements, but they are difficult to use in estimating overall sound levels for mixed traffic or the effects of sound that is reflected by adjacent structures and barriers.

A common far-field roadway sound measurement technique in the U.S. is the Statistical Pass-By Method (SPB), which uses a roadside microphone, positioned at a standard height and distance from the roadway, to measure sound levels from normal vehicles (representing three specific vehicle classes) that have been selected from the traffic stream and are operating under approximately constant speed conditions and without interference from other vehicles. The sound pressure data collected from the passage of the selected vehicles is processed, weighted according to the proportions of the various vehicle classes on the test roadway, combined, and converted back to an average sound level for the assumed mix of vehicles. This value is called the SPB index. A complete description of the SPB test method can be found in ISO 11819-1. Discussions of the principal advantages and drawbacks of this method are detailed in Sandberg and Ejsmont (2002) and summarized in ACPA (2006).

Common near-field measurement techniques include the Close-Proximity Method (CPX) and the Sound Intensity (SI) method. The CPX method consists of rolling a test tire (commonly mounted in an acoustically enclosed trailer) on the driving surface with two or more microphones mounted close to the tire and the pavement surface at each end of the contact patch. Two-to-four standard reference tires with different tread patterns are used at a specified speed over a specified length of pavement surface and the collected data are used to determine average sound pressure levels at the tire-pavement interface. CPX measurements can be obtained relatively quickly and inexpensively without having to close the roadway to normal traffic, have good repeatability, and correlate well with SPB measures of tire-pavement noise. However, CPX does not completely account for the directionality of tire-pavement noise and the impact of that noise in the far field and there are potentially large influences of the test vehicle and other background noises on sound measurements (ACPA 2006). An international standard for conducting CPX tests can be found in ISO 11819-2.

The SI method also uses two or more microphones mounted near a test tire, but the microphones are phase-matched so that they can be used without an acoustical enclosure and signal processing is used to eliminate sounds not produced by tire-pavement interaction. The result is a measure of the intensity of tire-pavement sound being radiated perpendicular to the plane of the tire. Like the CPX method, SI measurements can be conducted at highway speeds and correlate well with far-field (SPB) test values. Figure 10 is a photo of sound measurement equipment typically used for the current version of this test, the On-Board Sound Intensity (OBSI) Method. Additional information concerning the SI test and equipment are presented in Rasmussen et al. (2012a) and AASHTO T 60-16.

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Figure 10. Example OBSI probe configuration.

Source: FHWA

Figure 11. Burlap drag and resulting surface texture.

CONCRETE PAVEMENT SURFACE TEXTURE TYPES

The following sections describe techniques for constructing different types of surface texture in plastic and hardened concrete, in keeping with FHWA's Technical Advisory on pavement surface texture that states: "While safety considerations are paramount, tire/surface noise should be considered when specifying pavement and bridge surfaces. Both asphalt and concrete pavements can provide safe, durable, and low-noise surfaces when properly designed and constructed." (FHWA 2005).

Textures Constructed in Plastic Concrete

Several techniques have been used for texturing the surface of concrete pavements while the concrete is still in a plastic (unhardened) state. Each can be designed and constructed to provide a safe, high-friction surface with considerations to reduce tire-pavement noise, although some texture types and orientations are inherently more prone to noise production than others. The most common plastic concrete texturing techniques (currently and historically) are briefly described below. Rasmussen et al. (2012b) presents detailed recommendations for constructing several of these textures in a manner that reduces tire-pavement noise while maintaining adequate friction.

Burlap Drag

A texture produced by dragging moistened coarse burlap over the plastic pavement surface. The resulting texture is typically very shallow (~0.008-inches [0.2 mm] – very little macrotexture) with longitudinal striations (see figure 11 from Cackler et al. 2006); texture depth varies with coarseness of the burlap, concrete mix design, timing of the drag and finishing conditions.

Burlap drag was the most common new PCCP texturing technique in the U.S. until the mid-1960s. It is relatively quiet but may not provide adequate wet-weather friction at high speeds unless combined with other features. In addition, the frictional characteristics of this type of texture can decrease rapidly with time and vehicle wear (Rasmussen et al. 2004).

Artificial Turf Drag

A texture produced by dragging an inverted (grassy side down) section of artificial turf over the plastic pavement surface. The resulting texture is typically longitudinal striations with depth ranging from 0.06 to 0.12 inches (1.5 to 3 mm) when using weighted turf with 7200 blades/ft^2 [77,500 blades/m^2] (see figure 12). Texture depth varies with the density, length and stiffness of the turf blades, weighting of the turf, concrete mix design, timing of the drag and finishing conditions.

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Figure 12. Turf drag texturing and resulting surface texture.

Artificial turf drag texturing was pioneered by the Minnesota DOT in the 1990s and is now used or allowed by a few other agencies. Minnesota's current specification requires production of an MTD of 0.04 inches (1.0 mm), although that number is typically reduced by about 1/3 after the first winter of operation. Noise and friction data indicated values that are comparable to those of asphalt pavements with good durability (Hansen and Waller 2005). A stiff, high-quality, low w/cm concrete mixture design is essential producing a good, durable turf drag texture (ACPA 2006).

A guide specification for turf drag texturing can be found at: http://publications.iowa.gov/13147/1/CPSCP-GS2-TurfDrag-110301-1.pdf.

Transverse Tining

A texture (commonly constructed in combination with burlap drag) to produce transverse grooves in the plastic concrete by drawing a rake-like structure with long, thin metal teeth across the surface, generally perpendicular to the direction of vehicle travel. The resulting texture is intended to consist primarily of grooves at specified spacing patterns with width 0.12 inches (3 mm) and depths between 0.06 and 0.25 inches (1.5 mm and 6.0 mm) (figure 13); actual groove widths and depths vary with concrete mix properties, adjustment of down-pressure on the tines and timing of the tining operation.

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Figure 13. Transverse tining operation and resulting surface texture.

Transverse tining was the most common plastic concrete texturing method from the mid-1970s until relatively recently. It has proven to be an effective and economical technique for consistently providing durable, high-friction, hydroplaning-resistant surfaces for concrete pavements (ACPA 2006). Unfortunately, many transversely tined surfaces also produce objectionable types and levels of noise, both within and outside of the vehicle. Noise levels and frequencies vary significantly with texture depth and tine pattern (i.e., random vs. uniform spacing, as well as average tine spacing). For example, 1- and 1.5-inch (25- and 37-mm) uniformly spaced transverse tining patterns often produce highly objectionable noise (especially as depth of tining increases).

Transverse tining is still sometimes used in concrete pavement construction. A uniform spacing of 0.5-inches (13 mm) with a nominal 0.12-inch (3 mm) depth is often used to produce the least objectionable noise characteristics (although other texture options may be preferred).

A guide specification for transverse tining can be found at: https://intrans.iastate.edu/app/uploads/2018/08/CPSCP-GS4-TransTining-110301-1.pdf.

Longitudinal Tining

A texture constructed similarly to transverse tining except in a longitudinal orientation (parallel to the direction of vehicle travel). The resulting texture is intended to consist primarily of grooves at specified spacing patterns (typically 0.75 inches [19 mm]) with widths of approximately 0.12 inches (3 mm) and depths between 0.06 and 0.25 inches (1.5 mm and 6.0 mm); actual groove widths and depths vary with concrete mix properties, adjustment of down-pressure on the tines and timing of the tining operation. Best results are often obtained by using a tining machine that is "tied" to the pavement line and grade to ensure that tining grooves are produced parallel to the roadway centerline and with constant depth.

Longitudinal tining has increased in popularity throughout the U.S. in recent years and is generally reported to result in acceptable friction levels along with lower noise levels (both interior and exterior) and less tonality than transversely tined surfaces (ACPA 2006). Some longitudinally tined pavements have been prone to splash and spray problems, particularly on flat grades and in sag areas in wet climates; these problems can be mitigated with pavement cross-slopes that promote better surface drainage (e.g., 2.0 to 2.5 percent) (Rasmussen et al. 2004).

A guide specification for longitudinal tining can be found at: https://intrans.iastate.edu/app/uploads/2018/08/CPSCP-GS3-LongTining-110301-1.pdf.

Broomed Texture

A texture created by lightly dragging (by hand or by mechanical device) a stiff-bristled broom across the surface to produce either longitudinal or transverse striations with 0.06 to 0.12 inch (1.5 to 3 mm) depth in the pavement surface (figure 14); texture depth varies with stiffness of the bristles, down pressure on the bristles, concrete mix design, timing of the operation and finishing conditions.

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Figure 14. Typical mechanical brooms and resulting concrete pavement texture.

Broomed textures are constructed easily and cost effectively and are relatively quiet. Shallow broomed textures may not provide adequate wet weather friction at high vehicle speeds unless combined with other textures that provide additional macrotexture (e.g., tining or grooving), but may be acceptable for lower speed facilities (Rasmussen et al. 2004).

Exposed Aggregate

A texture generally created by incorporating hard, angular, polish-resistant coarse aggregate in the surface concrete mixture and then exposing that aggregate at some time after placement using either water or a surface-applied set retarder and mechanical brushing (figure 15). This type of texture is not commonly constructed on roadway pavements in the U.S. (ACPA 2006).

Figure 15. Typical exposed aggregate surface.

When designed and constructed properly, exposed aggregate pavements are generally reported to have reduced noise, improved friction and good durability (Sandberg and Ejsmont 2002; Rasmussen et al. 2004). The cost of constructing an exposed aggregate surface typically adds about 10 percent to the paving cost, although much higher costs have been reported on some short demonstration projects (Wu and Nagi 1995).

Textures Constructed in Hardened Concrete

Several techniques have been used for texturing the surface of hardened concrete pavements in order to improve their tire-pavement noise characteristics, friction properties, or both. These techniques include diamond grinding (in various configurations), diamond grooving and shotblasting. The most commonly used grinding and grooving techniques are discussed below. Note that surface milling using carbide teeth, which is often used for asphalt removal and other purposes, is not considered to be an acceptable method of providing concrete pavement surface texture for service conditions because it can damage pavement joints and often creates unacceptable levels of tire-pavement noise.

Conventional Diamond Grinding

Diamond grinding removes a thin layer of the hardened concrete surface (typically 0.1 inches to 0.8 inches [2.5 mm to 20 mm] using closely spaced diamond saw blades (typically 50 – 60 blades per ft. [160 – 200 blades per m]) mounted on a rotating shaft. The resulting texture (see figure 16) varies primarily with aggregate hardness, blade spacing and any post-grind treatment to remove “fins” of concrete left by the grinding head.

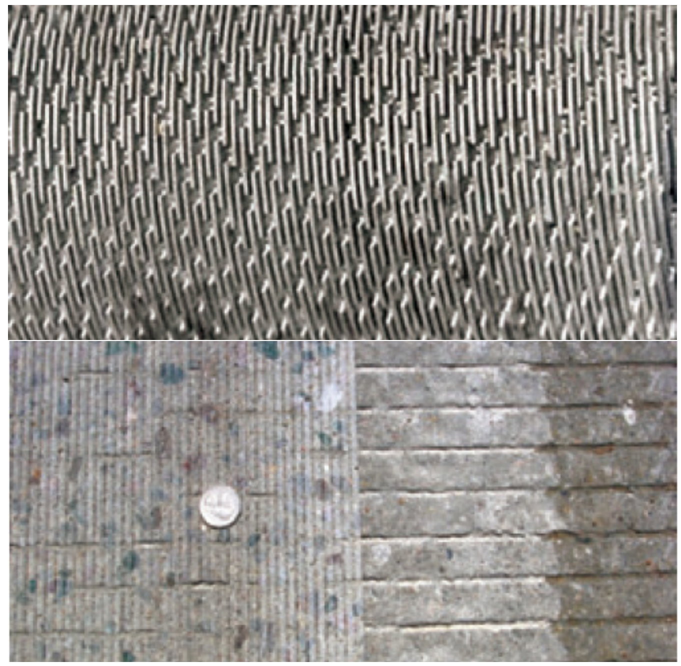

Figure 16. Close-up of diamond grinding head (top) and typical diamond ground surface (bottom left).

Diamond grinding technology today has advanced significantly since its inception in 1956; it is now recognized as a highly effective pavement texturing and surface profiling technique that improves pavement ride quality while restoring surface friction and reducing tire-pavement noise. While it is most commonly used in pavement rehabilitation and restoration programs, diamond grinding is also a viable option for new construction applications, where the cost of grinding may be partially offset with savings realized by reducing or eliminating finishing crews.

The friction and noise-reducing benefits of diamond grinding diminish with age and wear by traffic (depending primarily upon traffic levels and coarse aggregate hardness) but can be renewed with additional grinding operations. The structural reductions associated with slight pavement thickness reductions due to grinding are generally offset by increases in concrete elastic modulus (stiffness) over time (Rao et al. 1999).

A guide specification for diamond grinding can be found at: https://intrans.iastate.edu/app/uploads/2018/08/CPSCP-GS1-DiamondGrind-110301-1.pdf.

Diamond Grooving

Diamond grooving provides macrotexture to hardened concrete by cutting grooves in the pavement surface to produce a texture that resembles tining (figure 17). The grooves are typically cut longitudinally with a blade spacing (center-to-center) of 0.75 inches (19 mm) and a depth of 0.12 to 0.25 inches (3 mm to 6 mm). Grooves are sometimes cut transversely at intersections and on airfield runways.

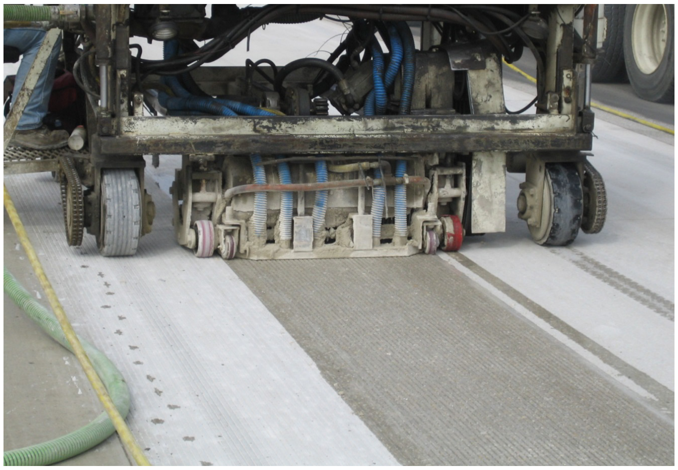

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Figure 17. Diamond grooving of concrete pavement.

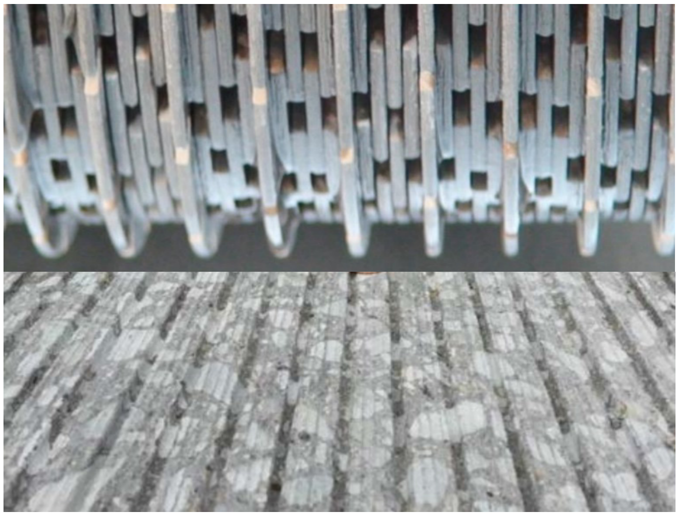
Grooving is highly effective in preventing hydroplaning and improving wet weather pavement friction. Longitudinal grooving also provides increased resistance to lateral skidding in curve sections (ACPA 2006).

Next-Generation Concrete Surface (NGCS)

NGCS is a diamond saw-cut concrete pavement texturing technique, developed around 2006, that produces a texture that resembles a hybrid of diamond grinding and grooving (figure 18). It can be produced on a single pass using a spindle of closely spaced blades with some larger diameter blades to produce the grooves but is more commonly and effectively produced in two passes using a flush grind (with a spindle of single-sized, closely spaced blades) followed by a grooving operation. Close-spaced blade stacks typically use spacers with approximately 0.035-inch (0.9-mm) thickness. The resulting predominantly "negative texture" (i.e., a level surface with grooves and very little upward-oriented texture) provides good dry- and wet-weather friction and is one of the quietest concrete pavement textures available (Scofield 2012).

NGCS is typically constructed on pavement surfaces that are already reasonably smooth (either new construction or recently diamond ground using conventional equipment. NGCS construction costs are usually significantly higher than the costs of conventional diamond grinding because of the need for up to three equipment passes (i.e., conventional diamond grinding, flush grind and grooving). NGCS is suitable for both pavement restoration and new construction and has been used on projects in many states.

Industry-produced specifications for the construction of NGCS can be found at: https://www.igga.net/wp-content/uploads/2018/08/NGCS_Construction_Existing_Newly_Constructed_Roads_093014.pdf .



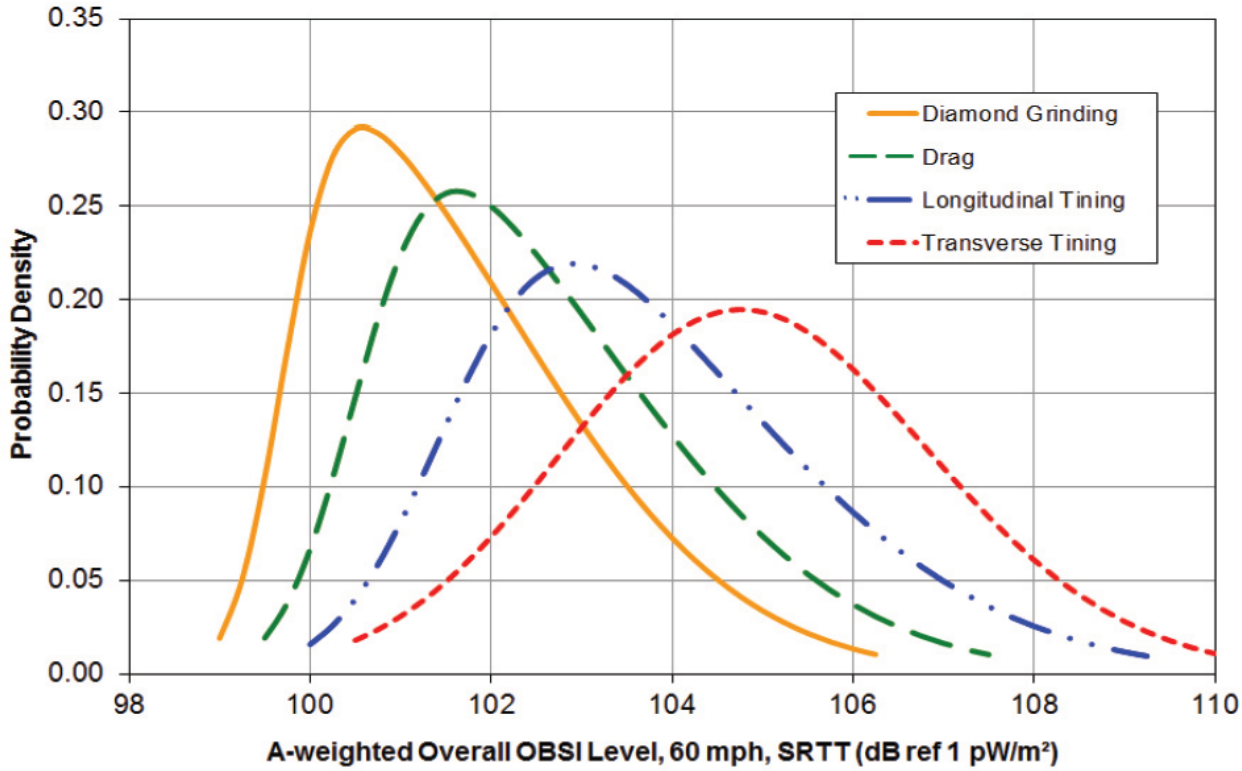
Top: © 2017 Larry Scofield; bottom source: FHWA

Figure 18. Close-up of single-pass NGCS grinding head (top) and resulting texture (bottom).

Noise and Safety Characteristics of Concrete Pavement Surface Textures

The friction and potential tire-pavement noise characteristics of each of the texturing techniques described previously can vary significantly within any given texture type because they are impacted by many factors. These factors include texture design, depth and orientation, polish-susceptibility of the coarse and fine aggregates, paste strength and density, pavement age and amount of traffic wear, environmental conditions, and others. The impacts of these factors on sound intensity levels due to tire-pavement interaction can be seen in figure 19 (Rasmussen et al. 2012b), which summarizes a portion of the On-Board Sound Intensity (OBSI) data collected from more than 1600 pavement test sections in North America and Europe between 2004 and 2012. It can be seen that the sound levels associated with longitudinally oriented textures (i.e., grinding, drag textures and longitudinal tining) were generally quieter and exhibited less variability than those associated with transverse tining.

The researchers state that, based on these data, it appears that a reasonable target sound threshold for new concrete pavements is 101 – 102 dB(A) measured using an OBSI at 60 mi/h (97 km/h) and they concluded that most diamond ground textures and about 1/3 of the longitudinal drag textures studied met this goal. The few transversely tined pavements that met this goal had spacings of 0.5 inch (13 mm) or less. The pavements included in the study represented both new and in-service pavements; however, the conclusions may not be applicable to short paving sections and hand placements where profile and texture are more difficult to control.



Source: FHWA

Figure 19. Normalized distributions of OBSI levels for conventional concrete pavement textures.

Hall et al. (2009a) collected texture, friction and noise data for 57 existing pavement test sections in 13 states, as well as for several test sections that were newly constructed in 2007. Table 1 presents a summary of texture depth, friction and noise value ranges for some of the pavement textures evaluated and shows the range of values measured for each texture type, along with the differences in texture, friction and noise that are measured using different techniques. It clearly illustrates the impact of texture depth and type both friction and roadway noise. In addition to the pure measures of sound presented in table 1, spectral analyses of sound from the existing transversely tined pavement sections found prominent tonal spikes, sources of sonic irritation, for pavements with 0.5-inch (13 mm), 0.75-inch (19 mm) and 1-inch (25 mm) tine spacings.

In general, Hall et al. (2009b) concluded the following:

- Longitudinal tining, longitudinal grooving and diamond grinding offered the greatest potential for reducing tire-pavement noise while providing adequate friction.
- Variable-spaced transverse tining and skewed tining offered the potential to eliminate objectionable tones in the tire-pavement sound while achieving high levels of friction.
- Turf drag textures offered the potential for low noise generation, but "significant texture depth is needed to ensure adequate friction at high speeds."
- "Positive" textures (i.e., aggressive protruding surfaces, such as those created by exposed aggregate) are generally noisier than "negative" textures (i.e., flat, pocketed surfaces, such as those created by grooving and NGCS); diamond ground textures, which were classified as positive textures, were the exception to this finding, exhibiting low noise.

Table 1. Typical texture depth, friction and noise ranges for various types of PCC surface textures (after Hall et al. 2009a).

Method	Texture Range MTD, mm	Texture Range MPD, mm	Friction Range FN40R	Friction Range FN40S	Noise Range CPX, dB(A)	Noise Range CPB Lmax, dB(A)
Transverse Tining (0.75 in.)	0.53 to 1.1	0.50 to 0.52	41.0 to 56.0	30.6 to 34.4	100.4 to 104.8	83.0 to 84.0
Transverse Tining (0.5 in.)	-	0.35 to 1.00	54.0 to 71.0	37.6 to 62.0	-	81.9 to 83.0
Transverse Tining (variable)	1.14	0.42 to1.02	-	50.0 to 69.5	-	81.0 to 87.3
Transverse Groove	1.07	-	-	48.0 to 58.0	-	84.1 to 84.6
Transverse Drag	0.76	-	22.0 to 46.0	-	-	-
Longitudinal Tine	1.22	-	-	36.0 to 76.6	96.6 to 103.5	79.0 to 85.0
Longitudinal Groove	1.14	-	-	48.0 to 55.0	99.4 to 103.8	80.9
Longitudinal Grind	0.30 to 1.20	-	35.0 to 51.0	29.9 to 46.8	95.5 to 102.5	81.2
Longitudinal Burlap Drag	-	-	-	-	101.4 to 101.5	-
Longitudinal Turf Drag	0.53 to 1.00	-	23.0 to 55.6	20.0 to 38.0	97.4 to 98.6	83.7
Longitudinal Plastic Brush	-	-	48.0 to 52.0	23.0 to 24.0	101.8 to 102.2	-
Exposed Aggregate Concrete	0.9 to 1.98	-	35.0 to 42.0	-	-	-

- No data

Durability and Maintenance of Concrete Pavement Surface Textures

It is inevitable that pavement texture becomes worn with time and traffic, thereby impacting measures of texture, friction and noise, generally in an adverse manner. The degree to which this loss of texture takes place in concrete pavements varies with the aggregate type/hardness and mix proportions, environmental conditions, traffic levels, and also initial texture type (as finely textured pavements, such as are created using drag techniques, are generally more susceptible to significant texture loss than textures with more constructed macrotexture, such as tining, grooving, exposed aggregate or porous concrete). Table 2 presents a summary of macrotexture data collected by Hall et al. (2009a) for typical texture types before and after age/traffic for common concrete pavement texturing techniques.

Hall et al. (2009a) also noted significant impacts of aggregate type and quality on the rate of microtexture loss. For example, the use of granitic rock in Colorado and Minnesota test sections resulted in high initial friction values that remained high after large amounts of traffic, while the use of limestone in Kansas and Illinois test sections resulted in greater rates of microtexture deterioration.

Table 2. Summary of typical macrotexture values for new and aged concrete pavement textures (after Hall et al. 2009a).

Pavement Age	Texture Type	Typical MTD for Aged/ Trafficked Textures, mm	Typical MTD for Newly Created Textures, mm
New Pavement Applications	Burlap. Broom and Standard Turf Drags	0.30 to 0.45	0.35 to 0.50
	Heavy Turf Drag	0.40 to 0.80	0.50 to 0.90
	Transverse and Transverse Skewed Tining	0.50 to 1.15	0.60 to 1.25
	Longitudinal Tining	0.50 to 1.15	0.60 to 1.25
	Longitudinal Diamond Grinding	0.50 to 1.25	0.70 to 1.40
	Longitudinal Grooving	0.70 to 1.40	0.80 to 1.50
	Exposed Aggregate Concrete	0.75 to 1.50	0.90 to 1.60
Restoration of Existing Pavement	Longitudinal Diamond Grinding	0.50 to 1.25	0.70 to 1.40
	Longitudinal Grooving	0.70 to 1.40	0.80 to 1.50

BEST PRACTICES FOR SURFACE TEXTURE SELECTION, DESIGN, AND CONSTRUCTION

The selection of a texturing technique for any given concrete pavement must consider the specific needs of the facility, and should recognize that those needs (and, therefore, the most appropriate texturing technique) can vary significantly over relatively short distances. For example, friction demands vary with traffic characteristics (i.e., speed, volume and composition), vertical and horizontal highway alignment, highway geometric features (e.g., intersections, driveways, turn lanes, etc.) and more. Similarly, noise abatement considerations may vary over relatively short distances with right-of-way dimensions, noise mitigating features (e.g., vegetation and/or noise walls), land use type (i.e., industrial, commercial or residential) and traffic considerations (Hall et al. 2009a).

Other factors that may be considered in pavement texture selection include ease and cost of construction, future user costs (in the form of fuel consumption) due to rolling resistance and tire wear, and other factors. Regardless of these considerations, however, the overarching consideration in pavement texture selection is safety (FHWA 2005).

A rational approach for selecting concrete pavement texture should be used. One such approach has been proposed by Hall et al. (2009a) and is illustrated in figure 20. The proposed process uses key project information to establish target levels for friction, noise and other surface characteristics (Step 1), and then combines this information with the consideration of available aggregate types and contractor experience with texturing options to identify feasible texturing options (Steps 2 and 3). It then considers the cost (both initial and over the pavement life cycle) of each feasible texturing option in the context of economic constraints to arrive at one or more texturing alternatives that are preferred for the specific project or project segment. Expanded explanations and discussions of each step in this selection process are presented in Hall et al. (2009a).

Hall et al. (2009a) also prepared table 3, a summary of the relative friction values, noise characteristics, costs and constructability of various concrete pavement texturing techniques based on data collected from their study sections. It provides useful information for decision-makers that must select concrete pavement texturing options when it isn't feasible to perform a detailed analysis process of the type described above.

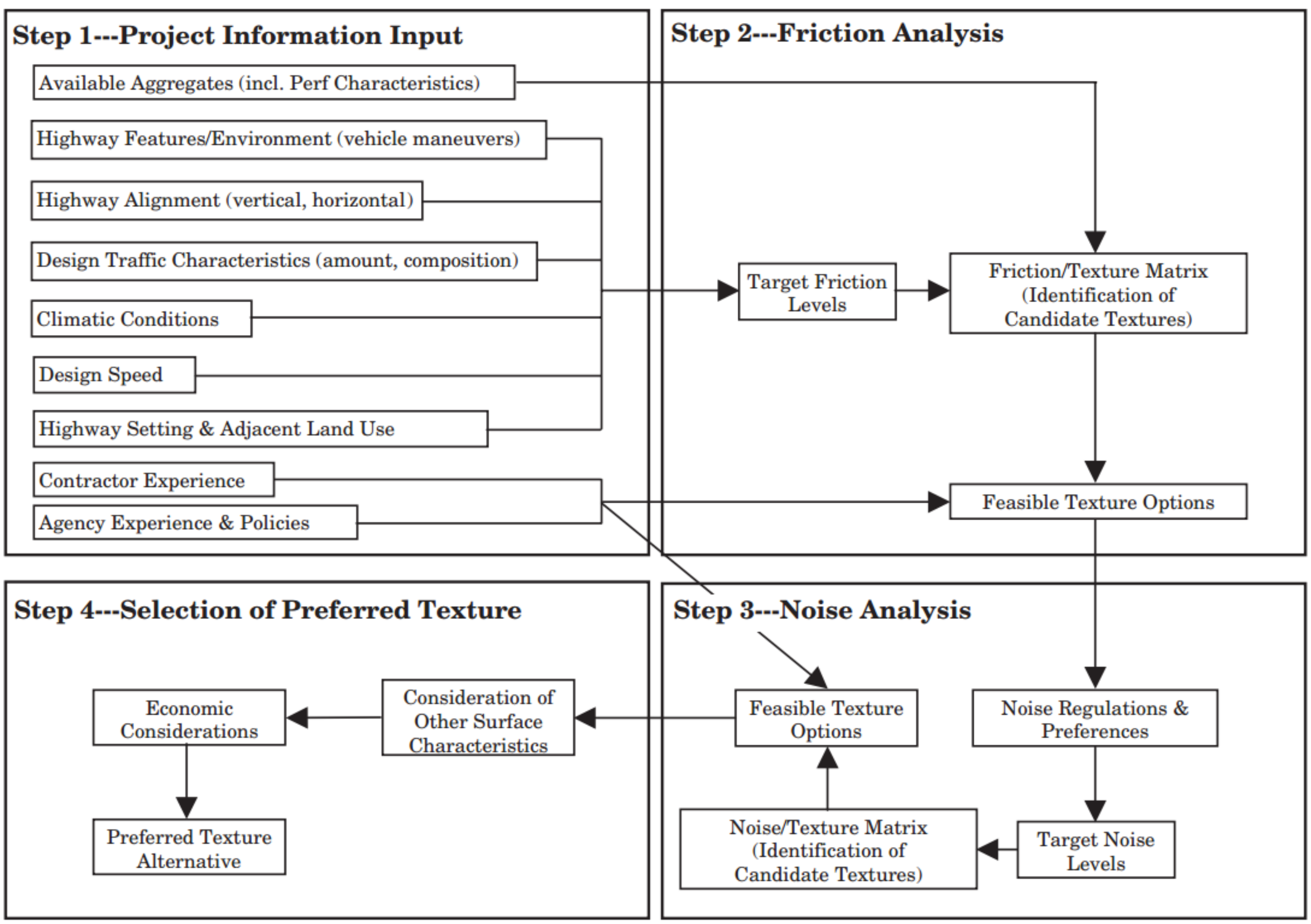


Figure 20. Process for identifying pavement surface texturing options.

Table 3. Relative ratings of various concrete pavement texturing options over several possible decision criteria (after Hall et al. 2009a).

Method	Friction	Exterior Noise	Cost	Constructability
Transverse tine (0.75-in spacing)	1	8	1	2
Transverse tine (0.5-in spacing)	1	6	1	2
Transverse tine (variable spacing)	1	7	1	2
Transverse groove	1	7	4	3
Transverse drag	2	6	-	2
Longitudinal tine	1	4	1	1
Longitudinal groove	1	5	3	3
Longitudinal grind	1	3	3	3
Longitudinal burlap drag	4	3	1	1
Longitudinal turf drag	2	3	1	1
Longitudinal plastic brush	3	3	1	1
EAC	2	3	3	4
Shotblasted PCC	1	7	2	3
Porous PCC	1	1	5	4
Ultra-thin epoxied laminate	1	2	6	3
Ultra-thin bonded wearing course	2	2	3	3

1 = Best/highest ranking

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