Influence of Material Properties on Tire/Road Noise for Non-destructive Pavement Condition Assessment

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Abstract: With the purpose of using tire/road noise for pavement condition assessment as a non-destructive test method, an investigation on the influence of pavement material characteristics on tire/road noise is conducted. The acoustic data is collected by a directional microphone mounted behind the rear tire on the passenger’s side of a test vehicle, driving over different sections of pavements with different material properties. The tire/road noise under 2000 Hz is extracted to investigate how it is influenced by the pavement features, such as macrotexture, porosity, top-layer thickness, and top-layer stiffness. The macrotexture, which mainly reflects pavement friction, exhibits high relevance to the tire/road noise below 1000 Hz. The top-layer stiffness of pavement could be distinguished from the sound pressure level at peak frequency between 700 ~ 1300 Hz, the larger stiffness coming with higher amplitude of sound pressure level (SPL) at peak frequency. The results show high potential to assess pavement friction by the tire/road noise starting from macrotexture measurement. Moreover, the consistency of paving quality or sudden change of pavement subsurface structure can be recognized by looking into the spectrum features at peak frequency area of tire/road noise.

1. Introduction
Pavement health monitoring is very important to our nation. The current road situation is in need of improvement according to the ASCE report card [1]. Different road surface problems will cause different safety concerns. Too much bleeding on the road’s surface will reduce the friction between tire and pavement interface, causing vehicles to skid. Segregation is “a lack of homogeneity in the hot mix asphalt constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distresses” [2]. Severe segregation will lead to pavement raveling, or even potholes. Besides, the invisible subsurface delamination or other kinds of deterioration may cause the sudden collapse of the top layer of the road. This is a potential danger for drivers on city roads, especially on interstate highways. Accordingly, both surface distresses and subsurface delamination need to be effectively monitored and transportation authorities must be alerted when the condition reaches critical levels. The vision is to use vehicles of opportunity, which regularly travel on city roads and interstate highways, to collect and integrate sensor measurements and to perform onboard judgments about surface distresses and subsurface integrity of roadways and bridge decks.
To avoid variation due to the subjectivity of human ears, an acoustic sensor, namely a microphone, is used to “hear” and sense the road condition through the vehicle noise generated by tire. The microphone application idea allows testing at normal traffic speed, and makes continuous monitoring of road condition possible.

Generally, drivers and passengers can distinguish a difference in road condition as the vehicle travels from one type of surface to another \[3; 4; 5\]. Also, from the daily experience, people could also “hear” the road condition instead of “see”. When the vehicle drives over the smooth roads, the vehicle noise from tire/road interaction is very quiet; while the vehicle drives over the damaged roads or rough roads, the vehicle noise is loud. Besides, Sandberg and Ejsmont concluded from a noise source distribution of a 74 dB vehicle study in driven-by test that noise generated by tire is the predominant one among all the noise from a moving vehicle, compared with other sources such as exhaust system, intake system, engine and remaining unidentifiable noise \[3\]. A pilot study in Netherlands indicated that 90% of the equivalent sound energy in urban traffic is generated by tire/road noise \[3\]. The most important noise source on the vehicle, during a driving-by test according to ISO 362 \[6\], is the tires. Hence, tire/road noise is selected for pavement feature analysis. In order to make use of the tire/road noise for road feature detection, the first issue is to understand the frequency content of tire/road noise that is related to road features, i.e., the influence of road features on tire/road noise. In this study, the influence of road features on tire/road noise will be investigated and validated by the field test.

The challenge of this study is that no current technology is using acoustic measurements collected by microphone to directly assess pavement conditions. Some related literature discusses the use of tire-road noise for quiet pavement application \[3\], and also mentions that there exists some relationship between tire-road noise and pavement macrotexture – one road feature \[3; 4\]. The primary challenge is to determine the frequency band of tire/road interaction that related to road conditions. Hence, before to apply the tire/road noise for pavement condition assessment, the purpose of this study can be addressed as to understand the fundamental frequency content of vehicle noise related to road features.

The significance of this study is summarized as follows:

- Driver’s safety is very important. Real time monitoring of road characteristics most closely related to safety is necessary decisions regarding maintenance and repair priorities.
- Real-time pavement condition monitoring through an under mounted microphone is cost effective and user friendly. It eliminates the need to find the location from a large area or digging for potential subsurface delamination.
- Measurements can be conducted at traffic speed without traffic interruption. It not only eliminates the danger and expense from work zones, but also improves safety for inspection personnel who would otherwise be exposed to traffic hazards.

2. Theoretical Background
Pavement features include surface and subsurface parameters. Pavement surface features contain texture (microtexture, macrotexture, megatexture and unevenness), tining, and friction. Pavement subsurface features include stiffness, porosity and thickness of top layer \[7\].

2.1. Texture
Pavement texture is “the deviation of a pavement surface from a true planar surface” \[8\]. The type of pavement texture is distinguished according to the ranges of texture wavelength \[6\]. Four types of pavement texture are classified as follows: microtexture, macrotexture, megatexture, and unevenness \[3\]. Microtexture in the order of single grains of sand, with wavelength less than 0.5 mm, can influence the friction and adhesion between the tire and the road surface \[7\]. Note the equation \( f = \frac{v}{\lambda} \), where \( v \) is vehicle driving speed (m/sec), \( \lambda \) is texture wavelength (m), and \( f \) is the corresponding frequency (Hz). Assuming that the driving speed is 8.9 m/sec, and wavelength is <0.5 mm, the frequency is >17.8 kHz. Hence, the influence of microtexture on tire/road noise is in high frequency content, larger than 1 Hz \[9\]. Moreover, microtexture is highly related to pavement friction, especially at lower speed less than 64 kph \[10\]. Larger microtexture depth will increase friction.
Macrotexture in the order of wavelength of tire tread patch, with wavelength of 0.5 mm to 50 mm, can also influence the friction between the tire and road surface \([7]\). Referring to the same equation, the frequency range is between 0.178 kHz to 17.8 kHz within the macrotexture wavelength at driving speed 8.9 m/sec. Sas and Sandberg indicate the effective frequency for macrotexture with a very strong influence on tire/road noise is below 1 kHz \([9, 11]\).

Megatexture in the order of wavelength of tire-pavement content patch, with wavelength of 50 mm to 500 mm, exerts considerable influence on the noise generated, especially in the high frequency area larger than 1 kHz \([12]\). It can be a defect in the pavement surface, resulting from the wear and fatigue of the surface material. Moreover, wavelength of 0.5m to 50 m is termed as unevenness, or roughness, which is in the order of a stretch of pavement. Its influence on tire/road noise is not clear. Also, it is not in the scope of this paper.

2.2. Tinning
Tinning is one finishing technique for concrete pavement. Tinning is achieved by dragging metal prongs on semi-hardened concrete pavement to create grooves longitudinally or transversely. The purpose of tinning is to reduce hydroplaning in wet weather. However, sound level will increase significantly when the tinning is transverse, while longitudinal tinning has only a weak effect on sound levels.

2.3. Friction
Friction between tire and pavement will cause stick-slip noise. The mechanism of stick-slip noise is similar as the noise caused when running your palm over a smooth surface \([7]\). Macrotexture will tend to increase the stick-slip noise, so as the friction.

2.4. Stiffness
The stiffness here is referred to the effective hardness of the surface. Variations in stiffness are commonly attributed to variations in binder materials. For example, asphalt binder is relatively flexible compared to cement binder. To study the effects of stiffness to tire/road noise, Nilsson and Zetterling conducted an experiment to test if the top layer stiffness will influence the tire/road noise \([13]\). A set of measurements of tire/road noise was collected on a thin grinding paper that glued either directly on a smooth cement concrete base or on a rubber sheet that was placed on the concrete surface. The difference obtained was a 5 dB noise decrease at the peak frequencies 700 ~ 1300 Hz. Accordingly, it seems that the influence of pavement stiffness may be dramatic if a really soft surface like rubber is mainly used. The observations suggest a quite high stiffness effect when very soft surfaces are compared to conventional hard surfaces.

2.5. Porosity and thickness of top layer
Porosity is a measure of the void spaces in pavement top layer material. Porosity here is specially referred to the porous pavement. Porous pavement is a permeable pavement surface with a stone reservoir underneath. The reservoir temporarily stores surface runoff before infiltrating it into the subsoil. Runoff is thereby infiltrated directly into the soil and receives some water quality treatment. Porous pavement often appears the same as traditional asphalt or concrete but is manufactured without “fine” materials, and instead incorporates void spaces that allow for infiltration. Apparently, porous pavement are more acoustically absorptive than non-porous pavement, so porous pavements tend to be quieter than non-porous pavements. Porosity parameters are composed of percent voids, the size of voids, the layer thickness, and the shape factor, among which the layer thickness will affects the peak frequency of tire/road noise. According to the research by Sandberg and Ejsmont \([3]\), the porosity and thickness of top layer has a strong influence on tire/road noise above the frequency of 1 kHz.
In summary, Figure 1 presents the potential influence of tire/road parameters on tire/road noise \cite{3, 7, 9}. Three observations should be noticed from Fig. 1: (1) pavement macrotexture is highly relevant to tire/road noise, comparing with megatexture and microtexture; (2) tire tread pattern pitch also has a very high level of influence on tire/road noise; (3) the relative frequency range for pavement macrotexture on tire/road noise is below 1 kHz. These observations bring pavement macrotexture to the tire/road noise study. Since macrotexture strongly influences tire/road noise, the use of vehicle noise for pavement condition assessment starts from pavement macrotexture measurement.

Another interesting phenomenon in Fig. 1 is that the tire/road parameters’ influence on tire/road noise has an intersection at 1 kHz. The author also found from the collected data that there is a peak around 1 kHz in tire/road noise spectra. Sandberg named this peak around 1 kHz as “multi-coincidence peak” \cite{11}. He pointed out that it is a multi-functional region of frequency. Also, it is related to pavement macrotexture and vehicle tire tread pattern, both of which have many kinds of sound generation mechanisms coincidently over the frequency range from 700 to 1300 Hz \cite{11}, which need be avoided during macrotexture estimation. Meanwhile, frequencies from 700 to 1300 Hz are termed “peak frequencies”.

3. Test Verification
A field test conducted in September 2019 at Jinfeng Vehicle Research and Test Base in Chongqing verified the discussions above, especially on the factors of friction, porosity, thick of layer and stiffness. The test track consists of 16 sections of pavements, each 200 meters in length. A test vehicle drove at 3 different speeds over the track, 32 kph, 56 kph, and 80 kph, 3 rounds for each speed. The following discussions will demonstrate how the pavement macrotexture influences tire/road noise from the experiment data, and how the top layer thickness affects peak frequency of tire/road noise.

3.1. Test Configuration
The microphone configuration mounted underneath the test vehicle is shown in Fig. 2. The sensitivity of the directional microphone is from 44 ~ 52 mV/Pa. The sampling frequency of this test is 50 kHz. Since the type of tire will influence the frequency spectra of acoustic signal, especially in the typical “tire - band” range 500 ~ 1300 Hz \cite{24}, the same tire is used throughout the experiment to eliminate the possibility of the tire effect.
In September 2019, the test was conducted at Jinfeng Vehicle Research and Test Base in Chongqing. The track is 3.2 km long, consisting of 16 sections of pavement, each 200 meters in length. The vehicle collected over 100 GB of acoustic data as it drove around the track for different testing configurations. The 16 pavement types are listed in Table 1. The vehicle drove at 3 different speeds over the track, 32 kph, 56 kph, and 80 kph, 3 rounds for each speed. For each round there are 16 measurements corresponding to the pavement sections listed in Table 1.

Table 1. Pavement Properties at Jinfeng Test Base

| Section | Design  | MTD (mm) | Section | Design  | MTD (mm) |
|---------|---------|----------|---------|---------|----------|
| 1       | SMA     | 0.8      | 9       | OGFC    | 1.3      |
| 2       | Superpave | 1        | 10      | OGFC    | 1.5      |
| 3       | Superpave | 0.5      | 11      | PFC     | 1.4      |
| 4       | SMA     | 1.2      | 12      | SMA     | 0.9      |
| 5       | SMA     | 0.9      | 13      | PFC     | 1.3      |
| 6       | Superpave | 0.5      | 14      | PFC     | 1.2      |
| 7       | SMA     | 1.5      | 15      | SMA     | 1        |
| 8       | Novachip | 0.8      | 16      | OGFC    | 1.2      |

(Note: SMA = Stone Matrix Asphalt; OGFC = Open Graded Friction Course; PFC = Porous Friction Course.)

Based on the experience of a previous study \(^{(15)}\), acoustic data collected by the directional microphone behind rear tire on the passenger’s side is chosen for the macrotexture investigation, since the acoustic signal spectra from the microphone represents good correlation with pavement macrotexture. The microphone is directed to the interface of rear tire and ground, which is expected to be the source of most tire/pavement sound, and shielded from wind and engine noise, 5.1 cm away from the ground surface as shown in Fig. 2.

3.2. Pavement macrotexture and tire/road noise

In the Jinfeng test, different frictions are represented as different macrotexture depths (MTD). The MTD value is known for all pavement sections of the test track. A Fourier transform was performed to the collected acoustic measurements with the microphone mounted underneath the vehicle behind the driver side rear tire. Four pavement sections with different MTD’s are presented in Figure 3. From Pavement A to Pavement D, the MTD’s in order are 0.5 mm, 0.8 mm, 1.2 mm and 1.5 mm. The texture of pavement gets rougher as MTD increases. Referring to Fig. 4, with the same speed (32 kph), as the MTD of pavement increases from 0.5 mm to 1.5 mm, the sound pressure level (SPL) of
tire/road noise goes up below 650 Hz, which is close to the peak frequencies (700 ~ 1300 Hz). The same trend is obtained by Sandberg’s research [3], which indicates the acoustic energy increases as coefficient of friction increases below the peak frequency at around 1 kHz. This strong correlation between MTD and tire/road noise below 1 kHz verifies the conclusion in Fig.1 regarding the macrotexture part.

Figure 3 Pictures of Pavements with Different MTD Values (Note: width of picture is 12 cm.)

Figure 4 Sound Pressure Level (SPL) of Pavements with Different Friction Properties

3.3. Pavement subsurface features and tire/road noise
Pavement subsurface features include porosity, thickness of the top layer, and stiffness. Fig. 5, Fig. 6, and Fig. 7 respectively show the influences of porosity, top layer thickness and top layer stiffness on the tire/road noise based on Jinfeng test data.

The porosity of asphalt mixture pores is composed of connected pores, semi-closed pores and fully closed pores. Tire/road noise is influenced by the connected and semi-closed pores, which is named effective porosity. Three OGFC pavements with effective porosity of 20.5%, 17.93% and 15.24% are tested under the same experimental condition. The average sound pressure level below 1 kHz for these three pavements are 75.6 dB, 77 dB, and 78.5 dB accordingly. The relationship between the porosity and the sound pressure level is shown in Fig. 5.
Fig. 5 shows the linear relationship between sound pressure level and pavement porosity as Equation (1):

\[
SPL = -0.5514 \times \text{Porosity} \times 100 + 86.90
\]

where,

- SPL = average sound pressure level of tire/road noise below 1 kHz, unit: dB; and
- Porosity = effective porosity of pavement, unit: %.

The sound pressure level decreases as porosity increases of the tested OGFC pavements.

Pavement A and B shown in Fig.6 have the same subsurface profile and macrotexture value except the thickness of the top layer, 10 cm for Pavement A and 5 cm for Pavement B. However, the frequency spectra of both pavements are very similar to each other. No significant difference is detected. Sandberg and Ejsmont \cite{3} have investigated the influence of top layer thickness of porous pavement on the tire/road noise. It is concluded that the peak frequency will shift for different thickness. Nevertheless, for non-porous pavement, it seems that the thickness of the top layer has little influence on the frequency spectrum.

In Fig.7, the only difference of both pavements is the stiffness of the top layer: the stiffness of Pavement B is harder than that of Pavement A. Based on the conclusion from the experiment by Nilsson and Zetterling \cite{13}, the SPL at peak frequency of pavement B is higher than that of Pavement A, which means the stiffness of stone matrix asphalt (SMA) is larger than that of epoxy. Hence, the
conclusion that the top layer with larger stiffness produces larger amplitude of SPL at peak frequencies 700 ~ 1300 Hz is demonstrated by the consistent performance in Fig.7. Moreover, the porosity study proved the influence of top-layer stiffness to the tire/road spectra from another perspective, which indicates that higher average sound pressure level comes with lower porosity, while lower porosity means harder surface layer.

![Figure 7 Influence of Top Layer Stiffness on Tire/Road Noise](image)

The study on the influence of pavement subsurface features on tire/road noise indicates some potential for non-destructive pavement subsurface monitoring with moving vehicle at real time. Generally, the stiffness of top layer pavement within 10 cm from surface could be sensed by microphone. The harder surface layer will produce higher amplitude in sound pressure level at peak frequencies 700 ~ 1300 Hz.

4. Conclusion
This paper conducts an overall study to investigate the influence of material characteristics on the tire/road noise for non-destructive pavement assessment. Different pavement characteristics influence the spectra of tire/road noise at different frequency ranges. From the field test results, the following conclusions can be drawn:

1. Pavement macrotexture is highly relevant to the tire/road noise comparing with megatexture and microtexture, which is verified by the field test.
2. The relative frequency range for pavement macrotexture on tire/road noise is located as below 700 Hz, considering avoiding the multi-functional region of frequency range from 700 to 1300 Hz.
3. The top-layer stiffness difference of pavement is able to be distinguished by the sound pressure level at peak frequency between 700 ~ 1300 Hz. The harder surface layer will produce higher amplitude in sound pressure level at the peak frequency.

In the future, the tire/road noise will be further studied to evaluate the pavement condition as a cost-effective way. Since pavement surface friction is represented by macrotexture, it is recommended to assess pavement surface friction through tire/road noise starting from macrotexture measurement. Meanwhile, a non-destructive test method will be developed by using tire/road noise to evaluate the pavement subsurface consistency as a symbol of paving quality, even more, a warning for invisible potential damage.

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