

Effect of Air Temperature and Vehicle Speed on Tire/Pavement Noise Measured with On-Board Sound Intensity Methodology

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ABSTRACT

The objective of this paper is to show the variability of tire/pavement noise measured with the On-Board Sound Intensity (OBSI) method under different environmental conditions and vehicle speeds.

Temperatures ranging from 40 to 90°F and speeds in the range in which tire/pavement noise becomes predominant for the overall vehicle noise were tested. The selected speeds were: 35, 45, and 60 mph. The paper presents a brief literature review identifying the gaps of knowledge about the effects of different variables (e.g., environment, vehicle speed) on tire/pavement noise. It then presents a summary of different technologies used to determine noise measurements and introduces the OBSI methodology, its standards, and provides an overview of the system and software used for data acquisition.

The paper presents a series of seasonal field tests conducted on a primary road in Virginia over various months. The results were analyzed to quantify the variation of tire/pavement noise with respect to the test temperature and speed. Findings confirm the previously observed trend that tire/pavement noise slightly decreases as air temperature increases. The model shows a gradient of approximately -0.05 dBA/°F. Regarding the influence of vehicle speed, the test showed that for the surface studied tire/pavement noise increases an average of 2.5 dBA for every 10 mph of increased speed.

INTRODUCTION

This paper presents an overview about noise measurement methodologies focusing on the On-Board Sound Intensity (OBSI) method and a practical application of this methodology to determine the effects of environmental conditions and vehicle speeds on tire/pavement noise. A limited number of tests were performed on both directions of US-460 between Prices Fork Road and Toms Creek Road in Montgomery County, VA. Three different speeds: 35, 45, and 60 mph were used for measurements with the aim of determining the rate of change of the overall sound intensity level (IL) with respect to speed.

Different temperatures ranging from 40 to 90°F were also obtained measuring over several months. A literature review of different methodologies is followed by results of testing utilizing the OBSI system. Details about the experimental aspect are presented in the “Methodology” section.

BACKGROUND

Noise pollution is becoming an increasing issue in the U.S. as it has been in Europe and other countries. Traffic noise is considered a serious environmental problem, especially around critical zones such as hospitals, schools, recreational parks, neighborhoods located close to highways, etc. At highway speeds, it is known that tire/pavement noise is the greatest contributor to the overall noise level (further explanation below in the “noise and vehicle speed section”). In response to this concern, transportation agencies are considering solutions to address the noise pollution by reducing it at the source (i.e., tire/pavement interaction). With this issue in mind the Federal Highway Administration (FHWA) and several states, including Virginia, are already

working on and defining noise-abatement policies designed to avoid or mitigate traffic noise pollution.

Noise barriers are one of the most common ways to mitigate this problem, but this technology is not applicable for all cases and is not always cost effective. Therefore, using the knowledge gained from previous experiences, the use of alternative pavement surfaces points to innovative solutions with the goal of mitigating traffic noise at the source.

The basis, the importance, and the need for further research about tire/pavement interaction have been established. Additionally, specifications for measuring tire/pavement noise with the OBSI method are still under development.

Noise and Environmental Effects

The National Cooperative Highway Research Program (NCHRP) Report 630, 1-44 Project, indicates that previous work on the evaluation of test variables for OBSI measurements shows that there is a slight downward trend in noise with an increase in air and pavement temperatures, with a low coefficient of determination (R^2) from 0 to 0.4 (1). Tests conducted with this project show a decrease of approximately 1 dB for an air temperature increase of 10°C, or 18°F.

The precision and bias statements for the 1-44 Project subsequently recommended a temperature correction of -0.04 dB/°F to be applied to sound intensity data acquired with the analyzed set to standard conditions of 68°F (20°C) and 101.3 kPa atmospheric pressure to normalize reported levels to these conditions (2). These corrections have been used in the 2009 National Center for Asphalt Technology (NCAT) OBSI rodeo for normalizing data measured by different teams in different environmental conditions (3).

Another study conducted in Spain illustrates the same trend of the influence of temperature on noise measurements. In this case the testing was conducted with the close proximity (CPX) trailer Tiresonic Mk4-LA²IC rolling at a speed of 50 km/h (31 mph). The analysis of the results shows that the increase in pavement temperature leads to a reduction in the CPX sound levels assessed at a rate of 0.06 dBA/°C (4). Therefore, research with both OBSI and CPX measurements indicate the same inverse relationship between the temperature and the noise generated by tire/pavement interaction.

The literature also suggests that the effect of temperature is different when measured across different surfaces. The temperature effect is comparatively larger for a rough-textured surface than for a smooth-textured surface (5). As stated, however, this paper focuses on the effects of different ranges of temperatures and speeds on tire/pavement noise across one a typical surface used in Virginia.

When considering the relationship between air, road, and tire temperatures with noise, studies show that the association between noise and road temperature or noise and air temperature is more ideal than the relationship between noise and tire temperature (5). This was used as a starting point to establish air temperature as the focus of this study. Also, air temperatures do not vary across such a wide range as do road temperatures. Sandberg (5) also reports that work conducted by Liedever in 1999 and Landsberger in 2001 also showed a decrease in noise (sound pressure level) with the increase in road and air temperatures.

Noise and Vehicle Speed

The noise generated from tire/pavement interaction is just one of many noise sources for almost all roads and for most vehicles. It becomes the primary source of traffic noise for vehicular

speeds greater than 30 mph (6). Propulsion noise will dominate the total noise at low speeds. As speed increases, a crossover speed (the practical threshold above which quieter pavements will be most helpful) is reached at that point when the tire/pavement noise becomes the dominant source. Only at high speeds will aerodynamic sources begin to dominate (6). Figure 1 adopted from the Little Book of Quieter Pavements (6) shows the effect of speed on vehicle noise sources and the crossover speed.

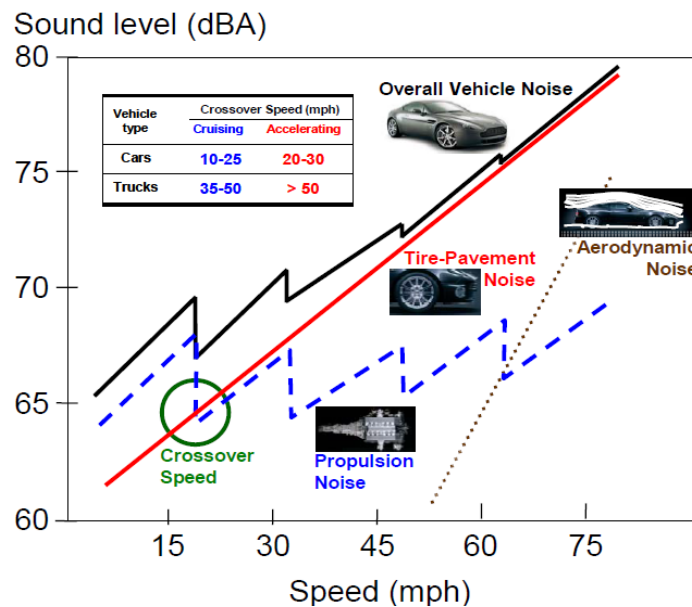


FIGURE 1 Sound level versus speed and crossover speed (6).

Another study states that the major facet of noise emitted on roads by vehicles traveling in the mid- to high-speed range (speed > 30 km/h) is tire/pavement noise (7). However, it is important to note that, due to advances made in the car industry (e.g., better and quieter engines), the so-called crossover speed is decreasing. Therefore the tire/pavement noise study is becoming imperative.

Research summarized in the NCHRP Report 630 shows the increase in the sound level as the vehicle speed increases. This phenomenon is similar across different vehicle types and different reference tires (8).

Noise Measurement Technologies

Wayside Noise Measurements

Wayside noise measurements are taken “at the side of the road,” either at a fixed distance or at the location of target receivers such as a residential neighborhood.

There are three types of wayside testing: 1) Statistical pass-by (SPB) in which a microphone at a fixed position measures the maximum sound level (L_{max}) of hundreds of individual vehicles. Using L_{max} the sound level is calculated for an average car, a medium truck, and a heavy truck. 2) Controlled pass-by (CPB) is similar to SPB in that a microphone at a fixed position measures L_{max} . In this case, however, a test is conducted for one or more known test vehicle/tire combinations. 3) Continuous flow traffic time-integrated model (CTIM) in which a microphone is set to record all of the traffic noise at a fixed time interval from 5 to 30 minutes. Traffic levels and speeds are simultaneously recorded, and an average equivalent sound level (L_{eq}) is calculated (6).

Source Noise Measurements

Source noise measurements are taken “near the tire,” a method that is more accurate than wayside noise measurements when the interest is to design and build quieter pavements.

There are two typical techniques for measuring tire/pavement noise using source noise: 1) CPX uses a single microphone that measures sound pressure, and testing is often conducted in an enclosed trailer to isolate the microphone from other sources of sound. 2) OBSI uses dual microphone probes that measure sound intensity. Because of the ability to identify the direction

of a sound source, the enclosed trailer is not required. Specifications for both CPX and OBSI remain under development.

A summary of noise measurement technologies is presented in Table 1.

TABLE 1 Noise Measurement Technologies

Technology	Noise Measurement	Type/Technique
Wayside noise measurement	At the side of the road	Statistical pass-by (SPB)
		Controlled pass-by (CPB)
		Continuous flow traffic time-integrated model (CTIM)
Source noise measurement	Near the tire	Close proximity (CPX)
		On-Board Sound Intensity (OBSI)

RESEARCH OBJECTIVE

The objective of this paper is to determine the effects of different environmental conditions (e.g., air temperature) and vehicle speeds on the noise generated by the interaction of the tire with the pavement surface in terms of the overall sound intensity (IL).

DATA COLLECTION AND REDUCTION

Obsi Methodology

Tire/pavement noise was measured following the American Association of State Highway and Transportation Officials (AASHTO) standard TP 76-12, “Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method” (9). Results are reported as overall A-weighted sound ILs. Results were calculated using the A-weighted, one-third octave band levels.

The Virginia Tech Transportation Institute (VTTI) OBSI equipment (shown in the left panel of Figure 2) was used during the test conducted on US-460 and was developed by Acoustical and Vibrations Engineering Consultants (AVEC), Inc. The schematic model of the

system is shown in the right panel of Figure 2 (10). It is noticeable that this aerodynamic configuration of the parts was conceived to reduce external noise picked up by the microphones in both probes. The main objective was the reduction of noise generated by wind hitting the parts while the vehicle was in movement during testing.

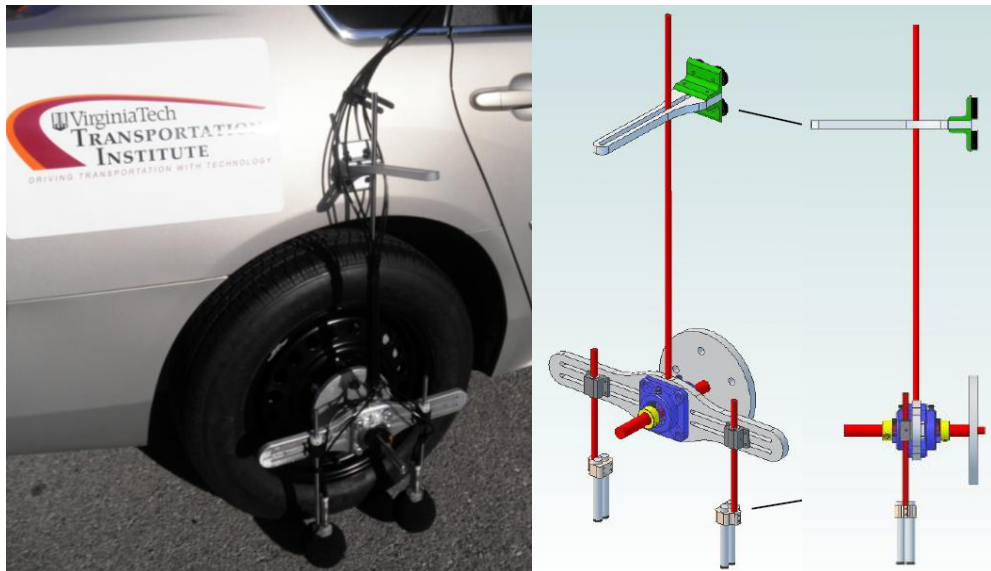


FIGURE 2 Virginia Tech Transportation Institute (VTI) On-Board Sound Intensity (OBSI) system (10).

Description of Test Parameters

Test Equipment

- The VTTI OBSI system used to attain actual measurements includes:
 - ✓ Hardware: Acoustic measurement instrumentations (one sound calibrator type 4231 Class 1 and LS, 94 and 114 dB, 1 kHz; four ½” microphone preamplifiers, two pairs of ½” condenser microphones for sound intensity, four 10 m extension cables, two spherical windscreens for ½” microphones, one microphone power module with 4 channels; and the physical parts for assembly [central plate sub-assy, intensity probe

mounting assembly fixture, rim-mount sub-assy, shaft slide sub-assy, stabilization sub-assy, central bearing mounting plate_v2, coupling nut, microphone holding block_v4, rim-mounting plate, stabilization rod, tightening plate, flange-mounted steel bearing, pillow block housing]).

✓ Software: AVEC, Inc. OBSI software versions 1.00 and 1.43 licensed to VTTI, Copyright © 2007-2011 AVEC, Inc. (11).

- A 2011 sedan with a gross vehicle weight rating (GVWR) of 2,064 kg (4,549 lb) was used for all OBSI measurements.
- A P225/60R16 97S Radial Standard Reference Test Tire (SRTT) was used for all OBSI measurements. The tire was selected according to ASTM F 2493 (12).
- A type “A” Durometer was used for the hardness measurements performed on the SRTT before every set of OBSI testing. The Durometer was chosen according to Section X1, “Durometer Selection Guide,” from ASTM D2240 – 05 2010 (13).
- A Pocket Weather Tracker was used to calculate air temperature, wind speed, barometric pressure, air density, and relative humidity for all OBSI measurements.
- A Class II laser thermometer was used for pavement temperature measurements.

Test Procedure

Speeds were selected based on Figure 1 to test the range in which tire/pavement noise interaction was the most dominant noise generator. Three speeds were used: 35 mph (56.4 km/h), 45 mph (72.5 km/h), and 60 mph (96.6 km/h). The timeframes for each speed were chosen to test 440 ft (134 m) of the sections according to AASHTO TP 76-12 (9). The tests were conducted as follows:

- ✓ Each set of runs was conducted in a timeframe during which environmental conditions were considered the same or within an acceptable 5°F range of variability.
- ✓ Temperatures within the 40s, 50s, 60s, 80s, and 90s (°F) were chosen for the testing. Where possible the temperatures were exactly 40°F, 50°F, 60°F, 80°F, and 90°F for the beginning of each set of runs.
- ✓ The tire inflation pressure used was 30 ± 2 psi (206.70 ± 13.78 kPa).
- ✓ The wind speed measurements, the hardness for the SRTT rubber, pavement temperature, barometric pressure, and air density were also recorded for each set of runs.

Sites

For the OBSI measurements two sites were selected on US-460 between Prices Fork Road and Toms Creek Road. The specific locations were 37°14'36.16''N - 80°26'2.5''W for US-460 eastbound (EB) and 37°14'6.93''N - 37°14'6.93''W for US-460 westbound (WB). Both sites had a 9.5 mm surface mix (SM9.5D) overlay placed in 2005 and presented an overall Critical Condition Index (CCI) of 78 with date rated 2/15/2011 (14). The two test sections are shown in Figure 3. The three-dimensional graphs depicting the noise as orange walls were generated using the web-based software KML generator (15).

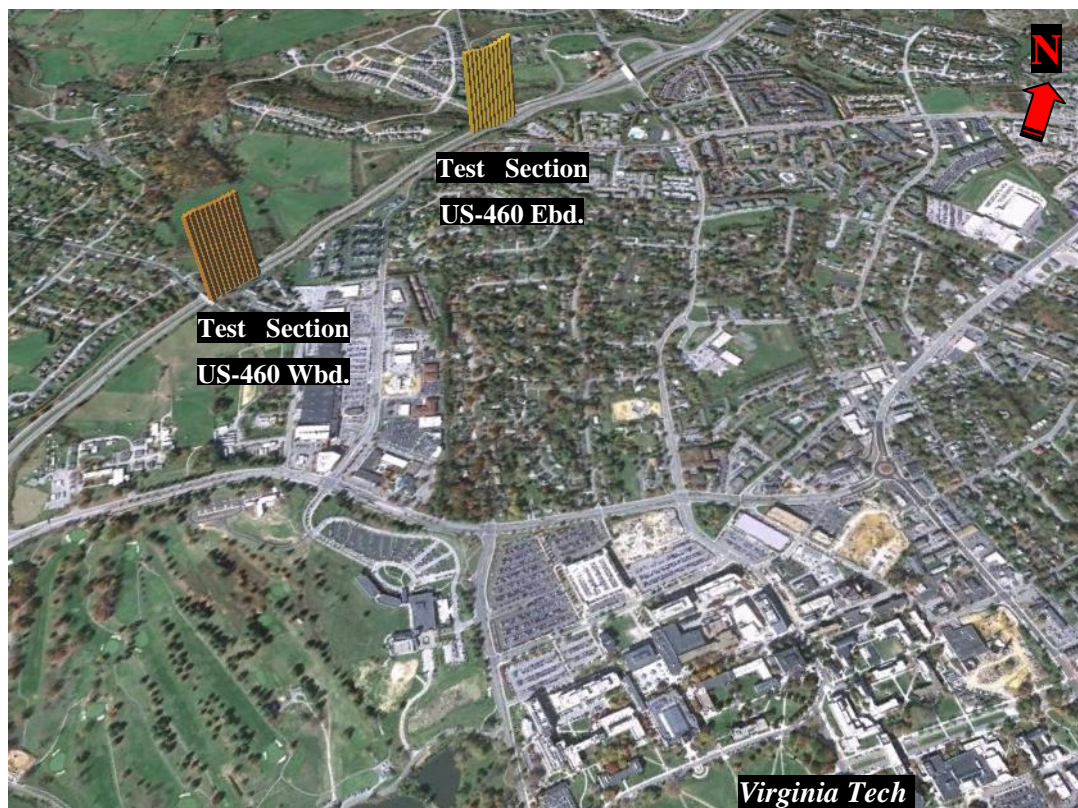


FIGURE 3 Test sections US-460 eastbound and westbound between Prices Fork Road and Toms Creek Road.

Parameters Evaluated

As mentioned, the objective of this project was to evaluate the sound intensity level (IL) generated in the tire/pavement interaction and its change due to the influence of different vehicle test speeds and air temperatures. Using previous parameters, other meteorological conditions (e.g., wind speed, barometric pressure, air density, and relative humidity) were evaluated for every combination of speed and air temperature. Pavement temperature was also measured for each set of runs.

ANALYSIS AND RESULTS

For both EB and WB sections on US-460 a limited number of runs was performed for each range of temperatures and for each vehicle speed.

Only valid results were used during the analysis and in the averaging of runs according to AASHTO standard TP 76-12 in terms of the following (9):

- Coherence: “The coherence of sound pressure between the two microphones of the sound intensity probe shall be equal to or greater than 0.8 for each one-third octave band with a center frequency between 400 and 4000 Hz and equal to or greater than 0.5 for the one-third octave band with a center frequency of 5000 Hz.”
- Pressure Intensity (PI) Index: “The PI index shall be less than 5.0 dB in each one-third octave band with a center frequency between 400 and 5000 Hz.”
- The direction of the sound intensity vector “must be positive for each one-third octave band with a center frequency between 400 and 5000 Hz.”
- Standard deviation: “The standard deviation of the overall ILs from the multiple valid runs shall be no greater than 0.6 dB(A)” and, “The standard deviation of the IL from the multiple valid runs within any one-third octave band with a center frequency between 400 and 5000 Hz shall be no greater than 1.2 dB(A).”

For a single run, the results are reported as A-weighted sound ILs (dBA referenced to 1 pW/m^2) for each frequency defined on the one-third octave band scale (Hz). For each set of valid runs the average overall sound IL is reported (dBA referenced to 1 pW/m^2).

The results of the average overall IL (dBA) for the three vehicle speeds and for each temperature range are presented in Table 2. Table 3 summarizes the different conditions for all tests.

TABLE 2 Average Overall ILs for All Runs (in dBA)

Air temp @ beginning of test °F (°C)		90 (32.2)	80 (26.7)	60 (15.6)		50 (10.0)		40 (4.4)	
Direction		Ebd.	Ebd.	Ebd.	Wbd.	Ebd.	Wbd.	Ebd.	Wbd.
Speed mph (km/h)	35 (56.4)	95.9	96.2	96.7	96.8	98.1	98.4	98.2	98.2
	45 (72.5)	98.1	99.1	99.8	100.3	100.4	101.0	101.0	101.4
	60 (96.6)	101.9	102.5	104.0	104.2	103.5	103.9	104.3	105.0

TABLE 3 Meteorological, Pavement, and Tire Conditions for All Test Air Temperatures

Air temp @ beginning of test (°F)	90	80	60	50	40
Barometric Pressure (inHg)	27.8	27.7	27.7	27.7	27.96
Air Density (lb/ft ³)	0.0669	0.0680	0.0734	0.0715	0.0734
Wind Speed (mph)	3.7	5	1.4	5.5	1.5
Pavement Temperature (°F)	124.1	113.3	82	55	44
Hardness (Durometer)	66	66	66	66	66

Figure 4 shows the variation of the sound IL with respect to the speed traveled on both directions of US-460 and at all temperatures. The partial differences (Δ dBA) shown in Figure 4 and summarized in Table 4 (fifth column) corresponding to the ratio of the speeds V_1/V_2 (Table 4, fourth column) were used to find the exponent “x” that is the indicator of the degree of influence of speed over the sound ILs (i.e., noise) following Equation 1:

$$IL \propto \left(\frac{v_1}{v_2}\right)^x \Rightarrow \Delta dBA = x 10 \log_{10} \left(\frac{v_1}{v_2}\right) \quad (1)$$

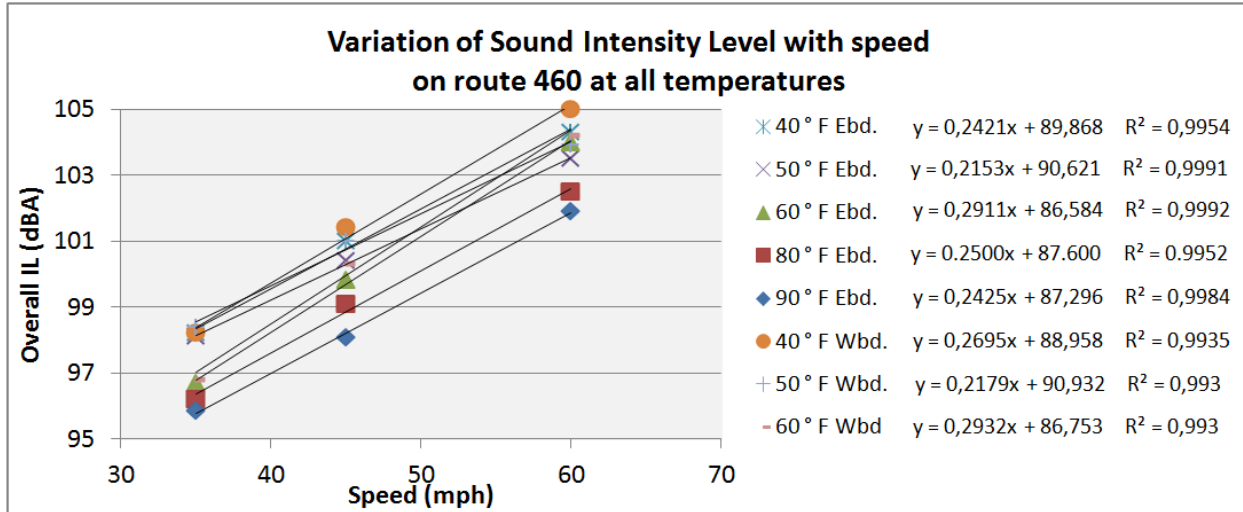


FIGURE 4 Variation of intensity level (IL) in A-Weighted Decibels (dBA) with speed for all test temperatures.

Table 4 shows the calculus of the exponent “x” for each temperature and its average. This exponent is calculated to state the degree of influence of speed on the Sound IL. Figure 5 shows the decrease of the sound IL when the temperature increases in both directions of US-460 and for the three selected speeds.

TABLE 4 Calculus of the Exponent “x”

Temperature °F (°C)	V ₁ mph (km/h)	V ₂ mph (km/h)	V ₁ /V ₂	Δ dBA	"x"	"x" for each temperature	Average "x"
90 (32.2)	45 (72)	35 (56)	1.286	2.2	2,016	2,542	2,707
	60 (97)	45 (72)	1.333	3.8	3,068		
80 (26.7)	45 (72)	35 (56)	1.286	2.9	2,657	2,689	
	60 (97)	45 (72)	1.333	3.4	2,721		
60 (15.6)	45 (72)	35 (56)	1.286	3.1	2,840	3,133	
	60 (97)	45 (72)	1.333	4.2	3,362		
	45 (72)	35 (56)	1.286	3.5	3,207		
	60 (97)	45 (72)	1.333	3.9	3,122		
50 (10.0)	45 (72)	35 (56)	1.286	2.3	2,107	2,323	
	60 (97)	45 (72)	1.333	3.1	2,481		
	45 (72)	35 (56)	1.286	2.6	2,382		
	60 (97)	45 (72)	1.333	2.9	2,321		
40 (4.4)	45 (72)	35 (56)	1.286	2.8	2,565	2,755	
	60 (97)	45 (72)	1.333	3.3	2,641		
	45 (72)	35 (56)	1.286	3.2	2,932		
	60 (97)	45 (72)	1.333	3.6	2,881		

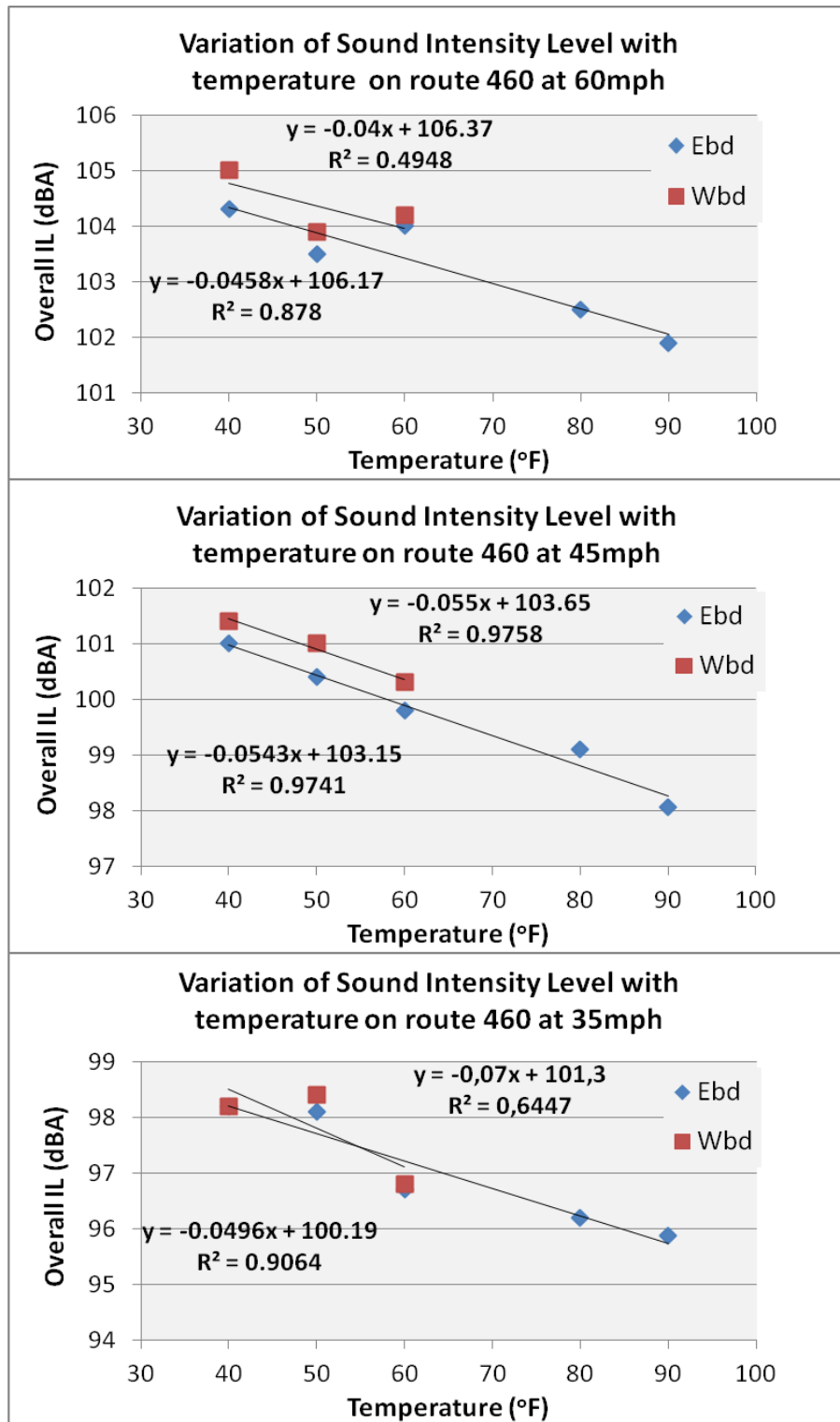


FIGURE 5 Variation of intensity level (IL) in A-Weighted Decibels (dBA) with air temperatures for different vehicle speeds.

Analysis for Test Speed Effects

Figure 4 shows that there is a linear trend for this specific range of speed. The average slope of all measurements reflects an increase in the overall IL noise of 2.5 dBA for every 10 mph increment. Although this equation is applied for this speed domain (e.g., principal roads, collectors, and highway speeds) and for slope comparisons, extrapolation is not recommended since tire/pavement interaction is not the main source of noise at lower speeds (e.g., below crossover speeds). The same is true for greater speeds where the aerodynamic noise becomes predominant. It is noticeable that there is a strong relationship between ILs and speed according to the eight R^2 values (all R^2 values greater than 0.993) for all different temperatures and directions.

Again referencing Table 4, Equation 1 can be expressed as: $IL \propto (V_1/V_2)^{2.707}$, which is valid for the analyzed range of temperatures and speeds. The exponent $x = 2.707$ in the equation suggests that speed has a high degree of influence on the sound IL (i.e., noise). For that reason it is essential to consider the speed differentials in any tire/pavement noise measurements and/or analysis made using the OBSI methodology.

Analysis for Temperature Effects

Although the effects of air temperature changes with OBSI measurements was studied only on one type of surface (a 2 inch dense-graded-asphalt overlay placed in 2005), the results are in line with previous research. The sound ILs in Table 2 and the slope values of the tendency equations in Figure 5 shows a decrease in noise when temperature increases. It is possible to ascertain an average for these slope values and to determine that the average decrease in noise for all measurements reflected a gradient of $-0.05 \text{ dBA}/^\circ\text{F}$. The number of performed tests was limited.

However, the R^2 values derived from the equations showing correlations between noise and air temperature are acceptable.

CONCLUSIONS

The study of seasonal variations of tire/pavement noise allowed drawing the following conclusions:

- ✓ There is significant variation on the noise generated by tire/pavement interaction measured at different speeds. The change in the ILs for every 10 mph variation is in the range that may be detected by human hearing, taking into account that a human ear can perceive a change in noise level as low as 3 dB.
- ✓ The overall IL increases by approximately 2.5 dBA for every 10 mph increment for the surface studied.
- ✓ A noise-temperature gradient of $-0.05 \text{ dBA}/^\circ\text{F}$ was observed for the surface studied, which indicates a small influence of air temperature on tire/pavement noise levels. For this reason corrections to measurements taken at different temperatures are recommended, especially if measurements are conducted over a relatively high range of temperatures, as is the case for measurements taken during different seasons.
- ✓ This gradient is similar as the ones stated in previous literature.

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