ISEIS

Journal of Environmental Informatics 24(2) 121-130 (2014)

Journal of Environmental Informatics

www.iseis.org/jei

Effects of Operation Time of Pavement and Traffic Flow on the Traffic Noise of the Highways in an Urban Area

K. Huang[1], L. M. Dai[1,2,*], and W. W. Huang[3]

[1]*Industrial Systems Engineering, University of Regina, Regina SK S4S 0A2, Canada*
[2]*Sino-Canada Research Centre for Noise and Vibration Control, Xiamen University of Technology and University of Regina*
[3]*Department of Civil Engineering, McMaster University, Hamilton ON L8S 4L8, Canada*

Received 15 May 2014; revised 14 Sep 2014; accepted 16 Sep 2014; published online 21 Dec 2014

ABSTRACT. In developed as well as less developed countries, traffic noise is one of the main sources of societal noise pollution. In this research, a series of field experiments are conducted on highways with new and old pavements. The variations of the traffic flow and traffic noise pressure levels together with the functional relationship between them are analyzed based on the noise data collected from the highways in an urban area. With the collected data, the maximum traffic flow and traffic noise pressure levels are determined in a time specified manner. Logarithmic functional relationships are found between the traffic noise pressure level and traffic flow for both the old and new pavements. It is also found in the research, the improvement in the road re-pavement may promote the absorption of the traffic noise. A single value index is developed for quantitatively and conveniently evaluating the acoustic quality of highways. The findings in this research may give some inspiration for construction and management of low noise highways.

Keywords: acoustic measurement, traffic noise, highway pavement, traffic flow, noise pollution, traffic noise pressure

1. Introduction

The pollution of environmental noise in urban areas has increasingly attracted the attentions of researchers and engineers in the recent years. Environmental noise causes various negative effects onhuman beings, such as cardiovascular effects in humans, a rise in blood pressure, an increase in stress and vasoconstriction, and an increased risk of coronary artery disease.

The sources of most outdoor noise worldwide are mainly caused by manufacturing factories, transportation systems, aircrafts, and trains. Among these noise production sources, road traffic noise contributes most significantly to the environmenttal noise in urban areas. In the U.S., for example, it contributes more to environmental noise exposure than any other noise sources.In Europe, the traffic noise accounts for about 80% of total noise pollution (EU SMILE, 2014). Consequently, regulations regarding noise emissions of road vehicles, have been introduced by most industrialized countries (Sandberg, 2001). Such regulations are generally coordinated internationally, with regard to measuring methods and noise limits (Sandberg, 2001). For example, some states and local jurisdictions in the U.S. have limits for light vehicles that are either 80 or 84 dB-(A), originally measured according to SAE J986 using a 15 m measuring distance, which would correspond to 86 and 90 dB(A) at the 7.5 m distance used in most standards outside North America (Sandberg, 2001). In Canada, the Motor Vehicle Safety Act & Regulations mandate noise limits for vehicles, in which 81, 83, 84 dBA is the noise limit for a vehicle with an engine producing ≤ 75, ≥ 75 and ≤ 150, and ≥ 150 kW, respectively. Road traffic noise is caused by the combination of rolling noise, consisting of the friction noise between the road surface and vehicle tires, and the propulsion noise caused by the exhaust systems or engines. The pressure of traffic noise is influenced by many factors such as the type of engines, exhaust systems and tires interacting with the road, weather and road conditions. Generally, those factors can be categorized into four clusters: traffic factors, road factors, environmental factors and weather factors. In detail, the traffic factors mainly involve traffic volume, average traffic speed, traffic composition, driving conditions (free-flowing). The road factors include road gradient, road pavement surface type and texture, road corridor cross-section (whether the road layout is at grade, depressed or elevated). The environmental factors mainly contain distance between the source and reception point, type of intervening ground cover between source and reception point (e.g. grass, water or concrete), and natural or artificial obstructions. The weather conditions influencing the traffic noise include temperature, wind speed, humidity, precipitation and so on. Heavier traffic volumes, higher speeds, and greater number of trucks are expected to increase the loudness of traffic noise (Abo-Qudais and Alhiary, 2005). People

* Corresponding author. Tel.: +1 306 5854498; fax: +1 306 5854855.
E-mail address: liming.dai@uregina.ca (L. M. Dai).

ISSN: 1726-2135 print/1684-8799 online
 doi:10.3808/jei.201400288

also notice that other factors may influence the traffic noise levels significantly. For example, according to the experiment conducted by Fang and Ling (2003), a tree belt could effectively reduce the noise emitted at a point source. Consequently, a clear view of impact factors on the traffic noise level in living environments will certainly help identify potential roles of those factors in traffic noise pressure and provide further support for traffic noise reduction.

Since the first comprehensive review of the noise problems in modern society proposed by the Wilson Committee Report (British Parliament, 1963), a number of studies were conducted in analyzing the traffic noise pressure and its negative effects on human beings. For example, major Canadian researches covering traffic noise evaluation, annoyance study and sound barrier performance investigation in large-sized or medium-sized cities of Canada were initiated in 1970's in Ontario (Harmelink and Hajek, 1972; Epplett and Gallagher, 1973; Johnston and Carothers, 1974; Hajek and Krawczyniuk, 1983). In Western Canada, several traffic noise studies were conducted in Vancouver, Calgary and Edmonton (Pyplacz, 1983; BCHEB et al., 1996; Love, 1986; ETPB, 1974). Recently, Wayson (1998) mentioned that an absorptive surface prevented effective reflection of sound energy and helped reduce the roadside noise. Kropp et al. (2007) provided the noise reduction rates for different road surface characteristics based on a pilot study in Sweden. Lou (2007) investigated the traffic noise reduction rate of new pavement through field traffic noise tests on a highway in Saskatchewan, Canada. Mehdi et al. (2011) analyzed spatio-temporal patterns of road traffic noise pollution in Karachi, Pakistan. Agarwal and Swami (2011) proposed a comprehensive approach for the development of traffic noise prediction model for Jaipur city. Dai et al. (2013) developed a traffic noise prediction model on inland waterway of China using the FHWA. Engel et al. (2014) proposed statistical analysis of a combination of objective and subjective environmental noise data using factor analysis and multinomial logistic regression. However, previous research mainly focused on traffic noise prediction or its impacts on human's cognition and health. For impact factor analysis for traffic noise, insightful investigation is required to explore the interactive effect among various impact factors. Specifically, traffic noise pressure and diffusion with respect to traffic flow, under the considerations of different operation time of pavements needed to be further analyzed. Significantly, our research introduces a single value index to evaluate the acoustic quality of a road with respect to the road conditions and traffic flow.

Take the considerations described above, the objective in this study is to investigate the operation time of the road pavement on traffic noise pressure corresponding to various traffic flow conditions along highways. Specifically, we aim to identify the differences of traffic noise pressure on new and old highway pavements in the city of Regina via a series of field experiments. Furthermore, the potential variation of the empirical and theoretical relationships between the traffic noise pressure and traffic flow, stemming from the aging of the road surface will be studied. Such a study may give some inspiration for efficient highway construction, pavement materials and traffic flow management in terms of traffic noise reduction.

2. Field Experiment Conduction

2.1. Experiment Background

Traffic noise may have two basic origins: the power-train unit of the vehicle (engine, air intake, exhaust, transmission) and the tyre/road interaction (Sandberg, 1987). For properly maintained vehicles, the tire/road interaction noise would be the main source of traffic noise when the speed is more than 50 km/hour (Bernhard and Wayson, 2005). However, the tire/road interaction noise is largely influenced by many factors, such as tire size, vehicle type, traffic volume, and pavement surface texture. Specifically, the pavement surface can significantly influence the traffic noise pressure levels. Road surface characteristics, such as macrotexture, megatexture, porosity, thickness of layer and pavement material properties, are known to significantly affect tire/road noise pressure. For example, the dense surface, semi dense surface, semi porous surface and porous surface can produce a noise reduction rate of 0 ~ 2, 2 ~ 4, 4 ~ 6, and > 6 dBA for a car over 120 km/h, respectively (Kropp et al., 2007). However, these road surface characteristics and pavement properties will change over the road's lifetime. As the increase of operation time of pavement, the noise-influencing characteristics would change dramatically. For example, Mega- and macrotexture will change as particles and other material are worn away and the pavement structure is compacted by traffic. The chemical effects of the weather, assisted by road salt, create a weathering and crumbling surface which affects both microtexture and macrotexture of the pavement. If the pavement of the road is porous, its pores will become clogged by accumulated dirt (Sandberg and Ejsmont, 2002). However, few previous studies were proposed to investigate the effect of operation time of pavement on traffic noise emission. Specifically, no research was reported to explore the interactive effects of operation time of pavement and traffic flow on the traffic noise.

In this study, a series of field experiment will be conducted to evaluate the differences in the traffic noise pressure on new and old highway pavements, and further investigate potential variation of the empirical and theoretical relationships between the traffic noise pressure and traffic flow on highways with old and new pavements.

2.2. Site Selection

Regina is the capital city of the province Saskatchewan, Canada, with population more than 200,000. The City of Regina can be reached by several highways including the Trans-Canada Highway (#1 highway of Canada) from both the west and east sides and four provincial highways from other directions. The city is served with the Ring Road, a high speed connection between Regina's east and northwest that loops around the city's east side (the west side of the loop is formed by a busy road named Lewvan Drive). Future plans will be conducted to construct another perimeter highway to encircle the city farther out. This type of highways with no traffic lights is one of the important sources of traffic noise in most cities in Canada.

To study the effects of the operation time of highway's pavement on the traffic noise pressure, three locations, including A, B and C as shown in Figure 1, are selected as the mea suring sites. These three sites are chosen since (1) the highway is free without any traffic lights, (2) there are no buildings or constructions around these three sites to disturb the sound propagation, and (3) communities are far from the three sites, leading to neglectful noise from other sources. As can be seen from Figure 1, these sites distribute along the Trans-Canada Highway on which the speed limit is 100 km/h. More significantly, the sites are very close to each other with similar traffic and road construction conditions. Site A is a special site located along Assiniboine Ave to Wascana Pkwy in the City. Before October 4th, 2013, this way was an old pavement, which was paved in fall of 2010, and then it was repaved with a new pavement. For the sake of comparison, experiments were conducted at this site before and after the repaving of the road. Site B, from Wascana Pkwy to Assiniboine Ave., is paved with new pavement materials and selected for measuring the noise data and comparing with another site with old pavement under very similar conditions. And site C, from Albert St. to Wascana Pkwy, is with an old pavement and was paved in Fall of 2010 and experiments were conducted here to find the noise effects of the old pavement.

As shown in Figure 1, the surrounding environmental and road construction conditions of these three sites are similar without considerable noise reduction barriers or trees. Therefore, they can be used to evaluate the influence of the operation time of pavement on the traffic noise pressure with reliable noise data.

Figure 1. Selection of the measuring sites.

2.3. Experimental Equipment

In order to analyze the traffic noise, the sound pressure levels for each selected site are measured by utilizing the B&K Modular Precision Sound Analyzer 2260 in the experiments which is produced by the Brüel & Kjær in Denmark. Sound Analyzer 2260 supports one-channel measurements of environmental noise and noise at work, including real-time analyses of sound, and measurements of reverberation time. The resolution/accuracy for this instrument is 6.3 Hz to 20 kHz in 1/3-octaves of the frequency range and it can be extended to allow measurements of reverberation time in 1/1- or 1/3-octaves. To ensure the quality of the experimental data, the equipment is firmly fixed on the measuring sites with cement blocks as shown in Figure 2. In addition, a power box is set beside the equipment to provide electric power for a longtime testing. As can be seen in Figure 2, the equipment and accessories were all set in a sealed case for protecting the instrument. The case was locked and fixed on the cement blocks to prevent any possible damage.

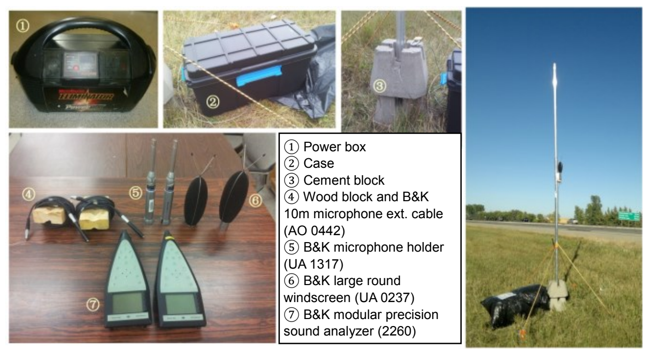

Figure 2. Experimental instruments and setup.

2.4. Experimental Methodology and Procedures

In noise studies, several different types of weighting networks are performed on sound spectra to calculate the equivalent sound level for different objectives. At low noise levels, the "A" weighting networks have been proved to correlate well with the sensitivity of human hearing and widely accepted as the sound level parameter in noise studies. Tire-pavement or traffic noise is rated as moderate sound, and thus it is usually measured as "A" weighted equivalent continuous sound level (Sandberg and Ejsmont, 2002; Brüel & Kjær Sound and Vibration Measurement A/S, 2007; Ahammed, 2009). Therefore, in the present study, the equivalent traffic noise levels and the corresponding requirements are collected in the form of "A" weighted equivalent continuous sound level (L_{Aeq}).

In addition, traffic noise from a stream of vehicles varies over time in strength depending on many different factors such as number of vehicles passed by, speeds of the vehicles, weather conditions in the tests and so on. The time averaged noise level is employed to convert the fluctuating values of noise in a certain time interval into a simple mean value. An important noise level indicator, adopted by many standards to estimate the impact of long-term noise to humans, is the continuous 24 hour time-averaged noise level ($L_{Aeq\ 24h}$), which is also adopted here as the long-term interval noise indicator. This is used for comparing the acoustic performances of new and old pavements in this study. Despite the fact that traffic flow conditions vary over time, they may not fluctuate significantly in a period of 1 hour. As a result, a 1-hour time-averaged noise level ($L_{Aeq\ 1h}$) is employed as another temporal noise indicator in the research.

Statistical Pass-By method (SPB), Controlled Pass-By method (CPB) and time-averaged method were developed for the roadside measurements to measure the traffic noise. Among them, the SPB method can be employed to account for all aspects of traffic noise including noise emitted by engine, exhaust and aerodynamic mechanisms, at the sideline of the test road section. As the SPB method is applicable for all aspects of traffic noise measurements, it is employed to study the influence of pavement conditions on environmental noise in this research. With this method, the maximum sound power of each vehicle passing by the measurement spot is measured. The standards selected for the measurements via the Statistical Pass-By and time-averaged traffic noise tests are ISO 11819-1 (1997) "Acoustics - Measurement of the influence of road surfaces on traffic noise" and ISO 1996/1 (2000) "Acoustics - Description and measurement of environmental noise". They are widely accepted as guidelines for traffic noise tests around world. The setup of the experiments also refers to Bérengier's research which considered the impact of traffic flow management on overall noise pressure levels (Bérengier, 2002). The layout of the microphone adopted in the experiment is shown in Figure 3. According to the standards, the microphone is placed 1.5 m above the ground, and 7.5 m away from the center line of the highway, as can be seen in the figure.

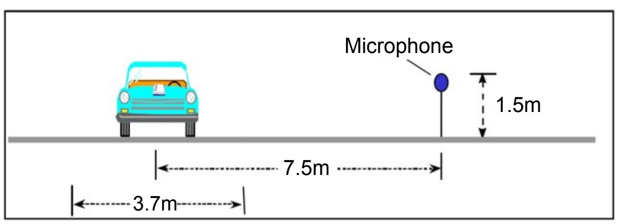

Figure 3. Layout of microphone adopted in the experiments.

The data collected and analyzed are the One-Hour Time-Averaged Noise Pressure Level in terms of equivalent continuous sound level L_{Aeq} (dB) and Traffic Flow Q is measured with the unit vehicle/hour, indicating the passing motor vehicles in a unit time. In this research, the 24-hour data of the traffic flow at the testing spots along Trans-Canada Highway are collected and supplied by the City of Regina.

3. Results and Discussion

3.1. Traffic Noise Pressure Level and Traffic Flow

Traffic noise is the collective sound energy emanating from motor vehicles which mainly consist of road surface, tire, engine/transmission, aerodynamic, and braking elements. To investigate the traffic noise for the old and new highway pavements, the traffic flow and traffic noise pressure levels are analyzed. As an important parameter affecting the traffic noise, traffic flow is studied with the traffic noise over a 24-hour period of time. It is also expected that an empirical relation between the traffic noise and traffic flow can be obtained based on the measurement data for the traffic noise pressure level and traffic flow. Though it is well accepted that the traffic noise pressure level follows a logarithmic relation with respect to the traffic flow, the relation needs to be specified with the testing conditions. In conducting the field experiments on the highway, the following conditions are assured:

1) Wind speed at the microphone height shall not exceed 5 m/s during the measurement.
2) Traffic flow, vehicle speed can be considered as constant on the segments of the highway (no traffic lights and road intersections).
3) During the measurement, there is no snow on the road surface. The measurement data in the raining time would not be adopted.
4) Unless the measurement specifically aims at determining the influence of weather or other environmental conditions on sound emission, ambient air temperature shall be within 5 to 30 ℃. The road surface temperature shall be within 5 to 50 ℃.

The measuring sites are divided into two groups to compare the effects of the old and new pavements on the traffic flow and traffic noise.

Group 1, i.e. sites A_1 and A_2, is from the Assiniboine Avenue to Wascana Parkway, in the City. Sites A_1 and A_2 are located at the same place (i.e. Site A in Figure 1). Site A_1 is considered with old pavement surface, and site A_2 is considered as new pavement surface since it was repaved on October 4th 2013. The experimental data for this group are measured before and after pavement for the sake of comparison. This site is along a road of three lanes.

Group 2 includes sites B and C. These two sites represent the old and new pavements with the same orientation respectively, and both them are located along a two lanes road, from Albert Street to Assiniboine Avenue in the City.

3.2. Group 1: Sites A_1 and A_2

The traffic flow and traffic pressure level for the old pavement at site A_1 (before the re-pavement) and new pavement at site A_2 (after the re-pavement) are compared and plotted in Figure 4. The curves in the figure are plotted on the basis of averaged data collected at the sites over a period of two months. As can be seen from the figure, the traffic flows for the old pavement at site A_1 and new pavement at site A_2 are close to each other, except some deviations around 16:00. The traffic volumes are low before 6:00 and after 22:00 than the other time periods. In addition, there are two obvious peaks for each curve in the morning between 7:00 and 9:00 and afternoon from 17:00 to 19:00 which are the rush hours for work. During these hours, the average traffic volumes vary sharply and reach the maximum value. With the variations of the traffic flows, the average traffic noise pressure levels are also fluctuated significantly. The variation tendency for the traffic noise pressure

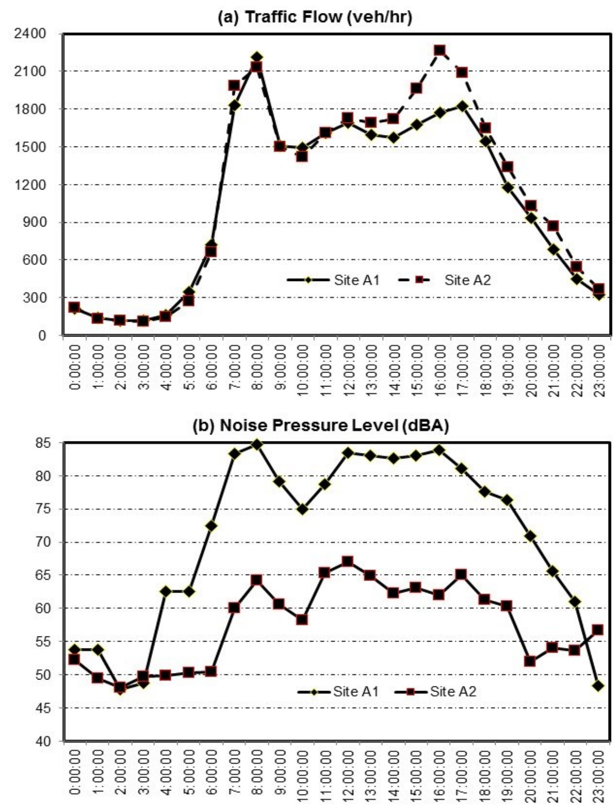

Figure 4. Comparison of (a) the average traffic flow and (b) the average noise pressure level for the old pavement at site A_1 and new pavement at site A_2.

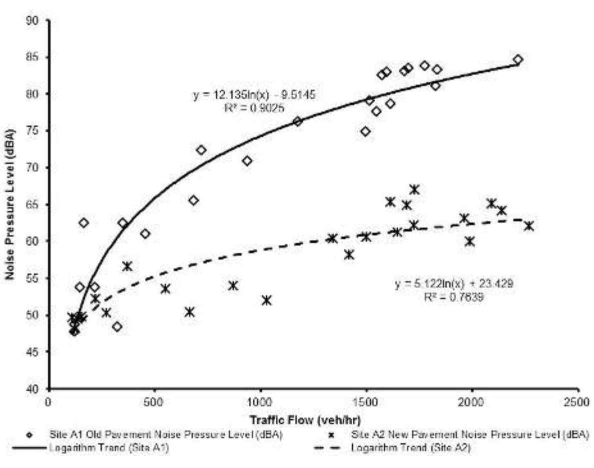

Figure 5. Logarithmic relationship between (a) noise pressure level and (b) traffic flow for the old pavement at site A_1 and new pavements at site A_2.

levels is similar to that of the traffic flow. The peak values appear in the morning (7:00 ~ 9:00) and afternoon (17:00 ~ 19:00). However, significant deviation appears between the average noise pressure level curves for the old and new pavements. As shown in Figure 4, the traffic noise pressure for the new pavement is much lower than that for the old pavement, especially for high noise pressure level higher than 55 dBA. At the rush hour around 8:00 am when the average traffic flows of the two sites are about the same, for example, the difference of traffic noise levels between sites A_1 and A_2 is about 20 dBA (19.21 dBA). The traffic noise reduction of the new pavement is obvious, more than 10 dBA when the traffic flow is large enough. When the traffic flow is low, at night, the environmental noise is affected by the background noise. The comparison shown in Figure 4 illustrates that, for the same traffic volume, the noise pressure level on the highway can be reduced considerably with the new pavement, indicating the significant effect of the new pavement on noise reduction. The noise reduction mechanisms by the pavement itself include acoustic and mechanical impedance (Neithalath et al., 2005). The acoustic impedance largely depends on the system of interconnected voids on the surface i.e., pavement surface type (porous or non-porous) and the pavement surface texture (Ahammed, 2009). The mechanical impedance is related to the relative stiffness of the tire and pavement. It has been demonstrated that decreasing pavement stiffness decreases the noise generated on the pavement. For the same pavement materials, the new pavement has lower relative stiffness, and thus produces lower tire/road interaction noise. Conversely, as time goes on the relative stiffness would increase, leading to louder noise.

The varying tendency of the average traffic flow with respect to the average traffic noise pressure level usually obeys a logarithmic relation (Rao and Rao, 1991; Steele, 2001; Agarwal and Swami, 2011). Based on the data collected in the experiments at the testing sites and the least square method, the following logarithmic fitting function can be constructed to explore the relation between the traffic flow and noise pressure level:

$$L_{Aeq} = A \ln Q + B \quad (1)$$

where Q is the volume of the traffic flow; A and B are parameters relying on the pavement and test conditions and can be determined through the least square method based on the experimental data.

The specific fitting relation for the old pavement is determined as:

$$L_{Aeq} = 12.135 \ln Q - 9.5145 \quad (2)$$

based on the obtained experiment results, with a correlation coefficient of $R^2 = 0.9025$, as shown by the solid line in Figure 5. Similarly, the fitting function for the new pavement can be obtained as:

$$L_{Aeq} = 5.122 \ln Q + 23.492 \quad (3)$$

which is presented by the dashed line in Figure 5, with $R^2 = 0.7639$. The value of R^2 ranges from 0 to 1, with higher values indicating less error variances, and typically values greater than 0.5 are considered acceptable (Santhi et al., 2001; Van Liew et al., 2007; Moriasi et al., 2007).

To further investigate the accuracy of the theoretical traffic noise prediction model presented by Equations (2) and (3), the calculated traffic noise levels and the observed values are compared. As shown in Figure 6, for the old pavement, the calculated traffic noise levels obtained through Equation (2) are much consistent with the observed values, except some deviations at low traffic noise levels (45 ~ 65 dBA), indicating a high precision of prediction. In comparison, the precision of the theoretical prediction model for the new pavement, as expressed by Equation (3), is less than that for the old pavement. As indicated in Figure 6, for the prediction model of the new pavement, there are some underestimates at low traffic noise levels (< 55 dBA), and some overestimates at high traffic noise levels (> 75 dBA).

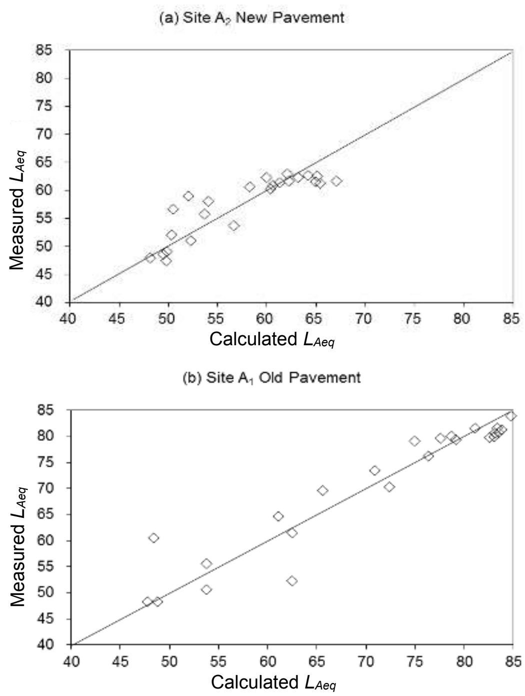

Figure 6. Comparison between measured L_{Aeq} and calculated L_{Aeq} of the new pavement at site A_2(a) and the old pavement at site A_1(b).

As shown in Figure 5, the parameter (*A*) for the new pavement is 5.122, less than that for the old pavement at site A_1, indicating that the increasing tendency of traffic noise for the new pavement is much slower than that of the old pavement. For the field experiment at site A, the observation time period is continuous, covering both the old and new pavement periods. Consequently, the characteristics of the traffic volumes (e.g. the speed, type and percentages of vehicles) usually do not change significantly, and thus the propulsion noise from the exhaust systems or engines would also not vary dramatically. The inherent principle for the new pavement in noise reduction is due to the decrease of the interactions between vehicle tires and road surface. As shown in Figure 5, the dramatic decrease of the traffic noise for new pavement indicates that, for traffic noise, the interactions between the vehicle tires and road surface would account for a large component for the traffic noise. Consequently, renewing the road surface would be an effective measure for traffic noise reduction.

3.3. Relative Traffic Noise Pressure Level Index

Based on the analysis above, the traffic noise on highway is closely related to the traffic flow along the road. Their relationship can be described by a logarithmic function relying on the collected noise and traffic flow data. To compare the noise level of different pavements or different testing locations, the noise pressure level measured can be comparable only if the corresponding traffic flows are identical. In order to avoid searching for the noise intensities of different road pavement corresponding to an identical traffic flow, a relative traffic noise pressure level index is introduced, such that:

$$I_r = \frac{n_a}{q_a} \tag{4}$$

where n is a single noise pressure level measured and n_a is the average traffic noise; and q is a single traffic flow measured and q_a is the average traffic flow corresponding to a specified time interval. Therefore, in practice, relative traffic noise pressure level index for the *i*th time interval can be given by the following expression, over a time segment considered:

$$I_{r,i} = \sum\nolimits_{j=1}^{k} \frac{n_j}{k} / \sum\nolimits_{s=1}^{l} \frac{q_s}{l} \tag{5}$$

where k is the number of measured noise pressure level data and l is the number of recorded traffic flow data.

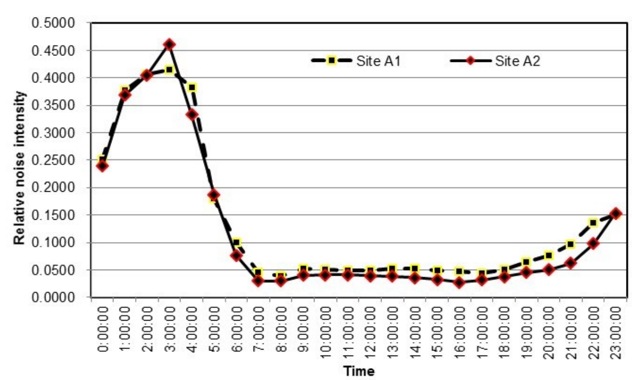

Figure 7. Comparison of the relative noise intensities corresponding to sites A_1 and A_2.

All the I_r values determined are plotted in Figure 7 over the considered time intervals. As can be seen from the figure, the relative noise pressure level index value is very high at night. This is because that the traffic flow at night is low. In considering the background environmental noise at night, the low traffic flow may lead to high I_r per the equation defined.

In order to evaluate the traffic noise with respect to the road pavement, it is rational to concentrate only on traffic noise. This can be done if the traffic flow is high enough such that the traffic noise is high and the background noise becomes negligible. Indeed, as can be seen from Figure 7, the relative noise pressure level index I_r becomes stable between 7:00 am and 19:00 when the traffic flow is more than 1000 vehicles per hour.

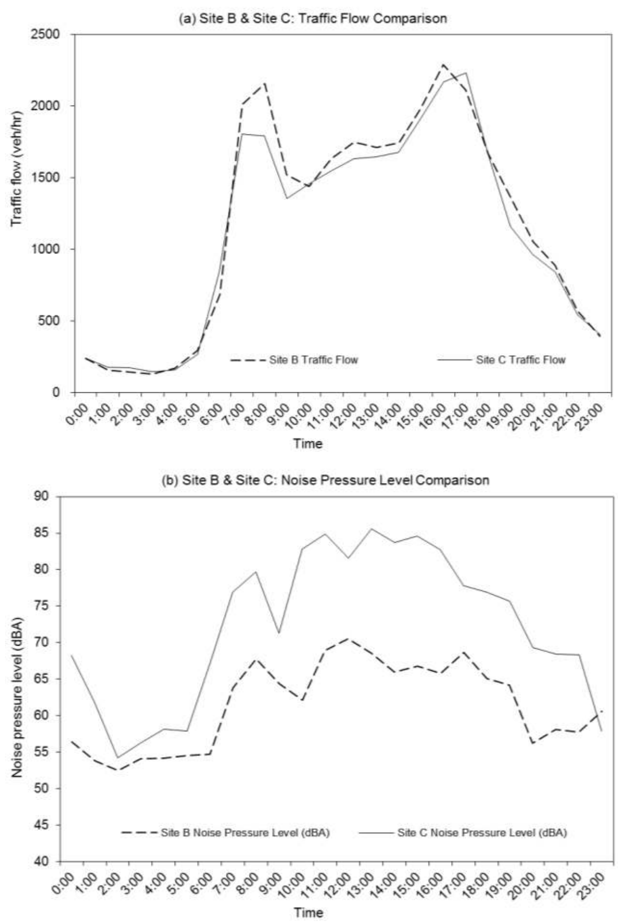

Figure 8. Comparison of (a) the traffic flow and (b) the noise pressure level for the old pavement at site C and new highway pavement at site B.

In order to evaluate the effect of the operation time of road pavement on the noise level, it would be much convenient to provide a single value index relating to the stabilized relative noise pressure level index. We therefore introduce an averaged relative traffic noise pressure level index as defined below:

$$I_{ra} = \sum_{p=1}^{w} I_{r,p} \tag{6}$$

where w is the number of considered time intervals, in which the relative traffic noise pressure level index is stable.

Based on the data collected, the stabilized averaged relative traffic noise pressure level index I_{ra} is 0.0489 for site A_1 (old pavement) and 0.0353 for site A_2 (new pavement). By the definition as shown in Equation (6), I_{ra} indicates the ave- rage traffic noise pressure level per vehicle. Therefore, the pavement at site A_2 generates much less noise per vehicle, or 27.8% noise reduction in dBA, under the same conditions. As can be seen from the description above, the single value index I_{ra} considers only the average traffic noise pressure level per vehicle. The index is therefore convenient for application in practice to evaluate the quietness (or loudness) of a road or compared the acoustic quality of roads with different pavements.

3.4. Group 2: Sites B and C

The measurements of the traffic flow and the traffic pressure levels for the old pavement at site C and new pavement at site B are compared in Figure 8. As can be seen in the figure, high traffic flows also occur from 7:00 to 19:00 in a day, and the traffic flow is low at night. The shapes of the curves in Figure 8 are almost identical to that shown in Figure 4. Similar to Group 1 (i.e. site A), the traffic noise pressure level for the new pavement at site B is much lower than that for the old pavement at site C. As presented in Figure 8, as the traffic volume increases, the reduction effect for traffic noise on the new pavement is more significant. This indicates that, the new pavement, as a control measure for traffic noise, is quite effective at city center (with high traffic volume) and highway (with high driving speed). Furthermore, compared with site A, the traffic noise level at site B is slightly higher, especially for the new pavements. This is because that the road at site A is three lanes while site B is two lanes, and most traffic travels through the inner two lanes, leading to a longer distance between the noise pressure source and the detector.

Also, the logarithmic functions are formulated for sites B and C, based on the field observations, to reflect the relationship between traffic flow and the traffic noise level. As shown in Figure 10, the fitted function for site B is expressed as:

$$L_{Aeq} = 5.1721 \times \ln(Q) + 26.761, \tag{7}$$

with a correlation value of 0.7699. For site C, the obtained logarithmic function is formulated as:

$$L_{Aeq} = 9.1897 \times \ln(Q) + 10.071, \tag{8}$$

with a correlation value of 0.7646. From Equations (7) and (8), the slope of the logarithmic function for site B is much smaller than that for site C, meaning that as the increasing of the traffic volume, the increase of the noise level at site B is less than that at site C, indicating an significant effect for the new pavement at site B in noise reduction.

The relative traffic noise pressure level is also determined similar to that of Group 1. Figure 10 illustrated the I_r values for sites B and C. As can be seen from the figure, the traffic noise pressure level of the new pavement at site B is always lower than that of the old pavement at site C. Also, we will focus on the I_r values of sites B and C during 7:00 ~ 19:00, where the index values are stabilized.

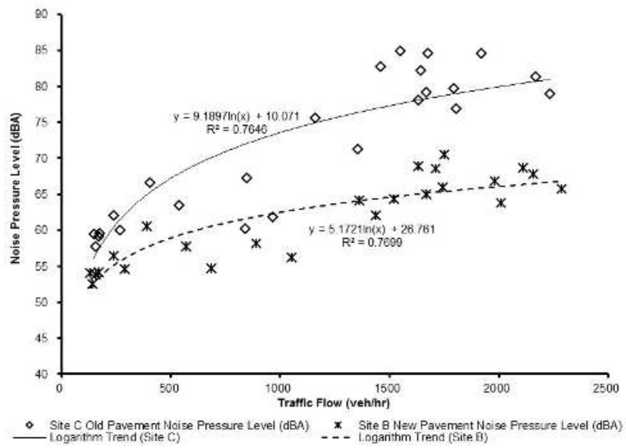

Figure 9. Logarithmic relationship between noise pressure level of the old pavement at site C and traffic flow for the new highway pavement at site B.

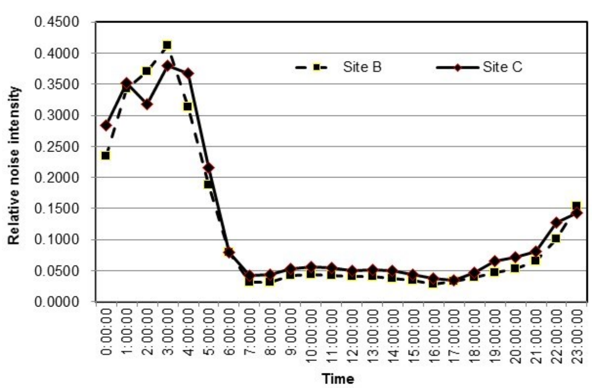

Figure 10. Comparison of the relative noise intensities corresponding to sites B and C.

For the sake of comparison for the noise levels of the new and old pavements, the stabilized averaged relative traffic noise pressure level index I_{ra} is also determined for sites B and C. For site C (old pavement), I_{ra} is 0.04730 and I_{ra} equals to 0.03688 for site B (new pavement). This implies that the new pavement provides a 22.04% noise reduction rate in dBA which shows the explicit effect of the new pavement on traffic noise reduction.

One may notice from Figure 1, there is some distance between sites B and C, leading to some differences in the surrounding circumstances. For example, the road at site B is straight while the road at site C is curving. However, based on the obtained logarithmic functions at sites B and C, as well as the results shown through Figures 8 and 10, the effect of the new pavement in noise reduction is still quite significant. In terms of traffic noise reduction, pavement and road surface conditions are essential to be considered.

3.5. Discussion

Several methods can be employed for traffic noise mitigation, such as traffic flow control and noise barriers construction. However, such methods are limited in application in some situations due to economics or public reaction (Lou, 2007). Moreover, the tire/pavement interaction noise contributes most to the traffic noise for cruise driving conditions, frequently appearing on light-free highways (Sandberg and Ejsmont, 2002). de Graaff and van Blokland (1997) indicated that nearly 90% of the equivalent sound energy was produced by the tire/pavement interaction in urban areas. Consequently, tire/road noise mitigation would be a potential efficient method for traffic noise control. Road repavement through low noise pavement materials is the major way to reduce the tire/road noise, has been applied in many countries in recent years (Lou, 2007).

In this study, the relative traffic noise pressure level index was proposed to compare the noise level under different pavement conditions or testing locations. Such an index can reflect the variations of traffic noise intensities under different traffic flow conditions, as shown in Figures 7 and 10. Through this index, the engineers can identify the variation rates of traffic noise with respect to traffic flow. For example, as the increasing of traffic flow, Figure 7 suggested a decreasing trend for the variation rates of traffic noise at site A_1 and A_2.

Furthermore, the averaged relative traffic noise pressure level index (i.e. I_{ra}) introduced in this study, can quantitatively reflect the noise reduction effect of the old and new pavement. This index can be applied to assess the noise reduction effect of road repavement. For example, the value of I_{ra} at site B (new pavement) and C (old pavement) is 0.03688 and 0.04730, respectively, indicating a reduction rate of 22.04% of new pavement for traffic noise mitigation

4. Conclusions

In this research, the traffic flow and traffic noise on old and new highway pavements are investigated via a series of field experiments along the Trans-Canada Highway in Regina. The variations of the traffic flow and traffic noise pressure level for the old and new pavements with respect to the time are analyzed. Based on the findings of the research, the following can be concluded:

The logarithmic relationships between the traffic flow and traffic noise pressure level are established. The results predicted by the logarithmic functions agree well with the experimental data, with correlation coefficients all above 0.75.

Comparing the results of the old and new pavements, new pavements may significantly reduce the traffic noise pressure level, with a reduction more than 20% under the experimental conditions of the present research.

A single value index named the relative traffic noise pressure level index is established to compare the acoustic quality of roads with different pavements. This index actually measures the contribution of each "averaged" vehicle to the noise of a road considered. The requirement for comparing the noise pressure level with identical traffic flow is therefore not needed. With the index, the acoustic quality of a highway road can be conveniently quantified.

This research provides a new approach for evaluating the acoustic qualities of a highway and gives new inspiration and ideas for road construction and traffic management in reducing the traffic noise.

Acknowledgments: This study is supported by the Department of Transportation, City of Regina, Canada Foundation for Innovation (CFI) and Natural Sciences and Engineering Research Council of Canada (NSERC). The collaboration of the Sino-Canada Research Centre for Noise and Vibration Control at the University of Regina is crucial to the performance of the research.

References

Abo-Qudais, S., and Alhiary, A. (2005). Effect of traffic characterristics and road geometric parameters on developed traffic noise levels. *Can. Acoustics,* 33(1), 43-50.

Agarwal, S., and Swami, B.L. (2011). Comprehensive approach for the development of traffic noise prediction model for Jaipur city. *Environ. Monit. Assess.,* 172(1-4), 113-120. http://dx.doi.org/10.1007/s10661-010-1320-z

Ahammed, M.A. (2009). *Safe, Quiet and Durable Pavement Surfaces*, Ph.D Dissertation, University of Waterloo, Waterloo, Ontario, Canada.

BCHEB (British Columbia, Highway Environment Branch), Wakefield Acoustics Ltd. and British Columbia, Ministry of Transportation and Highways (1996). *Lions Gate Crossing: South Shore Traffic Noise Study*, The Branch, Victoria, BC.

Bérengier, M. (2002). Acoustical impact of traffic flowing equipments in urban areas, *Proc. of Forum Acusticum*, Sevilla, Spain.

Bernhard, R., and Wayson, R.L. (2005). *An Introduction to Tire/Pavement Noise of Asphalt Pavement*, Institute of Safe, Quiet and Durable Highways, Purdue University.

British Parliament (1963). Wilson committee report on noise: A synopsis of the contents of the final report by the committee on the problem of noise, which relate to Aircraft Noise. *Aircraft Eng. Aerospace Technol.,* 35(8), 218-219. http://dx.doi.org/10.1108/eb033763

Brüel & Kjær Sound and Vibration Measurement A/S (2007). *Basic Frequency Analysis of Sound*, Brüel & Kjær North America Inc., Norcross, Georgia, No. BA 7669-11.

Dai, B.L., He, Y.L., Mu, F.H., Xu, N., and Wu, Z. (2013). Development of a traffic noise prediction model on inland waterway of China using the FHWA. *Sci. Total Environ.,* 482-483(1), 480-485. http://dx.doi.org/10.1016/j.scitotenv.2013.06.019

de Graaff, D.F., and van Blokland, G.J., (1997). *Follow-up Study on the Influence of Metrological Conditions on the Noise of Vehicles during Type Approval*, Report of MVM.95.3.1, M+P Raadgevende Ingenierus b.v.,'s Hertogenbosch, Netherlands.

Engel, M.S., de Vasconcelos Segundo, E.H., and Zannin, P.H.T., (2014). Statistical analysis of a combination of objective and subjective environmental noise data using factor analysis and multinomial logistic regression. *Stochastic Environ. Res. Risk Assess.,* 28, 393-399. http://dx.doi.org/10.1007/s00477-013-0759-1

Epplett, C., and Gallagher, J. (1973). *Motor Vehicle Traffic in Ottawa: Environmental Impact and the Energy/Transportation Interface*, Pollution Probe, Ottawa.

ETPB (Edmonton, Alberta, Transportation Planning Branch) (1974). *Noise in the City of Edmonton*, Transportation Planning Branch, Engineering & Transportation Dept., City of Edmonton.

EU Sustainable Mobility Initiatives for Local Environment (SMILE) (2014). *Guidelines for Road Traffic Noise Abatement*.

Fang, C.F., and Ling, D.L. (2003). Investigation of the noise reduction provided by tree belts. *Landscape Urban Plann.,* (63), 187-195. http://dx.doi.org/10.1016/S0169-2046(02)00190-1

Hajek, J.J., and Krawczyniuk, R. (1983). *The Accuracy of Highway Traffic Noise Predictions, Research and Development Branch*, Ontario Ministry of Transportation and Communications, Downsview, Ontario.

Harmelink, M.D., and Hajek, J.J. (1972). *Noise Barrier Evaluation and Alternatives for Highway Noise Control*, Ministry of Transportation and Communications, Downsview, Ontario.

ISO 11819-1 (1997). *Acoustics - Measurement of the Influence of Road Surfaces on Traffic Noise - Part 1, Statistical Pass-by Method*, International Organization for Standardization, Geneva, Switzerland.

ISO 1996/1 (2000). *Acoustics - Description and Measurement of Environmental Noise*, International Organization for Standardization, Geneva, Switzerland.

Johnston, G.W., and Carothers, R. (1974). *Urban Traffic Noise Annoyance Measurements and Derived Indices*, University of Toronto - York University Joint Program in Transportation, Toronto.

Kropp, W., Kihlman, T., Forssen, J., and Ivarsson, L. (2007). *Reduction Potential of Road Traffic Noise - A Pilot Study*, The Department of Applied Acoustics, Chalmers University of Technology, Goteborg.

Lou, Z. (2007). *An Experimental and Numerical Study of Tire/Pavement Noise on Asphalt Rubber Concrete Pavement*, Master's Thesis, University of Regina, Regina, Saskatchewan, Canada.

Love, B.C. (1986). *The Effect of Road Traffic Noise on Housing Prices in Calgary, 1978 to 1982*, National Library of Canada, Ottawa.

Mehdi, M.R., Kim, M., Seong, J.C., and Arsalan, M.H. (2011). Spatio-temporal patterns of road traffic noise pollution in Karachi, Pakistan. *Environ. Int.,* 37, 97-104. http://dx.doi.org/10.1016/j.envint.2010.08.003

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., and Veith, T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE,* 50(3), 885-900. http://dx.doi.org/10.13031/2013.23153

Neithalath, N., Garcia, R. Weiss, J., and Olek, J. (2005). Tire-pavement interaction noise: Recent research on concrete pavement surface type and texture, *Proc. of the 8th International Conference on Concrete Pavements*, Colorado Springs, Colorado.

Pyplacz, B.M. (1983). *Urban Traffic Noise Abatement: A Case Study of Boundary Road, Vancouver, BC*, Student Report, University of British Columbia, School of Community & Regional Planning, Vancouver.

Rao, R.P., and Rao, S.M.G. (1991). Environmental noise levels due to motor vehicular traffic in Visakhapatnam city. *Acustica,* 74, 291-295.

Sandberg, U. (1987). Road traffic noise - The influence of the road surface and its characterization. *Appl. Acoust.,* 21, 97-118. http://dx.doi.org/10.1016/0003-682X(87)90004-1

Sandberg, U. (2001). *Noise Emissions of Road Vehicles*, Effect of Regulations, Final Report 01-1, I-INCE WP-NERV, Stochholm.

Sandberg, U., and Ejsmont, J.A. (2002). *Tyre/Road Noise Reference*

Book, Informex, Kisa, Sweden.

Santhi, C., Arnold, J.G., Williams, J.R., Dugas, W.A., Srinivasan, R., and Hauck, L.M. (2001). Validation of the SWAT model on a large river basin with point and nonpoint sources. *J. Am. Water Resour. Assoc.,* 37(5), 1169-1188. http://dx.doi.org/10.1111/j.1752-1688.2001.tb03630.x

Steele, C. (2001). A critical review of some traffic noise prediction models. *Appl. Acous.,* 62, 271-287 http://dx.doi.org/10.1016/S0003-682X(00)00030-X

Van Liew, M.W., Veith, T.L., Bosch, D.D., and Arnold, J.G. (2007). Suitability of SWAT for the conservation effects assessment project: A comparison on USDA-ARS experimental watersheds. *J. Hydrol. Eng.,* 12(2), 173-189. http://dx.doi.org/10.1061/(ASCE)1084-0699(2007)12:2(173)

Wayson, R. L. (1998). *Relationship between Pavement Surface Texture and Highway Traffic Noise*, NCHRP Synthesis of Highway Practice 268, Transportation Research Board, National Research Council, Washington D.C.