ROAD AND TIRE NOISE EMISSION ASSESSMENT WITH CLOSED PROXIMITY METHOD ON AN ASPHALT RUBBER CONCRETE PAVEMENT

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Abstract

A road/tire noise emission assessment has been performed in Saskatchewan with the Close Proximity Method (CPX), a method based on test tire rolling on a road with microphones located close to the tire surface. In CPX road tests, the average A-weighted sound pressure levels emitted by one specified reference tire are measured with the vehicle speed over a specified road distance. The data are collected by microphones located close to the tires. In order to understand the acoustic characteristics of the newly paved Asphalt Rubber Concrete (ARC) pavement, a special test vehicle was built. Two uniquely different reference tires have been selected in order to represent the tire/road characteristics studied. The road/tire emission noise analysis was performed on 12 different surface types of a highway in Saskatchewan, Canada using the CPX test. This research aims to determine the noise characteristics of the road surface at selected sites, predict the road/tire emission noise and acoustic properties of different road surface materials, evaluate compliance with noise specifications of the specific surface materials, estimate the state of maintenance, damage or clogging and the effect of cleaning on porous surfaces.

Keyword: Traffic Noise, noise measurement, noise control, numerical simulations

1. Introduction

Noise affects nearly everyone in everyday life – at home, at leisure, during sleep, when traveling and at work. Noise is detrimental to human health in several respects, for example, hearing impairment, sleep disturbance, cardiovascular effects, psycho physiological effects, psychiatric symptoms, myocardial infarction and fetal development [1]. Furthermore, noise has widespread psychosocial effects including noise annoyance, reduced performance and increased aggressive behaviour [2, 3].

Traffic noise is a major issue associated with the design and construction of new transportation systems and improvement of existing systems. Many cities in different parts of the world are exposed to the continuous growth of road traffic accompanied with the growth of noise levels along highways [4]. This causes one of the most invasive forms of environmental pollution. However, human organisms are not prepared to shut off the noise. Hearing is a permanent process using cortical and sub cortical structures to filter and interpret acoustic information. Thus, the only solution to the problem is to reduce the source of traffic noise.

This research project looks at the importance of using crumb rubber from recycled tires to reduce traffic noise in Canadian cities. To emphasize, this research project aims to make a comparison between the emission noise generated from the interaction between Conventional Asphalt Concrete pavement and the tire versus the interaction between Asphalt Rubber Concrete pavement and the tire. Another goal is to establish a novel methodology for systematically assessing and comprehensively understanding the Sound Intensity mapping generated between a road and tire, including the analysis of experimental and simulated results.

2. Background

The noise generation mechanism involved in the interaction between the tire and road surface is of major importance to traffic noise reduction. To understand the physical mechanisms of traffic noise, mathematical models are necessary. They are needed to be able to distinguish between the various mechanisms and their respective impact on noise emission. This is necessary given the inevitability of simplifications during design and engineering. Much modeling has been focused on tire/road noise processes of passenger car tires on non-porous surfaces.

2.1 Tire/Road Noise Generation

To reduce or minimize noise from tires, a better understanding of the noise generation mechanisms involved in the interaction between the tire and road surface is of major importance. Tires hitting pavement can cause as much as 90% of road traffic noise, depending on traffic conditions, vehicle type and driving style [5]. The time-varying contact forces will cause vibrations of the tire, which will radiate sound is observed by [6]. The treads squeeze air as they strike the road and snap as they pull away, which sets the tread and sidewalls in vibration.

The aggregate at the top layer of the pavement forms the pavement texture. When the rubber blocks of the tire hit these stones, vibrations is generated in the tire structure. These vibrations generate noise typically dominated by the frequency range between 100 and 1000 Hz. With a smoother pavement structure, the generation of vibrations and noise is reduced.

Also the air resonance phenomenon, for example, the grooves of the pattern will act as Helmholtz resonators and the air is pushed out of the contact area in front of the tire and sucked into the contact at the trailing edge, the so-called air pumping effect is observed by [6]. The aerodynamic noise generated by air pumping, when air is forced out between the rubber blocks of the tire as the tire rolls on the road surface. This is typically most important in the frequency range between 1000 and 3000 Hz. If the road surface is porous with a high built-in air void, the air can be pumped down into the pavement structure, and the noise generated from air pumping will be reduced.

Further, compared to the road surface, the rubber in the tread is very soft with a low shear modulus and a high Poisson ratio. Small, rough peaks in the road surface will cause a local deformation in the tread around the peak when it comes into contact with the tire. This effect was investigated by [7] and was shown to be a possible noise source at medium and high frequencies.

Much research on the vibration properties of vehicle tires has been done during the past years. One of the first tire models is presented by [8] – the circular ring model which considers radial, tangential and lateral motions. Similar to the circular ring model, the tire belt as a circular beam under tension, supported by elastic bedding is modeled by [9]; however, lateral motion is not included in the model. Models for the lateral vibrations are developed by [10], where the tire was modeled as one or several strings. The viscoelastic effects, both for the belt and for the foundation in the circular ring model are included by [11]. These models are valid as long as the wavelength is large compared to the width of the tire, which is typically below 400 Hz.

Several examples where the finite element method has been applied to tires can be found in the literature [12-14]. At frequencies above the ring frequency, the curvature of the tire can be disregarded. The radial and the tangential motions can be considered as uncoupled. To model the vibrational tire properties in this frequency range, [15] proposed the orthotropic plate model, where the tire belt is modeled as a finite plate, having different properties in the tangential and lateral directions. A model where the belt and the side walls were modeled as a set of individual Mindlin plates coupled together to represent the curvature in the lateral direction was developed by [16].

2.2 Modeling

In general, models on tire/road noise can be divided in four major types. The first type includes statistical models. Here, the tire is considered a linear function of physical properties of the road surface and the resulting noise production. Statistical models are based on vast sets of data following from standard measurements. However, this approach does not attempt to understand and model the mechanics of the tire involved. The work of [17] is a popular example of this approach.

The second type is composed of physical models. These models simulate the physical processes involved in tire vibration and sound radiation from the tire. It is a physical approach in which the tire is addressed as a vibrating plate and its response to mechanical excitation and radiation of noise into the environment, is derived from basic physical laws or by means of a straight forward computational approach with Finite Element Modeling (FEM). The tire model by [18] is an example of such a modeling approach.

However, the applicability of physical models in engineering practice is limited because of their complexity. The third type of model for tire/road noise, hybrid theoretical models, attempts to address this problem. In this type of model, its preparation is a complex and time consuming task. Also, their experimental validation is complicated. To reduce the complexity of some elements, it can be described in a statistical (empirical) manner rather than a physical one. These statistical (empirical) relations follow from validation experiments. Examples of hybrid theoretical models were developed by [19-20].

Finally, the statistical models can be extended with pre or post processing based on known physical relations often derived from theoretical models. Hence, these models are considered hybrid statistical models. Examples of hybrid statistical models were developed by [21]. As stated at the beginning, existing models of light vehicles are too limited to characterize fully the influence of road surfacing. The direct applicability of the present modeling for truck tires is very limited [22] due to the different in size, material properties and tread profiles compared to passenger tire.

2.3 Traffic Noise Measurement

Simple measurements of noise cannot address all of the environmental factors encountered in noise problems, wherever they occur. Specialized measurement and evaluation systems have had to be developed which take into account a variety of additional factors. A numbers of traffic noise measurement methods have been developed in recent years. In general, they can be categorized into three groups: on-board measurements, roadside measurements and laboratory-based measurements. The choice of the method that would be used in tire/pavement noise evaluation may depend on the conditional limitation or whatever aspect of tire/pavement noise that would be emphasised.

The on-board measurement methods include the close proximity (CPX) method and the close proximity sound intensity (CPI) method. Basically, CPX is taken on a trailer using microphones located near the tire. The trailer includes a hood over the microphones such that wind noise is reduced and noise from other traffic is reflected. It was developed to allow measurements to focus on the tire/pavement interaction noise. The advantage is that the effect of other noise sources such as engine and exhaust sounds can be diminished to a minimum. However, the limitation of CPX measurements is that this method is made with a limited set of tires at one weight. Therefore, it does not account for the vehicle variation typical of traffic streams.

In Saskatchewan, Canada the Asphalt Rubber Concrete (ARC) has been paved without knowledge or historical data about this pavement's noise properties, there was a need to start a road/tire noise emission test. The Close Proximity Method (CPX) has been chosen to perform the tests on various pavement materials and different types of pavement surface treatment focusing only on road/tire noise emission and excluding the power train and aerodynamic noise sources.

3. Test objective

The objective was to measure and analyze the emission noise levels and emission noise spectra of individual passes of a test vehicle from as many different Saskatchewan pavement types as possible. The primary objective of this research focuses on the tire/road emission generated by the vehicle driven on ARC pavement, and to produce a high-quality historical data set that could be saved and tested by other researchers interested in the effects of tire/road emission noise from ARC pavement. To minimize as many variables as possible, the test plan was developed with the following parameters; three speeds, 50±3 km/h, 80±3 km/h, and 110±3 km/h; One vehicle with a single axle trailer; One tire type (the most popular tire used in Saskatchewan); Wind conditions less than 10 km/h with dry pavement; Tire pressure, 220 kPa; Weight on Axle, 2270 lb; No other vehicles within 50 m of the test vehicle. With ongoing research and experiments, this paper will only focus on one vehicle speed (80±3 km/h), 3 microphone locations, focusing on the front and rear microphones for each height and one test tire.

The custom built CPX trailer, as shown in figure 1 was adopted from ISO/CD 11818-2 "Method for Measuring the Influence of Road Surfaces on Traffic Noise-Part 2.

The layout of the microphones, as indicated in figure 2, was 45 and 135 degrees from the direction of travel with respect to the right tire on the trailer. The two locations represent the emission noise generated from the front and back of the tire. The two locations can also be adjusted in height from 50 mm, 100 mm and 150 mm, respectively for numerical comparison.

Figure 1 Custom made CPX trailer in cooperation between SK Department of Highway and Transportation and University of Regina

The microphones were Bruel and Kjaer (B&K) sound intensity level meter Observer 2260 and B&K microphones 4198 with matching cords. The 150 mm windscreens were also added to each microphone to reduce the effect of wind noise. A B&K 4231, sound pressure calibrator was used each time before initiating the test. Multiple runs were made with the test vehicle. For any runs during which another vehicle was within 50 m, the engine noise was unusually loud, or another noise source was present the pass was repeated until at least nine but usually ten, 30 second clean runs were obtained. Tests were conducted when traffic was at a minimum; all tests were conducted on 2 lane roads so the test vehicle could use the driving lane (first lane for the shoulder) and allow the traffic to flow.

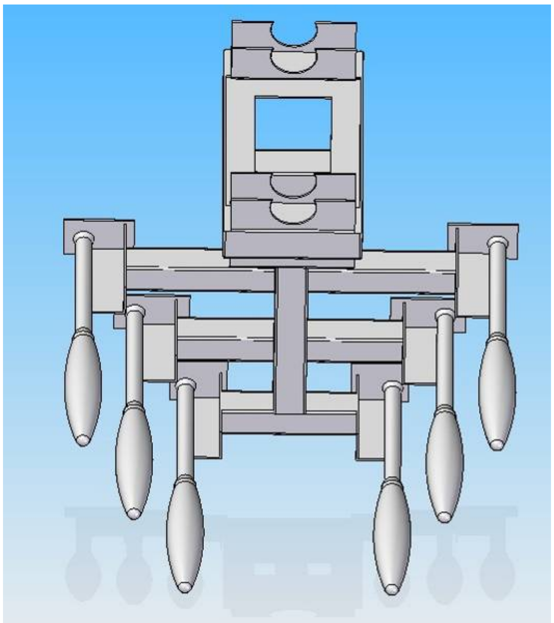

Figure 2 the drawing of microphones support frame

Table 1 The description of different highway surface and test sections in Saskatchewan considered for this research

Surface Type	Surface	Description
New rubber asphalt pavement	ARC	Rubber asphalt pavement
New conventional pavement	New AC	New conventional pavement overlay.
Newer conventional pavement	AC	Newer conventional pavement overlay.
Old pavement	Old AC1	Old conventional with a recent flushcoat.
Very old pavement	Old AC2	Very old and rough pavement.
New graded aggregate seal	New GAS	New graded aggregate seal.
New washed chip seal	New CS	New washed chip seal.
Old graded aggregate seal	Old GAS	Graded aggregate seal a few years old.
Old chip seal	Old CS	Chip seal a few years old.
Pavement with RACS	RACS	Rubber asphalt crack seal on newer pavement.
Thin lift overlay	TLO	Thin lift overlay on older pavement.
Pavement with thermopatch	Thermo	Older pavement with a recent thermopatch.

The CPX test was performed on different surfaces on the highway in Regina, Saskatchewan and the nearby town as shown in table 1. The tests mainly focus on 3 perspectives; 1. the comparison of different types of concrete pavement, namely Asphalt Rubber Concrete (ARC) and Conventional Asphalt Concrete; 2. the comparison of different types of surface treatments; 3. to generate a sound intensity map from the data collected from the ARC pavement and AC pavements. All pavements considered for this project are listed in Table 1. The test plan included identifying 12 test pavements of both asphalt concrete and asphalt rubber concrete, all with varying age and surface conditions.

4. Calculation of the constant sound power calculation from the constraints of obtained CPX emission noise

For this research, it was assumed the sound propagated from an omni-directional point source (the interaction point between tire and pavement) without any obstacles (free field). The wave front of propagation is an ever-expanding sphere. As the surface area of this sphere increases with $4\pi R^2$ distance the sound energy within a given area decreases, therefore the intensity of the sound decreases.

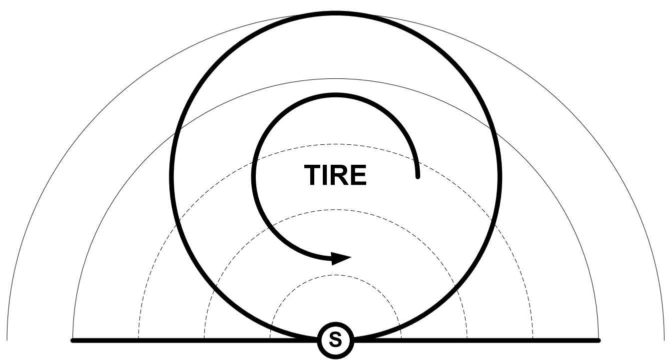

Figure 3 The illustration of the Inverse Square Law

Then, using the Inverse Square Law, the sound intensity in a free field is inversely proportional to the square of the distance from the source. Intensity is the sound energy passing through an area of one meter squared during one second. Hence given the surface area of a sphere is , one can express the intensity of sound from a point source when W is the total power radiated from a point source as;

$$I = \frac{W}{A} = \frac{W}{4\pi R^2} \tag{1}$$

The mathematical definition of Acoustic power, *W*, transmitted through a given surface areas *S* is

$$W = IS \tag{2}$$

The usual context of the noise measurement of Sound intensity, *I*, in the air at a receiver's location can be given by

$$I = \frac{1}{T}\int_0^T p(t) \cdot v(t)\, dt \tag{3}$$

Where *p* is the acoustic pressure and *v* is the acoustic particle velocity. Thus, acoustic power is a measure of sound energy density per time averaged across a surface area of the source per unit time. Acoustic power is neither room dependent nor distance dependent, like it is with sound pressure or sound intensity. It belongs strictly to the sound source, with no decrease of power with distance.

From the derived acoustic energy conservation law by [23], the acoustic sound intensity can be defined formally as

$$I = \left[(\tilde{\rho}\tilde{v}) \left(\frac{\tilde{v} \cdot \tilde{v}}{2} \right) + \tilde{p}\tilde{v} \right]_A^{'} \tag{4}$$

where $\tilde{\rho}$ is the fluid density and A denotes a quantity that consists of a sum of a mean part and a fluctuating part with zero mean. From equation(4), the first and second terms represent the kinetic energy flux and the compression strain energy flux in the fluid, due to acoustic motion of the particles. In both ideal and practical fluids, the total energy flux is obtainable over a unit surface of the sound waves.

[23] also wrote equation (4) briefly as

$$
\begin{aligned}
I &= \left[\tilde{m}\tilde{B}\right] \\
\tilde{m} &= \tilde{\rho}\tilde{v} \\
\tilde{B} &= \frac{\tilde{v}\cdot\tilde{v}}{2} + \frac{\tilde{p}}{\tilde{\rho}}
\end{aligned}
\tag{5}
$$

Here, $\tilde{m}$ is called the momentum density. $\tilde{B}$ is known in thermodynamics as the energy of a system [24]. Implementation of equation (5) depends on the information available about the fluctuating quantities. The case of interest is when the acoustic components of the fluctuations are known. Then the analysis is based on a small perturbation formulation of acoustic equations while neglecting non linear effects. As the main concern is the acoustic power, the first term in the energy flux need not be considered since it will approach zero upon time averaging. Therefore, the second term is the main focus.

Equation (5) is expressed by [25] as

$$
\begin{aligned}
I &= mB \\
m &= \rho_0 v + \rho v_0 \\
B &= v_0 \cdot v + \frac{p}{\rho_0}
\end{aligned}
\tag{6}
$$

Where the mean and fluctuating quantities come from the problem solution. The results of equation (6) can only be as accurate as the problem solution.

From the closed approximately method test, ρ is the average of the air density and ρ_0 is the standard deviation of the air density, which can be calculated from

$$
\rho = \frac{P}{R \cdot T} \tag{7}
$$

Where *P* is the air pressure at different altitude of the microphone which is approximately equal to 101.493 kPa. *T* is the temperature at the test time in Kelvin, and *R* is the gas constant $\left(R_{dryair} = 287.05\frac{J}{kg \cdot K}\right)$. *v* is the acoustic particle velocity which is the velocity of a particle in a medium as it transmits a wave. When applying this to a sound wave through a medium of air, particle velocity would be the physical speed of an air molecule as it moves back and forth in the direction of the sound wave as it passes.

$$
v = \frac{p}{Z_0} \tag{8}
$$

$$
Z_0 = \rho \cdot c \tag{9}
$$

$$
c = 331 \bullet \sqrt{1 + \frac{T}{273.15}} \tag{10}
$$

p is the acoustic pressure of the emission noise from the road/tire. Z_0 represents the characteristic impedance of a medium (air), this impedance is a material constant and equal to the product of the density of air and the speed of sound as shown in equation (9). The speed of sound in air varies which temperature and can be calculated from equation(10).

In the end, the constant acoustic power, *W* should be obtained from the measured data from the closed proximity method and varies with the following factors; microphone location (R and Altitude), temperature, CPX emission noise level, vehicle speed and acoustic pressure.

With the known constant value of acoustic power, *W* and the distance from the point source, the sound intensity map can then be simulated from the simple equation(1). A figure representing the sound intensity mapping comparison between ARC and AC pavement will be generated at the end.

5. Data Analysis

The on-board data from the two microphones mounted on the trailer near the test tire were recorded to capture a noise signal that was predominately road/tire interaction noise and less vehicle machine noise or aerodynamic noise. The data were collected from 9 to 10 runs on each of the twelve pavements. The measured emission noise from the behind-the-wheel microphone locations and in-front-of-the-wheel locations are only 1.1 dBA with a standard deviation of 0.4 dBA, this means wind speed and a little effect from aerodynamic noise may cause an increase in the emission noise level.

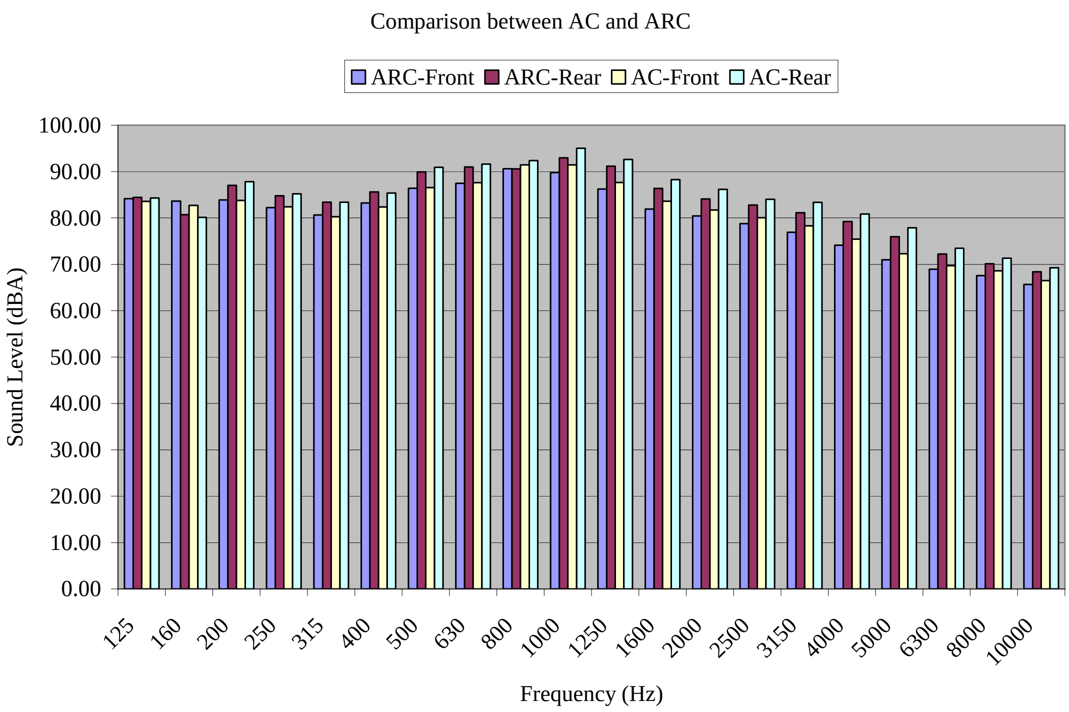

Figure 4 The comparison between sound level on ARC and AC pavement both at front and rear microphones

The one-third octave band frequency spectrum of the Conventional Asphalt Concrete and Asphalt Rubber Concrete pavement of the same age are presented in Figure 4. The plots show a very consistent difference of approximately 2.38 dBA between the front and rear microphones for the ARC pavement, and 2.9 dBA for the AC pavement. The consistent difference of 1.1 dBA between ARC and AC pavement in the one-third-octave bands is measured in the interval of most concern for highway noise, 500 to 2000 Hz.

The energy equivalent sound pressures from the twelve pavements tested with the CPX method are presented in Table 2 and Figure 5. The results are the average numbers from all the runs conducted on individual pavements. From the on-board measurement, the difference between the noisiest and quietest pavements was over 5.35 dBA, ARC being the quietest pavement and New Graded Aggregate Seal being the noisiest pavement, respectively. The outcomes from newly paved Chip Seal and graded Aggregate Seal are doubtful and in need of further research.

Table 2 The Energy equivalent sound pressure level for the surface materials (dBA)

Road/Freq (Hz)	125	160	200	250	315	400	500	630	800	1000
New CS	86.1	84.6	84.7	83.4	80.9	83.6	85.9	87.4	91.4	91.5
New AC	97.6	94.7	91.9	88.8	85.7	85.6	86.5	88.5	91.0	90.4
Thermo	83.5	83.9	84.7	82.9	81.4	84.6	87.1	88.6	92.6	92.2
Old AC2	95.3	92.3	89.7	86.7	84.0	85.2	85.6	87.9	91.7	90.8
New GAS	82.7	83.7	85.2	83.9	83.2	86.4	88.5	89.9	94.2	92.8
Old CS	90.0	88.5	90.2	88.0	87.2	88.9	90.9	91.0	94.8	93.3
Old GAS	92.6	90.6	91.9	89.6	88.7	89.7	91.6	91.8	94.7	93.3
RACS	90.5	89.4	91.4	89.3	88.0	89.5	90.8	91.0	95.0	93.8
TLO	93.9	92.5	95.8	93.6	92.5	94.1	95.4	94.2	97.0	92.8
Old AC1	93.9	92.4	94.7	92.6	91.5	93.7	94.5	93.8	97.2	93.5
ARC	84.1	83.6	83.9	82.2	80.6	83.2	86.4	87.5	90.6	89.8
AC	83.5	82.7	83.8	82.4	80.2	82.3	86.5	87.6	91.4	91.4

Road/Freq (Hz)	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
New CS	88.3	84.6	82.9	81.0	79.5	77.0	73.9	70.0	67.9	64.8
New AC	87.7	84.0	82.3	80.7	78.7	75.6	72.0	69.6	68.0	65.9
Thermo	88.9	84.6	82.3	80.5	78.4	75.4	71.8	69.3	67.7	65.1
Old AC2	88.6	85.4	84.3	82.7	80.9	78.0	73.8	70.5	68.4	65.6
New GAS	88.5	83.7	81.3	79.4	77.0	74.3	70.6	68.2	66.4	64.2
Old CS	88.4	84.0	81.7	79.6	77.4	75.1	72.1	69.2	67.8	65.2
Old GAS	88.6	84.9	82.9	80.4	78.1	75.5	73.2	70.3	70.5	68.4
RACS	89.3	84.9	82.7	80.7	79.1	76.8	73.8	70.5	68.6	65.8
TLO	86.3	82.8	80.0	77.4	74.9	73.0	72.0	68.9	68.1	66.1
Old AC1	86.8	82.0	79.6	77.8	75.3	72.6	71.7	70.3	72.1	71.1
ARC	86.2	81.9	80.4	78.8	76.9	74.1	71.0	69.0	67.6	65.6
AC	87.6	83.6	81.7	80.0	78.3	75.4	72.3	69.7	68.6	66.5

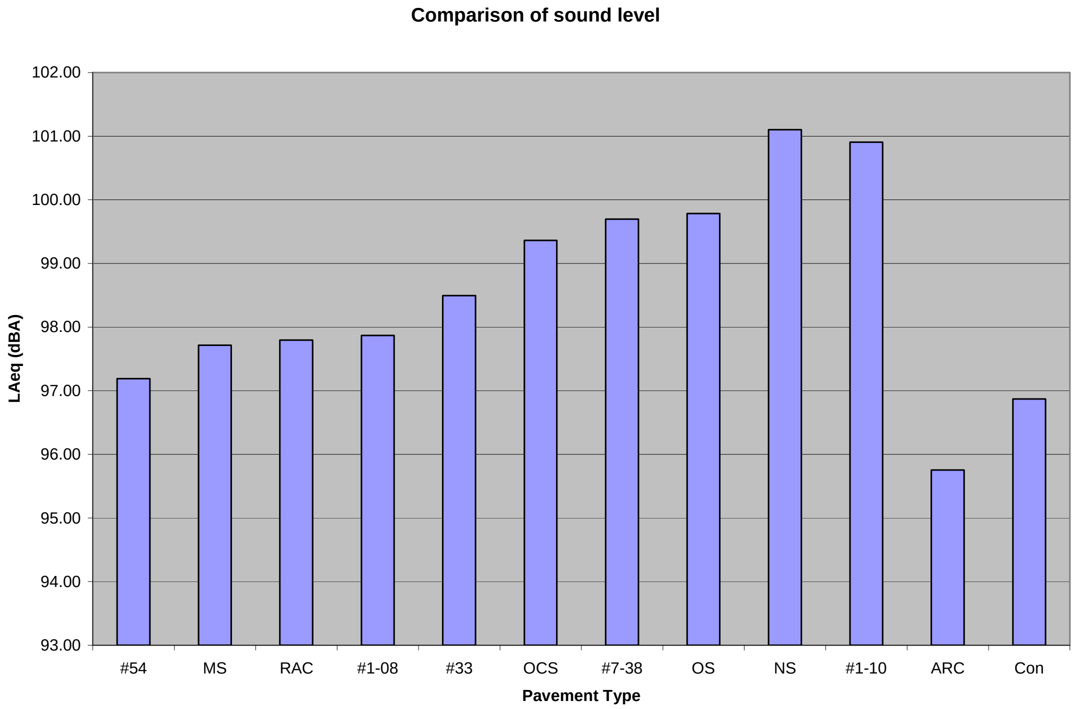

Figure 5 The comparison of the emission noise level between various surfaces

Base on the calculation from section 4 and the collected data from the experiment, sound intensity maps are generated from the vehicle driven on the ARC and AC pavements at 80 km/hr. Figures 6 and 7 show the sound intensity map of the noise emission generated from the interaction between tire/ARC and tire/AC pavements, respectively, at 350 Hz.

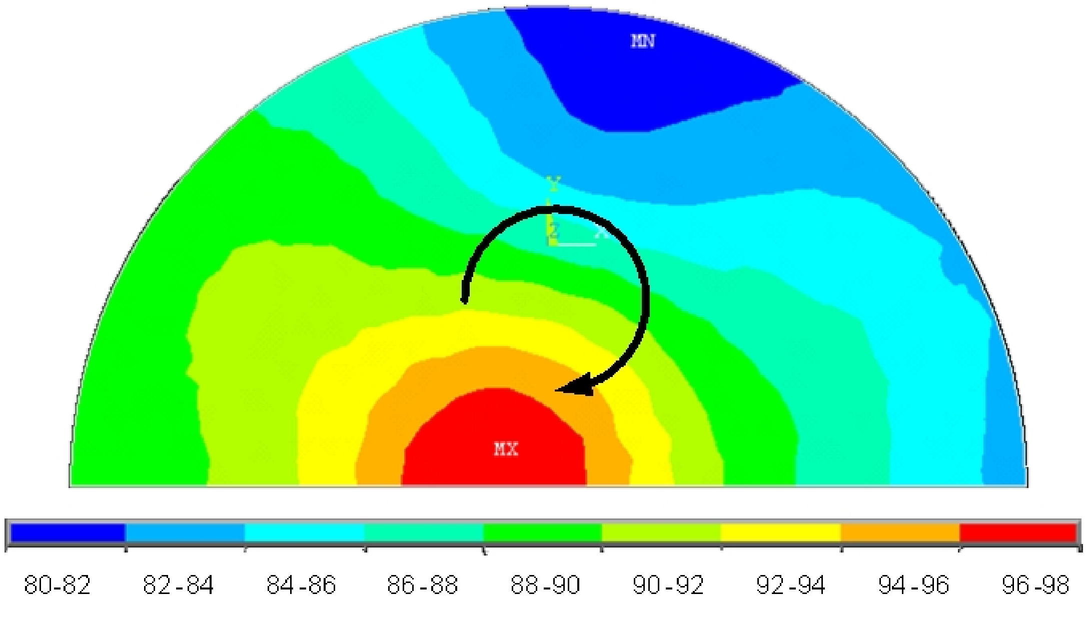

Figure 6 Sound Intensity mapping around the tire on the AC pavement at the speed of 80 km/hr and 350 Hz

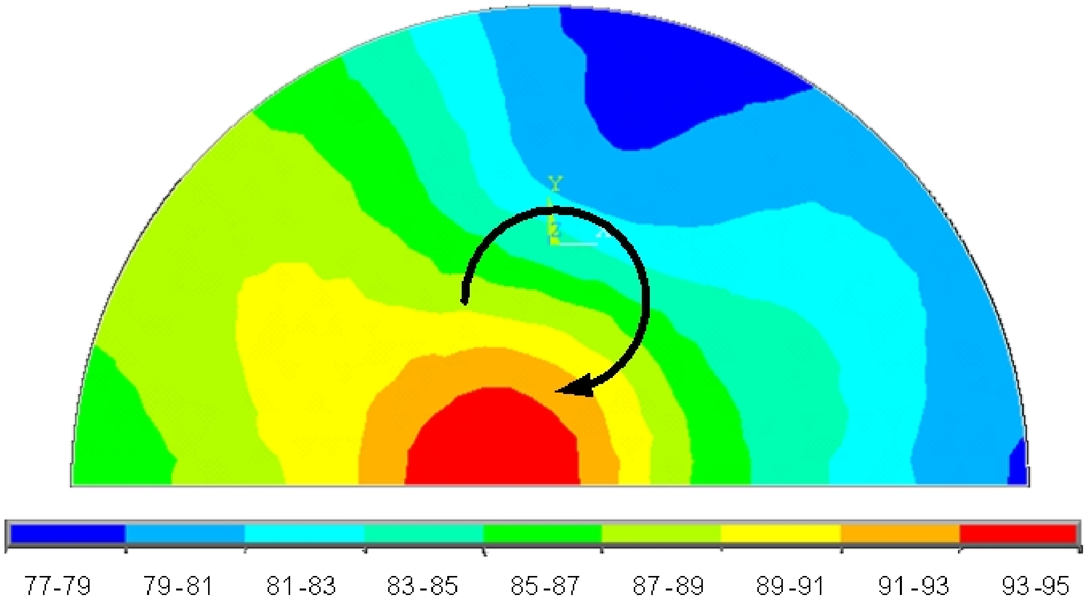

Figure 7 Sound Intensity mapping around the tire on the ARC pavement at the speed of 80 km/hr and 350 Hz

6. Conclusions and recommendations

Conclusively, the Closed Proximity Method can often be used in situations where the roadside method is impractical. A simple method to estimate the traffic noise level from the road/tire emission noise level would be to assume a sound level reduction due to spherical spreading of the sound field from the source and excess attenuation due to absorption during propagation. However, the noise measured from the CPX trailer is primarily from only one tire and the overall traffic noise has always been composed of all the tire/pavement interactions and from the engine and aerodynamic sources. Also, the microphones installed on the CPX trailer are well inside the near field of the source, and it is not clear how far they are from the effective source of the noise. Finally, the excess attenuation is usually uncertain. However, based on the data obtained so far, the CPX test appears to be a reasonable tool to estimating relative noise levels between different types of pavement.

The simulation results of the sound intensity mapping clearly show the difference between emission noise generated from ARC pavement and AC pavement, the intensity field from both pavements have very similar patterns, and however, the sound level (dBA) in ARC is approximately 3 dB lower than AC pavement.

The pavements tested in Saskatchewan, Canada showed significant differences in the level of emission noise generated from the interactions between tire and pavement during the test drive by, where noise level differences between the quietest and nosiest pavements was 5.35 dBA. The results indicate that the noise characteristics of the pavement surface types are significant and should be a consideration before selection of highway surfacing. The frequency spectra measured in the one-third octave band shows significant differences in spectrum analysis when noisy pavements are compared with quiet pavements. In particular, the ARC pavement has a significant drop in the mid-range frequency content between 400 and 1600 Hz. It is clearly stated in the results that the ARC pavement is very beneficial to the highway pavement for two reasons; 1) ARC pavement generates lower traffic noise than AC pavement in the environment and 2) ARC has the lowest road/tire emission noise among 12 types of surface materials applied in Saskatchewan.

Further investigation of other constraints, including sound propagation, acoustic power generation by the vehicle driven at various speeds, sound damping coefficients from the tire, and sound transmission coefficients are needed to quantify some of the adjustments necessary and the uncertainty present during the experiments.

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