inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 1.3

THE EFFECT OF PAVEMENT POROSITY ON TIRE TREAD BLOCK NOISE GENERATION

S. Jones, D. Karnopp, N. Sarigul-Klijn

University of California at Davis, C/O Professor Sarigul-Klijn, Transportation Noise Control Center (TNCC), Dept of Mechanical and Aeronautical Engineering, 95616-5294, Davis, California, United States Of America

Tel.: (530)-752-0682 / Fax: (530)-752-4158 / Email: nsarigulklijn@ucdavis.edu

Keywords:
TREAD BLOCK IMPACT NOISE, LOW NOISE PAVEMENTS

ABSTRACT
Tire noise has long been recognized to be a major contributor to traffic noise. Although any type of tire carcass vibration can generate noise, this paper will only discuss the mechanism of a tread block impacting a highway surface. To isolate the pressure signature generated by a single tread block, a tread block impact device has been developed. The acoustic pulses produced can be associated with the changing volume velocity of the air displaced as the tread block approaches the surface. By testing impact surfaces with known porosity and frequency characteristics, experimental relationships between the shape of the acoustic pressure signature, and noise attenuation can be determined. By evaluating the frequencies generated by tread block impacts, tuned pavements which attenuate the most irritating frequencies could be developed.

1 - INTRODUCTION
Extensive testing has been completed to determine the individual contributions to tire noise. However, most tests analyzing tread vibration, aerodynamic noise, tread block impacts, and air pumping noise were performed on an entire tire. By using a complete tire, extracting the distinct components is extremely difficult. Thus, the need to develop a method of isolating tread block impacts from all other tire noise components was apparent.

2 - BACKGROUND
While research on isolated tread block impact noise was limited, work has been performed on euphonic pavements and general impact. The OCED Scientific Expert Group [1] reported that a ten-fold reduction in traffic noise could be obtained using a series of resonators tuned to attenuate specific frequencies in a highway surface. Additionally, both Richards [2] and Koss & Alfredson [3] investigated and quantified impact noise as applied to industrial machines. They predicted impact noise in terms of energy dissipation of an accelerating or decelerating body.

3 - EXPERIMENTAL RESEARCH CONFIGURATION
To isolate tread block impacts from other tire/pavement interactions, the tread block impactor was developed, as shown in Figure 1. Much like two freely suspended pendulums, the initially motionless impact block was steadied and the tread block impactor was released from various heights to simulate a variety of velocities. The experiment, performed in an anechoic chamber, involved a piece of smooth, non-porous concrete, various impact surfaces, tread block impactor, a high-speed camera, and an accelerometer. The digital PULSE Sound System developed by Bruel & Kjaer was used to record, store, and analyze the pressure signals sensed by the free-field microphones (B&K 4155 type/half-inch diameter). The microphones were placed at known distances from impact, and the sound system was triggered to record both the impact, and rebound of the tread block impactor.

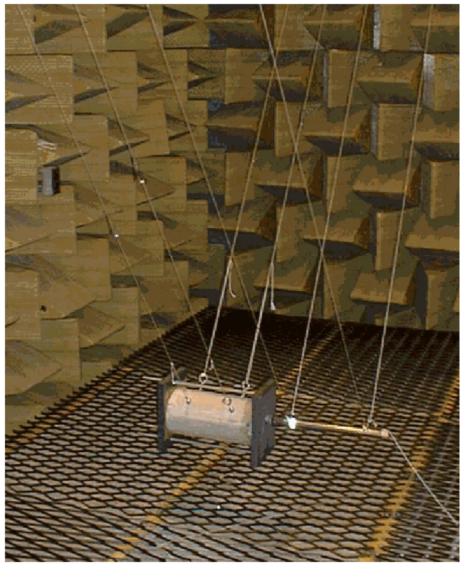

Figure 1: Tread block impact tester.

4 - SIMPLE MONOPOLE SOURCE THEORY

Computing the volume velocity for a simple monopole source can approximate the sound from a single tread block impact with a highway surface. The vibratory effects will be neglected. The volume velocity of a spherical sound source where the source size is much smaller than the wavelengths radiated is:

$$Q = \left(4\pi a^2\right) u_r\left(t\right) \tag{1}$$

where:

- a=radius of the small sphere
- u_r=radial velocity at the surface where r=a
- r=distance from spherical source.

The pressure from a spherical source at a distance r, is [4], [5],

$$p\left(r,t\right) = \frac{\rho_0 \dot{Q}\left(t - \frac{r}{c}\right)}{c} \tag{2}$$

If a perfectly reflecting rigid boundary is in close proximity to a simple monopole source, the pressure magnitude perceived by the receiver at distance r is doubled. Thus, the pressure pulse is modified to:

$$p\left(r,t\right) = \frac{G\rho_0 \dot{Q}\left(t - \frac{r}{c}\right)}{c} \tag{3}$$

where G=absorption coefficient of the impact/roadway surface (G=1 for a completely reflective surface). For the tread block impact device, the theoretical equations for a simple monopole source can be modified to represent the pressure pulse generated during impact. Because tread blocks on a tire contact the pavement surface over a finite time, the tread block impactor was given a slight wedge shape.

The volume velocity of the air in the impact region is given as:

$$Q = S\left(x\right) v_0 \tag{4}$$

where:

- $S(x)$=$(A_0/x_1)(x_1$-$x)$=planar area of the impact surface (assumed linear)
- v_0=velocity of the impactor
- x=amount of compressed distance
- x_1=amount of compressible distance

- A_0=total planar surface area
- t_0=contact time.

The volume acceleration of the air in the impact region can be expressed as:

$$\dot{Q} = v_0 \frac{dS(x)}{dt} + S(x) \frac{dv_0}{dt} \tag{5}$$

If the tread block velocity during compression is assumed constant, the $[dv_0/dt]S(x)$ term vanishes. The absorption factor G is assumed to be one for the concrete and the maximum pressure value occurs when x=x_1. Thus, the pressure can be written as shown below.

$$p(r,t) = \frac{\rho_0 \dot{Q}}{2\pi r} = \frac{\rho_0 v_0}{2\pi r}\left(\frac{dS(x)}{dt}\right) = \frac{\rho_0 v_0 A_0}{2\pi r}\left(\frac{-1}{x_1}\right) \tag{6}$$

Highly simplified volume velocity and pressure profiles are shown in Figure 2. The first negative slope of the volume velocity plot represents the displacement of the air from the contact region. Once the tread block is in full contact with the concrete, the volume velocity decreases to zero. When the tread block rebounds, from the concrete in the opposite direction of impact, air is pulled into the voided region; thus, an additional negative volume velocity slope was generated. When the air fills the void, the volume velocity is nearly constant. The pressure profile is a function of the derivative of the volume velocity.

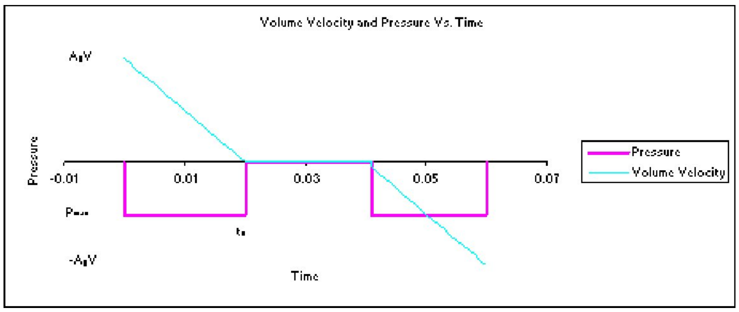

Figure 2: Theoretical volume velocity and pressure plots.

Another method of modifying pressure equations was to equate the area under the linear pressure curve to a more experimentally representative parabolic curve. By equating the areas of the theoretical square and parabola pulse, the maximum value for the pressure pulse is:

$$p_{parabolic}(r,t) = \frac{3\rho_0 \dot{Q}}{4\pi r} = \frac{-3\rho_0 r_0 v_0}{4 r x_1} \tag{7}$$

5 - EXPERIMENTAL RESULTS

Several different types of rubber impact surfaces were tested. It was found that a flat soft porous rubber induced the fewest vibrations and produced the most repeatable pressure impact results. The results of the soft rubber/concrete impact are shown in Figure 3. The maximum experimental pressure was -1.34 Pa. Using equations (6) and (7), the theoretical pressure pulse values are -0.608 Pa and -0.913 Pa, respectively.

Contact was assumed to occur in the range of 0.049 and 0.05 seconds. The time over which air was expelled during compression was approximately 0.0005 seconds. The compression pressure wave occurring at 0.005 seconds was assumed to be related to the rubber bulging under the compression forces. The additional compression and rarefaction waves occurring after the first major positive and negative pressure pulses are due to the vibration of the materials. Once the rubber was fully compressed, the tread block impactor rebounded at approximately 0.085 seconds causing a negative pressure pulse.

Once several nylon impact surfaces with known porosities were shown to reduce the magnitude of the pressure pulse, impact surfaces with built-in Helmholtz oscillator were then tested. Helmholtz oscillators have been used to dissipate acoustic energy at their tuned natural frequency and behave similar to one degree of freedom vibrational systems. Using two PVC sheets to form the resonators, a 1000 Hz tuned resonating surface was fabricated.

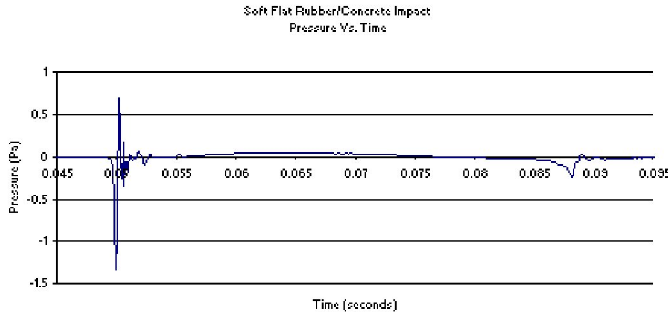

Figure 3: Soft rubber/concrete impact; impact velocity was approximately 1.22m/s and microphones were placed 34 cm along the axis of impact; no acoustic weighting.

When compared to impact on non-porous surfaces, the Helmholtz resonators attenuated the first negative pressure pulse by approximately 50%; however, the time duration of sound was increased. A small amount of fibrous material was then added to the neck of the Helmholtz oscillators to determine if the response could be modified. The magnitude of the first pressure pulse and the frequency oscillations were very similar, but the rate at which the damped vibration decreased dramatically. For the test shown in Figure 4, adding viscous damping to the neck of the oscillator increased the damping ratio and the fraction of total energy dissipated per cycle by greater than 50%.

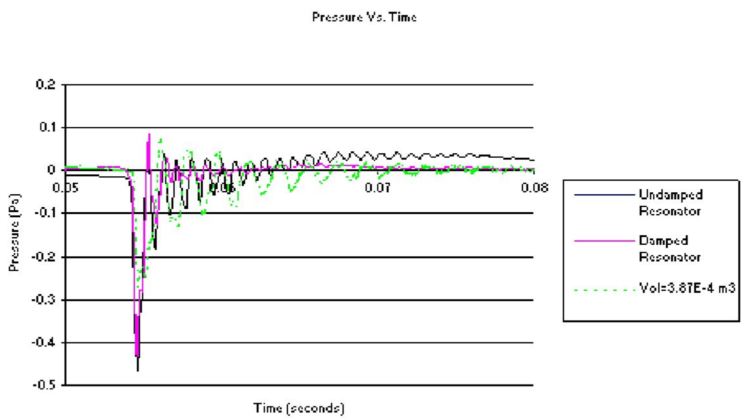

Figure 4: Soft flat rubber vs. various impact surfaces; impact velocity was approximately 1.22m/s and microphones were placed 34 cm along the axis of impact; no acoustic weighting.

To determine if a more practical highway impact surface could be developed, a voided impact surface was fabricated. An air volume was constructed behind a PVC sheet with 0.25" diameter through-holes. With increasing volume, the frequency of oscillation and maximum pressure values decrease, as shown in Table 1.

Volume (m^3)	Frequency (Hz)	Minimum Pressure Value (Pa)
3.87E-4	541.7	-2.66E-1
2.83E-4	583	-3.77E-1
2.47E-4	625	-4.17E-1
1.94E-4	750	-4.78E-1
Helmholtz Resonator	1000	-4.63E-1

Table 1: Volume dimensions for voided impact surfaces.

6 - CONCLUSIONS

From the tread block impact device, it has been shown that a simple monopole source can fairly accurately predict the range of pressure magnitudes from tread block impacts. In addition to attenuating general

highway noise, porous surfaces, built-in Helmholtz oscillators, and voided surfaces can be used to reduce the magnitude of the pressure pulses upon impact.
By modifying the parameters of the Helmholtz oscillators and voided surfaces, the impact noise response can be controlled much like spring-mass-damper systems. It is then feasible to tune surfaces to achieve attenuation at specific frequencies. The small-scale tests reported upon here must be extended to assess the practicality of these types of surface treatments.
The Helmholtz resonators and voided porous surface produce less noise during tread block impact. Therefore, this surface type would reduce noise from this mechanism. In addition, these types of surfaces generally increase absorption of sound from all noise sources. Helmholtz structures can be tuned to increase absorption of sound at specific frequencies.

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