IMPLICATIONS of TIRE-PAVEMENT NOISE & TEXTURE MEASUREMENTS

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ABSTRACT

Tire-pavement noise emissions exceed those from other highway noise sources even at low vehicle speeds. The on-board sound intensity (OBSI) technique for tire-pavement noise measurement has been used to rank various pavements but little has been done applying OBSI results to a priori pavement design. Tire–pavement noise is the summation of sub-sources—of which texture is an important contributor. This paper examines the influence of texture on sound intensity based upon a review of the measurements performed to date.

Pavement texture is best described by texture profile level, a logarithmic measure of the profile depth. Texture profile level as function of profile *wavelength* can be transformed to a function of *frequency* considering vehicle speed. After accounting for speed, the correlation of texture geometry and tire–pavement noise is apparent—such that texture is a controlling factor below about 1600 Hz at standard test conditions. Testing at a single, reference speed, i.e., 60 MPH, is inadequate to understand the texture contribution to overall tire–pavement noise and to quantify pavement contributions in highway noise predictions. Texture-induced noise may negate the benefits porous pavements. Vehicle noise emission levels for highway noise prediction (REMELs) that include tire-pavement noise must be deconstructed into sub-source "REMELs" for the various tire-pavement noise mechanisms.

Further testing is needed to confirm these conclusions: OBSI should be measured simultaneously with pavement texture level (as a function of profile wavelength); and vehicle speed. Measured OBSI should be analyzed with respect to A-weighted texture level in the frequency domain.

INTRODUCTION
The on-board sound intensity (OBSI) technique*(1)* for tire-pavement noise measurement has been used widely in the United States to create a database that ranks the performance of various pavements allowing the empirical selection of preferred designs and providing qualitative design guidance. With the exception of work by Rasmussen, et. al.*(2)* little has been done in the U.S. applying OBSI results to a priori quantitative pavement design. In Europe, more thought has been expended towards the analytical characterization of tire-pavement noise—but, without taking advantage of OBSI measurement capabilities.

This paper examines the influence of texture on tire-pavement sound intensity without consideration of other pavement parameters (e.g., porosity and stiffness) and tire design. It is based entirely upon measurements performed by others. Other pavement performance considerations, such as, wear and skid resistance, also are not addressed.

NEED
Quieter pavements will permit the reallocation of limited resources away from noise barriers ("vertical pavement") to other highway needs. First, quieter pavements must prove their effectiveness. Then, tire–pavement noise emissions must be quantified as a function of vehicle operating condition to allow the assessment of a highway with respect to Federal Regulation 23 CFR Part 772.*(3)* Ultimately, the goal for research is the ability to design quieter road surfaces.

Reduced-Noise Pavement Currently, roadways can be designed to be quieter by selecting from pavements which have been found to perform better in standardized testing. However, low-noise performance has been found to degrade over time. Pavement texture can have considerable influence (both magnitude and tonal content) on noise generation—as demonstrated by transversely tined surfaces. Understanding the trade-offs of texture and other pavement design features (e.g., porosity) is needed. Knowing the contributions of all design features affecting noise may enable the a priori optimization of noise performance with other pavement design requirements, such as, skid resistance, water spray, and durability.

Reference Noise Emissions Pavement-specific, speed-dependent noise emission levels are needed for highway traffic noise predictions to assess compliance with Part 772 via the FHWA Traffic Noise Model (TNM)*(4)*. Procedures for quantifying quieter-pavement benefits beyond the right-of-way are prerequisite to acceptance of low-noise pavements. The noise generated by vehicles in traffic is currently quantified in terms of the speed-dependent reference energy mean emission levels (REMELs) shown in FIGURE 1.*(5)* As implemented for Part 772 compliance, REMELs are required to be an *average* of measurements with Portland cement concrete (PCC), dense-graded asphalt concrete (DGAC), and open-graded asphalt concrete (OGAC) roadways. If pavement design is to be considered in TNM, new algorithms are needed—functions of pavement texture, etc.
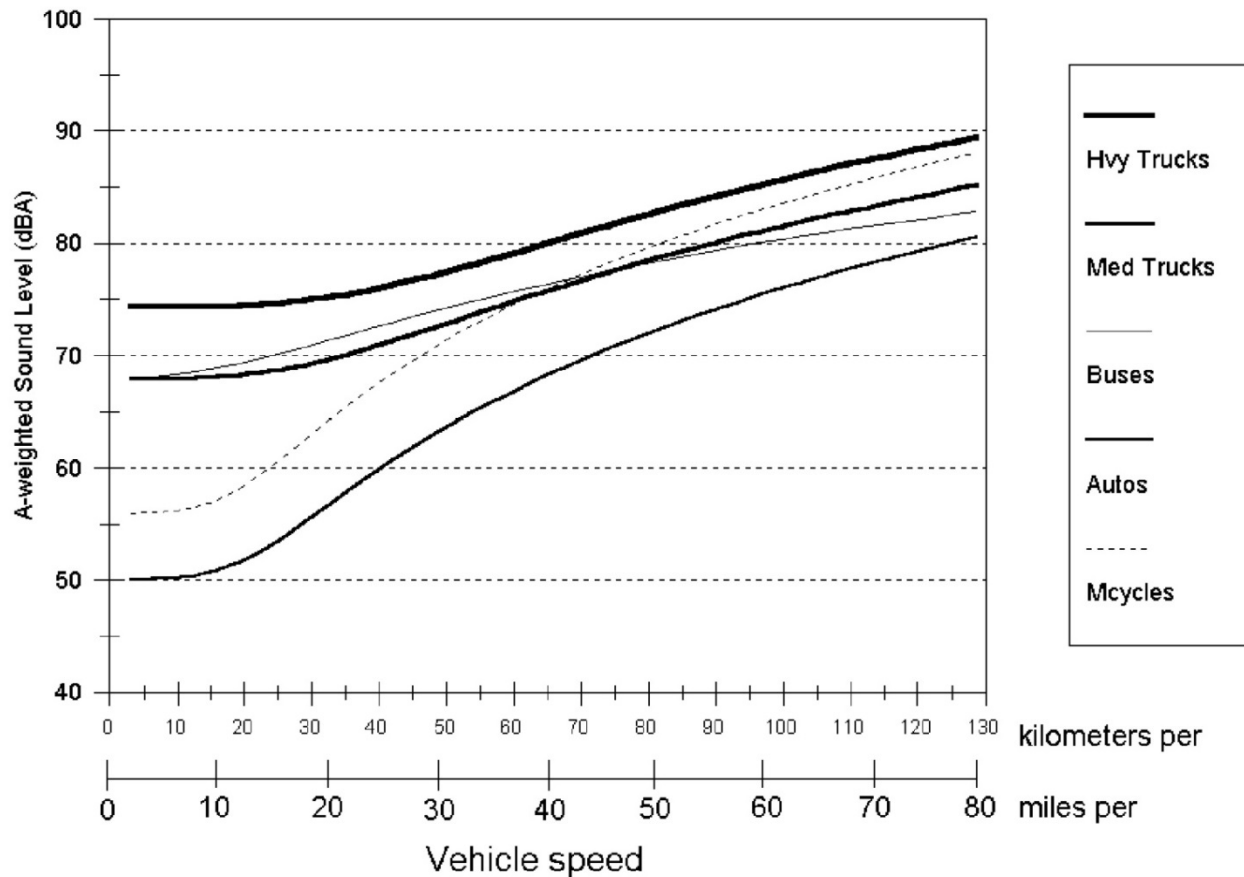
FIGURE 1 Speed-Dependent Vehicle Noise Emission Levels

A-Weighted Reference Energy Mean Emission Levels (REMELs) under
cruise conditions on "average" pavement

BACKGROUND

Total vehicle noise is the result of emissions from the—engine, exhaust, cooling fan, and tire-pavement interaction. Donovan concluded that the tire-pavement contribution dominates other sources for "almost all" noise from vehicles in cruise at ≥35 MPH.*(6)* Tire-pavement noise itself is the summation of a number of mechanisms*(7)*

- Generation Mechanisms
  - Tread impact ("The Hammer")
  - Air pumping ("The Clapper")
  - Stick-slip ("The Sneaker")
  - Stick-snap ("The Suction Cup")
- Amplifying Mechanisms
  - Acoustical Horn ("The Horn")
  - Helmholtz Resonance ("The Pop Bottle")
  - Pipe Resonance ("The Organ Pipe")
  - Sidewall Vibrations ("The Pie Plate")
  - Cavity Resonance ("The Balloon")

These processes each vary with vehicle speed and potentially result in a concurrence of causes—or, per Sandburg and Ejsmont, a "multi-coincidence peak." Each mechanism has characteristic frequencies.*(8)* For example, the prominent OBSI peaks in FIGURE 2 are the consequence of one or more mechanism—or their coincidence.*(9)* (A periodic 1-in. pavement or tire tread perturbation corresponds to about 1100 Hz at 60 MPH.) These mechanisms can be expected to be a function of vehicle speed, v,

$$\text{OBSI} = k_1 \log_{10}(v) + k_2 \log_{10}(v) \ldots + k_n \log_{10}(v).$$

where the k_i are determined from OBSI testing in conjunction with measurements of pavement texture, porosity, layer thickness and number, stiffness, etc. An example of the summation of component noise sources is shown in FIGURE 3 for high-speed trains.*(10)* For tire–pavement noise, Goubert speculated the coefficients, k_i, given in TABLE 1.*(11)*

       The pavement part of the OBSI equation is a function of:*(12)*
o   Texture,
o   Porosity, and
o   Stiffness.
The importance of texture is evident from the tonal noise produced by transversely tined PCC pavements—clearly related to the tining spacing interval.

       Texture is the deviation of the pavement surface from a true planar surface. Texture itself is defined by three parameters:*(12)*
o   Profile Depth, a;
o   Wavelength, λ; and
o   Skewness (profile asymmetry or bias).
The texture profile is the texture depth as a function of longitudinal or lateral distance along the pavement. Texture wavelength is the Fourier transform of the texture profile (analogous to the time-frequency transform). The texture forcing function depends upon the characteristic dimensions within the texture continuum—often illustrated by FIGURE 4—where tire–pavement noise generally is considered to fall in the 0.5–500-mm wavelength (macrotexture–megatexture) range.

| SOURCE	SPEED RELATIONSHIP	FREQUENCY RANGE
Air Pumping	40→50	1→3 kHz
Tire Vibration (surface irregularities coupling to tire sidewalls)	20→30	500 Hz→3 kHz
Stick-Slip & Snap-Stick	30→50	1→6 kHz
Resonances (leading/trailing edge contact zone channels—Helmholtz resonances)	0	500 Hz→3 kHz
Resonances (tire cavity)	0	1→2 kHz

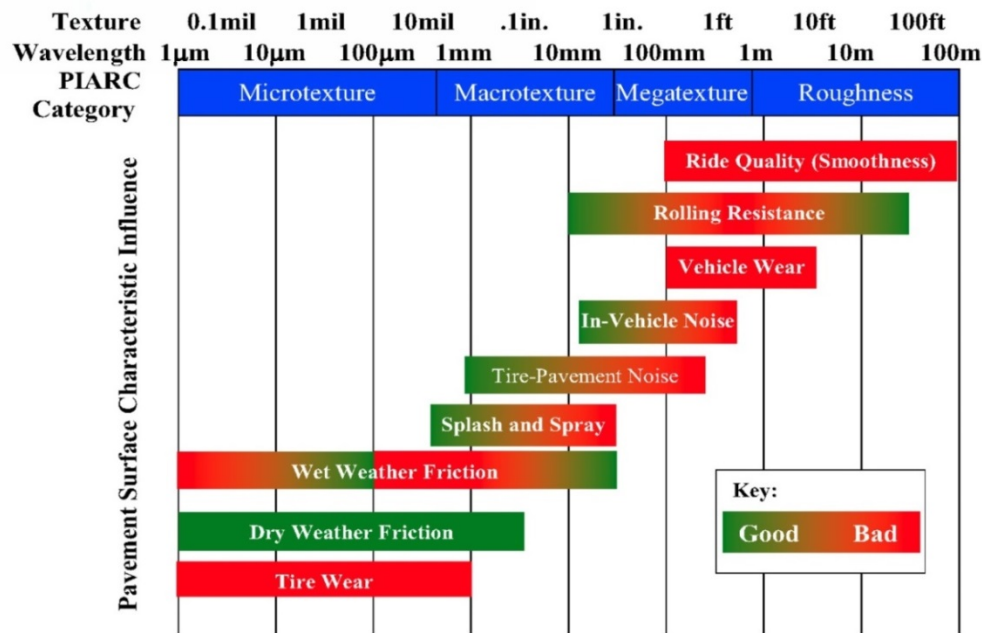**TABLE 1 Tire-Pavement Noise Source Speed Relationships, k**

Per Goubert
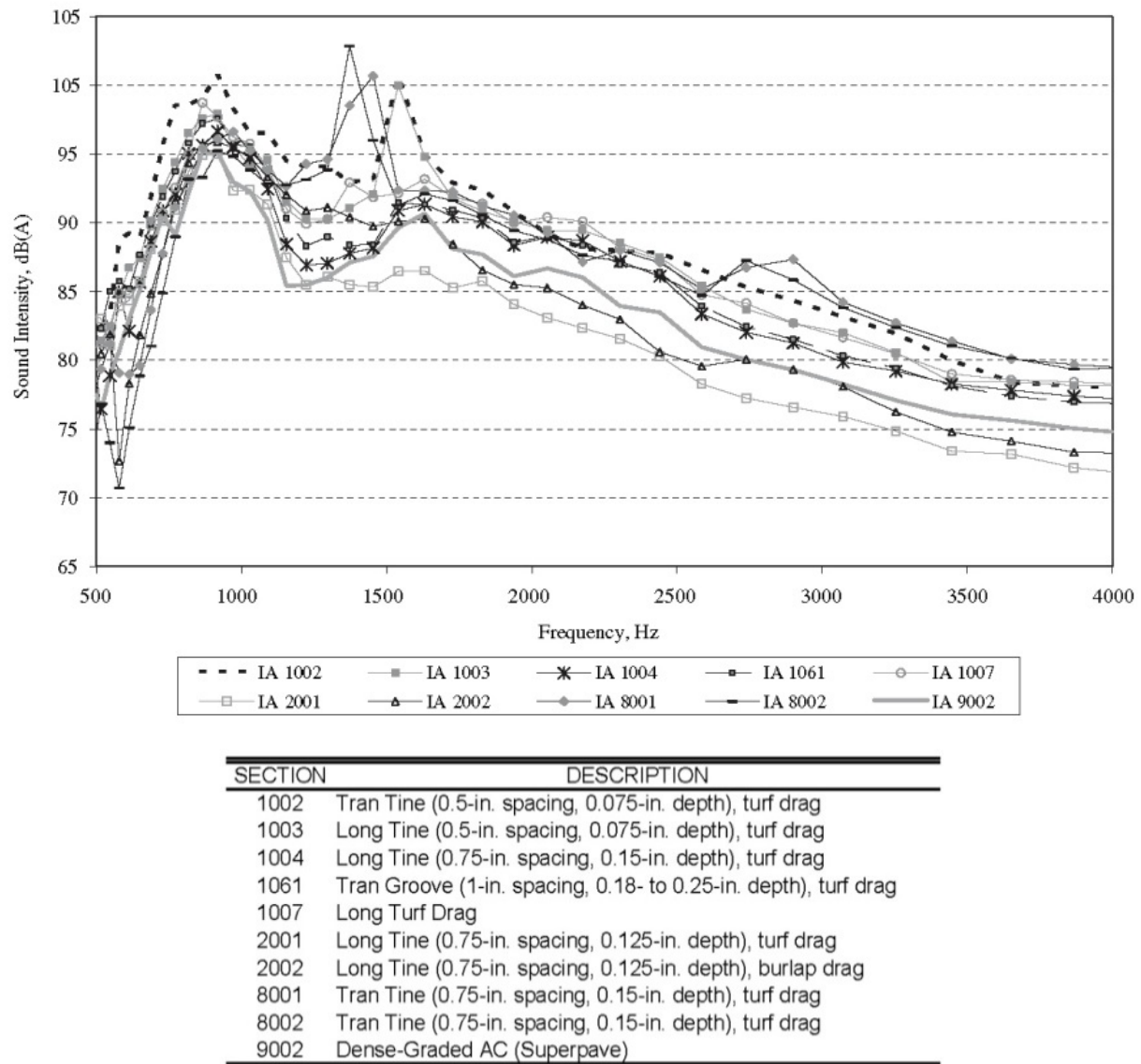
FIGURE 2 Tire-Pavement Narrowband OBSI Spectra

1/12th octave band spectra, Goodyear Aquatred III test tire, Iowa roads per NCHRP 634
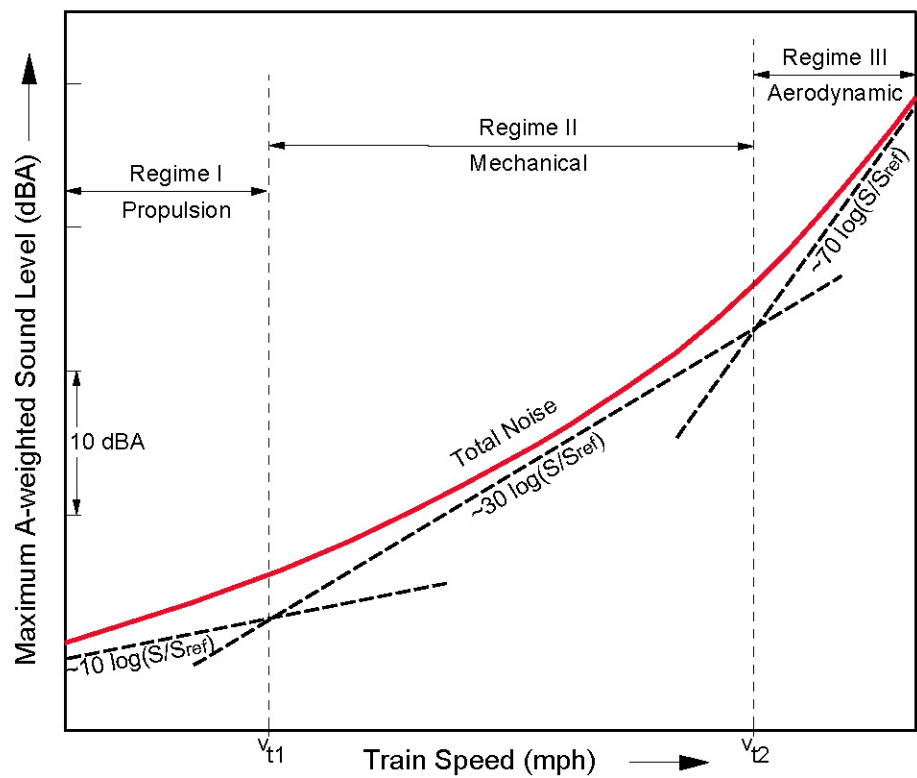
FIGURE 3 Example of Summation of Speed-Varying Noise Sources

noise source speed dependence for high-speed train per FRA

FIGURE 4 Texture Categories and Importance

texture classification per Permanent International Association of Road Congresses (PIARC)

For a given profile depth, skewness (the bias of the texture depth illustrated by FIGURE 5) may significantly affect noise generation. Positive skewness is characterized by peaks with respect to some reference measure of texture depth. Negative skewness is characterized by the valleys. Several descriptors to quantify skewness have been proposed but none have been standardized.

Profile depth and skewness are understood to affect the noise magnitude of the tire-pavement noise. The profile spacing interval of texture perturbations (texture wavelength) affects its frequency.

Profile depth can be quantified in terms of mean profile depth (MPD) or texture profile level (L_{tx}). MPD is an average over a 100-mm length of pavement in the direction of travel—measured per ASTM standard.*(13)* In this method, profile depth is defined relative to the peak in a 50-mm segment, $\lambda > 2.5$ mm, where the profile may be determined via a contact method with a stylus. As can be seen in FIGURE 6, MPD discards much of the texture information since it is an average over an extended distance. On the other hand, texture profile level retains the details using Fourier analysis of the periodically sampled profile depth, per ISO standards.*(14,15)* Furthermore, as a "level" quantity it can be related more directly with sound levels. (That is, $L_{tx} = 10 \log 10 \ (a/a_{ref})^2$, where a is texture depth.)
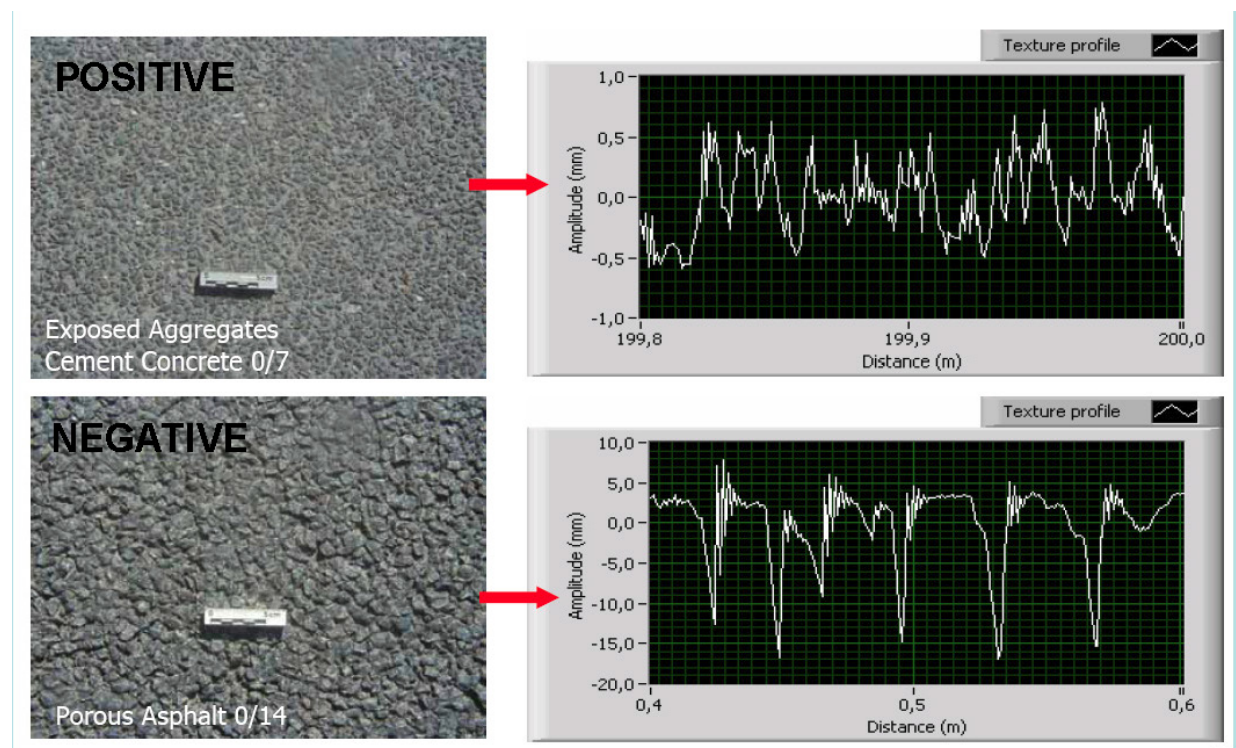
FIGURE 5 Skewness

per Goubert
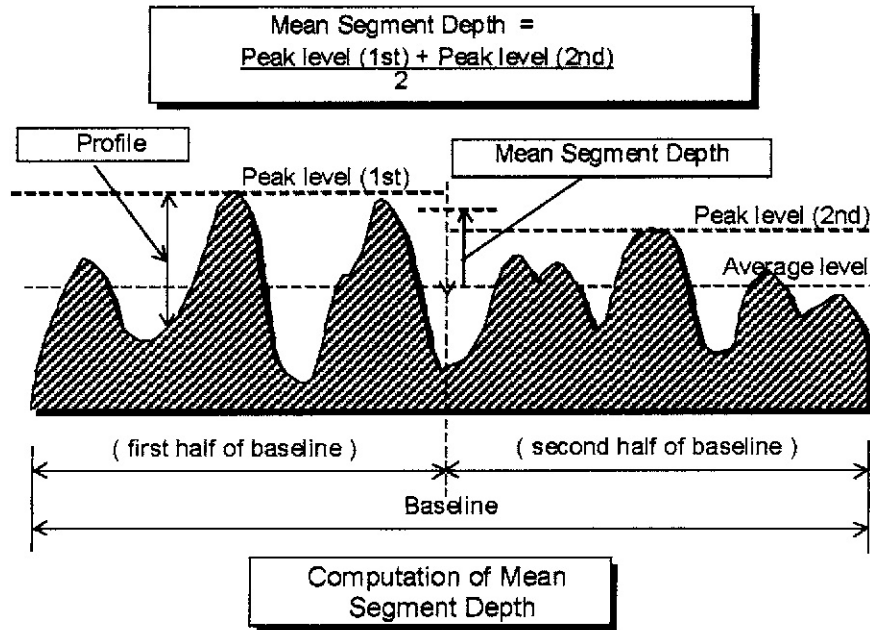
FIGURE 6 Mean Profile Depth

procedure for calculating pavement macrotexture Mean Profile Depth per ASTM E1845

SOUND INTENSITY v. TEXTURE

Speed–Frequency Dependency An example of a texture profile level *wavelength* spectrum, $L_{tx}(\lambda)$, was reported by Rasmussen, et. al.*(2)* and is shown in FIGURE 7. Rasmussen conjectured a "bridging filter" to improve the correlation of texture and OBSI. This "filter" is the result of the tire treads spanning the pavement surface irregularities (i.e., the texture profile peaks not penetrating the tread rubber) with a 1-kHz roll-off frequency.

However, a wavelength spectrum does not fully describe the texture relationship with noise—just as the spacing of the pickets of a picket fence alone does not determine the frequency of sound produced by running a stick along the fence. The wavelength spectrum must be transformed into a frequency spectrum. Therefore, vehicle speed must be considered, i.e., $f = v/\lambda$ where v is vehicle speed. Human hearing sensitivity varies with frequency (reaching a maximum at about 2500 Hz). Consequently, the frequency-dependent A-weighting also should be added if texture is to be related to OBSI. The pavement texture described by FIGURE 7 will result in the texture level *frequency* spectrum, $L_{Atx}(f)$, given in FIGURE 8, at 60 MPH.

Rasmussen, et.al.*(16)* documented the results of extensive measurements of on-board sound intensity including on the four transversely tined surfaces also shown in FIGURE 8. These spectra have the same tining interval as the pavement shown in FIGURE 7. The correspondence between OBSI and texture level is clearly evident ≤1.6 kHz. This strongly suggests that pavement texture is responsible in the lower frequencies.
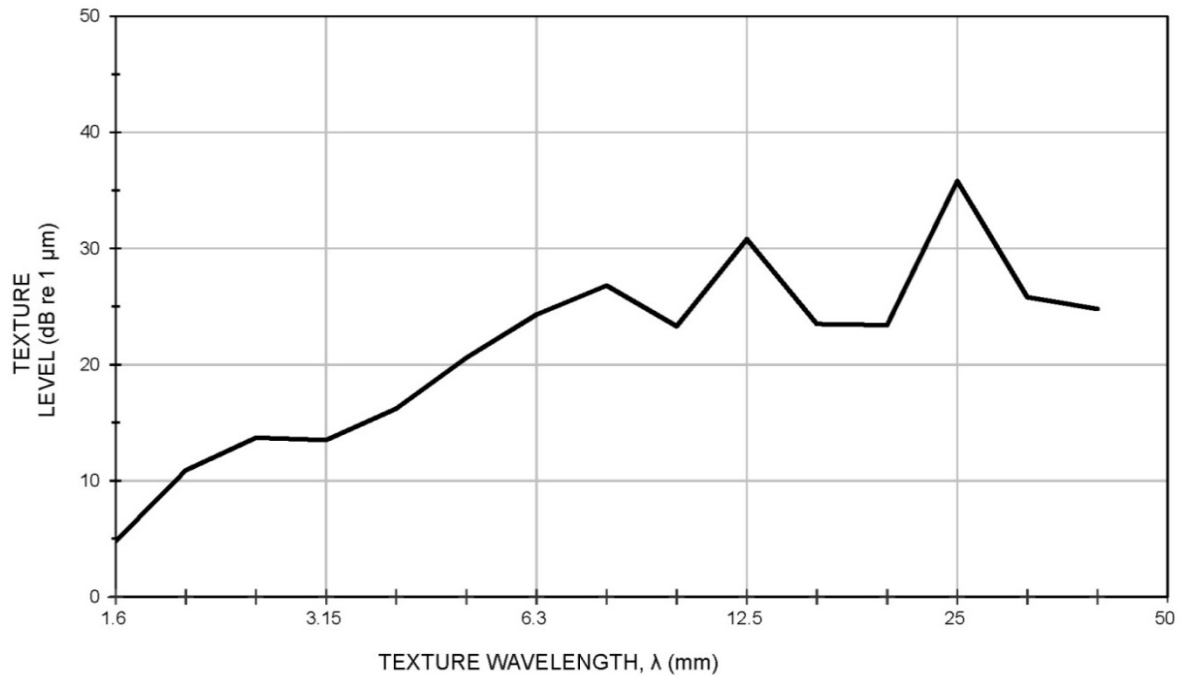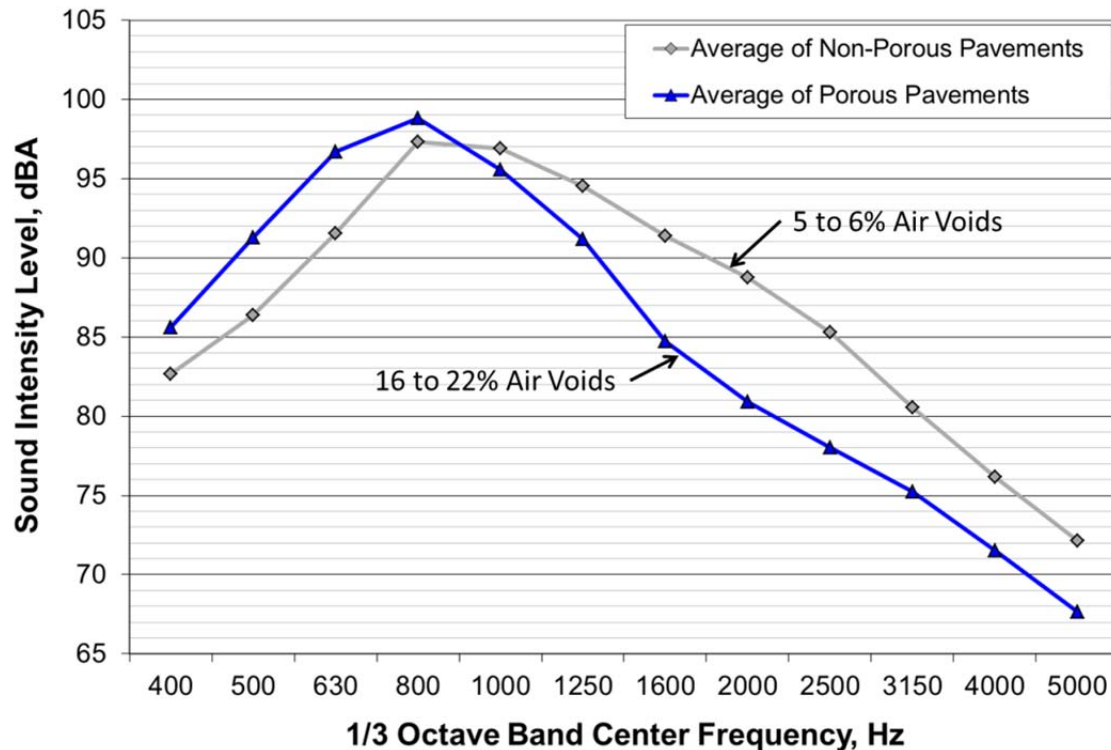
FIGURE 7 Wavelength Spectrum—Texture Level

transverse tined pavement, per Rasmussen et. al.
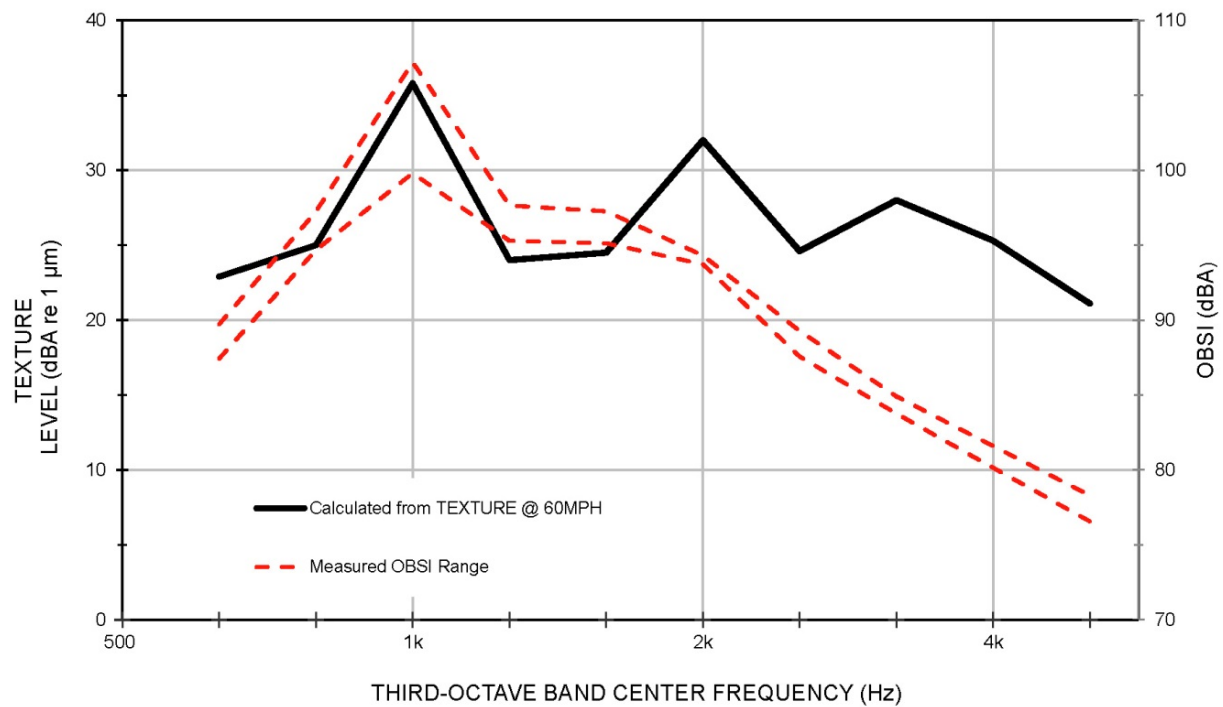
FIGURE 8 Frequency Spectra—Texture Level And OBSI

A-weighted texture level @ 60 MPH calculated from FIGURE 7 and OBSI from Rasmussen et. al.

FIGURE 9 OBSI of Porous and Non-Porous Pavements
Comparison of OBSI ⅓ octave band spectra for averages of porous and non-porous pavements
as measured at the National Center for Asphalt Technology test track

The texture-predicted OBSI spectrum in FIGURE 8 also is consistent with the porous pavement measurements by Donovan for asphalt surfaces (per FIGURE 9). National Center for Asphalt Technology (NCAT) testing cited by Donovan showed the differences in spectral shape indicative of the influence of pavement porosity. In FIGURE 9, average OBSI levels of tested porous and non-porous pavements are shown along with their percent of air voids. Donovan noted:

> "For OGAC [open-graded asphaltic cement] pavements, increased porosity is often achieved with larger aggregate size which creates more void area in the pavement. The larger aggregate size also generates higher lower frequency noise due to increased surface roughness. For the non-porous OGAC, the aggregate is smaller creating less roughness and lower frequency noise, but also resulting in less void area and porosity."

Donovan's measurements found that—compared with non-porous pavements—porous-pavement sound levels were lower above about 1600 Hz, but were *higher* at lower frequencies (630–1000 Hz).*(17)* FIGURE 8 and FIGURE 9 both suggest that the tire may be functioning as a filter, but with cutoff frequency of about 1600 Hz. These results are reasonably consistent with Rasmussen's 1000-Hz "bridging filter." The implication is that pavement texture is not only important for tined PCC pavements but also asphalt concrete surfaces.

If this hypothesis is correct, at least some of the features found in an OBSI spectrum measured at 60 MPH will be seen at other speeds with scaled amplitudes and frequencies. Results reported as part of the Noise Intensity Testing in Europe (NITE) Study (*18*) provide a test of this premise   In that study, measurements of a—relatively quiet—porous, single-layer, fine-aggregate DGAC pavement were reported at 35 MPH and 60 MPH. The 60-MPH spectrum was

scaled to 35 MPH—assuming a 30 log (v) relationship—and compared to the 35-MPH measurement. The result is shown in FIGURE 10. The ≤1600 Hz portion of the 60-MPH spectrum when scaled to 35 MPH agrees well with the corresponding ≤1000 Hz portion of the measured 35-MPH spectrum. This lends support to the texture influence (although the effect of the tire cannot be ruled out).

Implications for Quieter Pavement Porous pavements have shown promise as a noise control. However, the findings above suggest that texture may be a limiting factor to the sound level reduction provided by increased porosity. If the low-pass-filtered character of texture-induced noise is a result of bridging or other fixed-geometry mechanism, the filter cutoff varies with *vehicle speed*. Consequently, the attenuated portion of the OBSI varies as the texture-profile-generated frequencies. This is illustrated in FIGURE 11 where the texture spectral content at 60 MPH—which correlates well with OBSI in FIGURE 8 (630–1600 Hz)—is scaled to 40 MPH and 75 MPH (referenced to 1000 Hz texture-induced sound level at 60 MPH) with source strength assumed OBSI ≈ 30 log (v) consistent with Goubert and NITE Project data. Clearly, relative to a 60-MPH OBSI, the importance of texture will become less at lower speeds. At higher speeds, the noise from longer texture wavelengths will migrate to the higher frequencies to which humans are more sensitive. For porous pavements such as tested at NCAT, the implication is profound—at high vehicle speeds, the benefit of porous pavements will be diminished or emissions may even increase. Furthermore, the longer megatexture wavelengths, not currently considered significant (~250-800 mm) will play an increasing role. At some vehicle speed, texture, acoustic, and mechanical mechanisms may coincide producing the multi-coincidence peak per Sandberg and Ejsmont.
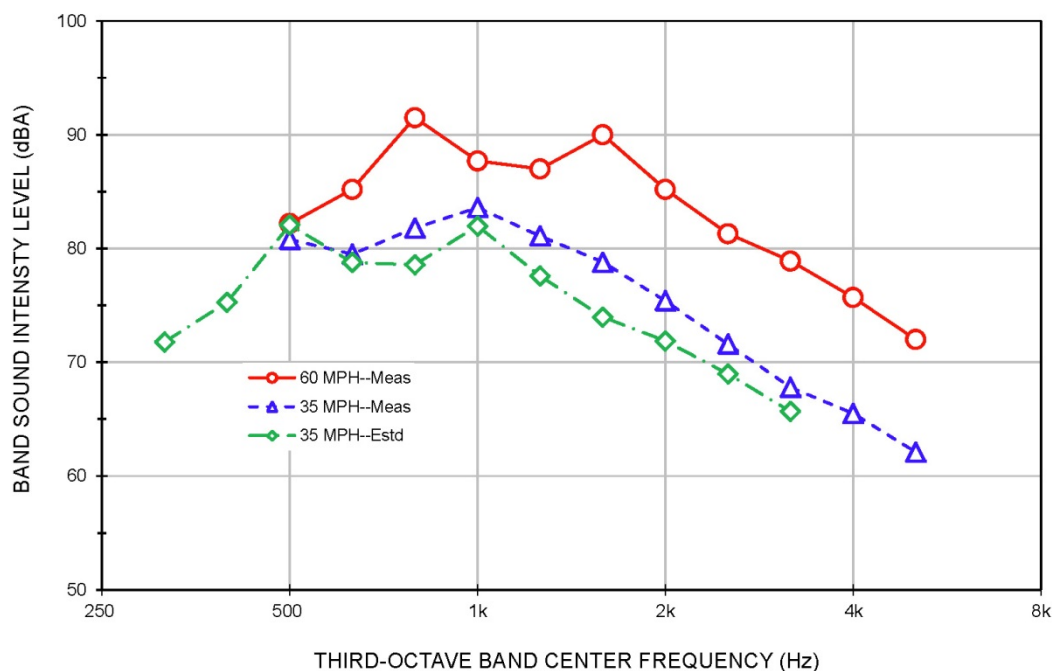
FIGURE 10. OBSI Spectra at 35 MPH and 60 MPH
NITE Project CA/AZ #4 DGAC Fine Aggregate pavement, "35-MPH Estd" = measured 60-MPH spectrum scaled to 35 MPH as 30 log (v)
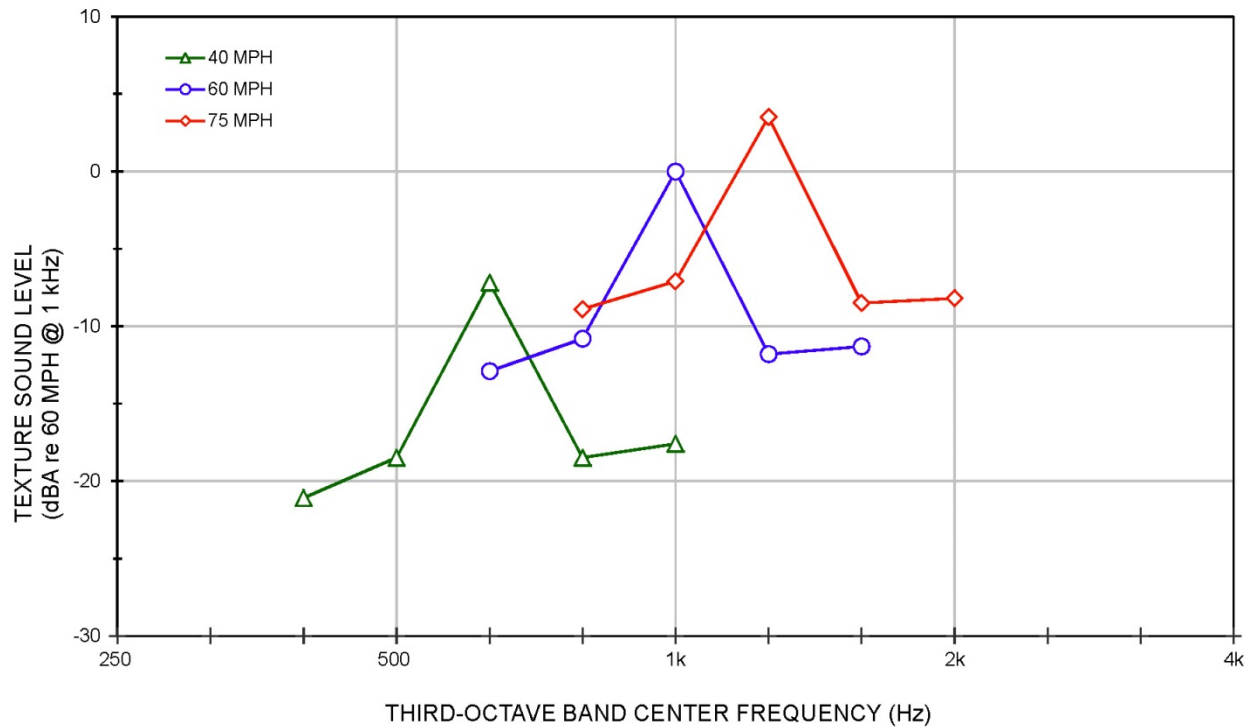
FIGURE 11 Hypothetical Texture-Induced A-Weighted Sound Levels

630–1600 Hz Texture Level Spectrum (at 60-MPH per FIGURE 8) estimated at 40 MPH and 75 MPH
with OBSI ≈ 30 log (V); referenced to 1000 Hz at 60 MPH

Implications for REMELs Over the years, traffic speeds have increased greatly in the author's experience in Northeast U.S. such that flow at 80 MPH is common. To the extent that speed limits are an indicator of vehicle operating speeds generally, a history in Texas may be illustrative—albeit an upper bound. In Texas, speed limits steadily increased despite no significant changes in roadway characteristics, as shown in FIGURE 12.*(19,20)*

The American Association of State Highway and Transportation Officials (AASHTO) OBSI standard method(*1*) specifies testing at 60 MPH. This reference speed is useful for *rating* pavements, but is inadequate for quantifying pavement *emission levels* for noise predictions for real highways to evaluate wayside impacts—especially given increasing vehicle speeds. Measurements for reference vehicle emissions (REMELs) must include speeds to about 80 MPH. An emissions model—such as illustrated by FIGURE 3—is necessary, with various k_i values accounting for the numerous tire-pavement noise mechanisms as influenced by the pavement design parameters (texture, porosity, and stiffness). The texture contribution will migrate across the frequency spectrum with vehicle speed and may be very discrete tonally. On the other hand, porosity effects *may* be more broadband and less influenced by speed. Consequently, a pavement-specific REMEL likely will be the summation of component source REMELs.
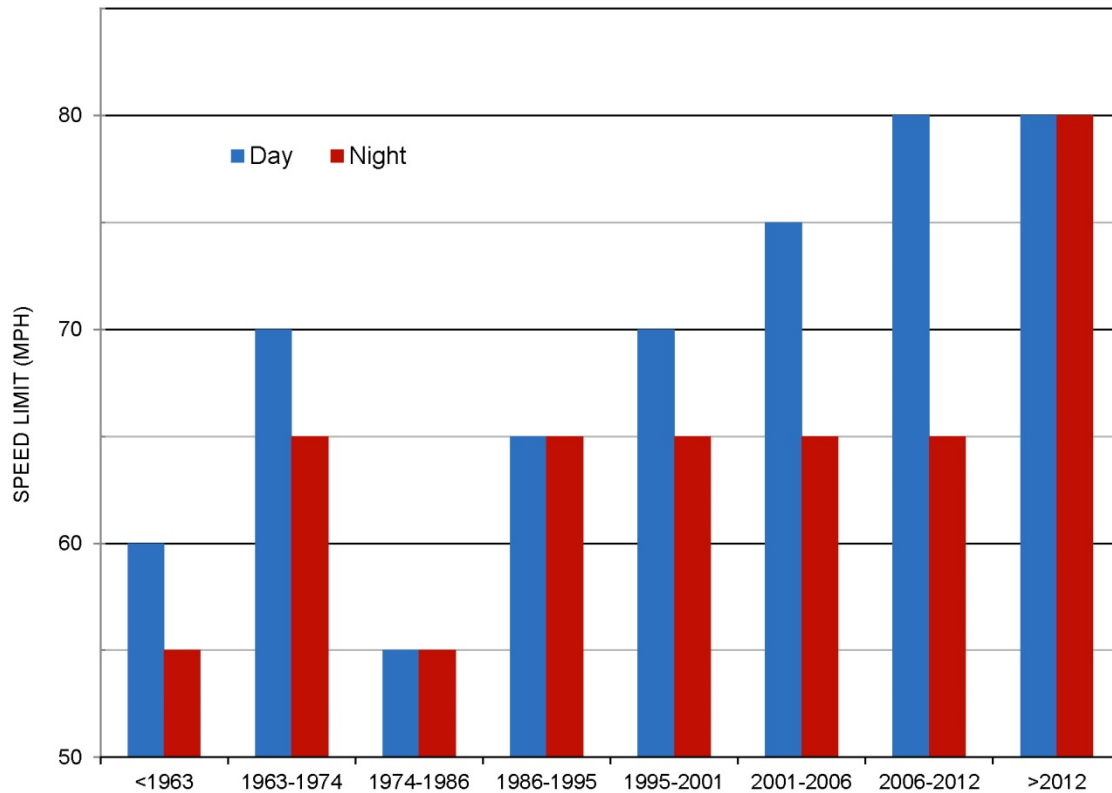
FIGURE 12 Speed Limits in Texas

Since 1974 when a national maximum speed limit of 55 MPH was implemented as a response to the 1973 Arab oil embargo, speed limits for I-10 and I-20 in far west Texas increased steadily despite no significant changes in roadway characteristics. (Speed limits are applied here as a correlate to highway speeds generally since the 85th percentile traffic speed is a major factor in establishing posted speeds. The 85th percentile speed is the speed at or below which 85% of vehicles travel. It is used extensively in traffic engineering since it is presumed the majority of drivers are reasonable and prudent.)

CONCLUSIONS

- OBSI is a function of pavement texture and vehicle speed.
- The texture influence is significant $\leq$1600 Hz in standardized OBSI testing at 60 MPH.
- The impact of texture in highway noise is greater at vehicle speeds above 60 MPH due to the migration of frequencies to regions of greater hearing sensitivity.
- The standard 60-MPH OBSI measurement speed is inadequate for contemporary ($\approx$80-MPH) highway speeds.
- Texture will limit the noise-reduction benefits of porous pavements.
- Tire-Pavement Reference Noise Emission Levels (REMELs) for highway noise prediction must include texture, porosity, and stiffness as distinct speed-varying parameters.

RECOMMENDATIONS

Testing is needed to substantiate the above conclusions regarding texture and to ultimately incorporate the influence of other parameters (porosity and stiffness):

- Simultaneously measure OBSI; pavement texture level, $L_{tx}(\lambda)$, to 800-mm profile wavelength; and vehicle speed.
- Measure OBSI in third-octave bands and either proportional or constant narrowbands.
- Measure at discrete speeds (30, 45, 60, and 75 MPH) and swept speed (via OBSI measurements at regular intervals during 75–30 MPH coast down).
- Measure a variety of pavement types—including very noisy asphalt surfaces.
- Test one or more tire designs in addition to the Standard Reference Test Tire (SRTT)—to assist separation of tire influences vis-a-vis pavement effects.
- Regression analyze test results as a function of A-weighted texture level, $L_{Atx}(f)$, and texture skewness.
- Examine the variation of narrowband OBSI as a function of swept speed.
- Ultimately, incorporate porosity and layer thickness and number (such as via ground penetrating radar, GPR), and pavement stiffness (such as by falling-weight deflectometer, FWD).

REFERENCES

[1] American Association of State Highway and Transportation Officials (AASHTO), "Standard Method of Test for Determining the Influence of Road Surfaces on Traffic Noise Using the Continuous-Flow Traffic Time-Integrated Method", TP 99-11, May 2011.

[2] Rasmussen, R.O., Sohaney, R., Wiegand, P., and Harrington, D., "Measuring and Analyzing Pavement Texture," National Concrete Pavement Technology Center, January 2011.

[3] Federal Highway Administration, U.S. Department of Transportation, Procedures for Abatement of Highway Traffic Noise and Construction Noise, 23 CFR Part 772, 13 July 2010 (effective 13 July 2011).

[4] Menge, C.W. , C.F. Rossano, G.S. Anderson, and C.J. Bajdek, FHWA Traffic Noise Model, Version 1.0—Technical Manual, U.S. Dept. of Transportation Report No. FHWA-PD-96-010, February 1998.

[5] Fleming, G.G., Rapoza, A.S., and Lee, C.S.Y., "Development Of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM®), Version 1.0," U.S. Dept. of Transportation Report No. FHWA-PD-96-008, November 1995.

[6] Donavan, P., "The Effect of Pavement Type on Low Speed Light Vehicle Noise Emission," SAE 2005-01-2416, 2005.

[7] Rasmussen, R.O., Bernhard, R.J., Sandberg, U., and Mun, E.P., The Little Book of Quieter Pavements, U.S. Federal Highway Administration Report No. FHWA-IF-08-004, July 2007.

[8] Sandberg, U. and Ejsmont, J.A., "Tire/Road Noise—Generation, Measurement, and Abatement," Handbook of Noise Control, Crocker, M.J. (Ed.), 2007

[9] Hall, J.W., Smith, K.L., and Littleton, P., Texturing of Concrete Pavements, National Cooperative Highway Research Program NCHRP REPORT 634, 2009.

[10] Hanson, C.E., Towers D.A., and Meister, L.D., Transit Noise and Vibration Impact Assessment , U.S. Federal Transit Administration Report No.FTA-VA-90-1003-06 , May 2006.

[11] Goubert, L., "Road Surface Texture and Traffic Noise," Presentation to NPRA Workshop on Texture and Road Traffic Noise, 14 February 2007.

12 Morgan, P. (Ed.), <u>Guidance Manual for the Implementation of Low-Noise Road Surfaces</u>, Forum of European National Highway Research Laboratories (FEHRL) Report 2006/02, 2006.

13 American Society for Testing and Materials, "Standard Test Method for Calculating Pavement Macrotexture Mean Profile Depth", ASTM Standard E 1845, 1996.

14 International Organization for Standardization, "Characterization of Pavement Texture by Use of Surface Profiles—Part 4: Spectral Analysis of Surface Profiles", ISO TC 43/SC 1, ISO/CD 13473-4, 2006..

15 International Organization for Standardization, "Characterization of Pavement Texture by Use of Surface Profiles—Part 5: Determination of Megatexture", ISO TC 43/SC 1, ISO/CD 13473-5, 2005.

16 Ferragut, T., Rasmussen, R., Wiegand, P., Mun, E., and Cackler, E.T., <u>ISU-FHWA-ACPA Concrete Pavement Surface Characteristics Program Part 2: Preliminary Field Data Collection</u>, National Concrete Pavement Technology Center Report DTFH61-01-X-00042, Project 15, Part 2 , August 2007.

17 Donovan, P.R., "The Effect of Porous Pavement on Wayside Traffic Noise Levels," Paper presented at the Transportation Research Board 93rd Annual Meeting, January 2014.

18 Donavan, P.R., <u>Comparative Measurements of Tire/Pavement Noise in Europe and The United States—NITE Study</u>, U.S. Federal Highway Administration Report No. FHWA/CA/MI-2006/09, 26 July 2006

19 Wikipedia contributors. "Speed Limits in the United States." Wikipedia, The Free Encyclopedia, 20 May. 2014. Web. 20 May. 2014.

20 Wikipedia contributors. "National Maximum Speed Law." Wikipedia, The Free Encyclopedia, 15 May. 2014. Web. 20 May. 2014.