Exploring Spatial and Temporal Heterogeneity of Environmental Noise in Toronto

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Introduction

Goal Analyzing the spatial and temporal variability of environmental noise in Toronto.

Rationale Recent research associates exposure to high levels of traffic-related noise with increased risk of hypertension and ischemic heart disease. Understanding the noise exposure of Torontonians is of interest.

Data

Public Health Ontario collected noise level data in Toronto in two cycles. Here, we focus on the cycle 1 data. For the following data, noise measurements were taken between 29 and 60 minutes for each site.

Lattice
70 equally spaced sites were sampled in order to cover entire Toronto. The blue point had wrong coordinates recorded.

Random
130 sites at locations that were selected at random. The blue point is omitted in our analysis due to missing measurements.

Additional
41 sites at locations within 200 meters from either the lattice or the random sites were selected to capture spatial correlation within short distances.

For these sites, the following data were recorded:

Equivalent steady (root-mean-squared) sound pressure level in decibels (dB) measured over a period of 29-60min and then averaged.

Longitude, Latitude, Date, Start and End Time of sampling.

Total number of vehicles passing.

Distance to nearest express way.

Population density within 100 meters.

Area of each: commercial land use, industrial land use, open space, recreational land use within 100 meters.

In an additional study, measurements were recorded for a full week to explore the temporal variability. No additional variates were recorded.

Weeklong
10 sites were conveniently selected for continuous measurement over a full week.

Acoustics

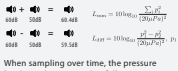
It is very important to have a good understanding of acoustics in order to appropriately analyze the data.

Sound waves are usually measured as root-mean-squared pressure in Pascals (Pa).

The pressure range for audible sound is from 20μPa to 100Pa. It is common to convert sound pressure p into sound pressure level in decibels (denoted by L) as follows:

$$L = 10\log_{10}\frac{p^2}{(20\mu Pa)^2}$$

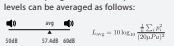
Addition and subtraction of sound sources have to be made in the squared pressure space.



$$L_{sum} = 10\log_{10}\frac{\sum_i p_i^2}{(20\mu Pa)^2}$$

$$L_{diff} = 10\log_{10}\frac{p_1^2 - p_2^2}{(20\mu Pa)^2},\ p_1 > p_2$$

When sampling over time, the pressure levels can be averaged as follows:

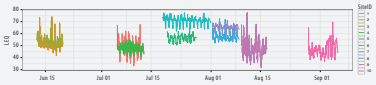


$$L_{avg} = 10\log_{10}\frac{\frac{1}{n}\sum_i p_i^2}{(20\mu Pa)^2}$$

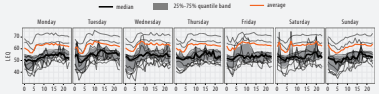
Loudness perception depends on many factors such as sound pressure, frequency, bandwidth, and duration. As a rule of thumb, an increase in sound pressure level from L1 to L2 is perceived $2^{\frac{L2-L1}{10dB}}$ times louder. For example, a 10dB increase is perceived twice as loud.

Temporal Variation

The weeklong data vary between a fairly quiet 30dB noise to a heavy traffic equivalent noise level of 80dB.



Special care has to be taken when modeling or analyzing noise data so that the principles of sound physics are not violated. In the following figure, we plot the sound pressure levels LEQ and three summary statistics by week day and day time.



Arithmetically averaging LEQ is not sensible and has no physical meaning. Quantiles are more appropriate to show spread and location.

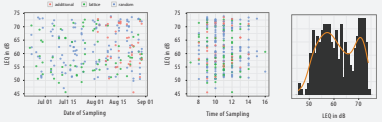
The curve of the hourly average was constructed by using the formula for averaging sound pressure levels over time. It is therefore dominated by the high noise sites. This hourly average needs a special interpretation. A probabilistic argument can be made as follows: if an individual changes location hourly and at random between sites, then the average curve represents the expected noise exposure of that individual.

The range of the hourly noise average is around 10dB during a day; the perceived loudness is twice as high at morning rush hours compared to 3-4am. However, between morning rush hours and 8pm, the average noise level changes only slightly, varying between 2dB ("barely perceptible") and 5dB ("noticeable").

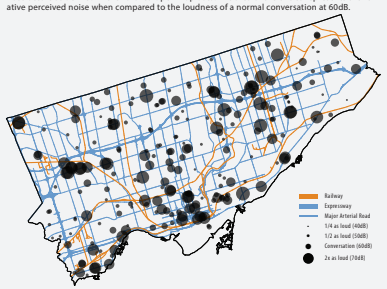
On Sundays, the noise level increases less rapidly in the morning compared to the other days.

Spatial Variation

The cycle 1 data (Lattice/Random/Additional) is used to analyze spatial variation. Note that most measurements were taken between 8am and 4pm. Based on our temporal analysis, the median sound level does not change substantially during this time period.



The following map shows the extent of noise at different sites and the major transportation infrastructure as defined in the Toronto Open Map data. The area of the circles represents the relative perceived noise when compared to the loudness of a normal conversation at 60dB.



Compared to a normal conversation, there is a fairly large variation of noise in Toronto. Spatially, there are several clusters of high noise sites, one of them being downtown Toronto. However, the map also suggests that high noise sites are located close to major traffic infrastructure.

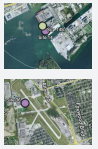
View of Site Locations using Google Earth

We have imported the cycle 1 data into Google Earth. Often, the detailed images provided by Google Earth can help explain the level of noise at certain locations. Below are satellite images of several site locations that we found interesting or relevant.

Loud Sites

Quiet Sites

Unusual Sites



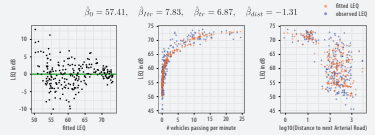
Contribution of Site Characteristic to Noise Level

The model that we found to predict LEQ best is the following weighted regression model:

$$\begin{aligned} LEQ \;=\; & \beta_0 + \beta_{Ltr}\,\mathrm{I}(\text{traffic}) \\ & + \beta_{tr}\,\mathrm{I}(\text{traffic}) \times \log_{10}(\#\text{ vehicles passing per minute}) \\ & + \beta_{dist}\,\log_{10}(\text{distance to next Major Arterial Road}) \end{aligned}$$

where the sites within 33m distance from a major arterial road receive more weights to account for heteroscedasticity, as these sites have generally high LEQ. The indicator function $\mathrm{I}(\text{traffic})$ returns 1 if there was at least one vehicle passing and 0 otherwise. We calculated the distance to the closest major arterial road using the Toronto Open Maps. This model explains 87% of the total variation in LEQ after six outliers were removed.

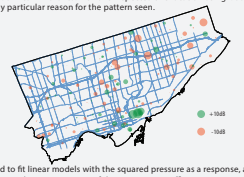
$$\hat{\beta}_0 = 57.41, \quad \hat{\beta}_{Ltr} = 7.83, \quad \hat{\beta}_{tr} = 6.87, \quad \hat{\beta}_{dist} = -1.31$$



The interpretation of the model parameters should only be made by LEQ differences. For example, a site with 3 passing vehicles per min is perceived twice as loud compared to a site with no cars passing by, when the sites are located at the same distance to the nearest major arterial road. As expected, heavier traffic and shorter distance to arterial roads are associated with higher noise.

None of the variables that captured a certain characteristic within 100m from the site (e.g., industry, commercial, etc.) was useful in explaining the variation in LEQ. According to the sound physics, in free space, the squared sound pressure level from a source decreases proportionally to the inverse squared distance. Hence, site characteristics might be better measured within 20m from the site, rather than within 100m, as done in this study.

The model residuals (in dB) can be seen below on the Toronto map. There is one obvious cluster of residuals near downtown Toronto. We have inspected this location using Google Earth, but could not find any particular reason for the pattern seen.



We have also tried to fit linear models with the squared pressure as a response, as this would have resulted in a simpler interpretation of the regression coefficients. However, none of the investigated models fitted the data well.

Conclusions

Working with sound data is challenging. A solid understanding of acoustics is important in order to obtain useful and correct conclusions.

None of our findings is surprising or counter-intuitive. Noise levels tend to be low during the night, then they increase substantially around 8am and have little variation until 8pm. On Sundays, the noise levels increase at a lower rate, but eventually reach similar levels during the day as in the rest of the week. Heavier traffic is associated with higher levels of noise; also, sites located closer to a major arterial road experience higher levels of noise.

A satellite view using Google Earth can help greatly in understanding the patterns in the data.

Acknowledgments

Noise Data is provided by Public Health Ontario

Contains public sector Datasets made available under the City of Toronto's Open Data Licence v2.0.

Satellite Images by Google Earth

Some of the vector drawings are from http://openclipart.org/

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