APPENDIX D. TIRE NOISE PARAMETRIC STUDIES

Following is the text from two memorandums that were prepared on the pilot study to determine whether relatively simple mathematical models of tire/pavement noise that are based on fundamental acoustical principles can predict how different pavement parameters affect levels of tire/pavement noise. The ultimate goal was to have tools that provide insights about how variations in different pavement parameters will affect noise and that can be applied to developing pavements that are optimized for low noise levels. The first memorandum provides and overview of the tire noise issue and the second memorandum presents the results of the pilot study.

D.1 OVERVIEW OF TIRE NOISE STUDY

The following material is from the memorandum "Overview of Tire Noise" submitted by Hugh Saurenman to the Technical Advisory Committee on Jun 16, 2004.

Introduction

Attached is a technical memorandum from Dr. Joel Garrelick of Applied Physical Sciences, Inc. summarizing his investigations into parametric models of tire/pavement noise. Although there have been numerous studies of the noise generation properties of different types of pavements, we are not aware of any tools that can be used in the design of an optimized "quiet" pavement. This is largely due to the number of different mechanisms by which a pneumatic tire rolling on pavement generates noise, each of which can be affected independently by different pavement parameters. In fact, sometimes there are counterbalancing effects. For example, long wavelength texture (roughness) may tend to increase noise while short wavelength texture tends to reduce noise.

Our goal on this task was to determine whether relatively simple mathematical models of tire/pavement noise that are based on fundamental acoustical principles can predict how these parameters affect levels of tire/pavement noise. The ultimate goal is to have tools that provide insights about how variations in different pavement parameters will affect noise and that can be applied to developing pavements that are optimized for low noise levels.

The mathematics of the modeling are described in Dr. Garrelick's memo. The purpose of this memo is to provide an introduction to the mechanisms of tire/pavement noise that will give a clearer context for the study results and to summarize the results of Dr. Garrelick's pilot study.

Noise Generating Mechanisms

Before summarizing the results of Dr. Garrelick's study, it is important to have some understanding of the mechanisms of tire/pavement noise. The generating mechanisms thought to be most important are summarized in Table 10 and discussed below. This discussion is largely based on the information in Chapter 11 or Ulf Sandberg's book on tire/pavement noise (Ref. **Error! Reference source not found.**).

The primary noise generating mechanisms are:

- **Roadway Roughness:** First are the forces generated at the tire/pavement contact patch caused by irregularities in the pavement surface. Excitation is at the wavelength of the surface irregularity and the frequency of excitation depends on the vehicle speed:

  $$f = speed/\lambda$$

  where f = frequency in Hz, λ = wavelength in inches, and *speed* = vehicle speed in inches per second.

For example, at 60 mph we expect the following relationship between roughness wavelength and frequency:

Wavelength	Frequency
21”	50 Hz
11”	100 Hz
2”	500 Hz
1.1”	1,000 Hz
0.5”	2,000 Hz
0.2”	5,000 Hz
0.11”	10,000 Hz

The values above illustrate that roughness at wavelengths of about 0.1 to 20 inches affect noise radiation for this mechanism. Because other mechanisms are more important at frequencies of 1000 Hz and higher, it is actually wavelengths of about 1/2 inch and greater that are important. Having a smoother road surface at these wavelengths will reduce noise levels at frequencies below 1000 Hz.

Table 10. Noise Generating Mechanisms

Noise Generating Mechanism	Freq Range	Relevant Pavement Parameters	Effect on Noise
Tire casing excitation at roadway roughness frequency	<1000 Hz	Surface smoothness, aggregate size	Increase
Tread block Impact	800-1250 Hz	Texture	Increase
Air Pumping	>1000 Hz	Roughness Porosity	Decrease Decrease
Stick-slip (friction)		Microtexture	Increase
Stick-snap (adhesion)		Texture	Decrease
Horn effects (amplification)		Texture/Porosity	Decrease
Absorption (source strength and propagation)		Porosity(1) Coatings	Increase Decrease?
Closed cavity effects with tire tread or pits in pavement surface (resonator, pipe modes)		Unconnected pits in pavement surface	Increase

Notes:
(1) Porosity parameters that affect sound levels include percent voids, size of voids, thickness of porous layer, flow resistance and void shape factor (tortuosity).

- **Tread Block Impact:** This mechanism is important in the mid-frequency range of about 800 to 1250 Hz. Noise is caused by tread blocks hitting the roadway at the leading edge of the tire plus a sort of inverse impact as tread blocks leave the roadway surface at the trailing edge. Presumably a smoother road surface will reduce the impact forces and the noise radiation, although the relationship is not all that clear.
- **Air Pumping:** Air trapped in the interstices of the road surface and the tire tread is pumped in and out as the tire rolls along the surface. This is particularly important if the tire tread or the road surface has unconnected interstices so there is no air pressure relief. Short wavelength roadway texture on the order of 1/2 inch or less and porosity reduces the air

pressure buildup and will tend to reduce air pumping noise, although there may be counterbalancing effects such as increasing tread block impacts.

- **Stick-Slip:** Slip-stick is caused by the friction between the tire and the roadway. The mechanism is much the same as the noise caused when running your palm over a smooth surface. Things that increase friction, such as micro-texture with size similar to single grains of sand, will tend to increase slip-stick.
- **Adhesion:** Adhesion between the tire surface and the roadway will generate noise as the adhesive bonds are broken. Although it is possible that this mechanism contributes to overall noise levels, tests that have been done to date do not seem to show this as an important noise source. Increasing micro-texture should reduce the bonding and the noise generated by this mechanism. Sandberg (Ref. 1) refers to this mechanism as stick-snap.
- **Horn Effects:** This is not really a noise generating mechanism; rather it is a mechanism by which sound levels are amplified. At the leading and trailing edges of the tire, the angle between the tire and the road surface acts like a small horn increasing the radiation efficiency of the vibrating tire. Acoustically absorptive (porous) pavements and possibly increasing texture at wavelengths of 1/2 inch or smaller may reduce the efficiency of the horn effect.
- **Absorption:** Increased absorption is one of the key effects of a porous pavement. This is not really a noise generating mechanism, but is included since it can have a strong effect on sound levels. Pavements that are acoustically absorptive will reduce the effective source strength by reducing the reverberant buildup in the under-vehicle area and will result in attenuation as the sound propagates across the pavement. Also, as discussed above, absorptive pavements may reduce the horn effect.
- **Closed Cavities:** This is a special case where either the tire tread or the pavement has closed cavities (open at the top, closed on the sides and bottom). The air pumped in and out of the closed cavities can substantially increase noise levels. This is not really applicable to either current tires or modern, well constructed roads.

Pavement Parameters

In Table 11 we show which mechanisms are affected by key pavement parameters. To some degree this is repeating the information in Table 10. The pavement parameters and their effects are:

- **Texture:** By texture we are referring to all unevenness in the pavement surface. The texture at wavelengths of about 0.4 to 20 inches affects the basic excitation of the tire casing and the radiation of noise below about 1000 Hz. In this range, increased texture will increase noise levels. The next level is 0.02 to 0.4 inches. This texture range affects air pumping; the greater the texture, the lower the noise from air pumping. Very small wavelength texture will affect adhesion and friction; it is not clear whether this has more than a small to moderate effect on noise levels. Sandburg (Ref. 1) indicates that there may be noise generating mechanisms related to longer wavelength unevenness, although it is not clear what the mechanism would be or what frequency ranges would be affected.
- **Tining:** Tining of concrete pavements to reduce hydroplaning in wet conditions can cause significant sound level increases. This is particularly true when the tining is transverse. Longitudinal tining is thought to have only a small effect on sound levels.

Table 11. Effect of Pavement Parameters on Tire/Pavement Noise		
Parameter	**Mechanism**	**Degree**
Pavement Texture		
0.4 to 20 inches	Tire excitation	Strong
0.02 to 0.4 inches	Air pumping	Strong
Micro	Friction/adhesion	Moderate
Unevenness (>20 in.)	Not clear	
Tining		
Transverse	In phase excitation	Strong
Longitudinal	No special mechanism	Weak
Irregular	Similar to texture	Moderate
Porosity Parameters		
% voids (porosity)	Air pumping Absorption	High High
void size	Absorption Air pumping?	Moderate Moderate
layer thickness	Air pumping Absorption	Moderate Moderate
airflow resistance	Air pumping Absorption	Moderate Moderate
shape factor (tortuosity)	Absorption	Moderate
Stiffness and binders	Tread block impact Other?	Not clear Not clear
Friction	Stick-slip	Moderate
Adhesion	Stick-snap	Moderate

- **Porosity:** It is well understood that porous pavements tend to be quieter than non-porous pavements. This is apparently because porous pavements are more acoustically absorptive than non-porous pavements and because the porosity reduces the effects of air pumping. Important porosity parameters include the percent voids (generally speaking, the higher the better), the size of the voids (smaller is better), the layer thickness (affects the peak frequency), the resistivity (affects peak frequency and range of effectiveness), and the shape factor (affects peak frequency and range of effectiveness).
- **Stiffness and Binder Additives:** Given the widespread conventional wisdom that adding crumb rubber to the asphalt binder is a key factor in making a quiet pavement, we are hesitant to say too much here. However, it is not clear how adding rubber to the binder would change any properties that affect noise levels unless the rubber affects the texture or the porosity. The added resilience of rubberized pavements compared to standard pavements is not sufficient to affect the excitation of the tire. The pavement stiffness is still effectively infinite compared to the stiffness of a pneumatic tire.
- **Friction:** Reducing friction will reduce stick-slip noise. A relatively recent development on rail systems is use of “positive” friction material on the rail head to reduce stick-slip noise. Generally the coefficient of friction will drop as soon as friction forces are exceeded and two

surfaces start to move relative to each other. With positive friction materials, the friction forces continue to increase even after there is slippage between the two surfaces.

- **Adhesion:** A final property of pavements that can affect noise generation is adhesion. The greater the adhesion forces between tires and the roadway surface, the higher the level of stick-snap noise will be. Increasing microtexture will reduce adhesion as well as introducing artificial materials between the tire and the roadway (e.g., dirt or talcum powder and spray-on material as were used in some tests).

Summary of Conclusions from Structural-Acoustic Modeling

The overall conclusion is that the quietest pavements will be very smooth in the macro and mega texture ranges, be highly porous with about 25% voids, have a thickness of 1 inch or more, be self-cleaning so the porosity does not change, have a non-stick surface that minimizes stick-snap, and have a friction characteristic that minimizes stick-slip. Following is a more detailed summary of our observations and conclusions:

- **Propagation over an elastic/porous surface:** The modeling shows a substantial potential benefit from enhanced acoustical absorption properties for porous pavements. The modeling only looked at propagation over a porous pavement. Based on the modeling, we conclude that:
    1. **Thickness:** Increasing porous layer thickness will reduce the peak absorption frequency and broaden the range of effectiveness.
    2. **Resistivity:** Increasing flow resistance will tend to broaden the range of effectiveness. With low flow resistance, the propagation loss will have strong peaks. As the resistivity increases, the peaks flatten out.
    3. **Porosity (% Voids):** Increasing the percent voids will tend to increase the absorption.
    4. **Tortuosity:** The tortuosity (void shape factor) mainly affects the peak frequency of the absorption coefficient.
    5. **Multiple Layers:** A couple of cases were run to test the effect of having multiple porous layers. For the test cases, the extra layer provided only small benefits compared to a single layer of the same thickness as the two layers.
- **Radiation from pavement:** The modeling indicates that sound radiation from the pavement is probably small compared to the radiation from the tire casing.
- **Pavement stiffness:** There is no indication that pavement stiffness affects radiated sound levels.
- **Pavement texture:** The modeling tends to support the empirical observations that macro texture on the order of 3/4” and greater will affect sound levels. Averaging over the contact patch area tends to diminish the effects of small wavelength texture at least in terms of harmonic forces driving the tire.
- **Air pumping:** We only took a quick look at modeling of air pumping noise. Intuitively, we expect an increase in porosity to reduce noise by increasing the effective cavity size, at least when tire and pavement pores line up. However, the available modeling indicates that an increase in porosity could increase the effective number of cavities and the effective cavity volume displacement, both of which would be expected to increase noise levels. Based on the available data, we believe that the net effect of increasing porosity will be reduced noise from air pumping.

D.2 TIRE NOISE RAMIFICATIONS OF PAVEMENT CHARACTERISTICS

Applied Physical Sciences Corp.
2 State Street, Suite 300
New London, CT 06320
Phone: (860) 440-3253, Fax: (860) 440-3075

TO: Hugh Saurenman, ATS Consulting, LLC

FROM: Joel Garrelick

SUBJECT: TIRE NOISE RAMIFICATIONS OF PAVEMENT CHARACTERISTICS

DATE: 10 May 2004

TECH MEMO: ATC-3038.1

I. INTRODUCTION AND SUMMARY

This report is intended to enhance the Arizona Department of Transportation's (ADOT) ability to evaluate trade-offs between noise and other pavement design criteria by assessing the gross design characteristics of pavements that likely influence tire noise over a broad range of traffic and environmental conditions. Specifically, the pavement characteristics that may be significant contributors to tire noise, as indicated by current research, are identified and evaluated using first principle structural-acoustic predictive models. Our focus is that portion of the overall vehicle noise spectrum typically attributed to "tire noise" (frequencies in the vicinity of 1 kHz).

Although the current state of the art precludes definitive findings, the conclusions presented below provide a preliminary rationale for assessing the acoustic performance of alternate pavements based on their gross features, namely, texture, stiffness, and porosity. These features and their relative significance are summarized below:

- **Pavement Texture – micro-texture: minor significance, macro/mega texture: moderate significance**. The length scales of pavement texture (e.g. micro texture, macro texture, and mega texture) are correlated with the characteristic wavelengths of a vibrating tire. Micro-texture on the order of single grains of sand, can affect the friction and the adhesion between the tire and the road surface. With more micro texture, friction increases and adhesion decreases which results in increased stick-slip noise and decreased stick-snap noise. The overall result is a minor effect on noise. However, this is not necessarily the case for the longer wavelength portion of the spectrum, say texture the order of 10 mm or higher, covering the upper end of the macro- and the mega-texture range. These length scales are the order of the characteristic wavelengths of the vibrating tire. Assuming contact is maintained between tire and pavement, lowering the spectral levels of texture may be moderately beneficial. This moderation is a consequence of the increase in the amplitude of the individual tire impacts tending to be cancelled by the decrease in the number of impacts over the tire-pavement contact area. Note that there is a counterbalancing effect with increased texture at wavelengths in the 1 to 10 mm range. Texture at these wavelengths will tend to reduce air-pumping noise.

- **Relative Pavement Stiffness: minor significance**. The stiffness of all candidate pavements is much greater than that of a tire. Therefore, as related to the tire, all pavements act as rigid surfaces in terms of source mechanisms. This feature applies to rubber-modified bituminous binders whose introduction may have an acoustic influence (only) to the extent that they modify pavement porosity.

- **Pavement Porosity: major significance**. Pavement porosity has a major influence on tire noise. This is a consequence of absorptive influence on the source strength of noise generating mechanisms, and more generally on the near grazing propagation of the noise along the pavement. For a typically thin porous layer, the acoustic performance is frequency dependent, with peak performance near the natural frequency of the "tortuous" air path through the thickness. Peak noise reductions of about 5 dB have both been measured and predicted based on porosity. The four primary design parameters that affect the acoustical performance of a porous pavement are the layer thickness, porosity (percent voids), flow resistivity through the pores, and the tortuosity. The term "tortuosity" refers to the path through the pores and is also referred to as "structural" factor or "shape" factor. The thickness and tortuosity are crucial in centering the peak performance frequency (e.g., typically around 1 kHz for passenger vehicles), whereas porosity and flow resistivity are key in determining the absorption coefficient. Test procedures are available for these pore parameters, either in situ or with core samples.

- **Other Factors.** Other pavement factors that may affect tire noise that are not addressed in this report as they are outside the scope of our analysis include: adhesion between the tire and the pavement, tining of concrete pavements, air pumping as air is squeezed out of tire tread gaps, and resonating tread blocks caused by roadway impacts.

II. DISCUSSION OF RESEARCH TO-DATE

The relevant research into tire noise is quite extensive, extending over thirty years and involving an international group of investigators. However, definitive findings of the role of pavement design characteristics remain somewhat elusive, a consequence of the complexity of the overall tire noise problem. A recent and comprehensive review of general tire noise research can be found in Ref. 1*, *Tyre/Road Noise Reference Book* by Sandberg and Ejsmont. In this reference, the role of pavement design is summarized (reproduced below as Table 1) and candidly described

* References for Garrelick memo are listed separately on page 158.

as “Road surface characteristics known or believed to affect tyre/road noise emissions.” Our discussion focuses on surface texture, stiffness (or impedance), and porosity.

Table 1. Parameters with a potential influence on tire/road noise (reproduced from Table 11.1 of Ref .1)

No.	Parameter	Degree of Influence
1	Macrotexture	Very High
2	Megatexture	High
3	Microtexture	Low-moderate
4	Unevenness	Minor
5	Porosity	Very High
6	Thickness of Layer	High, for porous surfaces
7	Adhesion (normal)	Low/moderate
8	Friction (tangent)	See microtexture
9	Stiffness	Uncertain, moderate

Texture

Three categories of texture are often distinguished according to wavelengths as follows:

Category	Wavelengths	Peak Amplitude
Microtexture	< 0.5 mm <0.02 inches	0.01 to 0.5 mm 0.0004 to 0.02 inches
Macrotexture (wavelengths on order of tread elements)	0.5 to 50 mm 0.02 to 2 inches	0.1 to 20 mm 0.004 to 0.8 inches
Megatexture (wavelengths on order of tire-pavement contact patch)	50 to 500 mm 2 to 20 inches	0.1 to 50 mm 0.004 to 2 inches

The correlation of tire noise to texture is ambiguous. For example, a compendium of 23 measurements using ISO compatible metrics, Mean Depth Profile (MDP) for texture and Close Proximity Index (CPXI) for noise level, show a strong correlation for only very rough surfaces (reproduced/modified from Ref. 2 in Fig. 1). Oriented texture achieved through tining or grooving, also affects noise levels. Transverse orientation tends to increase noise levels while longitudinal striations can be beneficial.

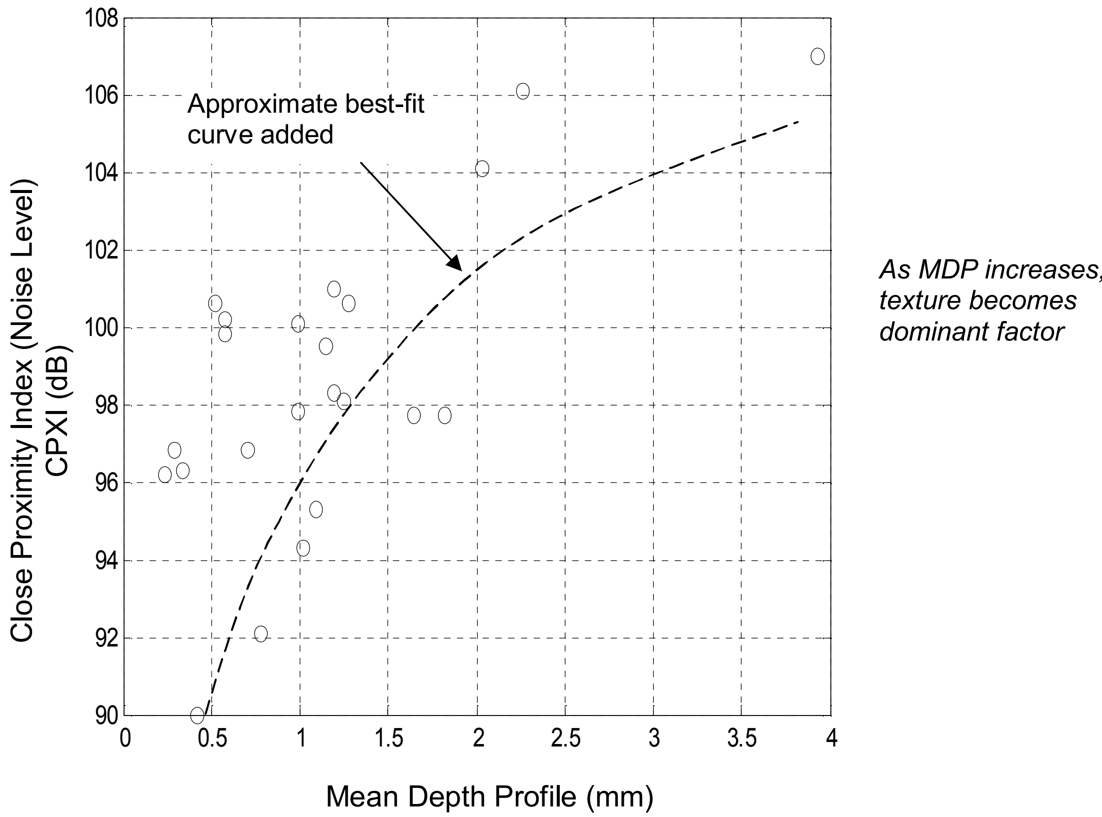

Fig. 1. Tire/road noise level versus road texture for 23 various surfaces (reproduced/modified from Fig. 6 of Ref. 2.)

Stiffness

We next consider the effective hardness, or stiffness of the surface (i.e. its reactive impedance). Typical pavements consist of stones, sand, filler and binder, in various proportions. Variations in stiffness are commonly attributed to variations in the binder material(s). For example, bitumen or "asphalt" binders are relatively flexible in relation to portland cement binders. To enhance the mechanical performance of the binder, fibers, plastic, and rubber have also been added. Certain measurement projects, perhaps unpublished, and involving pavements with alternate binders, viz. with rubber additives, apparently suggest a substantial influence on noise. However, as noted in Ref 1, "…where a direct comparison has been possible between the binder effects, no influence on noise has been demonstrated." For example, Sandberg and Ejsmont report that they conducted controlled tests on "…surfaces with and without 8% of rubber powder added to the binder and found no significant noise difference." They also note similar studies for binders with and without added fibers and for cement and bitumen binders. (On the other hand, a "plastic" binder is reported to have yielded a 1 dB relative reduction.) Thus, the acoustical benefits attributed to differences in binders and in turn "stiffness", are more likely associated with related pavement characteristics that also varied during testing, e.g. porosity.

Porosity

The potential benefits of porous pavements are twofold, (1) a reduction in the source strength of tire-pavement noise mechanisms and (2) an enhanced propagation loss across the pavement at grazing angles. Noise data for porous pavements generally encompass both effects, and are complicated by the propagation loss being strongly dependent on overall roadway-receiver geometry. Nevertheless, measurements indicate that: "A new porous pavement can produce a 3-5 dB reduction, or more, in A-weighted sound level with respect to nonporous pavements." [Ref 3] Data showing measured reductions along with the relative contributions of the source and propagation effects are reproduced here from Ref. 1, in Fig. 2. These results are believed to be typical (see Section III), with a broad peak in performance at a frequency depending principally on the porosity and layer thickness. Finally, it should be noted that the overall acoustic benefits of porosity may also be affected, positively or negatively, by the extent to which porosity influences surface texture.

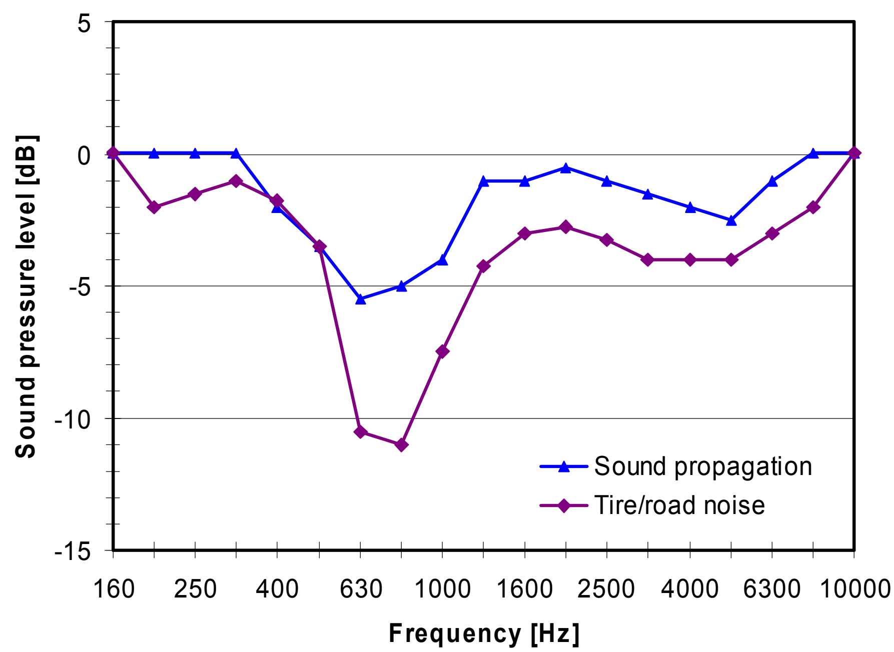

Fig. 2. Measured reductions in tire/road noise with porous versus dense asphalt pavements.
Also shown is the reduction component attributable to propagation.
Data averaged over three tire types.
[Reproduced from Ref. 1, Fig. 11.34]

III. **STRUCTURAL-ACOUSTIC MODEL INSIGHTS**

The effects of roadway pavement design on both the intensity of tire noise sources and the propagation efficiency of such sources are addressed separately in the following sections.

A. Acoustic Propagation over an Elastic/Porous Surface

The issue of propagation efficiency is addressed in this section by considering the idealized mathematical model of noise from a compact (point) acoustic source propagating over a planar boundary (Fig. 3). The boundary is characterized by its normal impedance and may be wave bearing, contain pores, and of finite thickness.

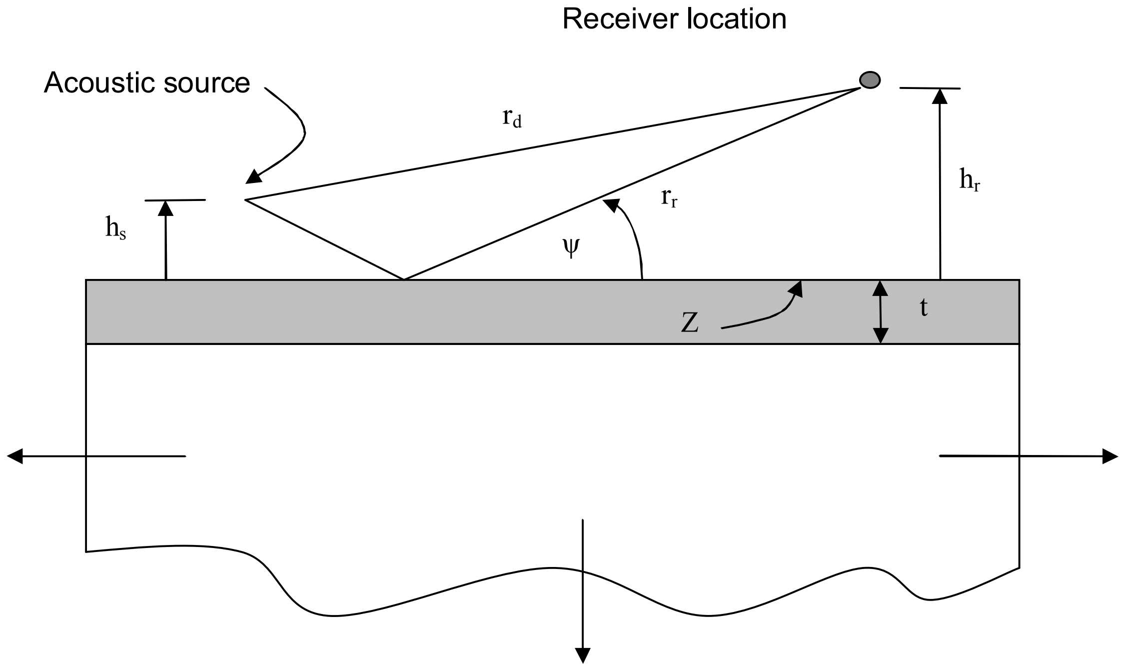

Fig. 3. Idealized geometry for a compact acoustic source propagating over an elastic/porous half space

Refs 3, 4 give the harmonic pressure propagated by a unit source over a locally reacting half space with impedance Z as:

$$p(r,\psi) = \frac{\exp(ikr_d)}{r_d} + \frac{\exp(ikr_r)}{r_r}[(1-R_p)F + R_p] \tag{A1}$$

where r_d and r_r are the direct and reflected ray path lengths, $k = \omega/c$ is the acoustic wavenumber with $\omega = 2\pi f$ circular frequency, c sound speed, ψ is the incident angle on the ground of the specular ray reaching the receiver, the reflection coefficient

$$R_p = (1 - \rho c / Z \sin\psi)/(1 + \rho c / Z \sin\psi) \tag{A2}$$

and

$$F = 1 + 2iw^{1/2}\exp(-w)\int_{-iw^{1/2}}^{\infty}\exp\left(-u^2\right)du \tag{A3}$$

with

$$w = ikr_r[\sin\psi + \rho c / Z]^2 / 2 \tag{A4}$$

In the limiting case of $r_r \to \infty$, $F \to 0$, and in the limit of $Z \to \infty$, $F \to 1$.

With an acoustic wave bearing ground medium, Eqs. A1-A4 still holds but now:

$$Z \to Z / \chi \tag{A5}$$

with

$$\chi = [1 - (k / k_g)^2 \cos^2\psi]^{1/2}$$

where the ground wavenumber $k_g = \omega/c_g$ with c_g the effective ground sound speed.

With a finite thickness surface stratum of thickness t,

$$Z = Z_c \frac{[Z_{term} /(Z_c / \chi)] - i\tan(kt)}{1 - [Z_{term} /(Z_c / \chi)]\tan(kt)} \tag{A6}$$

where Z_c is the characteristic impedance of the layer (the product of effective sound speed and mass density), and Z_{term} its termination impedance. Wenzel [Ref. 5] expresses Eq. A1 more insightfully as

$$\begin{aligned} p(r,\psi) = {} & \frac{\exp(ikr_d)}{r_d} + \frac{\exp(ikr_r)}{r_r} - \frac{\exp(ikr)}{r}[2 + \frac{ik}{\gamma^2 r}(2 - 2\gamma h + (\gamma h)^2 + O(r^{-2})] \\ & + \varepsilon i 2\pi\gamma \exp(-\gamma h) H_0^{(1)}[\sqrt{k^2 + \gamma^2}\, r]] \end{aligned} \tag{A7a}$$

or

$$\begin{aligned} p(r,\psi) = {} & \frac{\exp(ikr_d)}{r_d} + \frac{\exp(ikr_r)}{r_r} - \frac{\exp(ikr)}{r}[2 - \frac{i}{\overline{Y}^2 kr}(2 - 2i\overline{Y}kh - (\overline{Y}kh)^2 + O(r^{-2})] \\ & - \varepsilon 2\pi k\overline{Y} \exp(-ikh\overline{Y}) H_0^{(1)}[kr\sqrt{1 - \overline{Y}^2}\,] \end{aligned} \tag{A7b}$$

provided that

$$kh(h / r) << 1, \tag{A8a}$$

and

$$|\gamma|(r/k)^{1/2} >> 1 \qquad \text{(A8b)}$$

where $h = h_s + h_r$, $r \cong (r_d + r_r)/2$, and $\gamma = ik\overline{Y} = ik(Z/\rho c) \equiv \alpha + i\beta$. (It follows that $\overline{Y} \equiv \beta/k - i\alpha/k$ and the inequality in Eq. A8b may be expressed equivalently as $|\overline{Y}|(kr)^{1/2} >> 1$)

For source and receiver on the ground, $r \cong r_d \cong r_r$, the first two terms are cancelled by the leading term of the expansion and Eq. A7a becomes

$$p(r,\psi) = \exp(ikr)[\frac{ik}{(\gamma r)^2}[2 - 2\gamma h + (\gamma h)^2] + \varepsilon i 2\pi\gamma \exp(-\gamma h) H_0^{(1)}[\sqrt{k^2 + \gamma^2}\, r]] \qquad \text{(A9)}$$

The first term is a "ground" wave and it attenuates as r^{-2}. The second term is a "surface" wave that decreases with height as $\exp(-\gamma h)$, and with distance as $r^{-1/2}$. It exists ($\varepsilon = 1$) provided that

$$\beta \geq 0 \qquad \text{(A10a)}$$

and

$$0 \leq \alpha \leq \beta / \sqrt{1 + (\beta/k)^2} \qquad \text{(A10b)}$$

or equivalently $\mathrm{Re}\{k\overline{Y}\} \geq 0$ and $0 \leq -\mathrm{Im}\{\overline{Y}\} \leq \mathrm{Re}\{\overline{Y}\} / \sqrt{1 + [\mathrm{Re}\{\overline{Y}\}]^2}$. Otherwise $\varepsilon = 0$.

Eqs. A10 ensure that the phase velocity of the surface wave in the far field is subsonic, since $\mathrm{Re}\{\sqrt{k^2 + \gamma^2}\} > k \;\; \rightarrow \;\; k^2(\alpha^2 - \beta^2) + \alpha^2\beta^2 > 0$. Also, since $\beta - i\alpha = k\rho c Y$, this requires a passive, stiffness-like, boundary.

To accommodate the above analysis to a porous boundary, one utilizes a relatively simple phenomenological model that characterizes a porous medium as a dissipative compressive fluid [Ref. 3]. The effective complex density and bulk modulus are given by

$$\rho_g = \rho_0 q^2 (1 + if_\mu / f) \qquad \text{(A11)}$$

and

$$K_g = \gamma P_0 [1 + \frac{\gamma - 1}{1 - if/f_\theta}]^{1/2} \qquad \text{(A12)}$$

where the viscous term $f_\mu = \Omega R_s / 2\pi\rho_0 q^2$ and the thermal term $f_\theta = R_s / 2\pi\rho_0 N_{pr}$.

In these equations P_0 is ambient atmospheric pressure, γ is the specific heat ratio, N_{pr} is the Prandtl number, R_s is the flow resistivity of the porous structure, Ω is the porosity of the air-filled (connected) pores, and q^2 is the tortuosity (structural factor).

The associated complex wave-number and characteristic impedance are

$$k_g = k_0 q F_\mu^{1/2} [\gamma - \frac{\gamma - 1}{F_\theta}]^{1/2} \tag{A13}$$

and

$$Z = (\rho_0 c q / \Omega) F_\mu^{1/2} [\gamma - \frac{\gamma - 1}{F_\theta}]^{-1/2} \tag{A14}$$

with $F_\mu = 1 + i f_\mu / f$.

With the above model, and for a given layer thickness t, three input parameters are required, R_s, Ω, and q^2. In Ref. 3 the flow resistivity was computed from (ISO 9053) measurements of the flow resistance on a sample of area S and thickness l, i.e. $R_s = RS/l$. Values of Ω, the porosity of the air-filled (connected) pores, were measured using gamma ray dosimetry. (Although such data include obstructed as well as connected pores, it is argued that with aggregate greater than 10 mm the former is less than 5% by volume.) Finally, values of the tortuosity, q^2, were obtained indirectly from curve fitting absorption measurements on a sample, in a free-field or pulse tube, especially the frequency position of the resonant peak. (Two other parameters suggested by a micro-structural model, thermal pore and material viscosity "shape factors" were found to be of minor significance. [Ref. 6])

An example is presented in Ref. 3 for a sample with a resonant peak at 1 kHz, t = 4cm, q^2 = 2.5, Ω = 15%, and R_s = 15,000 Ns/m^4. This is reproduced here as Fig. 4. An absorption coefficient of almost unity is obtained within a bandwidth of roughly 400 Hz centered around 1.2 kHz.

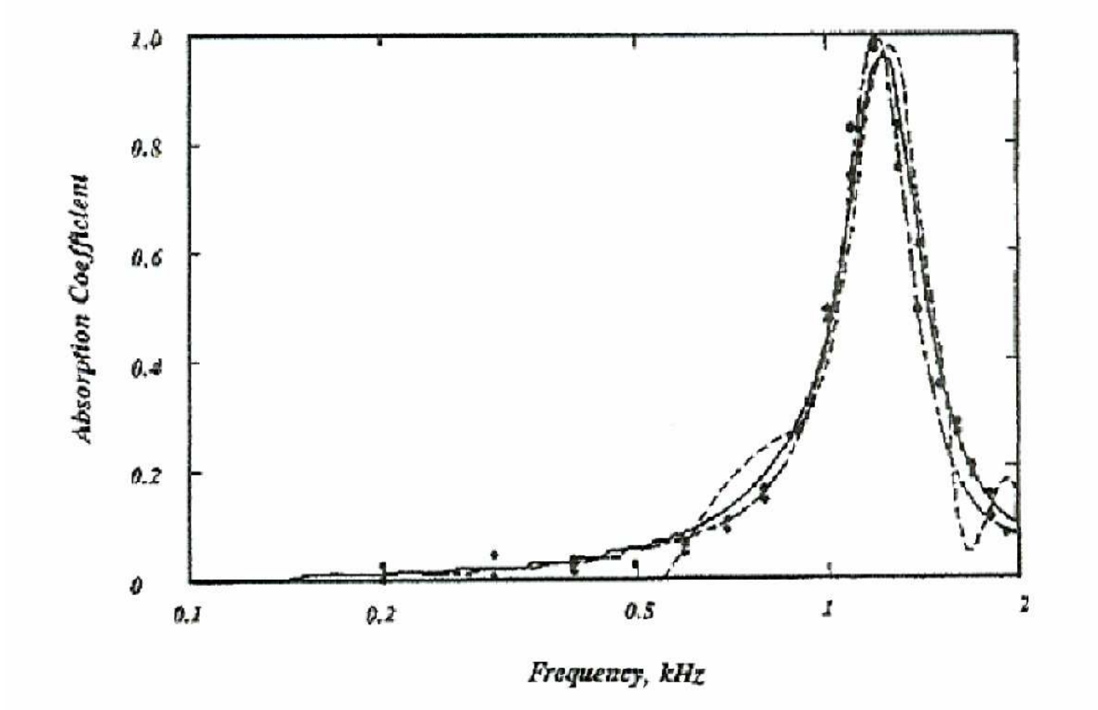

Fig. 4. Absorption coefficient results obtained by different approaches for a 10 cm diameter and 4 cm thick porous pavement sample:

- - - - - - - - - - - standing wave tube measurements
———————— theoretical prediction using phenomenological model,
-·-·-·-·-·-·- theoretical prediction using a micro-structural model

[Reproduced from Fig. 2 of Ref. 3]

Additional model calculations have been performed for this report in order to explore the relationship between acoustic performance and source-receiver geometry and pavement design characteristics. For this purpose, predictions will be presented in terms of the excess reduction in noise level relative to that with a perfectly rigid surface. The basic porosity design is as above, with t = 4 cm, q^2 = 2.5, Ω = 15%, and R_s = 15,000 Ns/m^4.

First to illustrate the issue of geometry, two source heights above the pavement are considered, h_s = 0 and 0.2 m. The receiver height is kept constant at h_r = 2 m, (with reciprocity dictating that h_s and h_r are interchangeable). Results are presented in Fig. 5. The four curves in each panel refer to differing horizontal stand-off distances of the receiver, viz. 2 m, 5 m, 10 m and 20 m. The exact level of performance clearly varies with source-receiver geometry, although the fundamental performance, i.e. that in the vicinity of the fundamental thickness natural frequency of the porous layer, is reasonably robust.

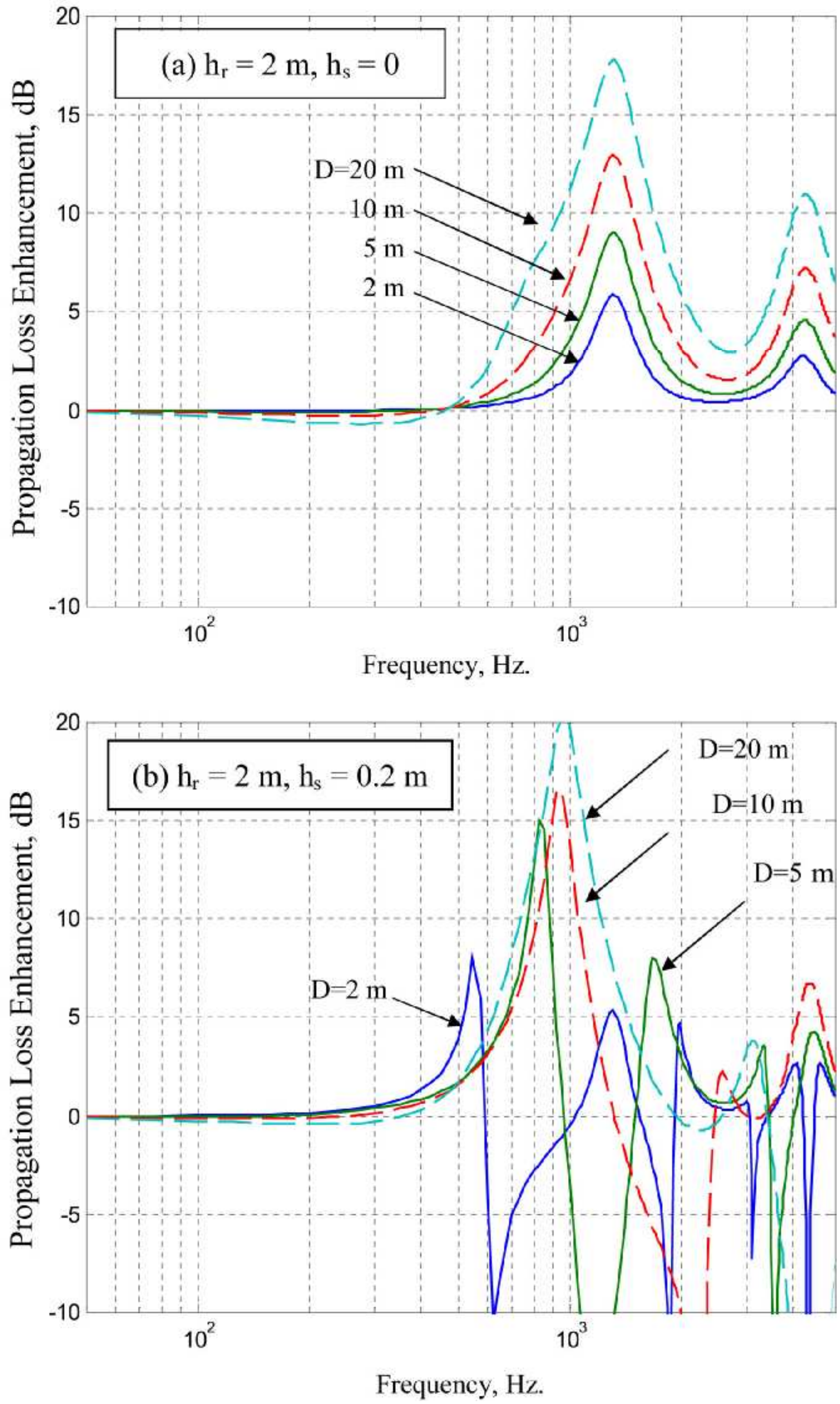

Fig. 5. Calculated propagation loss enhancement of porous pavement design relative to an effectively rigid surface: Influence of source height and receiver stand-off distance

With the source positioned off the surface (lower panel in Fig. 5), and especially at the higher frequencies, interference between the direct and reflected paths is prominent. (For perspective, the height (h_s) measures ½ acoustic wavelength in air at about 850 Hz.)

The influence of varying the thickness of the porous layer is shown in Fig. 6. Thickening the layer has the effect of lowering the center frequency of peak performance and the value of peak performance, at the same time increasing performance bandwidth. This is the case up to the asymptotic limit of a semi-infinite layer.

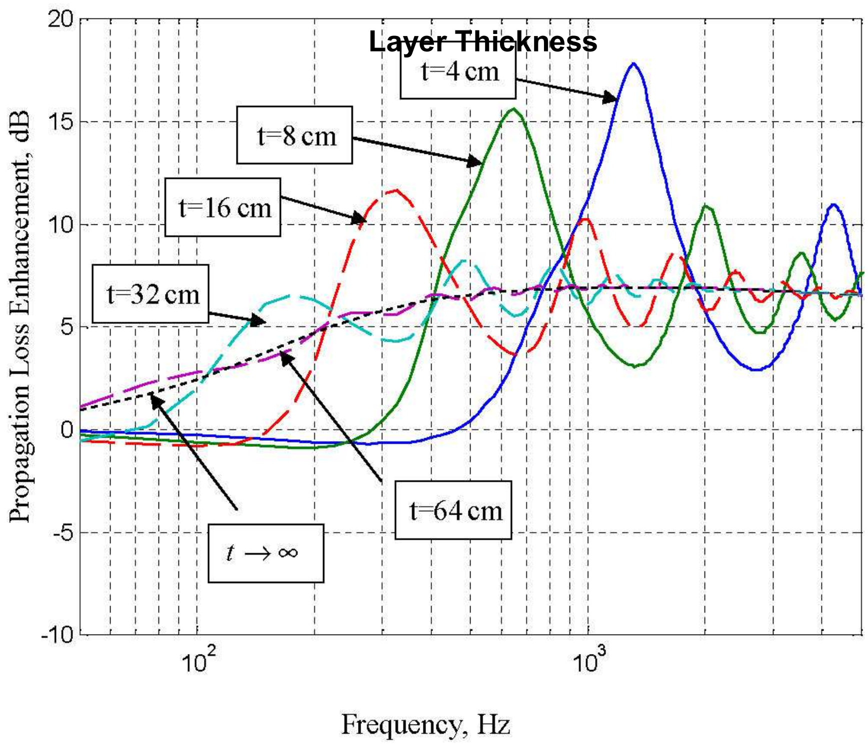

Fig. 6. Calculated propagation loss enhancement of porous pavement design relative to an effectively rigid surface: Influence of layer thickness (D=20 m, h_s=0, h_r=2 m)

In Figs. 7, 8, and 9 we show the effects of changing the resistivity, percent porosity, and tortuosity, respectively. Increases in resistivity lower and broaden peak performance while porosity tends to increase and broaden performance, although it is noted that the analysis is applicable only to moderate values of Ω. An increase in tortuosity lowers the frequency of peak performance much like an increase in layer thickness.

Finally, our discussion to this point has been limited to the acoustic performance of a single porous layer, that is, a layer whose properties are constant across its thickness. We now explore performance with multi-layers, specifically a two-tiered surface. The analysis follows the general format presented earlier, but here with Eq. A.6 cascaded in the fashion of a transmission line. To illustrate, we return to a basic layer with total thickness t = 4cm and porosity Ω = 15%, but now also consider two-tier configurations with each tier 2 cm thick. The tortuosity and resistivity of each layer have values of q^2=1 or q^2=4 and R_s = 15,000 Ns/m^4 or R_s = 3*15,000 Ns/m^4. As with the single layer, the second, or bottom, layer is terminated with an effective rigid boundary.

Results are compared in Figs. 10. It is observed that for the (albeit limited) variations considered, there is no apparent performance gain over the uniform layer when the total thickness is kept constant.

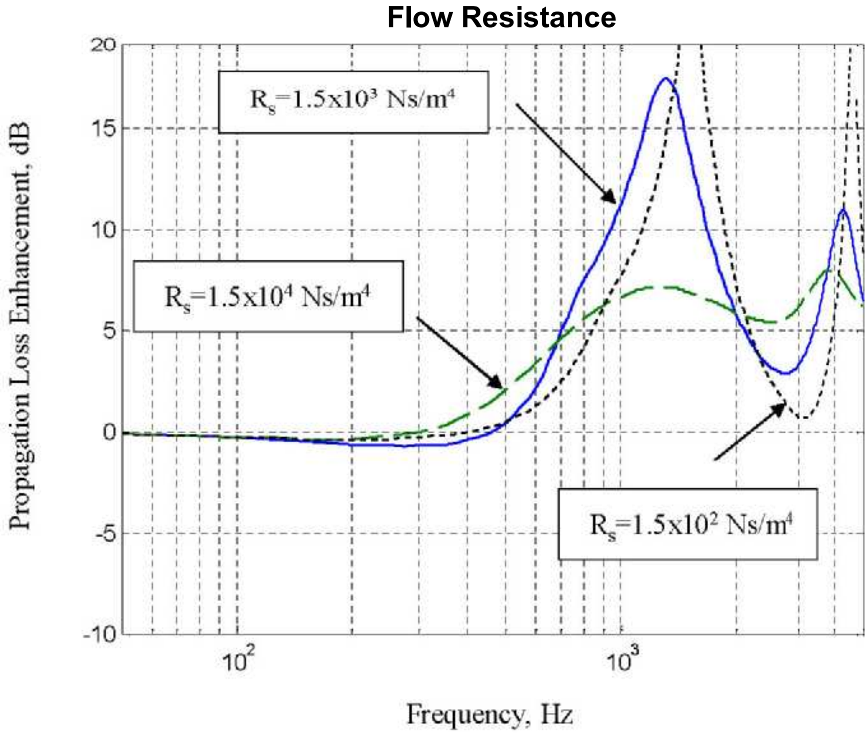

Fig. 7. Calculated propagation loss enhancement of porous pavement design relative to an effectively rigid surface: Influence of flow resistance (D=20 m, h_s=0, h_r=2 m)

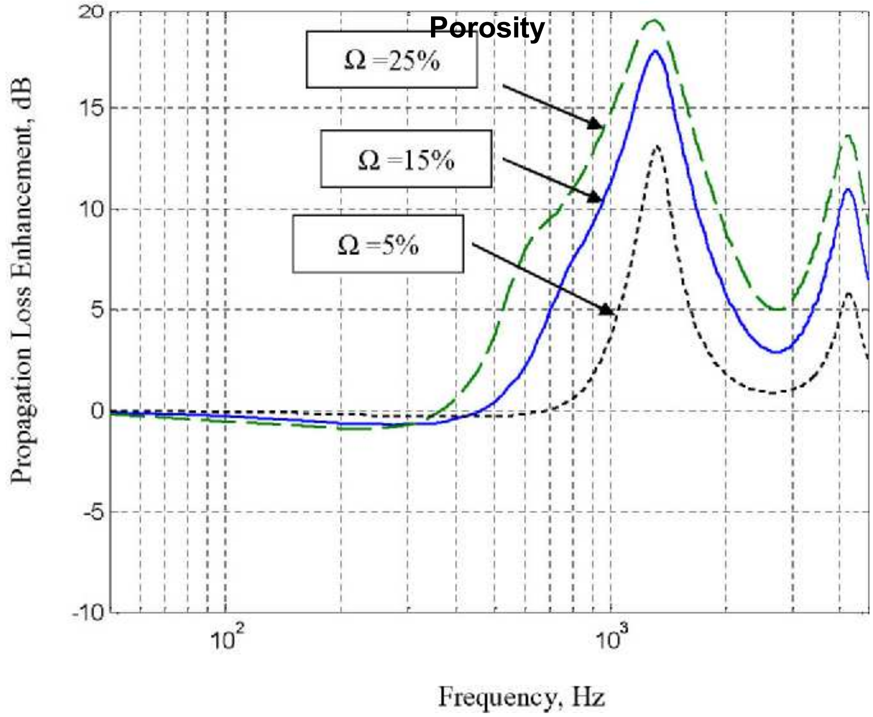

Fig. 8. Calculated propagation loss enhancement of porous pavement design relative to an effectively rigid surface: Influence of porosity (D=20 m, h_s=0, h_r=2 m)

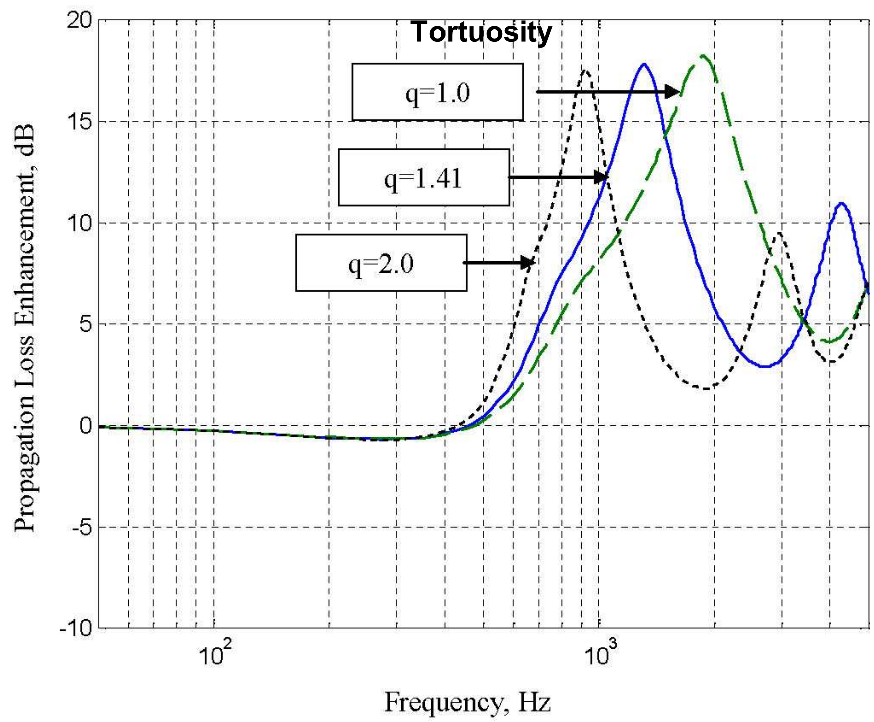

Fig. 9. Calculated propagation loss enhancement of porous pavement design relative to an effectively rigid surface: Influence of tortuosity (D=20 m, h_s=0, h_r=2 m)

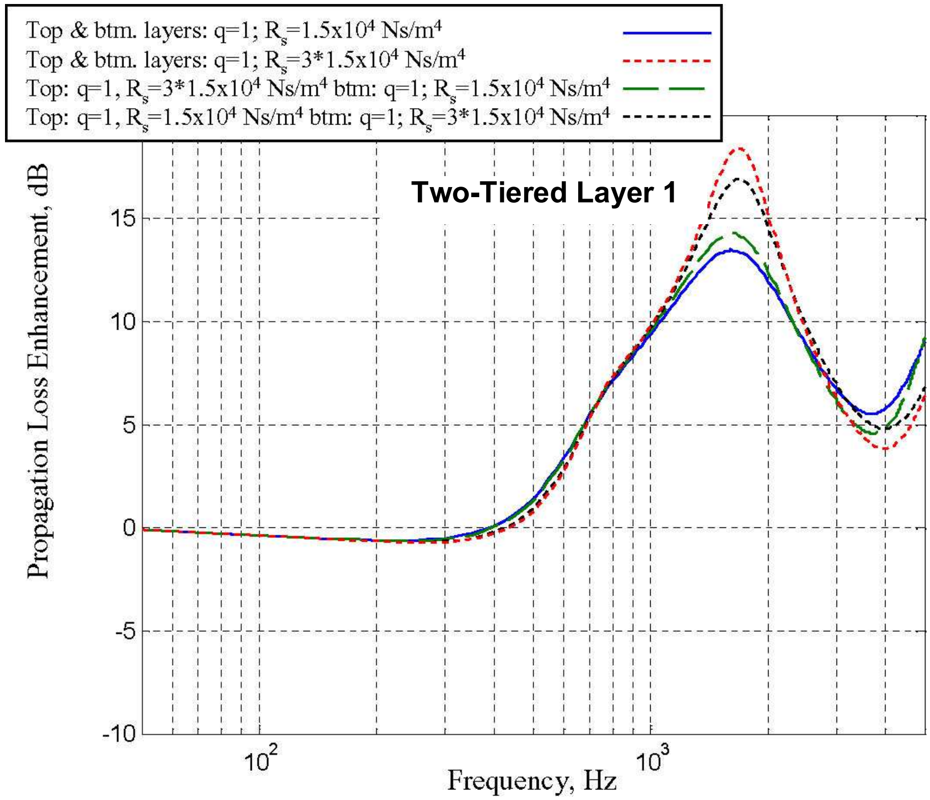

Fig. 10a. Calculated propagation loss enhancement of porous pavement design relative to an effectively rigid surface: Influence of two tiered layer (D=20 m, h_s=0, h_r=2 m)

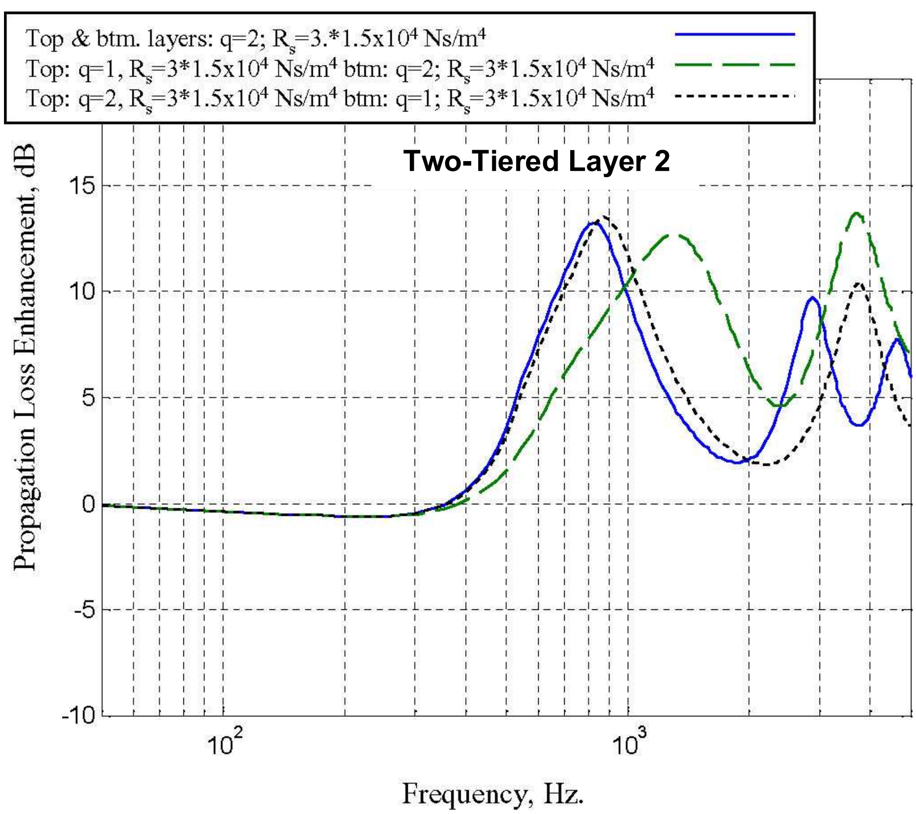

Fig. 10b. Calculated propagation loss enhancement of porous pavement design relative to an effectively rigid surface: Influence of two-tiered layer (D=20 m, h_s=0, h_r=2 m)

B. Radiation from Tire-Pavement Vibrations

In this section, we consider the influence of roadway pavement on the source strength of certain tire noise mechanisms, rather than on their propagation characteristics. Our focus is radiation from interface force-induced vibrations, both tire and pavement. Ignoring the effects of surface porosity and finite layer thickness, we consider the idealized model of radiation from the vibrations of a viscoelastic, planar, half space driven by a compact harmonic force [Fig. 11]. The noise field may be expressed in terms of the (Fourier) wavenumber transformed normal response of the surface. [Ref 7]

$$|p_{rad}(R,\theta;\omega)|R/F = \frac{(2\pi)^{-2}(c_{air}/c_{shr})^4(\omega/c_{air})\sqrt{\sin^2\theta-(c_{air}/c_{dil})^2}}{[2\sin^2\theta-(c_{air}/c_{shr})^2]^2-4\sqrt{\sin^2\theta-(c_{air}/c_{dil})^2}\sqrt{\sin^2\theta-(c_{air}/c_{shr})^2}} \quad \text{(B1)}$$

where θ is elevation angle, *R* range, the ratio p_{rad}/F is the radiated pressure normalized to the applied force (*F*), c_{air} is the sound speed in air, c_{dil} and c_{shr} the dilatational and shear speeds in the pavement, and ρ_{air} is air density.

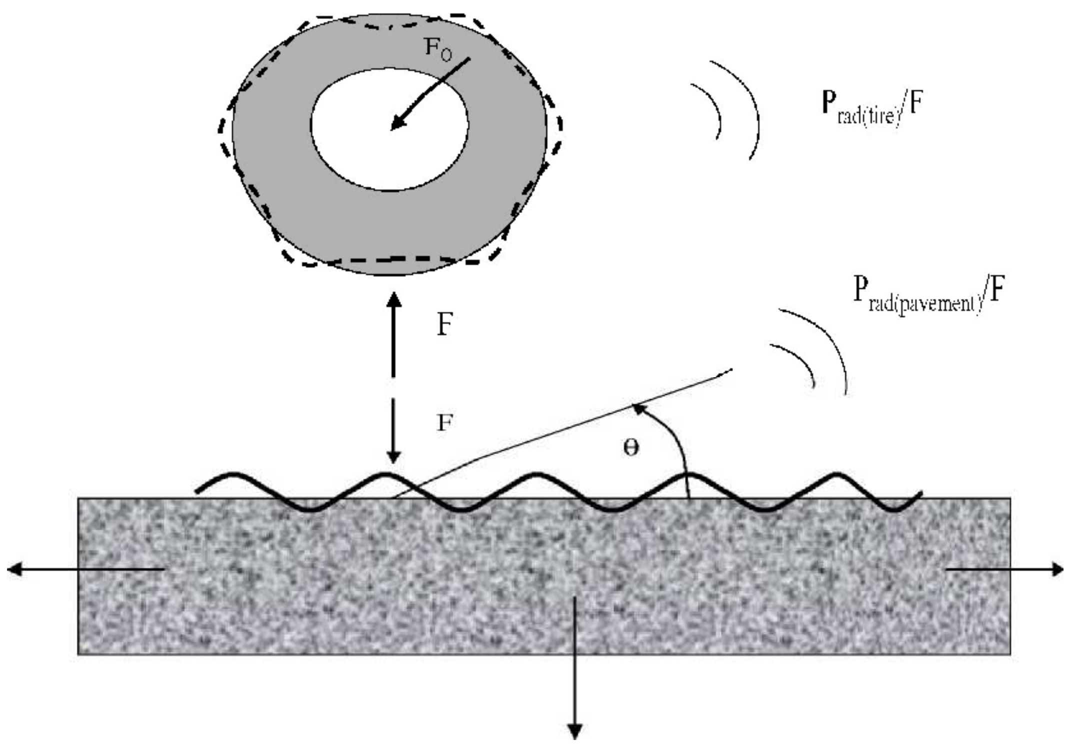

Fig. 11. Radiation from tire-pavement vibrations in response to interaction forces

At grazing, $\sin^2\theta \to 1$, and Eq. B1 reduces to

$$|\, p_{rad}(R,\theta;\omega)\,|\, R/F = \frac{(2\pi)^{-2}(c_{air}/c_{shr})^4(\omega/c_{air})\sqrt{1-(c_{air}/c_{dil})^2}}{[2-(c_{air}/c_{shr})^2]^2 - 4\sqrt{1-(c_{air}/c_{dil})^2}\sqrt{1-(c_{air}/c_{shr})^2}} \tag{B2}$$

with the shear and dilatational speeds given by

$$c_{shr} = \sqrt{\frac{G}{\rho}} \text{ and } c_{dil} = c_{shr}\sqrt{\frac{4-E/G}{3-E/G}} > c_{shr}\,.$$

Viscous effects are taken into account by allowing for complex wave speeds, viz.,

$c_{shr} \to c_{shr}(1-i\eta_{shr})^{1/2}$ and $c_{dil} \to c_{dil}(1-i\eta_{dil})^{1/2}$ with η_{shr} and η_{dil} effective loss factors. For acoustically “slow” pavements $(c_{air}/c_{dil}),\ (c_{air}/c_{shr}) >> 1$, and at grazing, Eq. B2 becomes

$$|\, p_{rad}(R,\theta=\pi/2;\omega)\,|\, R/F \cong (\omega/c_{dil})/(2\pi)^2 \tag{B3}$$

For acoustically “fast” pavements, which will typically be the case, $(c_{air}/c_{dil}),\ (c_{air}/c_{shr}) << 1$ and again at grazing, we have

$$|\, p_{pvmnt}(R,\theta=\pi/2;\omega)\,|\, R/F \cong [(\omega/c_{dil})/(2\pi)^2](c_{air}/c_{shr})^2/4 \tag{B4}$$

For a crude evaluation of the corresponding radiation from this interaction force driving the tire casing (a detailed analysis is quite complex and well beyond the present scope [Ref. 8]), we express the admittance at the natural frequency of a hypothesized natural vibration mode of the tire as

$$|\, v_{tire}/F\,|_{\omega=\omega_{res}} = \frac{1}{\omega_{res.}(mS)_{tire}\eta} \tag{B5}$$

and the associated radiation as

$$\begin{aligned} |\, p_{tire}(R,\theta;\omega_{res})\,|\, R/F &= (\rho_{air}\omega_{res}/2\pi)(vS)_{tire}/F) \\ &= (\rho_{air}/m_{tire})/2\pi\eta \end{aligned} \tag{B6}$$

where m_{tire} is the effective tire mass per unit surface area, S_{tire} is the effective surface area of the tire casing, η the effective dissipation (loss) factor of the resonant tire mode, and v_{tire} is the average resonant casing velocity at the natural frequency $\omega_{res} = 2\pi f_{res}$.

From Eqs. B5 and B6

$$\left|\frac{p_{pvmnt}(R;\omega_{res.})}{p_{tire}(R;\omega_{res.})}\right| = (\omega_{res.}t_{tire}/c_{dil})(c_{air}/c_{shr})^2\eta(\rho_{tire}/\rho_{air})/8\pi \tag{B7}$$

Taking the casing thickness to be small in terms of the dilatational wavelength, we estimate $\omega_{res}t_{tire}/c_{dil} = O(10^{-1})$. Also, for typical rubbers, $(c_{air}/c_{shr})^2 = O(10^{-2})$ and $\rho_{tire}/\rho_{air} = O(10^3)$. Thus, the order of magnitude of Eq. B7 becomes

$$\left|\frac{p_{pvmnt}(R;\omega_{res.})}{p_{tire}(R;\omega_{res.})}\right| = O(10^{-1})\eta << 1$$

In other words, we conclude that radiation from pavement vibrations driven by tire-pavement interaction forces is insignificant relative to that radiated by (resonant) tire-casing vibrations.

C. Pavement Stiffness

We now address an issue concerning the parametric dependence of the interaction force magnitude itself. While the detailed dynamics of the tire-pavement interaction are clearly beyond the scope of this report [Ref. 8, 9], a number of generic conclusions are suggested from the consideration of highly idealized, elementary models and insights.

First, consider the relative magnitude of the harmonic interaction force(s) between the tire and pavement. It is assumed that the "ultimate source" mechanically drives the tire elsewhere, e.g. through the tire hub, and that the tire and pavement remain in contact over a specified and compact contact area. It follows that the interaction forces on the tire are equal (and opposite) to those on the pavement, and may be expressed as

$$\vec{F}_{Interface} = \frac{V_0\vec{Z}_{Tire}\vec{Z}_{Pavement}}{\vec{Z}_{Tire} + \vec{Z}_{Pavement}} = \frac{V_0\vec{Z}_{Tire}}{1+\vec{Z}_{Tire}/\vec{Z}_{Pavement}} \tag{C1}$$

where V_0 represents the actual drive source strength (taken to be pavement invariant) and Z_{tire} and $Z_{pavement}$ denote the interface drive impedances of the tire and pavement, respectively, with the arrow over-score indicating a direction vector. Under the premise that typically, along any given direction, the impedance of the pavement greatly exceeds that of the tire, Eq. C1 reduces to

$$\vec{F}_{interface} \cong V_0\vec{Z}_{tire} \tag{C2}$$

In other words, the magnitude(s) of the interface drive force(s) are invariant to pavement characteristics, viz., its normal impedance or "stiffness". This is consistent with the above mentioned findings from Ref.1 indicating that pavement stiffness has not been shown to affect sound levels**.**

D. Pavement Texture

Next, we consider the potential influence of pavement texture, or roughness, as a source of tire vibration and in turn, noise. Here, it is again supposed that the pavement is essentially rigid relative to the flexible tire and contact is maintained. (The influences of air turbulence and pumping mechanisms are also ignored.) Consequently, the pavement profile is impressed onto the tire over a specified contact area, generating harmonic forces that drive the tire. Representing the pavement texture as a packed grid of intruding hemispheres of radius a, assuming that each such hemisphere generates an uncorrelated force on the tire proportional to the indentation, i.e. radius, and that the tire surface is smooth, the overall rms force becomes

$$F_{texture}^2 = [K_t a]^2 [S/(2a)^2] = K_t^2 S/4 \qquad \text{(D1)}$$

where S is the contact area, and K_t the effective dynamic stiffness of the tire. The first term in brackets is the magnitude of the individual forces, and the second is the number of such forces. Note that Eq. D1 actually turns out to be invariant to a, the characteristic roughness scale, at least under the assumption of a smooth, e.g. worn, tire. This is consistent with Sandberg's rejection of the "myth" that "the coarser the texture, the higher the noise emission becomes" [Ref. 2]. Also, since Eq. D1 indicates a 6 dB per doubling of contact width, and in turn area, it is also consistent with the comment in Ref. 2 that "the width of the tire is a very influential factor" and, roughly, the observation that a regression analysis of data is linear with a logarithmic width scale and a change from 155 mm to 195 mm tires would mean almost 2 dBA of noise increase (viz $10 \times \log(195/155) \cong 1 dB$).

Pursuing the issue further, tire casing vibrations are dominated by length scales associated with compressional, shear, and flexural wavelengths in the sidewall and perhaps the acoustic wavelength of the enclosed air volume [Refs. 8, 9]. Of these, only flexure is dispersive, at least to first order, and it provides the shortest wavelength at frequencies of interest.

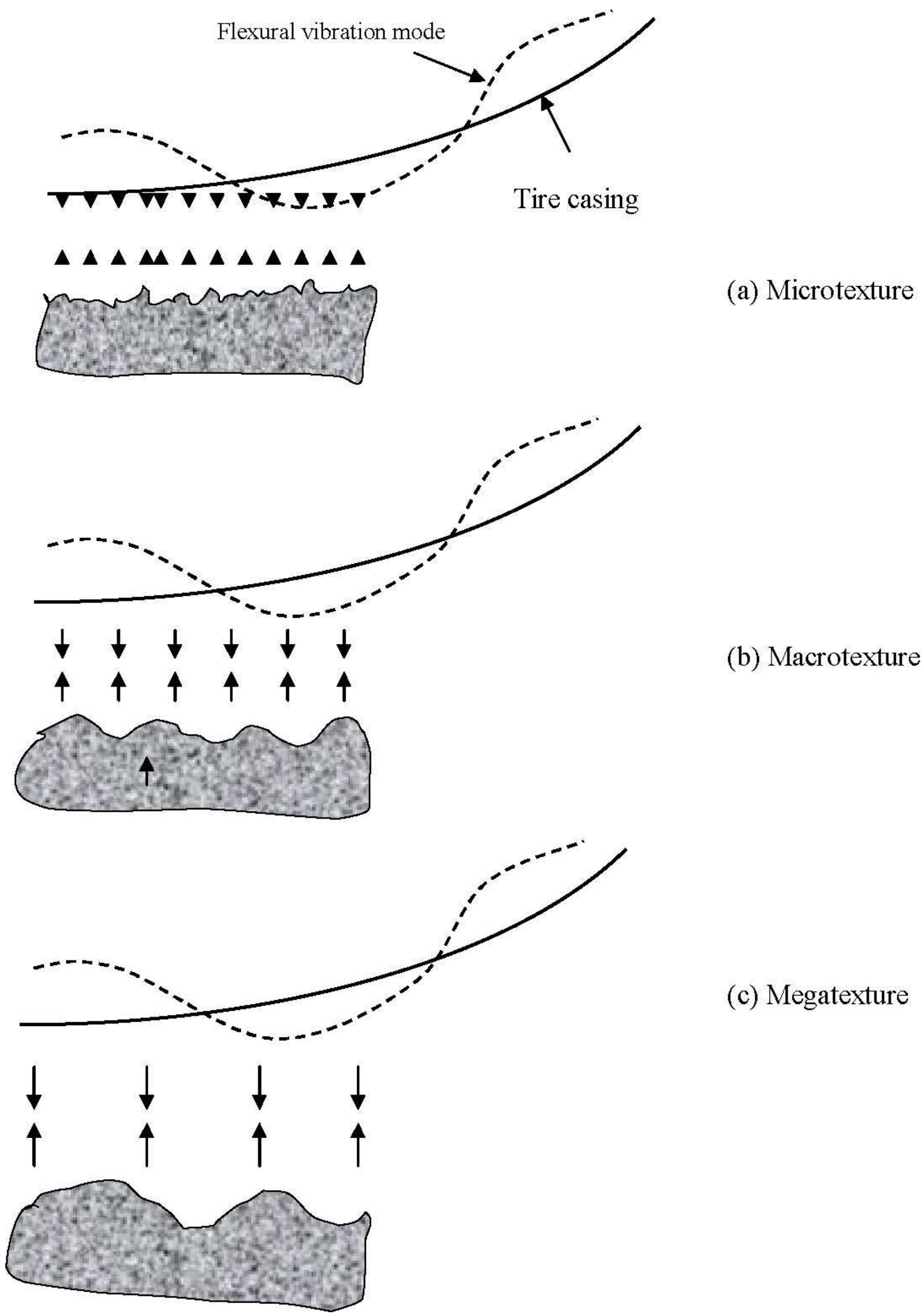

Fig. 12. Illustration of texture length scales relative to (flexural) wavelength in tire casing

To illustrate, taking $G = 4.9\text{x}10^8$ N/m^2, and $\rho \cong 1.2x10^3 kg/m^3$, we have $c_{shr} \cong 200m/s$ and $\lambda_{shr}(m) \cong 0.2/f(kHz)$ with $E \cong 3G$, $c_{comp} \cong 340\,m/s$ and $\lambda_{comp}(m) \cong 0.34/f(kHz)$. Using the simplest Euler bending model, the wavelength of flexural waves is $\lambda_{flex} \cong (2\pi/12^{1/4})\sqrt{c_{tire}t_{tire}/\omega}$ where c_{tire} is the effective plate speed in the tire sidewall, and t_{tire} is the sidewall thickness. Thus, letting $t \cong 8x10^{-3}\,m$, $c_{flex} \cong 7.x10^{-2}\sqrt{f(kHz)}m/s$ and

$\lambda_{flex}(m) \cong 7x10^{-2} / \sqrt{f(kHz)}$ or about 70 mm at 1 kHz. Since $c_{air} \cong 340 m/s$, we have flexural waves with phase velocities that are highly subsonic at frequencies of interest (e.g. around 1 kHz), and shear and compressional (membrane) waves that are transonic/supersonic. It is also observed that with frequencies on the order of 1 kHz, the tire-pavement contact area is typically small when measured in terms of (squared) compressional wavelengths, somewhat less so in terms of shear wavelengths, but large with respect to flexural wavelengths. Regardless, each wave type will tend to average over, and thus diminish the relative influence of texture length scales less than say 25% of their characteristic wavelength, e.g. at 1 kHz about 85 mm for compression and 18 mm for flexure. In other words, if a factor at all, one should expect the larger (macro) texture scales to be the more efficient drivers of tire vibrations. This holds for transversely oriented, as well as random, texture. With this simplified view, longitudinally oriented texture, via tining or grooving, is benign. On the other hand, transverse striations, with characteristic spatial scales of macro- or mega-texture, will be more problematic than comparable random texture, being coherent across the tire width.

The situation is more complex for tires that are not deemed smooth, i.e. those with pronounced tread. Here the scale of the tread block likely provides an upper limit on the scales driving the tire vibrations and thus, texture of all scales may be considerably less important. It is noted that Sandberg [Ref 1, Sect 11.5] suggests that tread block impact may dominate the overall tire noise levels in the vicinity of a cut-off frequency $f_c \cong 1 kHz.$, with lower frequency levels increasing with pavement texture wavelengths in the range of 10 to 500 mm (0.4 to 20 inches) and with higher frequency levels decreasing with pavement texture wavelengths in the range of 0.5 to 10 mm (0.02 to 0.4 inches). The latter is related to the influence of texture on air displacement mechanisms.

E. Air Pumping

As the tire interacts with the pavement surface and compresses under load, it forces air in and out of pockets in both the tire tread and the road surface. This air pumping potentially affects tire noise and, although well beyond the present scope, is briefly considered below.

The pressure radiated from air pumping in and out of tread interstices may be expressed in the form [Ref. 10]

$$<|p|^2> = Const[(m\delta f_\delta w)V^2 / RS]^2 \qquad \text{(E1)}$$

where is δ is cavity depth, w is cavity width, S the circumferential cavity spacing, V vehicle speed, f_δ the fractional change in cavity volume, m the number of cavities per tire width, and R range. Pavement porosity may have the effect of increasing the radiated pressure levels either by reducing S and in turn increasing the frequency, $\omega=2\pi V/S$, or, at a constant frequency, by increasing the effective cavity volume displacement, $m\delta f_\delta w$. On the other hand, should the pavement and tread pores line-up, noise levels may be lowered, e.g. by a reduction in f_δ.

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