Pavement noise measurements in Poland

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Abstract. The objective of this study is to investigate the feasibility of the On-Board Sound Intensity (OBSI) system to measure tire-pavement noise in Poland. In general, sources of noise emitted by the modern vehicles are the propulsion noise, aerodynamic resistance and noise generated at the tire-pavement interface. In order to capture tire-pavement noise, the OBSI system uses a noise intensity probe installed in the close proximity of that interface. In this study, OBSI measurements were performed at different types of pavement surfaces such as stone mastic asphalt (SMA), regular asphalt concrete (HMA) as well as Portland cement concrete (PCC). The influence of several necessary OBSI measurement conditions were recognized as: testing speed, air temperature, tire pressure and tire type. The results of this study demonstrate that the OBSI system is a viable and robust tool that can be used for the quality evaluation of newly built asphalt pavements in Poland. It can be also applied to generate reliable input parameters for the noise propagation models that are used to assess the environmental impact of new and existing highway corridors.

1. Introduction
Noise pollution has long been recognized as an influencing quality of life and well-being. Over past several decades it has also recognized as an important public health issue. According to a recent report from the World Health Organization (WHO) [1], at least 1 million healthy life years are lost every year in Europe due to health issues associated with the traffic noise alone. The traffic noise can be generated by different sources including propulsion noise, transmission noise, aerodynamic resistance noise or tire pavement interaction [2]. In typical internal combustion engine car (ICE) majority of the noise is generated by its propulsion system up to a certain speed (also called crossover speed). Above this speed tire/pavement contact noise plays a prevailing role in the overall vehicle noise. The crossover speed varies between 16 and 40 km/h for the passenger cars whereas for trucks it varies between 50 and 80 km/h. In modern hybrid-electric vehicles (HEV), electric vehicles (EV) or fuel-cell electric vehicles (FCEV) the propulsion and transmission noise becomes insignificant, so tire/pavement interaction noise becomes dominant regardless of the vehicle speed. Thus there is an urgent need to prepare, verify and validate robust methodology that focuses on tire/pavement noise and can be used by pavement engineers, tire manufactures and traffic safety engineers especially in urban environments.

2. OBSI review
There are several methods to assess noise generated by moving vehicle traffic [3]. These methods can be briefly summarized as follows:
OBSI – On-Board Sound Intensity method (OBSI) – uses two synchronized sound intensity probes mounted on regular vehicle’s wheel next to tire/pavement interface [4]. No special sound insulation is needed since intensity probes are directional and insignificantly (if at all) affected by the adjacent environment. Since it is attached to a passenger car it is highly maneuverable and noise assessment can be performed on any road network. This method was developed by General Motors in 1980’s but it has been commercially available since 2000’s [5]. More details are provided in later paragraphs.

OBSIe – it is an evolution of OBSI system mounted on an electric (EV) or hybrid electric (HEV) vehicle. The main reason is to eliminate the propulsion noise and to conduct assessment of tire/pavement noise at lower speeds, preferably in the urban areas. The tire/pavement interaction noise can be measured from as low speeds as 10 km/h. This method was first time demonstrated by Road and Bridge Research Institute (IBDiM) in Poland in 2015 [6][7].

SPB – Statistical Pass-By method that measures overall noise generated by passing traffic. This method utilizes set of microphones located in a certain distance from the road. Microphones record the overall sound pressure generated by randomly passing vehicles while the observer measures their actual speed. This method records all noise sources from passing vehicles mentioned above as well as amplification phenomena. Different vehicles and different pavement types can be assessed by this method.

CPB – Controlled Pass-By which is similar to SPB method. The difference is that the speed of passing vehicles is strictly controlled as well as the type of vehicle (passenger car, truck or bus) is intentionally selected for evaluation.

CPX – Close Proximity method is another method that focuses on tire/pavement interaction. CPX method typically uses a trailer attached to a leading vehicle (typically a passenger car). Trailer which can be opened or closed-cover comprises a set of microphones mounted around a tested wheel (or wheels). Microphones measure sound pressure that is later processed to obtain sound pressure level (SPL). It is also possible to mount microphones next to a vehicle’s wheel however this approach is not common. This method is primarily used in Europe since late 1970’s [2].

While both OBSI and CPX are used in the ongoing study in Poland, this paper only discusses the OBSI method. The following paragraphs include the concept of operations and a brief discussion on the effect of surface type and speed on the OBSI noise measurements.

2.1. Concept of operations
The main hardware components of the OBSI system are presented in Figure 1. As mentioned earlier, there are two intensity probes (front and back) located in the close proximity to tire/pavement interface. Each probe consists of two microphones and each microphone measures sound pressure; in order to calculate the sound intensity from each probe, the sound pressure signals from two microphones are combined using so called p-p method [8]. The particle velocity component in the direction of the axis of the probe is obtained by a finite-difference approximation to the pressure gradient in Euler’s equation of motion, and the sound pressure is the average of the two pressure signals. The most important limitations of this measurement technique are caused by the finite difference approximation, scattering and diffraction, and instrumentation phase mismatch. More details on computational data processing can be found elsewhere [9]. Overall intensity level from each probe is determined from the energy sum of corresponding A-weighted sound intensities within the one-third octave bands ranging from 400 to 5000 Hz as follows:

\[
\text{Overall Sound IL} = 10 \cdot \log_{10} \left( \sum_{i=400}^{5000} \left( 10^{L_i/10} \right) \right)
\]  

The overall ILs from the two probes (measured simultaneously during a single run) are energy averaged to yield an average sound intensity level per test run. The formula for energy averaging is as follows:

\[
\text{IL}_{\text{E-avg}} = 10 \cdot \log_{10} \left( \frac{1}{N} \sum_{i=1}^{N} \left( 10^{L_i/10} \right) \right)
\]
Finally in order to calculate the average of several test runs, overall ILs from the individual valid runs are arithmetically averaged to calculate a single average intensity level value.

![Figure 1. Schematic of OBSI system mounted on a vehicle wheel.](image)

It should be noted that there are two immediate data quality checks that control the validity of each test run: coherence and pressure-intensity index (PI Index). Coherence is defined as a measure of the linear dependency of two signals with a value of zero (0) being no dependency, and a value of one (1) being perfect linear dependence. After AASHTO [10] it was assumed that coherence of sound pressure between the two microphones of each intensity probe should be at least 0.8 for each one-third octave band between 400 and 4000 Hz. On the other hand, PI Index is defined as an arithmetic average of the SPLs of both microphones on each probe minus the calculated sound intensity level (IL) for that probe. The PI index for each one-third octave band is calculated using the sound pressure levels and intensity level corresponding to that one-third octave band. Allowable ranges of PI Index are presented in Figure 4 together with example results of PI Index.

A single testing run is conducted for 5 s which translates to 133 m under constant speed of 96 km/h. For other testing speeds the measurement distance is kept constant which in consequence leads to different testing duration. OBSI measurements can be affected by a number of factors that should be either controlled during testing or accounted for in data processing. Those factors can be attributed to vehicle speed, pavement type, tire type/pressure/temperature, air temperature and pressure, adjacent road furnishing (e.g. barrier, noise walls), vehicle axle load and suspension characteristics among others. The following paragraphs briefly present a summary of relevant literature on the effect of speed and surface type as well as comparison between OBSI and CPX.

2.2. OBSI measurements on different pavement surfaces

There are numerous documented studies showing the OBSI measurements on different pavement surfaces, for example [5][11][12][13]. Extensive study presented in [5] demonstrated OBSI measurements on various pavement sections both in Europe and the USA. 127 combinations of surface, speed, and test tire were evaluated. In terms of pavement surfaces, measurements were taken on dense-graded asphalt (DGA), SMA, single layer porous asphalt (PA), double layer porous asphalt (DLPA) as well as on textured and regular PCC surfaces. At 96 km/h, the loudest pavement (107.6 dBA) was a transversely tined PCC while the quietest at 94.6 dBA was DLPA. While many observations were made in that study it should be noted that measurements were not normalized due to
different test temperatures that ranged between 15 and 32 °C. Another study [11] shows OBSI measurements on four sections in the USA: two PCC (burlap drag and longitudinally tined) and two asphalt pavements: open-graded (OGA) and dense-graded (DGA). The results showed similar average overall ILs for PCC section (burlap drag) and OGA section (104 dBA) while both have distinct spectral content. The OGA showed lower level of high-frequency noise, which is indicative of the absorption effect, and high levels of low frequency noise caused by raveling. The quietest pavement was the DGA section (99.7 dBA) while the second PCC (longitudinally tined) had IL of 103.5 dBA. With the intention to reduce noise levels, sections with added rubber component to asphalt wearing surface were assessed in [12]. Specifically, this study focused on the open-graded rubberized asphalt concrete (RAC-O) and gap-graded rubberized asphalt concrete (RAC-G) compared to sections with OGA and DGA. The results indicated that indeed the rubber contributes to noise mitigation but its effectiveness depends on the section age. On average, the reduction is in the order of 1.6 to 2.9 dB. Finally, recent study in Australia [13] presented the OBSI measurements on the OGA, SMA and double layer OGA. The best performing in terms of noise reduction was the OGA section (average of 98 dBA) while the SMA was the loudest with the average IL of 102 dBA. It should be noted that these observations were confirmed not only the OBSI but also by the CPX and SPB measurements.

2.3. Effect of vehicle speed on OBSI measurements

Vehicle speed has indisputable effect on any noise measurements. Typically, regular OBSI measurements are conducted at 96 km/h but other speeds (e.g. 72, 56 or 40 km/h) are also found in the literature. The following bullets provide a brief summary on several studies that accounted for various speeds during the OBSI measurements:

- [5]: testing at 96 km/h and 56 km/h on various surfaces; results at these speeds are highly correlated with average 0.9 dB deviation from line of equality (LOE),
- [14]: testing at several intervals between 56 km/h and 96 km/h allowed to determine a relationship between IL and speed; it depends on the surface and tire type but on average OBSI IL increases 0.18 dBA per 1 km/h,
- [15]: testing at 17 different pavement sections at National Center for Asphalt Technology (NCAT) showed consistent trends between measurements at 72 and 96 km/h,
- [16]: testing at 56, 72 and 96 km/h conducted on the regular asphalt surface and temperatures between 4 and 32 °C demonstrated that average incremental increase in OBSI IL per 1 km/h equals to 0.17 dBA however the observed range was between 0.12 and 0.21 dBA.

2.4. Comparison of OBSI vs. CPX

Table 1 presents several studies that compared the OBSI and CPX methods. In general, both methods show very good qualitative and quantitative agreement in terms of tire/pavement noise assessment.

| Reference | Year | Surface type | Observations / findings |
|-----------|------|--------------|-------------------------|
| [5]       | 2007 | Various      | average offset of 3.3 dB with average difference 0.5 dB (96 km/h) |
| [17]      | 2009 | Various asphalt | R² = 0.93, CPX = 1.04*OBSI-6.52 [dBA], highly correlated |
| [18]      | 2013 | Various asphalt | OBSI-CPX = 3.1 dB at 50 km/h, 2.4 dB at 80 km/h |
| [13]      | 2014 | SMA, OGA     | highly correlated, R² above 0.8 (100 km/h) |
| [19]      | 2015 | Various      | R² = 0.93, CPX = 0.98*OBSI-1.70 [dBA], highly correlated |
3. OBSI results from Poland
The following paragraphs demonstrate a subset of the OBSI results collected in Poland. It should be mentioned that all figures depict valid OBSI runs, i.e. runs that passed quality checks. Except for already recognized coherence and PI Index parameters, valid runs under the same conditions should have the range of overall ILs no greater than 1.0 dBA. Further the range of the ILs from the multiple valid test runs within any one-third octave band (between 400 and 5000 Hz) should be less than 2.0 dBA. In the testing presented below, the number of valid runs varied between 2 and 9. The air temperature for all tested runs was approximately 25 °C and all testing was accomplished within one week. The remaining testing conditions were assumed according to AASHTO [10].

3.1. OBSI on different surface types
Figure 2 demonstrates the OBSI measurements obtained for three typical pavement surfaces in Poland: Portland cement concrete (PCC), stone-mastic asphalt (SMA) and regular hot-mix asphalt (HMA). Similar to other studies, there is an apparent effect of surface type. This effect differs depending on the one-third octave bands and it is a function of surface finishing technology (e.g. drag texture, exposed aggregate for PCC pavements) and surface porosity and texture for asphalt pavements. The ongoing analytical research effort focuses on more objective and informative spectra interpretation that accounts for the frequency and connects with passenger annoyance effect inside modern vehicles and sound perception next to the road.

![Figure 2](image)

Figure 2. Average intensity spectra for one-third octave bands for different pavement surfaces at 96 km/h.

3.2. OBSI measurements as a function of vehicle speed
Figure 3 presents average values of the overall ILs collected on three surfaces at two different speeds 72 and 96 km/h. One can notice a qualitative agreement in terms of speed dependency for all three surfaces and rather high repeatability that is somewhat dictated by the rigorous data quality checks. It can be also noted that overall ILs clearly differentiate between different speed/pavement combinations and presented PCC pavement sections yields statistically lower sound intensity levels than the corresponding asphalt sections. The average increase in IL per 1 km/h was 0.19 dBA was consisted in the studies reported earlier.
3.3. OBSI data quality checks

Figure 4 depicts the example of data quality check in terms of average PI Index values. Measurements on all three pavement surfaces are located along the center of allowable range defined by the upper and lower bounds [10]. This observation demonstrates a very good accuracy of measurements and phase-matching of microphones.

4. Discussion

Since OBSI device comprises two intensity probes, one in the front and one behind tire/pavement interface, it is interesting to compare ILs from both probes. Figure 5 presents such a comparison for the measurements collected at 96 km/h on SMA and HMA pavement sections. It can be easily noted that ILs spectra differ for the front and back probes and this trend is consisted for both surfaces. This observation confirms that there are multiple phenomena responsible for the sound generation and they are not symmetrically distributed on both sides of tire/pavement interface. The following phenomena were identified based on the literature [2][8]: radial vibrations of tire tread, air compressing and decompressing during wheel pass, tread tangential motion (referred to as “stick-slip”) and breaking of adhesion of tread rubber to the pavement (called “stick-snap”). In addition to these phenomena, there
are also amplification mechanisms such as horn amplification, radiation of resonant air (Helmholtz resonance), pipe resonances in channels formed in the tire footprint, tire sidewall vibrations and cavity resonance in tire tube [3].

![Figure 5. Average Intensity Level (IL) spectra for the back and front probes for two pavement surfaces at 96 km/h.](image)

Basic Analysis of Variance (ANOVA) was performed in order to further assess the significance and contribution of the two main factors presented earlier: pavement surface and measurement speed. The ANOVA results shown in Table 2 confirm earlier observations that both factors are statistically significant and that the speed factor has greater contribution in explaining an observed difference in IL values than pavement type. Finally, performance of the statistical model associated with ANOVA is shown in Figure 6. While it is fairly accurate in predicting IL values for various speeds and pavement surface types, it is just an initial attempt limited only to two factors. More comprehensive analysis will be performed upon completion of the ongoing study in Poland using, for example, Principle Component Analysis (PCA) and Artificial Neural Networks (ANN).

**Table 2.** Analysis of Variance (ANOVA) table ($R^2 = 98\%$).

| Source          | DF | Adj SS | Adj MS | F-Value | P-Value |
|-----------------|----|--------|--------|---------|---------|
| Speed           | 1  | 173.657| 173.657| 1323.28 | 0.000   |
| Pavement Type   | 2  | 53.334 | 26.667 | 203.21  | 0.000   |
| Error           | 40 | 5.249  | 0.131  |         |         |
| Lack-of-Fit     | 2  | 2.020  | 1.010  | 11.88   | 0.000   |
| Pure Error      | 38 | 3.229  | 0.085  |         |         |
| Total           | 43 | 297.846|        |         |         |
5. Summary

The OBSI method gives an opportunity to evaluate tire/pavement noise using alternative methodology that is predominantly applicable in the urban environments. It is of particular importance due to future developments in vehicle fleet and general societal and economical changes. OBSI method can assist in development and evaluation of various aspects of traffic noise such as:

- tire / pavement noise generation,
- tire construction and thread type,
- sound signals outside the vehicle for VRU (vulnerable road users),
- additional equipment mitigating traffic noise.

In the near future the OBSI methodology will be further verified and validated through extensive testing in Poland. It is planned to conduct OBSI testing under various conditions (speed, temperature, tire pressure, tire hardness, axle weight etc.) on regular and “quiet” pavement surfaces. The detailed analysis will also include individual one-third octave bands and not only the overall OBSI noise level.

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