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SPECTRAL COMPARISON OF PASS-BY TRAFFIC NOISE

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ABSTRACT

Traffic noise is a major noise source in the study of environmental noise. Various noise generation mechanisms depict different spectral features. Some are wide-band noise, such as engine knocks; some have signature frequencies, such as gear transmissions; and some are in a certain frequency region, such as tire/road noise. These spectral features affect the façade design of a building in order to achieve sufficient exterior noise insulation and satisfactory interior noise due to the traffic noise. ISO standard 11819-1 specifies the measurement procedure of statistical pass-by tests. There are three ranges of vehicle speed: slow, medium, and fast. However, it requires that the vehicle must maintain constant speed when passing by the test point. Unfortunately, a vehicle tends to generate higher noise when accelerating, especially at low frequencies. Therefore, it is necessary to distinguish the noise levels at an intersection versus middle-points of the road between two intersections. Presumably, the traffic noise levels at an intersection would be higher. This research measured the traffic noise at various locations of different speed limits. Statistical analyses were conducted to compare the spectra at these locations. This is also an effort to refine the noise map.

1. INTRODUCTION

Road traffic noise, compared with rail and air transportation noise, is a greater problem since it affects many more people, not only drivers and passengers (interior noise), but only those in residential areas and commercial buildings (exterior noise), in their everyday lives. Although the sales of electric vehicles significantly increased in the last decade, most automobiles are still internal-combustion-engine based. Three main traffic noise sources of automobiles are power train noise, tire/road noise, and wind turbulence noise [1].

Power train noise is due to the engine, air inlet, exhaust, cooling system, and transmission. With the development of modern technology, such as muffler design, the power train noise of well-built automobiles is much attenuated except for acceleration in the first and second gears [1,2]. The two main noise sources of internal-combustion engines (both gasoline and diesel) are combustion forces (as cylinder pressure changes) and other mechanical forces. These forces produce vibration in the structure, and the vibration is transmitted to external components that can radiate sound [3].

Empirical formulas were proposed to estimate the A-weighted sound pressure level at 1 meter distance from the engine [3]. The frequency content of the combustion noise depends upon whether the cylinder pressure trace is smooth. If there are no engine knocks, then there will be very high amplitudes of low-frequency excitation to the engine structure but little high-frequency content [3]. Regarding other mechanical noise sources, there are two types: (1) noises caused by clearances that produce broadband, impact-like inputs to the engine structure and (2) other mechanical noise sources in an engine, such as gear and chain drives, oil pump, that are periodic in nature.

Tire/road noise has been studied by many researchers [3-7]. For automobiles driving at steady speeds, tire-road noise dominates, especially for speeds higher than 70 km/h. It is reported that there is little difference between the exterior noise of trucks whether they are accelerating, cruising at a steady speed, or coasting by [1,2]. The main tire/road interaction noise generation mechanisms include (1) impacts between the tire tread and the road, which cause radial, tangential, and sidewall tire tread and carcass vibration and consequent noise radiation, and (2) the "air pumping" between the tire tread and the road surface [2]. There are two experimental methods to investigate the tire/road noise: statistical pass-by method, and close-proximity method. Both methods are standardized by the ISO.

ISO 11819-1 standard specifies the statistical pass-by methods [6,7]. There are three categories of automobiles: passenger cars, 2-axle heavy vehicles, and multi-axle heavy vehicles. For each vehicle category, there are three speed ranges: slow (45~64 km/h), medium (65~99 km/h), and fast (above 100 km/h). Then a linear regression analysis is conducted to correlate maximum A-weighted sound level and speed for each vehicle category. This method requires that only one vehicle passes the test point at a time. Also, all vehicles must maintain constant speeds to eliminate the influence due to engine's acceleration noise. In addition, this method only records A-weighted overall noise levels instead of the noise spectra.

In the close-proximity (CPX) method, specified by ISO 11819-2, the noise generated by tire/road interaction is enclosed in an acoustical chamber and measured by two microphones (one front and one rear) located about 200 mm from the tire and 100 mm above the road surface. This method focuses on the tire/road noise generation because other noise sources are isolated by the acoustical chamber. In addition, this method measure noise spectra at different driving speeds. Previous measurement results conducted by different researchers agree that tire/road noise is concentrated usually in a frequency range around 1000 Hz at speeds up to about 100 km/h [1,2,4].

Both the ISO standards mentioned above exclude the influence of power train noise. In reality, however, people perceive the traffic noise as a whole. Additionally, when accelerating a vehicle tends to generate higher noise at low frequencies which is related to the engine's rotating speed. Therefore, it is necessary to distinguish the noise levels at an intersection versus middle-points of the road between two intersections. In this research, the traffic noise of five location pairs (intersection and a middle-point of a road) were measured and their spectral contents were compared. Statistical analyses, including the *t*-test and two-way ANOVA (analysis of variance), were carried out to compare the noise levels at these locations.

2. EXPERIMENTAL SETUP

2.1 Test Locations

Totally ten locations (five pairs) in Lake Charles, LA were tested for the purpose of the traffic noise comparison between intersection and the middle of a road. Table 1 lists all the ten locations along with their speed limits that are given in both miles per hour (mph) and km/h. These five pairs are with five different speed limits from 25 mph (40 km/h) to 50 mph (80 km/h) in order to account for noise variations caused by vehicle's speed.

Table 1. Summary of test locations.

Test Number	Road Name and Date	Location	Distance, ft (m)	Speed Limit, mph (km/h)
1	Common St. (04/11/2018)	Common – E. McNeese Intersection (North)	583 (178)	25 (40)
2		Middle of road (in front of Drew Hall parking)		
3	Ryan St. (04/17/2018)	Ryan – E. McNeese Intersection (North)	963 (293)	35 (56)
4		Middle of road (in front of Seed Center)		
5	E. McNeese St. (04/24/2018)	Common – E. McNeese intersection (West)	344 (105)	40 (64)
6		Middle of road (in front of Dorm Sallier)		
7	Common St. (04/19/2018)	Common – E. McNeese intersection (South)	1821 (555)	45 (72)
8		Middle of road (in front of Performance Evolution)		
9	E. McNeese St. (04/13/2018)	E. McNeese – Hwy 14 Intersection	1448 (441)	50 (80)
10		Middle of road (in front of Henderson's)		

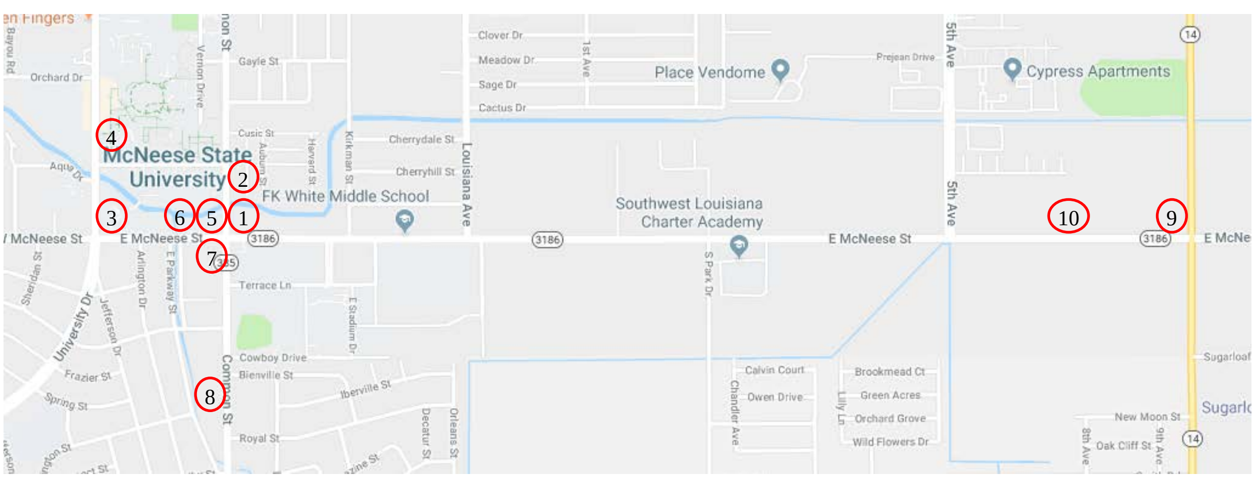


Figure 1. Map of test locations.

These locations are also labelled on the map shown in Fig. 1. These locations are numbered such that all the intersections are odd numbers while the corresponding middle-points are even numbers. All the locations are in Lake Charles, LA while most of them are around the McNeese State University campus. Three of them (Locations #1, #5, and #7) are at the three corners of the Common St. – E. McNeese St. intersection (north, west, and south, respectively).

All the test points are on the right of a road as vehicles accelerate and pass the intersection. The middle-points are chosen such that they are at least 100 m from the intersection counterpart. So presumably, vehicles reach their steady speeds and pass the middle-point with constant speeds. In addition, there is either not any or very little converging or diverging traffic between each pair test points. Therefore, it can be assumed that all vehicles that pass the intersection also pass the middle-point. Uncertainties between each pair of test points are thus reduced.

At each test point, the measurement lasted 30 minutes roughly between 4:30 PM and 5:00 PM for a few reasons.

(1) This period of time is when the afternoon rush hour starts, so the traffic condition is normal, not too dense or too sparse.
(2) All test pairs were recorded during similar time intervals such that uncertainty caused by different time of a day is excluded in the statistical analysis.
(3) 30 minutes are long enough to measure wide noise variations at a certain point. In addition, as shown in Table 1, all test dates were weekdays, instead of weekends, to ensure traffic conditions were similar.

2.2 Test Equipment

Two identical test stations were set up, so the two locations in a pair were measured over exactly the same period of time. The microphones used in these tests are PCB 377B02 free-field ½” condenser microphones integrated with ½” ICP preamplifiers. The microphones were mounted on tripods, as shown in Fig. 2. Every test point was 25 ft (7.5 m) from the center of the road, and the microphone was 4 ft (1.2 m) from ground, according to the ISO standard 11819-1. Before each test, each microphone was calibrated using a Larson Davis sound calibrator CAL 200 at both the 94 dB and 114 dB levels. Then microphone was then covered by a windscreen.

The data acquisition was conducted using USB-based devices National Instruments NI-9234. This device has four 24-bit synchronous channels and each channel can provide the ICP constant current power supply to the microphone. The maximum sampling rate is 51.2 kHz per channel which is high enough to cover the entire audio frequency range.

Figure 3 illustrates the software interface developed using LabVIEW. The entire system works as a computer-based sound level meter. User can configure parameters such as microphone sensitivity, averaging mode, frequency range, spectrum type (octave, 1/3 octave, or fractional octave), and frequency weighting. In these traffic noise tests, exponential averaging with fast (F) time mode (integration time is 125 ms) was used.

(a)

(b)

Figure 2. Experimental setup. (a) Location #1, (b) Location #2.

The software can display the time waveform, instantaneous sound pressure level, and spectrum. The user needs to specify the data acquisition time, in these tests, 30 minutes. Then the software will not allow users to make any changes or interrupt the recording. A progress bar is shown on the bottom. To save hard drive space, the software does not record all the raw time histories. Instead, it only saves the sound spectrum every second.

In this study, the recorded sound spectra are unweighted. This is mainly because the exterior traffic noise levels will be used to estimate the interior noise levels of a building along with the building façade’s sound transmission loss data, while the interior noise levels are studied using the NC curves which are unweighted. However, frequency weighting can be easily applied later in data analyses. In fact, both unweighted and A-weighted spectra are analyzed in this paper.

After 30 minutes, there are 1800 spectral records. For each frequency band, the percentile levels were calculated. Figure 4 illustrates the results of Location #2 from 20 Hz to 5000 Hz where L_{max}, L_{min}, L_{10} and L_{eq} are highlighted. Due to limited page number, not all the percentile level spectra are presented in this paper. Figure 4 serves as a typical example. Other test points depict similar spectra.

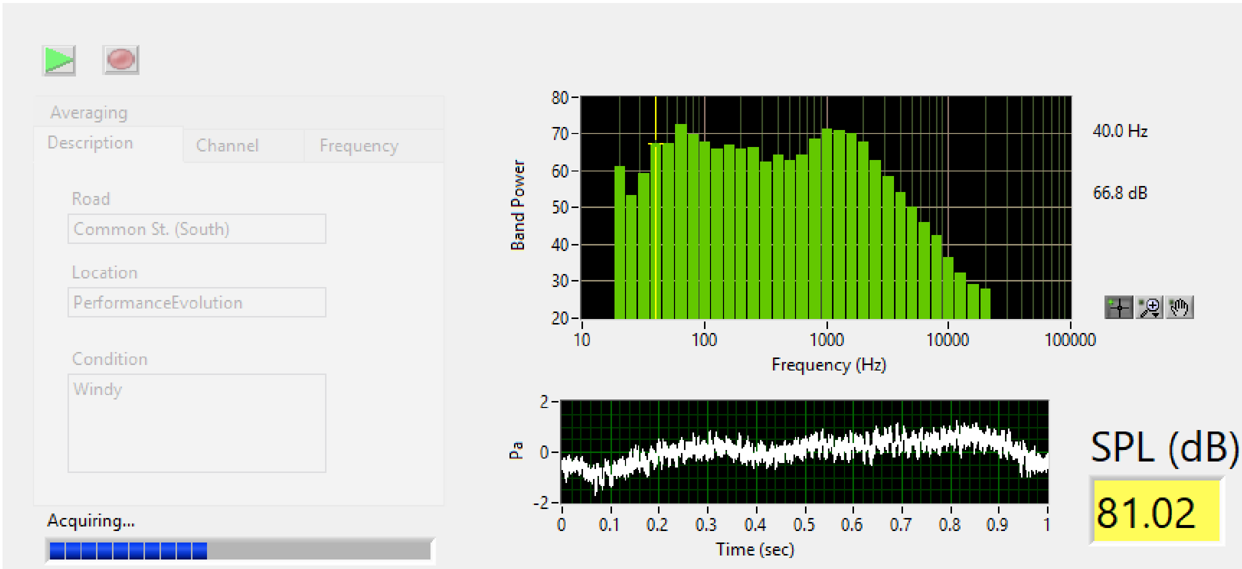


Figure 3. Test software interface.

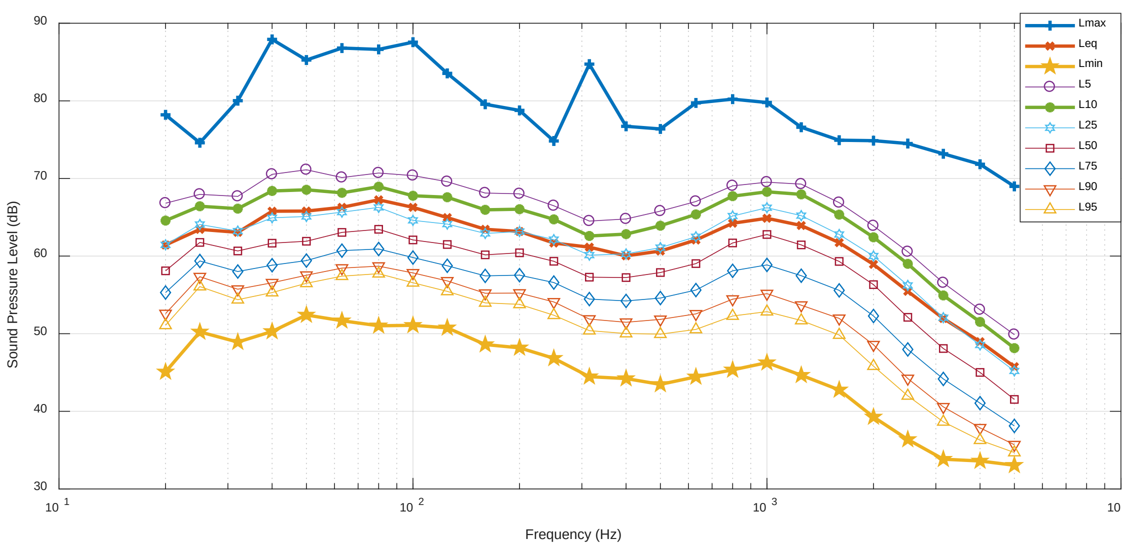


Figure 4. Percentile level spectra of Location 2.

3. RESULTS AND DISCUSSIONS

L_{10} is the noise level exceeded 10% of the time of the measurement duration. L_{10} represents intrusive sounds with short durations but high levels. L_{10} is often used to give an indication of the upper limit of fluctuating noise, such as that from road traffic and transient sounds in the environment. As shown in Fig. 4, L_{max} exceeds L_{10} spectrum by at least 10 dB in almost all frequency bands. These high noise levels are considered anomalies, such as honks, rather than normal traffic noise.

3.1 Comparison of Overall Levels

For all ten locations, the overall L_{10} levels are obtained by adding all frequency band levels. Both the unweighted and A-weighted results are summarized in Table 2. Each column is a pair of test locations. The average of each row is calculated. Note the overall levels are in the dB scale, so they are converted to the linear scale, averaged, and then converted back to the dB scale. Similarly, the calculations in *t*-test in this section were also conducted in the linear scale.

Table 2. Overall L_{10} of all test locations and averages.

Intersec-tions	Location	1	3	5	7	9	**average**
	dB	84.3	86.9	85.7	87.0	86.6	**86.2**
	dBA	73.8	76.2	76.9	79.0	76.4	**76.8**
Middle-points	Location	2	4	6	8	10	**average**
	dB	79.9	82.3	82.6	82.3	82.2	**82.0**
	dBA	75.1	78.3	78.1	78.7	79.4	**78.1**

Comparison of A-weighted L_{10} levels shows that intersection noise levels are lower than their middle-point counterparts, expect for pair #4 (Locations #7 and #8). The averaged intersection level 76.8 dBA is less than the averaged middle-point level 78.1 dBA. These results agree with previous research conclusions – tire/road noise in the middle frequency range dominates in A-weighted traffic noise levels. The spectral comparison in the next section (see Fig. 6(b)) further explains this observation.

However, if un-weighted levels are compared, it can be seen that in every pair, the intersection's overall L_{10} level is higher than that of the middle-point. The averaged intersection level 86.2 dB is greater than the averaged middle-point level 82.0 dB.

In order to study whether the differences are statistically significant, two paired *t*-tests were conducted in MATLAB.

1) Hypotheses

   H_0: Intersection's noise levels are not significantly different from those of middle-points;

   H_1: Intersection's noise levels are significantly different from those of middle-points.

2) Choose significance level $\alpha = 0.05$.

3) For A-weighted L_{10} levels, $p = 0.9484$. For un-weighted levels, however, $p = 7.62 \times 10^{-4}$.

4) For A-weighted L_{10} levels, the *p*-value is very close to 1. So A-weighted intersection L_{10} levels are not significantly different from those of middle-points with 95% confidence.

5) On the other hand, for un-weighted L_{10} levels, the *p*-value is much smaller than the significance level. It implies the un-weighted intersection L_{10} levels are significantly different from those of middle-points with 95% confidence.

3.2 Comparison of Noise Spectra

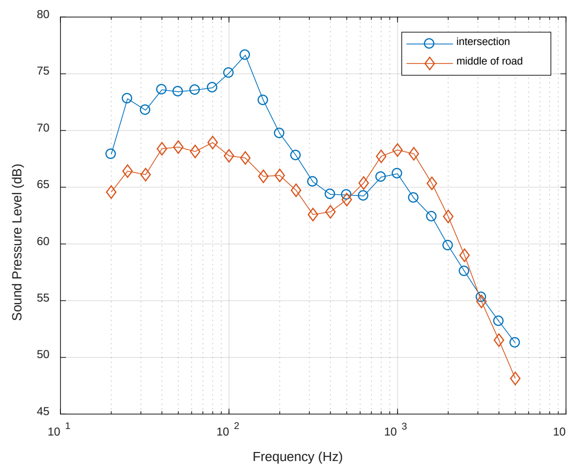
3.2.1 Comparison of individual pairs. In order to further investigate the difference between intersections and middle-points, all five pairs of unweighted L_{10} spectra are compared in Fig. 5.

It can be seen that all five pairs exhibit similar relationship.

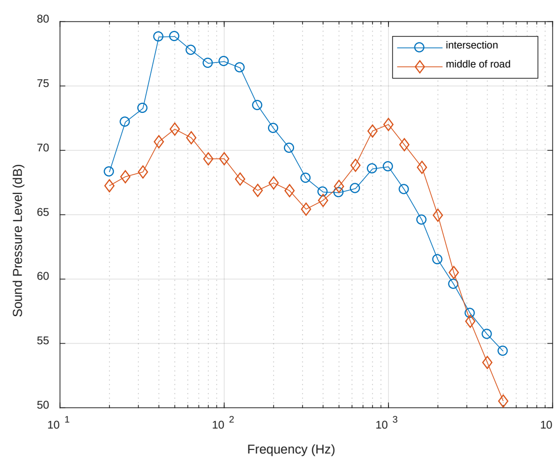
(1) In low frequency bands (up to the 400 Hz band) intersection's noise levels are higher than those of middle-point. Highest peaks occur around 100 Hz which are due to the engine noise, which consist of stronger low-frequency contents than middle to high frequency, when vehicles are accelerating passing the intersection. The greatest difference is seven to eight decibels.

(2) The two spectra cross around 500 Hz and 2500 Hz. All the road middle-points experience higher noise levels in middle frequency range between the 500 Hz and 2000 Hz bands. The highest peaks occur around 1000 Hz, which agrees with the tire/road noise spectral contents in previous research [1,2,4,6], as explained in Section 1 Introduction.

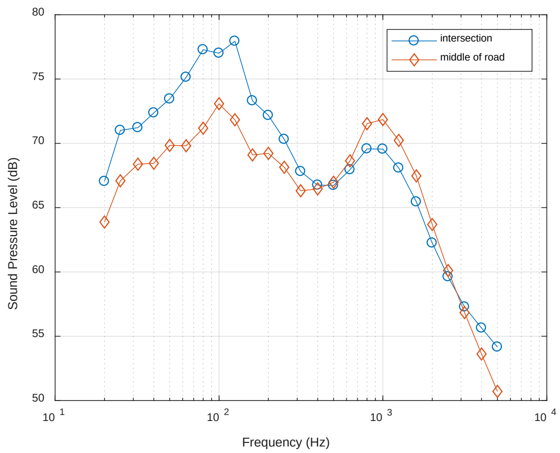
(3) At high frequencies (higher than 2500 Hz), the noise levels at both locations are relatively low compared with other frequencies.



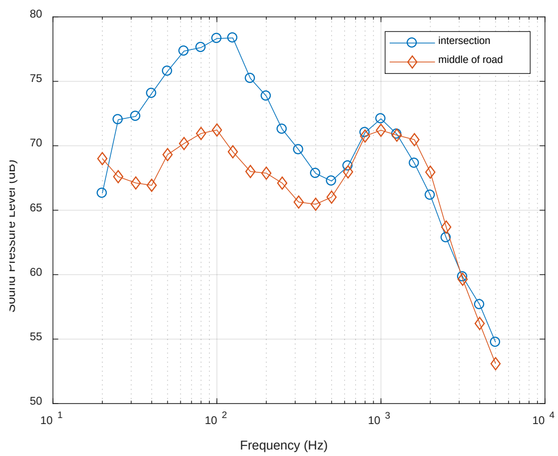
(a) Locations #1 and #2



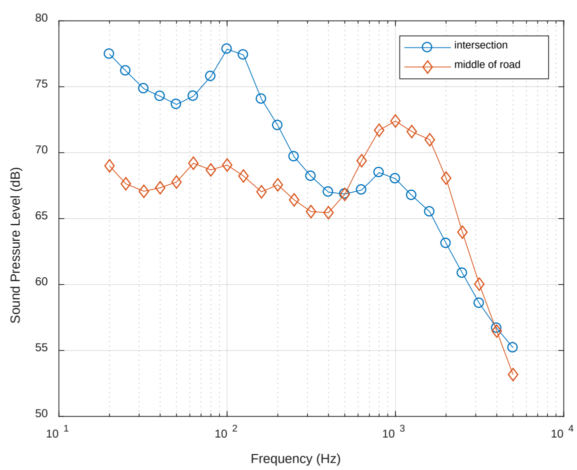
(b) Locations #3 and #4



(c) Locations #5 and #6



(d) Locations #7 and #8



(e) Locations #9 and #10

Figure 5. Comparison of all five pairs' L_{10} spectra.

3.2.2 Comparison of averages. Next, the averaged L_{10} spectra were calculated for each group of five test locations. The two plots in Fig. 6 compare the un-weighted and A-weighted results. The blue curves with circular markers represent averaged intersection spectra, while the orange curves with diamond markers are for middle-points. Along with these averages, 95% confidence intervals are also plotted to compare overlaps between the two distributions. Note the calculations were done in the linear scale and converted back to the dB scale. This is why the upper and lower 95% confidence curves are not symmetric about the average curve.

3.2.3 Analyses of variance. Finally, two-way ANOVA with replication of five were conducted, since there are five locations in each treatment. Factor *A* is location with two levels: intersection and middle-point as two columns. Factor *B* is frequency with 25 levels: 1/3 octave bands from 20 Hz to 5000 Hz. The null hypotheses are formulated as follows.

1st H_0: There is no significant interaction between the Location factor and the Frequency factor;

2nd H_0: Location (intersection vs. middle-point) has no significant effect on the noise level;

3rd H_0: Frequency has no significant effect on the noise level (spectrum is fairly flat).

For all the ANOVA tests, the significance level was set to be α = 5%. In each statistical test, if the *p*-value is less than α, then the null hypothesis is rejected. It is worth mentioning that first hypothesis listed above is the most important in two-way ANOVA. If the first hypothesis is rejected, it means a significant interaction exists between the Location (column) and Frequency (row) factors. Therefore, we cannot further assess the Location or Frequency effect. An interaction occurs when the effect of one factor changes for different levels of the other factor. As it can be seen in Figs. 5 and 6, the two average curves do cross at more than one frequencies in the full frequency range. Therefore, we anticipate small *p*-values for the interaction tests of full spectrum.

The first column of Table 3 lists the ANOVA results for un-weighted spectra in full frequency range using MATLAB. As highlighted, the interaction *p*-value is 5.365×10^{-24} which is much less than α. Therefore, the first null hypothesis is rejected. Because the interaction effect between Location and Frequency is statistically significant, we cannot interpret the main effects.

Table 3. Summary of *p*-values for unweighted spectra.

	Full spectrum	**Low freq.**	**Middle freq.**	**High freq.**
Interaction *p*	5.375×10^{-24}	0.174	0.3437	0.2977
Column *p*	4.633×10^{-22}	0	0.0001	0.6143
Row *p*	5.730×10^{-35}	0.028	0	0

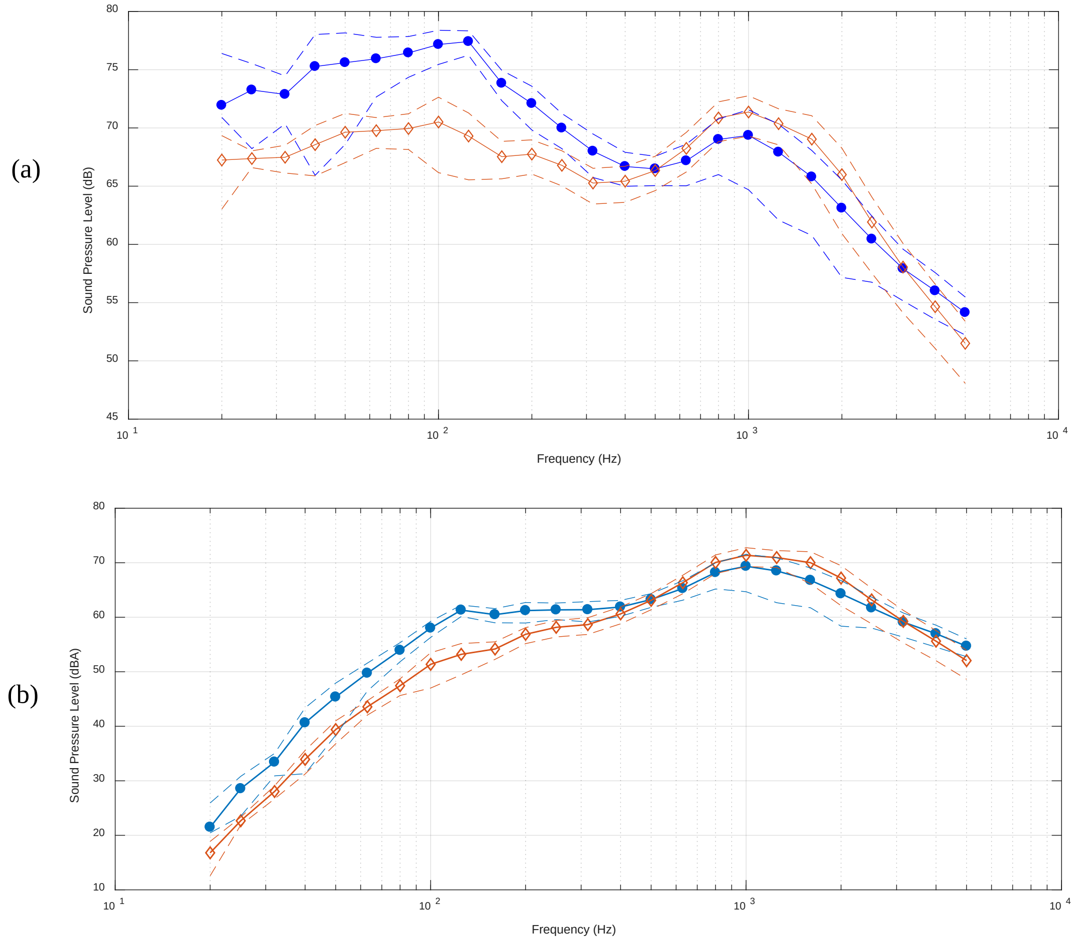


Figure 6. Comparison of averaged spectra with 95% confidence levels: (a) unweighted spectra, (b) A-weighted spectra.

Next, the entire frequency range is separated into three sub-ranges instead, to further study the difference between intersections and middle-points: low frequency (20 ~ 400 Hz, 14 frequency bands), middle frequency (500 ~ 2000 Hz, seven frequency bands) and high frequency (2500 ~ 5000 Hz, four frequency bands). The *p*-values are summarized in Table 3 and Table 4. Cells in yellow indicate significant interactions between the Location factor and Frequency factor. Further assessment of Location effect is only conducted if there is no significant interaction. In both tables, pink cells indicate the corresponding null hypotheses are rejected; green cells mean the corresponding effect is not statistically significant on the traffic noise level.

It can be seen in Table 3, for unweighted spectra, the column *p*-values are much less than the significance level α = 5% in low and middle frequency ranges. It implies that the location does play a significant role in the traffic noise. In another word, an intersection and middle-point counterparts experience significantly different noise levels in low and middle frequency ranges.

For A-weighted ANOVA results, the interaction *p*-value is very small in low-frequency range. As explained above, after taking the A-weighting compensations, the middle frequency noise dominates due to tire/road noise. The noise levels in low frequency bands are barely more than 60 dBA. In the middle frequency range, however, the column *p*-value is 0 which indicates that the intersections and middle-points experience significantly different noise levels.

For both the un-weighted and A-weighted ANOVA results, the column *p*-value in high frequency range are greater than α = 5%. High frequency noise levels are all relatively low at all locations. In addition, all the row *p*-values are very small which means the spectra are not flat. This is true by nature since every frequency band is independent and traffic noise is indeed frequency-dependent.

Table 4. Summary of *p*-values for A-weighted spectra.

	Full spectrum	Low freq.	Middle freq.	High freq.
Interaction *p*	0	5.75×10^{-14}	0.2673	0.3107
Column *p*	7×10^{-3}	5.06×10^{-21}	0	0.5757
Row *p*	0	4.87×10^{-45}	0	0

4. CONCLUSIONS

Road traffic noise of ten locations were tested in April 2018. All the tests were in the afternoon rush hour between 4:30 and 5:00 PM. It can be concluded, based on statistical analyses, that intersections where vehicles accelerate experience significantly higher noise levels than middle-points of roads in low frequency bands from 20 Hz to 400 Hz. However, middle sections of a road where traffic speeds are steady, noise levels are higher than their intersection counterparts in middle frequency range from 500 Hz to 2000 Hz which is mainly contributed by the tire/road noise. For high frequency bands above 2000 Hz, there is no statistically significant difference between intersections and middle sections.

These conclusions provide guideline for building façade design. Buildings close to intersections are exposed to much stronger low-frequency traffic noise than building located further away from intersections. The difference could be as high as seven to eight decibels. Windows and curtain walls have much lower sound transmission loss at low frequencies compared with middle to high frequencies. Therefore, buildings facing road intersections require special concern in the façade design to increase the sound transmission loss at low frequencies to provide adequate exterior-to-interior sound insulation. These special designs might be expensive since sound transmission loss at low frequencies is determined by mass law. Mass law indicates that the only method to increase the sound transmission loss at a certain frequency is to increase the thickness of the partition.

This is a preliminary research. More locations will be tested with longer monitoring time in the future. Although 4:30 PM to 5:00 PM represents relatively active traffic activities, more information is needed for longer period of time when traffic conditions are active.

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