ENVIRONMENTAL NOISE STUDY IN THE CITY OF TORONTO

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Abbreviations

AADT	Annual Average Daily Traffic
ANSI	American National Standards Institute
B	Unstandardized regression coefficient
Beta	Standardized regression coefficient
C.I.	Confidence interval
dBA	A-weighted decibels
dBC	C-weighted decibels
df	Degrees of Freedom
FHWA	Federal Highway Administration, US Department of Transportation
GIS	Geographic Information System
Hz	Hertz
kHz	Kilohertz
LAeq, *t*	Equivalent sound pressure level over a time interval *t*
ISO	International Organization for Standardization
LAM	Location-Allocation Model
LOOCV	Leave-One-Out Cross-Validation
LUR	Land Use Regression
MCA	Multicriteria Analysis
MEMS	Microelectrical-Mechanical System
m/s	Meters Per Second
NDVI	Normalized Difference Vegetation Index
OLS	Ordinary Least Squares
PAC	Project Advisory Committee
r	Pearson correlation coefficient
R^2	Coefficient of Determination
RMSE	Root-Mean-Square Error
S.E.	Standard Error
SIDI	Simpson’s Diversity Index
Sig.	Significance level
t	T-test statistic
TMN	Traffic Noise Model

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1. Executive Summary

This report summarizes the methods and findings of an environmental noise study in Toronto completed between August, 2016 and March, 2017. The study involved planning and implementation of a noise monitoring campaign under guidance from Toronto Public Health and the Noise Monitoring Project Advisory Committee. In total, 227 noise measurements of 220 different sites, each lasting a minimum of 1-week, were taken throughout the City of Toronto. The chosen sites captured areas where Toronto's population is concentrated as well as the diversity of land uses found in the city. In addition, 'Sites of interest' were selected due to particular concerns surrounding noise emissions or exposures.

In addition to conducting a comprehensive monitoring campaign, the study utilized modelling techniques to better understand the distribution of noise levels and population exposures in Toronto. This was based on the complementary use of a propagation model to estimate noise emissions from road traffic throughout the city and a receptor-based model to understand the influence of environmental characteristics on observed noise levels. The two approaches were combined to create maps that predict different noise levels for the entire city.

The 24-hour equivalent sound pressure level observed from measurement of 220 sites throughout Toronto was 62.9 dBA, ranging from 50.4 to 78.3 dBA. Daytime levels ranged from 51.6 to 79.5 dBA with a mean of 64,1 dBA, while nighttime levels ranged from 42.6 to 74.4 dBA with a mean of 57.5 dBA. The levels were higher Monday to Friday compared to weekends, with a weekday mean of 64.5 dBA and a weeknight mean of 57.6 dBA. The analysis showed that traffic noise explained 59% of the variation for observed 24-hour levels. Monitoring sites that were chosen based on public concern or assumed high levels of noise, such as construction sites or areas with amplified sound, were characterized by high noise levels compared to overall noise levels observed. This was also the case for sensitive areas including schools, long-term care facilities and hospitals.

The modelling exercise produced noise maps that performed well at predicting noise levels. The results are comparable to recent noise studies in Canada (Montreal and Vancouver) in terms of the percentage variance explained (R^2= 0.64-0.71). To analyze associations between noise levels and population and socioeconomic data, residential noise levels were estimated for the most exposed façade for all residences in Toronto. Household income data at the level of dissemination areas from the 2011 Canadian census were used to assess potential inequalities in exposure. The results indicate that a large number of residents in Toronto are exposed to noise levels higher than guideline levels set by the World Health Organization and the Ontario Ministry of Environment and Climate Change. Over 60% of residents are exposed to road traffic noise levels above 55 dBA during daytime hours, and over 92% of residents are exposed to total noise levels exceeding 45 dBA during the nighttime. Furthermore, the results show an inverse relationship between residential noise levels and household income at the dissemination area level. Specifically, dissemination areas in the lowest income quintile are nearly 11 times more likely than the highest income quintile dissemination areas to have 50% of their residents exposed to 55 DBA or higher nighttime noise levels.

Although all transportation related noise emissions influenced noise levels throughout the city, only the contribution of road traffic could be estimated specifically. This limits the ability to infer the specific compositions of noise sources influencing sound levels to information about traffic noise exposures and total noise exposures throughout Toronto. Localized characterization of soundscapes and the composition of noise sources within them is not possible until more detailed studies can be conducted.

2. Objectives and Goals

The objectives of this study are to:

1. ***Describe and quantify the range of environmental noise levels and sources encountered while outdoors in Toronto; and***
2. ***Identify areas and circumstances in Toronto with elevated environmental noise levels that could be injurious to health***

3. Introduction: Noise Assessment in Urban Environments

The assessment of environmental noise in urban environments consists of the following key aspects: noise monitoring; spatial analysis of noise distribution; emission- or receptor-based predictive noise modelling, and; population exposure and health risk assessment. At minimum, a measurement campaign of sufficient duration to capture noise emissions from sources of interest is recommended (ISO 1996-2:2007(E)). Additionally, appropriate site selection for sufficient coverage of different land uses is necessary. Depending on the goals of the assessment, this will ensure that noise levels that may be associated with urban land uses (e.g., residential, industrial, commercial etc.), known major sources (i.e., traffic, railways and airports) and specific sources of interest (e.g., outdoor entertainment venues, industrial sites, etc.) are captured.

In the past, the physical properties of noise necessitated fine resolution noise assessments to be based on extensive monitoring campaigns to capture spatial variability, even over relatively small areas. However, advances in computing technology and geo-statistical methods now permit fine scale prediction over large urban areas. Such methods are usually applied in conjunction with noise measurements for validation or extrapolation. The most commonly applied method involves the estimation of noise emissions from a particular source of interest and the subsequent prediction of its propagation through the environment. Different standards exist for emission-based modelling of air, road, and railway traffic, as well as a number of other stationary sources such as industrial facilities. Different jurisdictions often develop their own noise modelling standards to support, for example, land use planning and regulation. Examples of the application of such models in Ontario include required noise assessments for certain projects under the Environmental Assessment Act. On a broader scale, the European Noise Directive requires that cities with populations above 100,000 implement a noise prediction (or measurement) methodology to produce strategic noise maps every 5 years (Annex II, Directive 2002/49/EC).

An alternative modelling approach that has been applied more recently is land use regression (LUR) modelling. This mapping technique has been employed to understand the spatial processes underlying a number of environmental exposures, including magnetic fields, drinking water disinfection by-products, air pollutants and more recently, noise. LUR modelling can provide insights on how the environment (i.e., urban form and morphology) and associated mechanisms are responsible for the spatial variation of environmental exposures. This approach utilizes a geographic information system (GIS) to examine associations between spatial indicators of urban form or morphology and observed noise levels. A predictive, receptor-based model is consequently derived, which can be used to predict noise levels where monitoring was not conducted.

While LUR modelling presents a potentially powerful tool to predict the spatial distribution of noise as influenced by urban environment characteristics, the state of practice in environmental noise assessment still utilizes a modelling approach based on emission and propagation prediction methods. For this reason, this study utilized a noise assessment methodology for the City of Toronto based on a combination of environmental monitoring, emission and propagation modelling, as well as LUR modelling. This environmental noise study meets the objectives as outlined above, in addition to incorporating concerns and issues prioritized by various stakeholders.

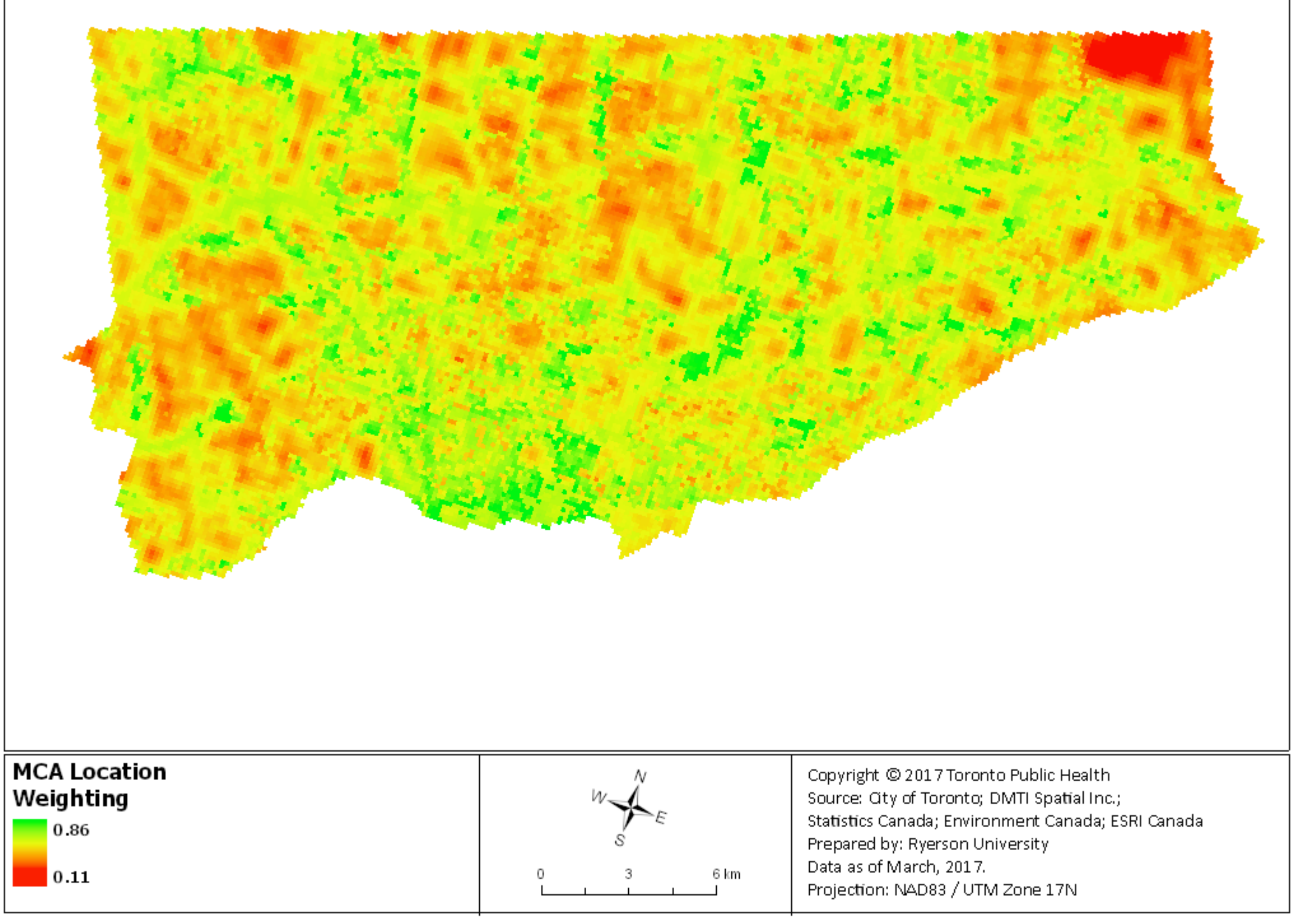
4. Methods and Materials

a. Site selection

The methodology for identifying potential and final monitoring sites was based on several objectives related to goals of the overall study as well as facilitating the noise modelling phase of the study. This entailed ensuring monitoring sites captured as much of the city as possible, noise levels where residents are concentrated, and a variety of land uses. Several GIS approaches were combined to satisfy these objectives: Multi-criteria analysis (MCA), location-allocation modelling (LAM), and constrained random allocation. Complementing this were categorical candidate sites of particular and general interest.

The MCA was utilized to identify candidate sites for monitoring based on known noise predictors and the location of potentially sensitive areas: Railways, major roads and expressways, population density and land use entropy (Simpson's Diversity Index; SIDI). These variables were represented as continuous surfaces, which were consequently

Figure 1: Final multi-criteria analysis (MCA) surface for site selection



rescaled to allow application of the following formula to identify candidate locations:

*MCA surface = (0.4*SIDI) + (0.3*[Residential Density]) + (0.2*[Distance to Major Roads and Expressways]) + (0.1*[Distance to Railways])*

Filtering of the resulting MCA surface with a cut value of 0.5 identified 8867 candidate locations for the LAM procedure. The final MCA surface was created with the raster calculator in ArcMAP 10.4 (ESRI, Redlands, USA).

Location-allocation modelling is a frequently used technique for solving location problems and involves the locating of facilities by selecting a set of sites from a larger set of candidate sites, while optimizing in terms of the allocation of potential demand to the sites in question (Fotheringham, Densham & Curtis, 1995). The approach has been extended to the sampling of environmental exposures where the location of facilities is substituted with the need to site, in this context, noise monitoring equipment. A GIS and the Network Analysis Toolbox was employed to implement a location-allocation model to find 100 suitable sampling locations among candidate sites identified in the MCA. We employed a p-median (P-MP) algorithm, or the problem of locating P "sampling sites" relative to a population at risk (i.e., demand points), such that the sum of the shortest demand-weighted distance between population demand and monitoring locations is minimized. The demand points were created from the centroids of Toronto's neighbourhoods in the Open Data Catalogue and weighted by populations from the 2011 census data. Neighbourhood centroids (140) were used to ensure appropriate spatial coverage of the study area.

Following the identification of these 100 monitoring sites, an additional 75 sites were chosen randomly within constrained land uses and at a minimum distance of 500m from other monitoring sites. This included 50 sites within residential areas and 25 sites within government/institutional, commercial and resource/industrial land uses. This was done to capture variability across land uses and population densities as well as to validate results of noise models.

A number of specific sites were targeted to support the City's goal of understanding how noise may affect residents and visitors in public spaces. The Delphi technique was employed to identify sites from the Toronto Open Data Catalogue Places of Interest and from PAC suggestions. Places with high volumes of visitors and representing different types of activities (e.g., entertainment, cultural, recreation etc.) were identified along with sites based on community concerns. the final number of 'sites of interest' was 59 (Appendix C). This included measurement of dBC (C-weighted decibels) at 7 locations, which is more sensitive to lower frequency sounds such as often observed near amplified sounds.

b. Environmental monitoring

A one week monitoring period per measurement was chosen to obtain an adequate representation of noise levels during different times of the weekday as well as weekends. Noise was measured using a Noise Sentry RT sound level meter data logger designed by Convergence Instruments. The instrument is a high-performance, Type 2 integrating sound level meter that includes a precision MEMS microphone, an accurate date/time clock and non-volatile 52,000-point recording memory. The device complies with IEC651/804 Type 2 and ANSI S1.4 Type 2 tolerances. The sensor has a Type 2 bandwidth sensitivity between 25Hz and 8kHz (normal human hearing range) and is stable up to 20KHz. It is capable of applying A and C weighting to sound pressure levels, which adjusts the sound pressure levels to account for varying sensitivity at different frequency ranges of human hearing. The A-weighted measurement adjusts the sound pressure level across the frequency spectrum to better represent human perceptions of loudness at different frequencies. For example, at the same sound pressure level, lower frequency sounds are perceived as less loud than high frequency sounds. Conversely, at very high frequencies, perceived loudness is higher compared to mid-range frequencies at the sample sound pressure level. The C-weighted measurement is essentially constant across the spectrum. This measurement is not commonly used in population noise exposure assessment, but when compared to A-weighted measurements, it provides some indication of the extent to which low-frequency sounds (e.g., amplified sound) characterize the soundscape.

Sound level meters were placed 3.5-4 m above the ground and at least 1 m from the nearest vertical surface on utility infrastructure (hydro or light poles). The monitoring strategy was to the extent possible consistent with criteria of the Ontario Ministry of the Environment and Climate Change Environmental Noise Guideline (Government of Ontario, 2016).

The monitors were placed at the closest possible location determined during the site selection phase, and actual locations were geocoded with a Dual GPS Receiver (XGPS160). Monitoring technicians also took pictures of all directions surrounding the monitoring site and recorded information with potential relevance to noise measurements. In this way, a number of sites were additionally classified as belonging to sites of interest categories.

c. Noise modelling

Road, rail and air traffic are primary sources of environmental noise in urban environments because of their ubiquitous presence. Other sources are generally referred to as stationary and include human activities (e.g., operating machinery and equipment), air-conditioners, and non-linear vehicle noise such as from construction activities. However, lack of data on stationary sources limits the ability of noise models on large scales such as covering entire urban areas to capture such emissions feasibly and efficiently. There is also a considerable resource requirement for large-scale emission modelling of linear sources. The current study did not permit consideration of all linear sources. Therefore, road traffic was prioritized due to its demonstrated influence in previous urban noise assessments. A traffic noise model was prepared for the current study using specialized noise modelling software (SoundPLAN GmBH, Backnang, Germany). Traffic noise emissions were estimated with the US Federal Highway Administration Traffic Noise Model (TNM2.5). The TMN2.5 model is similar to traffic noise emission models utilized in different Canadian jurisdictions. Attenuation standards for road surface reflectance and ground absorption were implemented from TNM2.5, while sound pressure propagation was based on the International Organization for Standardization calculation method (ISO 9613-2). Different time slices of the 24-hour period were modelled for equivalent A-weighted sound pressure levels from traffic: LAeq, 24-hour average; LAeq, 16-hour daytime average (0700-2300 hours); LAeq, 12-hour daytime average (0700-1900); LAeq, 4-hour evening average (1900-2300 hours), and; LAeq, 8-hour nighttime average

(2300-0700 hours). Additionally, day-evening-night levels (Lden) were predicted include a 5 dB(A) and 10 dB(A) penalty for evening and night noise, respectively. Percentage of people highly annoyed with noise has been established and these descriptors are commonly used for assessing the impact of environmental noise in North America and Europe (Miedema and Oudshoorn, 2001).

Noise models are inherently demanding in terms of data input. Geospatial inputs for the propagation model were prepared with ArcGIS 10.4 (ESRI, Redlands, USA). A digital elevation model (DEM) from the Ontario Ministry of Natural Resources was utilized to evaluate topographic effects on road network elevation changes and associated impacts on noise emissions. Building massing data from the City of Toronto Open Data Catalogue was used to account for façade reflection of noise (City of Toronto, 2016). The City of Toronto centreline network and associated traffic volume data based on a suite of past traffic counts were obtained from the Transportation Services Division. These were annual average daily traffic (AADT) counts, which were further refined by hourly road traffic histograms that differentiated different vehicle classes (heavy, medium, light) and their proportional representation on different road types. It should be emphasized that this data was not available for the current study and therefore inferred from previous studies VanDelden et al.,2008). On expressways and major arteries, heavy and medium weight vehicles were assumed to represent 10% of traffic flows during daytime hours, which was adjusted for lower road levels and evening/night hours (Government of Ontario, 2015).

Development of the complementary LUR model in the current study was similar to approaches described by Jerrett et al. (2007) and Oiamo et al. (2015). However, a key difference in the implementation of the model for noise in Toronto was its prediction of unexplained variance in noise *after* predicted levels of traffic noise were determined. Under the assumption that predicted traffic noise levels would be lower than measured noise levels, the LUR method was used to predict the difference between these two noise levels. The results of the two methods were consequently combined to gain a more accurate prediction of noise levels across Toronto. Potential predictors (Appendix B) of this difference were individually screened using bivariate regression analysis to identify variables from each of the categories previously associated with noise: Transportation; land use; land cover and vegetation, and; demographic data. These variables were subsequently included in a stepwise multiple Ordinary Least Squares (OLS) regression procedure to develop the LUR model. The stepwise procedure sequentially identified predictor variables from each category with regression coefficients significantly different from zero (t-test, $p < 0.05$). The final Independent variables included in the final regression models were identified with a stepwise procedure that included all candidate predictors and tested for collinearity with variables from other categories (variance inflation factor < 2). Several iterations with different subsets of independent variables were analyzed using stepwise regression to optimize the coefficient of determination (R^2) in the OLS regression. Raster-based surface maps were generated to represent that final variables in the LUR models at a resolution of 10x10m throughout Toronto. The surfaces were then multiplied with their respective coefficients and added to generate continuous predictions of the difference between estimated traffic noise and measured noise levels. The final step to produce the continuous noise level surfaces was completed by adding together the traffic noise surface and modelled difference surface. All models were validated with regression analyses and comparison of the full sample root mean square error (RMSE) and the RMSE produced from a leave-one-out cross-validation (LOOCV) procedure.

d. Analysis

A number of traditional noise metrics were calculated for all sites and different categories from noise measurement data at each site for the full week, weekdays and weekends: Lden; LAeq,24h; LAeq, 16h; LAeq, 8h, and; Lmax (Appendix A). The following metrics were calculated to evaluate exceedance levels: L1, L5, L10, L50, L90 and L95 describe the sound pressure level exceeded the corresponding percentage of time (e.g., L1 is level exceeded 1% of time). Another complementary set of metrics describe the proportion of time during different measurement periods that a certain noise level was exceeded: 55 and 65 for LAeq,24h; 55, 65 and 70 for LAeq, 16h, and; 40, 50 and 55 for LAeq,8h. These correspond to levels identified by Toronto Public Health as important thresholds. Finally, sound pressure levels were averaged hourly for all measurement sites. All noise measurements were converted to sound power levels in the linear space for averaging temporally and spatially continuous measurement series.

An estimation of the number of people in Toronto exposed to exceeding levels of noise were based on the modelled noise surface maps and data from the 2016 Canadian census (Statistics Canada, 2017). Sound pressure levels predicted for 10x10m parcels were used to assess levels on the most exposed façade for all buildings in Toronto. Population counts at the dissemination block level were used to estimate the number of residents in each building based on building size, which facilitated a detailed understanding of residential noise exposures. This was used to estimate the proportion of residents exposed to nighttime levels above 55 dBA in each dissemination area. This threshold was chosen as it corresponds to the European Union interim night noise level target, which reflects the fact that nighttime noise pollution is the most hazardous type of noise because of direct and indirect health effects (Halperin, 2014). Finally, a logistic regression analysis was used to assess the relationship between household income and excessive residential nighttime noise exposures at the dissemination area level. Socioeconomic data was obtained from from the 2011 National Household Survey (Statistics Canada, 2013).

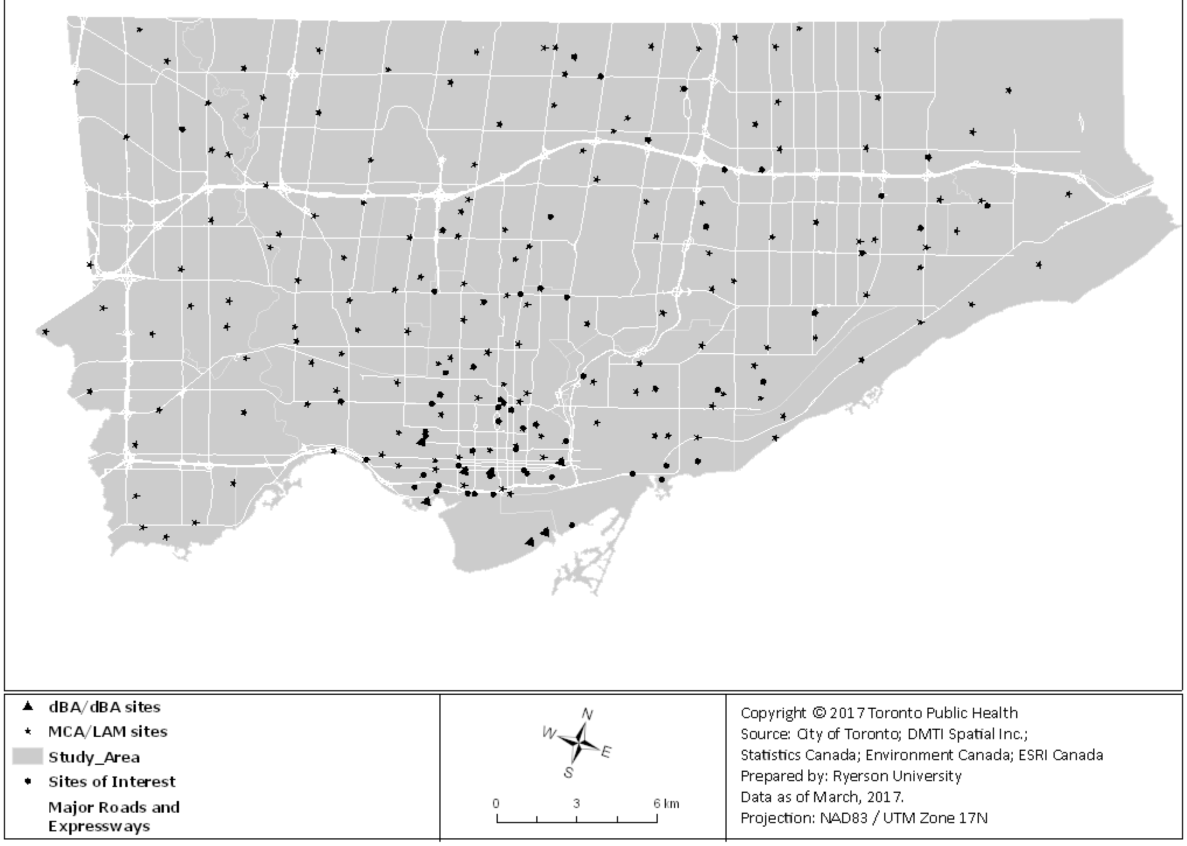
5. Results

a. Monitoring campaign

The monitoring was completed between August 17 and October 4, 2017. Weather conditions can have a significant impact on the reliability of noise measurements. This includes wind and rain in particular. Wind speeds above 5 m/s and 0.5 m/s during the day and night, respectively, can make measurements less reliable (ISO 1996-2:2007(E)). Weather conditions during the monitoring campaign in Toronto rarely exceeded these levels and rainfall was very infrequent apart from the last few days of the monitoring campaign. However, there did not appear to be a positive bias among sites measured during the last week of the monitoring campaign.

The final number of measurements was 227 in 220 sites (Figure 2). Multiple measurements were made for dBA and dBC in 7 locations, while two sites on Toronto Island were monitored for a period of two weeks. Due to resource and time constraints, the addition of numerous sites of interest resulted in the number of monitoring sites randomly allocated to different land uses being reduced from 75 to 51. Among 50 calibrated noise monitors deployed for the monitoring campaign, 1 was stolen and 1 was vandalized in sites that were subsequently resampled. The meters were set to sample on 250ms intervals and integrate on 1 second intervals.

Figure 2: Final noise monitoring locations in Toronto



b. Descriptive statistics for observed noise levels

Table 1 provides descriptive statistics for all dBA and dBC measurements separately. The LAeq, 24h for all dBA measurements was 62.9 dBA. There were significant differences between daytime and nighttime sound pressure levels for the entire week of measurement, as well as during weekdays and on weekends, but the but the difference was most pronounced for weekdays (6.9 dBA, t=31.04, p<0.001). The pattern was similar for dBC measurements, with the highest and a significant difference between daytime and nighttime levels during the week (3.1 dBC, t=5.32, p<0.005).

However, there was not a significant difference during weekends or the week as a whole. The dBC measurements were acquired in sites where public concerns about amplified sound levels are prominent. The implications are that overall sound pressure levels in these sites decreases during the night, but a corresponding decrease in dBC levels is not observed due to low frequency amplified sound. Table 2 provides further detail on sound pressure levels for various categories of interest: Schools, long-term care facilities and hospitals, community housing, sites sampled for assumed excessive levels of noise (i.e., amplified sound) construction, EMS station, BMO field, TTC yards and dBC. levels than the modelling sites. This difference was higher for nighttime noise and during the weekend. In general, all categories of special interest sites were louder than the overall equivalent sound pressures for different week and daytime periods.

Table 2 also provides averages for different usages (City of Toronto general zoning categories), as well as the type of road in proximity to monitoring site.

Table 1: Descriptive statistics for dBA and dBC sites for standard noise metrics												
	Full Week				**Weekday**				**Weekend**			
	Lden	**Leq24h**	**LeqD**	**LeqN**	**Lden**	**Leq24h**	**LeqD**	**LeqN**	**Lden**	**Leq24h**	**LeqD**	**LeqN**
dBA (n=220)												
Mean	66.4	62.9	64.1	57.5	66.7	63.2	64.5	57.6	65.3	61.2	62.4	56.8
Median	65.3	61.9	63.2	56.4	65.4	62.1	63.4	56.1	64.5	60.6	61.9	55.9
Std. Devi	6.9	6.4	6.3	7.8	6.9	6.3	6.2	7.9	7.3	7.0	7.0	7.9
Minimum	54.0	50.4	51.6	42.6	53.9	50.7	52.2	42.2	51.3	47.5	48.4	43.5
Maximum	82.3	78.3	79.5	74.4	82.9	78.9	80.1	74.8	80.8	76.5	77.8	74.1
dBC (n=7)												
Mean	76.8	71.4	72.0	69.7	76.5	71.5	72.2	69.1	76.6	71.3	71.5	69.1
Median	80.5	75.6	76.4	73.0	80.4	75.7	76.7	72.6	80.8	75.2	75.8	73.8
Std. Dev	11.8	11.1	10.7	12.5	11.1	11.4	11.4	11.1	13.2	11.1	10.2	15.1
Minimum	59.8	54.5	55.2	51.9	60.6	55.1	55.7	52.9	56.5	52.6	53.8	46.7
Maximum	89.1	82.4	82.0	83.1	87.3	83.3	84.3	79.0	89.9	81.7	79.6	84.3

Table 2: Arithmetic sound pressure level averages for sites of interest categories													
		Full Week				**Weekday**				**Weekend**			
	n	**Lden**	**Leq24h**	**LeqD**	**LeqN**	**Lden**	**Leq24h**	**LeqD**	**LeqN**	**Lden**	**Leq24h**	**LeqD**	**LeqN**
dBA	*220*	66.4	62.9	64.1	57.5	66.7	63.2	64.5	57.6	65.3	61.2	62.4	56.8
dBC	7	76.8	71.4	72.0	69.7	76.5	71.5	72.2	69.1	76.6	71.3	71.5	69.1
dBC Control (in dBA)	7	69.5	65.1	66.0	61.5	69.3	65.2	66.2	61.2	69.4	61.4	64.7	61.9
Zoning Categories													
Residential	*121*	63.4	60.1	61.4	54.0	63.7	60.6	61.9	54.1	61.9	58.1	59.3	53.2
Open space	*22*	68.0	64.1	65.3	59.3	68.3	64.5	65.7	59.6	66.8	62.6	63.7	58.3
Employment industrial	*15*	71.3	67.7	68.9	62.9	71.7	68.1	69.3	63.4	70.1	66.3	67.5	61.7
Commercial residential	*26*	71.9	67.6	68.7	64.0	72.0	67.9	69.0	63.9	71.6	66.8	67.6	63.9
Road Types													
Local	*98*	62.3	59.0	60.3	52.9	62.6	59.5	60.8	53.0	60.8	57.1	58.3	52.1
Collector	*36*	67.0	63.7	64.9	57.7	67.3	64.2	65.5	57.9	65.5	61.5	62.6	57.0
Major Arterial	*38*	74.7	70.4	71.5	66.8	74.9	70.7	71.7	66.9	74.2	69.6	70.5	66.4
Schools	*10*	68.2	64.4	65.6	59.4	68.6	64.8	66.0	59.7	65.8	61.8	62.9	57.6
Long-term/Hospitals	*9*	68.1	64.4	65.5	59.8	68.2	64.4	65.6	59.9	67.8	63.8	64.9	59.5
Community Housing	*3*	61.9	58.8	60.2	52.7	62.2	59.1	60.4	52.9	61.1	57.9	59.3	52.1
Amplified sound	*16*	70.9	66.7	67.8	62.6	70.8	66.8	67.9	62.5	70.5	66.1	67.0	62.4
Construction	*7*	71.6	67.7	68.8	63.5	71.7	68.3	69.5	63.0	71.2	65.8	66.2	64.0
EMS	*1*	74.4	71.0	72.3	65.9	74.6	71.3	72.6	66.0	73.9	70.1	71.3	65.4
CNE main gates	*1*	74.4	69.0	69.7	67.2	73.7	68.7	69.6	66.0	75.7	69.6	69.8	69.3
BMO Field	*1*	70.4	67.4	68.8	61.2	68.3	61.2	60.6	62.3	73.3	72.0	73.7	55.7
TTC Yards	*2*	76.1	71.8	73.0	68.0	76.2	72.0	73.2	68.1	75.8	71.4	72.5	67.6
Historic or Cultural	*10*	69.9	66.4	67.6	60.9	69.8	66.3	67.5	60.9	69.6	65.8	67.0	60.8
Toronto Island	*2*	64.8	60.7	61.9	56.0	65.2	61.2	62.4	56.3	63.1	58.7	59.8	54.9

Table 3: Percentile exceedance levels and proportional exceedance periods															
	L1	L5	L10	L50	L90	L95	24h	24h	Day	Day	Day	Night	Night	Night	Lmax1s
dBA sites (n=220)							55dB(A)	65dB(A)	55dB(A)	65dB(A)	70dB(A)	40dB(A)	50dB(A)	55dB(A)	
Mean	72.1	66.8	64.3	56.3	48.5	46.8	0.53	0.20	0.62	0.26	0.12	0.95	0.54	0.36	99.55
Median	71.5	66.3	63.7	55.3	47.4	45.7	0.52	0.07	0.68	0.10	0.02	1.00	0.51	0.21	100.29
Std. Dev	6.3	6.8	7.2	7.7	6.7	6.5	0.34	0.24	0.35	0.29	0.19	0.11	0.36	0.34	7.09
Minimum	60.1	51.7	49.0	43.1	36.9	35.7	0.03	0.00	0.04	0.00	0.00	0.36	0.02	0.01	85.51
Maximum	88.3	82.3	80.4	75.4	69.5	68.0	1.00	.99	1.00	1.00	0.99	1.00	1.00	1.00	112.81

Table 4: Percentile exceedance levels and proportional exceedance periods															
	L1	L5	L10	L50	L90	L95	24h	24h	Day	Day	Day	Night	Night	Night	Lmax1s
							55dB(A)	65dB(A)	55dB(A)	65dB(A)	70dB(A)	40dB(A)	50dB(A)	55dB(A)	
Zoning Categories															
Residential	69.4	63.9	61.2	52.9	45.5	44.0	0.38	0.11	0.47	0.15	0.06	0.92	0.38	0.21	97.06
Open space	73.1	68.6	66.2	57.8	50.0	48.6	0.61	0.27	0.69	0.34	0.14	0.94	0.59	0.47	99.98
Employment industrial	77.5	72.4	70.1	61.8	52.2	50.2	0.73	0.37	0.84	0.46	0.26	0.99	0.74	0.51	101.61
Commercial residential	80.0	74.1	72.0	65.3	57.2	55.0	0.93	0.53	0.98	0.60	0.21	1.00	0.97	0.85	109.89
Road Types															
Local	68.4	62.7	60.0	51.9	45.2	43.9	.34	.08	.42	.10	.04	.92	.37	.18	96.3
Collector	73.1	68.1	65.5	56.0	47.3	45.6	.53	.19	.64	.24	.11	.93	.47	.33	99.5
Major Arterial	83.2	78.7	76.7	69.2	60.1	57.6	.98	.73	1.00	.88	.59	1.00	.99	.94	105.2
Schools	73.0	67.8	65.5	57.0	47.0	45.2	0.55	0.19	0.69	0.25	0.09	0.96	0.52	0.28	99.8
Long-term care/Hospitals	72.6	67.3	65.3	59.4	52.2	50.9	0.67	0.24	0.76	0.29	0.14	1.00	0.68	0.48	101.1
Community Housing	69.3	63.3	60.2	51.3	46.8	46.0	0.33	0.05	0.43	0.07	0.02	0.99	0.45	0.13	95.4
Amplified sound	76.2	70.6	67.8	60.2	53.8	52.3	0.77	0.29	0.84	0.35	0.12	1.00	0.83	0.62	107.0
Construction	77.0	72.5	70.4	62.2	53.3	51.3	0.81	0.37	0.91	0.46	0.25	0.98	0.83	0.62	103.1
EMS	79.9	76.2	74.5	65.9	51.8	48.7	0.84	0.53	0.97	0.69	0.42	1.00	0.79	0.57	105.6
CNE main gates	77.7	71.7	69.6	64.1	57.4	55.9	0.98	0.41	1.00	0.52	0.11	1.00	1.00	0.94	109.8
BMO Field	80.2	69.5	64.0	56.7	54.1	53.4	0.81	0.09	0.95	0.10	0.06	1.00	1.00	0.53	105.8
TTC Yards	80.0	76.8	75.2	66.5	55.8	53.5	0.92	0.58	0.99	0.73	0.43	1.00	0.95	0.79	108.8
Historic or Cultural	74.5	69.7	67.5	60.4	52.5	50.7	0.77	0.31	0.85	0.40	0.13	0.97	0.76	0.61	104.0
Toronto Island	70.0	64.1	61.4	55.6	50.8	49.4	0.53	0.08	0.58	0.11	0.03	1.00	0.82	0.43	101.8

The lowest sound pressure levels were observed in residential areas and along local roads. Conversely, the highest observed levels were in commercial residential areas and along major arteries. Among categories of sites of interest, the highest measurements were observed near two Toronto Transit Commission facilities that accommodate streetcar or bus systems. The lowest measurements were observed in three community housing areas distributed throughout the city. However, it should be emphasized that there do not necessarily represent the overall average for all community housing areas in Toronto. Sound level meters placed in front of the main gates for the Canadian National

Exhibition and BMO Field also captured high noise levels. These were among a number of sites that were monitored during a specific range of dates to better understand the impact of special events on noise levels.

Monitoring locations in or near ‘quiet zones’ as defined in the Toronto Noise bylaw, near long-term care facilities, hospitals and community housing locations showed similar patterns to overall levels during different times of day and the week, with lower levels during the night and on weekends. This is demonstrated in Figure 3a, which shows hourly sound pressure levels for different groups of sites throughout the 24-hour period. For groups of special interest sites presented in Figure 3a, there is a commonly observed pattern of noise levels peaking mid-day to late afternoon. Notable observations include peaks for the Toronto Island sites during early afternoon and evening, likely corresponding to the Toronto air show and amplified sound events along the Toronto harbour. Figure 3b shows the 24-hour variation among sites and groups of sites with assumed high levels of noise. Notable observations include a sharp peak in noise during early evening near the BMO Field and the high noise levels produced near the EMS and TTC facilities. Figure 3c compares amplified sound sites to dBC and model site levels. This suggests presence of different sound sources throughout the day, but our methodology does not allow conclusions in this respect. The dBA levels for amplified sound sites are similar to overall levels, except during the evening hours when it is generally higher. than model sites throughout the 24—hour period, but in particular during evening and after midnight.

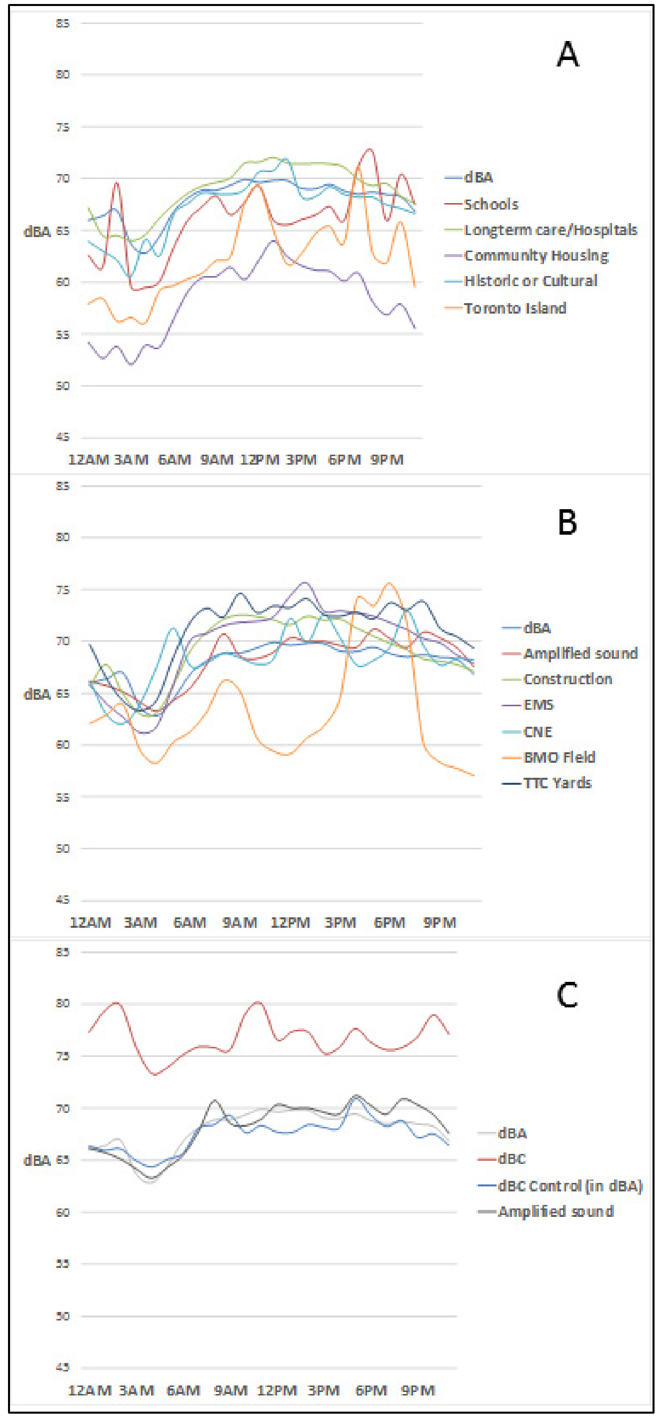


Figure 1: Hourly variations for different monitoring site categories

c. Propagation modelling of traffic noise

Table 5 presents the results of the traffic noise model as descriptive statistics for predicted level at model sites. As expected based on traffic input data there is a notable decrease in levels during the night. On average, predicted LAeq, 24-hour levels from road traffic alone were 3.8 dBA lower than observed levels. This difference was 3.6 dBA for daytime levels and 3.8 dBA for nighttime levels. The traffic noise Lden was not deemed reliable to carry forward in the analysis. This was due to the lack of information regarding temporal distributions of traffic counts on different types of roads and the particular difficulty in estimating this during evening and early nighttime hours. Figure 4 shows that higher levels of traffic noise are concentrated along major thoroughfares and expressways. The traffic noise models explained most of the variation in observed sound pressure levels. Specifically, the proportion of variation in observed noise levels accounted for by the traffic noise model was relatively high, ranging from 58% for daytime to 60% for nighttime noise (Table 6). This conforms to the fact that traffic noise is the most significant contributor to noise in cities. Note that the map in Figure 4 has empty areas where buildings with a footprint greater than 5000 square meters are located. The emission based model utilized in this part of the study relies on building forms to assess reflection and therefore does not estimate noise levels above buildings. However, the amount of missing data depends on the cell size used in the prediction settings; in this case, 10m cells interpolate through buildings that do not exceed 20-30m in any direction depending on their orientation.

Table 5: Descriptive statistics for predicted traffic noise levels at model sites (*n*=193)

	Leq24h	LeqD	LeqN
Mean	58.7	60.1	52.3
Median	57.0	58.0	50.0
Std. Dev	7.4	7.4	7.4
Minimum	40.0	41.0	33.0
Maximum	74.0	76.0	70.0

Table 6: Coefficients of determination (R^2) between predicted traffic noise levels and observed noise levels

		Traffic noise		
		Leq24h	*LeqDay*	*LeqNight*
Observed noise	*Leq24h*	**0.59**	0.59	0.57
	LeqDay	0.58	**0.58**	0.56
	LeqNight	0.62	0.62	**0.60**

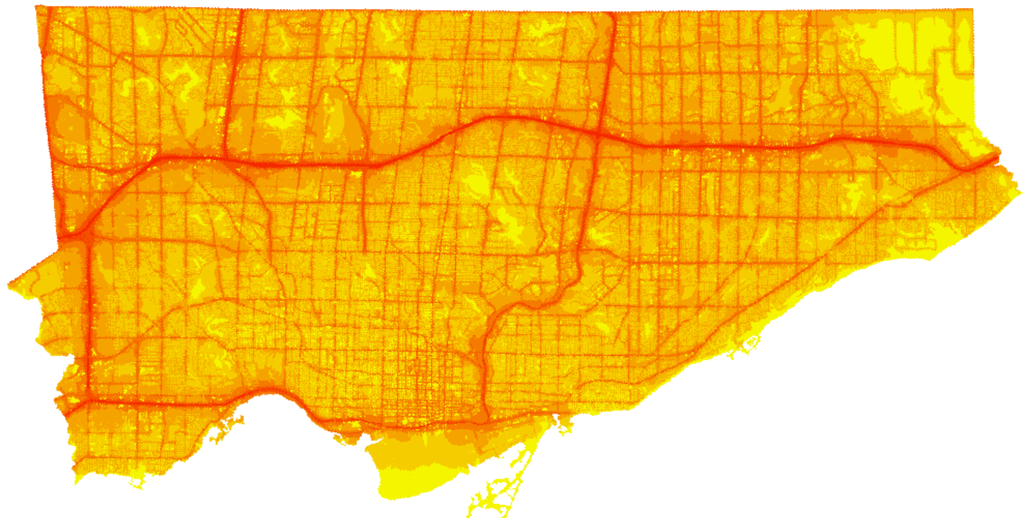
d. Combined land use regression and propagation noise model

As noted above, predicted traffic noise levels explained a significant proportion of observed variance in sound pressure levels. However, land use regression modelling is a technique that can predict unexplained variance using geospatial characteristics. The approach consisted of identifying a predictive ‘correction’ model of the dBA difference between traffic noise and observed noise, and combining this with the traffic model to improve the quality of predicted noise levels throughout Toronto. The details of the modelling procedure to produce the final noise maps are explained below, but the basic process involved four steps:

1) Use traffic and built environment characteristics to create traffic noise map (Figure 4)
2) Create a ‘correction model’ map of difference between predicted traffic noise levels and observed noise levels from monitoring campaign (Figure 5)
3) Overlay and sum traffic noise model surface and correction model surface to create final noise maps (Figures 6 and 7)
4) Validate final noise maps results against observed noise levels (Table 8).

The final regression models that best explained differences in traffic and observed noise levels are presented in Table 7. The modelling exercise produced a more parsimonious model for nighttime noise differences, with two predictors explaining 15% of the variation. These included a negative effect of relative vegetation coverage (NDVI) and a positive effect of population density. The interpretation is that the traffic noise model overestimated noise levels where NDVI values, or vegetation coverage was higher. Conversely, the traffic noise model did not explain high levels of noise where population densities within 1km were higher. The LUR model for daytime noise was generally less robust, likely due the higher spatial and temporal diversity of noise sources during this time.

Figure 4: Emission-based traffic noise model sound pressure levels

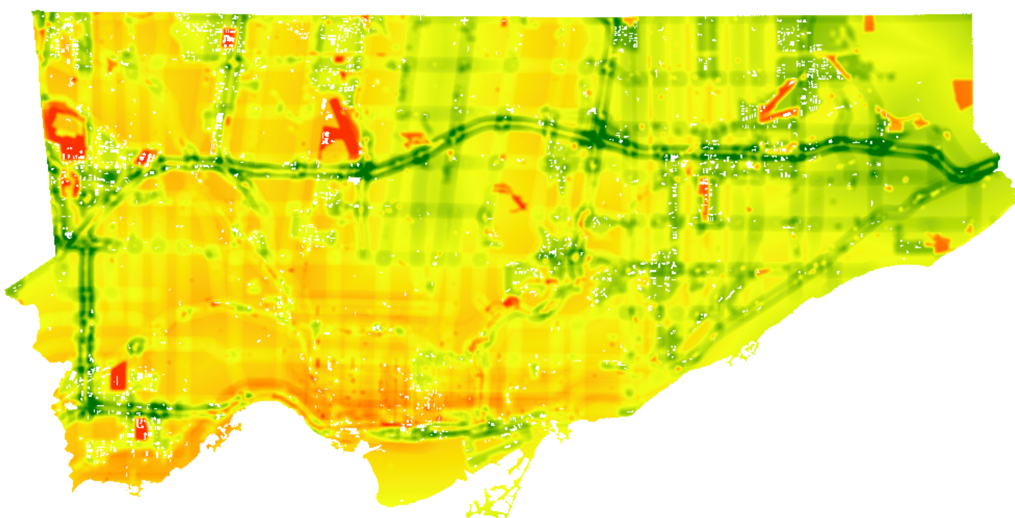


Traffic LAeq, 24h (dBA)
<= 40
<= 50
<= 60
<= 70
<= 80
<= 90
<= 100

N
W E
S
0 3 6 km

Source: City of Toronto; DMTI Spatial Inc.; Statistics Canada; Environment Canada; ESRI Canada
Prepared by: Ryerson University
Data as of March, 2017.
Projection: NAD83 / UTM Zone 17N

Figure 5: Land use regression correction model for daytime noise levels



LAeq, 16h (dBA)
Value
14.6
-7.3

N
W E
S
0 3 6 km

Source: City of Toronto; DMTI Spatial Inc.; Statistics Canada; Environment Canada; ESRI Canada
Prepared by: Ryerson University
Data as of March, 2017.
Projection: NAD83 / UTM Zone 17N

Figure 6: Daytime total noise levels

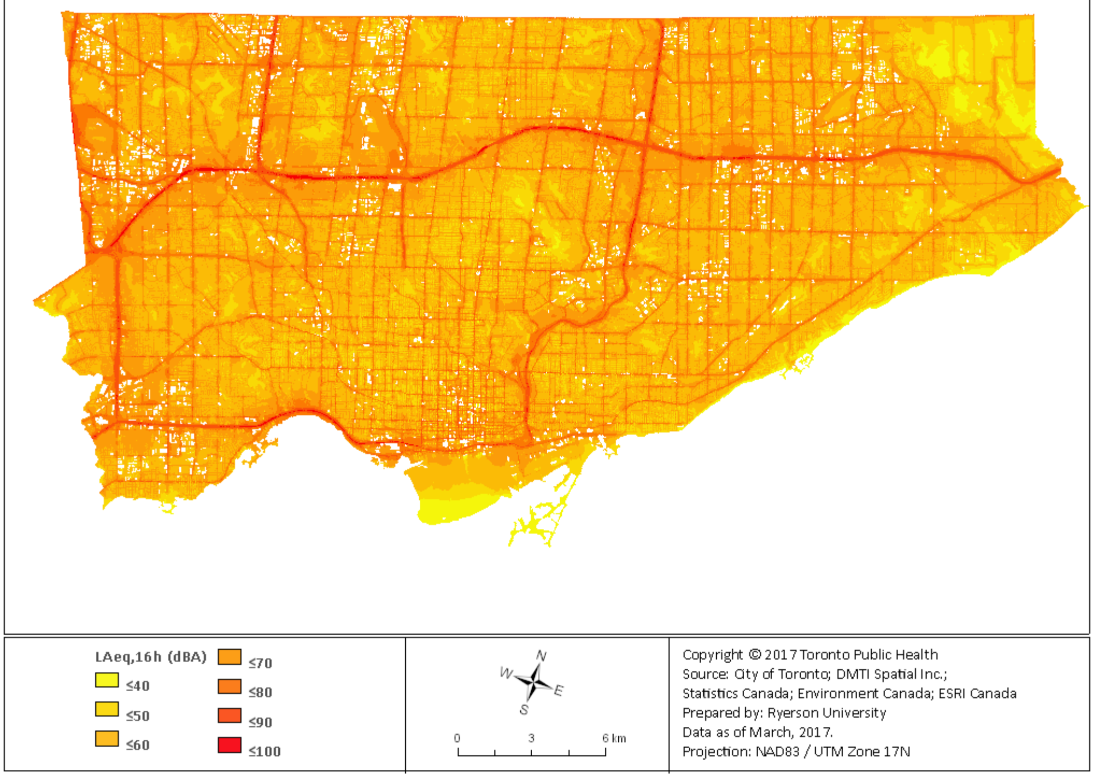


Figure 7: Nighttime total noise levels

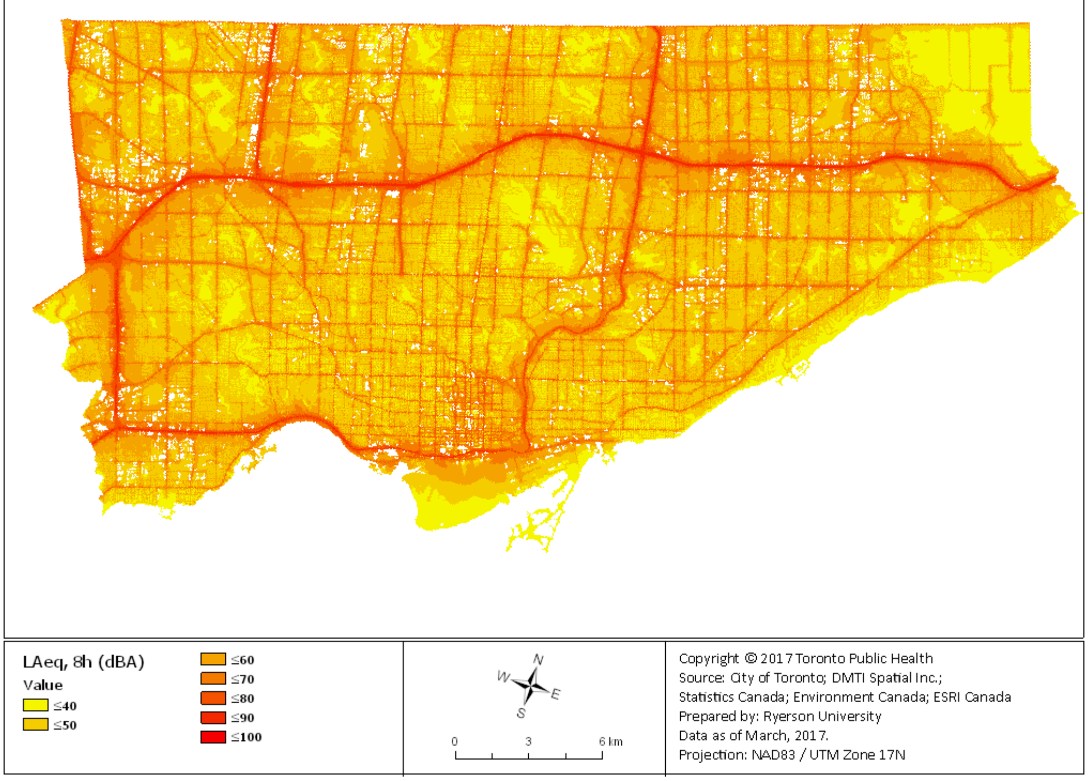


Table 7: Final land use regression models to predict differences in observed noise and predicted traffic noise levels										
Model		**B**	**SE**	**Beta**	**t**	**Sig.**	***r***	**Part *r***	**Part R^2**	**Tolerance**
LeqNight	*(Constant)*	10.876	3.089		3.520	0.001				
	NDVI	-0.066	0.022	-0.204	-3.027	0.003	-0.244	-0.202	0.041	0.983
	Population density (1000m)	0.435	0.094	0.312	4.636	0.000	0.339	0.310	0.096	0.983
	Adj. R2	0.15								
	RMSE	4.7								
	LOOCV RMSE	4.76								
LeqDay	*(Constant)*	8.541	1.554		5.497	0.000				
	Length streetcar route (700m)	0.486	0.156	0.233	3.123	0.002	0.175	0.213	0.045	0.840
	Open area (100m)	0.196	0.117	0.123	1.675	0.096	0.051	0.114	0.013	0.859
	Major roads (350m)	-1.220	0.362	-0.267	-3.369	0.001	-0.124	-0.230	0.053	0.744
	Distance to Pearson (exp)	-0.024	0.010	-0.160	-2.321	0.021	-0.132	-0.158	0.025	0.978
	Resource/industrial area (150m)	-0.043	0.020	-0.152	-2.161	0.032	-0.120	-0.148	0.022	0.945
	Distance to railways (lin)	-0.688	0.341	-0.147	-2.019	0.045	-0.121	-0.138	0.019	0.878
	Adj. R2	0.100								
	RMSE	4.620								
	LOOCV RMSE	4.670								

Table 8: Validation models for final noise prediction surfaces										
Noise Indicator		**B**	**S.E.**	**Beta**	***t***	**Sig.**	***r***	**Adj. R^2**	**RMSE**	**LOOCV RMSE**
Laeq, Night	*(Constant)*	7.07	2.55		2.78	0.01				
	Model estimate	0.87	0.05	0.85	19.30	0.00	0.85	0.71	4.10	4.12
Laeq, Day	*(Constant)*	15.04	2.91		5.16	0.00				
	Model estimate	0.74	0.05	0.81	16.47	0.00	0.81	0.64	3.70	3.72
Laeq, 24hour	*(Constant)*	15.81	2.64		6.00	0.00				
	Model estimate	0.74	0.04	0.82	17.43	0.00	0.82	0.67	3.60	3.62

A combination of 6 spatial indicators predicted 10% of the difference between traffic noise and observed daytime noise levels. The model suggests that noise levels in proximity to streetcars, open areas, Pearson Airport and railways exceeded what would be expected based on traffic noise alone. Conversely, the regression model in Table 7 for daytime differences in observed and traffic model levels of noise suggests that the traffic noise model alone overestimated noise in proximity to major roads and resource or industrial areas. This may be due to inaccurate traffic data or misrepresentations of the built environment (e.g., no noise walls in model). Validation testing for both models showed a relatively high, but commonly observed level of error (Root mean square error (RMSE)), consistent for both models as computed with the leave-one-out procedure. This reaffirms the challenges of predicting variations in noise levels above 60-70%, the range commonly observed in large scale noise modelling studies.

It should be emphasized that land use regression is a mathematical approach to predicting exposures, and in this case a mathematical approach to predicting 'leftover' noise from the traffic model. The predictors for vegetation coverage, population density, distance to airports and railways all have a logical relevance to noise levels. The interpretation of how other predictors influence noise levels is less straight forward. For example, it is unlikely that streetcars have a direct effect on noise levels within 700 meters. It is more likely that streetcar lines are a proxy for other noisy activities that take place in their vicinity, or that this variable represents a correction to traffic volume distributions in central areas of Toronto. Likewise, interpretation of the positive effect of proximity to open areas and negative effect of proximity to industrial and resource areas is not straightforward. It is possible that they are proxy indicators for construction noise as many open areas as classified by DMTI Spatial are being developed, or as in the case with streetcars, represent a general correction for traffic noise levels. Finally, the negative effect of major roads within 350m seems counterintuitive, but likely presents a correction to traffic data and environmental features and their effects on noise dispersion near major roads and expressways. For example, noise abatement walls can be found along most of Highway 401 throughout Toronto. However, due to the scope of the study, it was not feasible to input acoustic barriers such as sound walls and berms into the modelling environment.

Figure 5 shows the result of the daytime noise correction model. The final daytime noise surface was produced by adding this to the traffic noise surface. The procedure was repeated for nighttime noise, and a 24-hour noise prediction map was produced by a weighted combination of the daytime and nighttime surfaces. Table 8 shows the result of validating the final surface against observed levels at the model sites. The proportion of variance explained ranged from 64% for daytime noise to 71% for nighttime noise. The RMSE validation procedure suggests that these estimates are stable across different study sites. The final noise predictions for 24 hours, daytime and nighttime hours are presented in Figure 4, 6 and 7, respectively. The maps use the same classification ranges for ease of comparison.

e. Population exposures and associations with socioeconomic status

Noise estimates from the traffic and final surfaces were linked to Statistics Canada census data on demographics and socioeconomic status to understand population exposures and potential implications for environmental justice. The noise exposure thresholds assessed were derived from the Ontario Environmental Noise Guidelines and the WHO Environmental Nosie guidelines.

Ontario guidelines suggest the implementation of a mitigation strategy where daytime noise levels exceed 55 dBA. The analysis showed that that 88.7% of Toronto's population live in buildings where the most exposed façade exceeds this level (Table 9). The WHO guidelines suggest that people exposed to 24-hour levels above 65 dBA are likely to be seriously annoyed; 30.1% of Torontonians are exposed to this sound pressure level outside their residence. Guidelines for nighttime noise levels at 55 dBA are exceeded for 43.4% of residents and nighttime outdoor levels of 45 dBA are exceeded for 92.3% of residents. Figure 8 shows the proportion of residents predicted to be exposed to nighttime levels of noise at 55 dBA or higher by dissemination area.

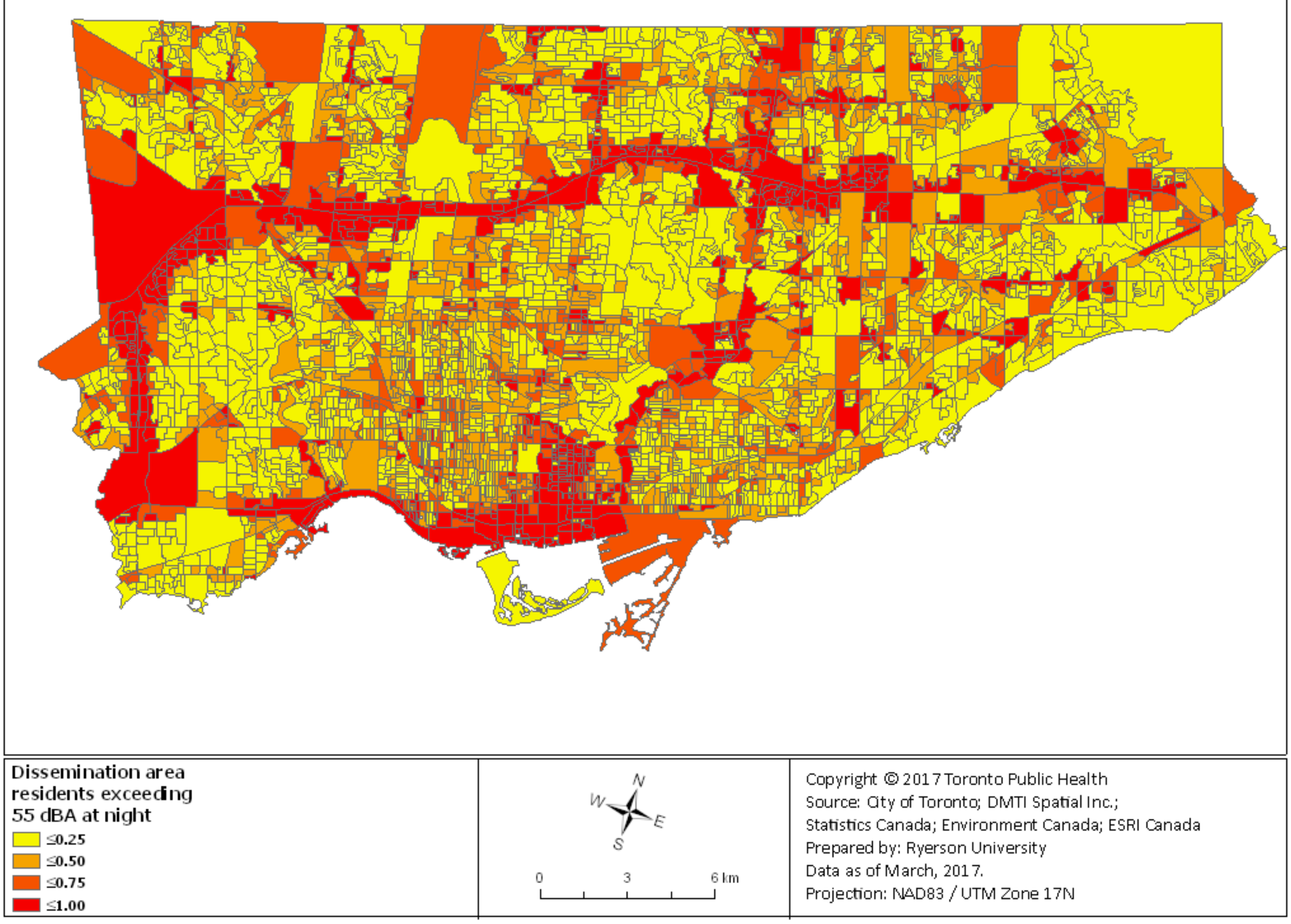
Table 9: Residential exposure assessment above guideline levels in Toronto

Noise Threshold	Residents exceeding threshold	Percentage of Toronto population
Total Noise		
LAeq, 24h, 65 dBA	845,904	30.1%
LAeq, 24h, 55 dBA	2,027,849	72.2%
LAeq, Day, 65 dBA	1,091,251	38.8%
LAeq, day, 55 dBA	2,494,251	88.7%
LAeq,night, 55 dBA	1,218,570	43.4%
LAeq, night, 45 dBA	2,595,191	92.3%
Traffic Noise		
LAeq, 24h, 65 dBA	633, 705	22.6%
LAeq, 24h, 55 dBA	1,501,219	53.4%
LAeq, Day, 65 dBA	762, 570	27.1%
LAeq, Day, 55 dBA	1,691,857	60.2%
LAeq, Night, 55 dBA	929,078	33.1%
LAeq, Night, 45 dBA	2,175,533	77.4%

The final analysis assessed potential inequities in exposure by linking household incomes by dissemination area to excessive nighttime noise exposure. A logistic regression model was used to link household incomes to dissemination areas where more than 50% of residents are exposed to nighttime noise levels above 55 dBA.

Table 10: Logistic regression model predicting dissemination areas with 50% of residents exposure to nighttime noise exceeding 55 dBA								
	B	S.E.	Wald	df	*Sig.*	Odds Ratio	95% C.I. for Odds Ratio	
High Income Quintile (reference category)			431.44	4.00	0.00			
Low Income Quintile	2.40	0.14	309.48	1.00	0.00	10.99	8.42	14.36
Income Quintile 2	1.32	0.14	92.39	1.00	0.00	3.76	2.87	4.92
Income Quintile 3	0.78	0.14	29.39	1.00	0.00	2.18	1.64	2.89
Income Quintile 4	0.61	0.15	17.21	1.00	0.00	1.84	1.38	2.44
Constant	-2.00	0.11	308.31	1.00	0.00	0.14		

Figure 8: Percentage of residents exceeding 55 dBA during nighttime



Compared to dissemination areas within the highest income quintile, dissemination areas in the lowest income quintile are nearly 11 times more likely have 50% of their residents exposed to excessing nighttime noise (Odds ratio: 10.99, p<0.001). Table 10 shows the odds ratios for other income groups.

6. Discussion and Outcomes

a. Spatial and source summary of noise levels in Toronto

This study utilized a combination of noise monitoring and modelling to assess environmental noise levels in the City of Toronto. The results provide specific and general insights on noise receptors throughout the city. In general, a large proportion of residents in Toronto are exposed to residential sound pressure levels that exceed commonly applied guidelines. Residents living near major arterial roads or in areas with mixed commercial and residential land uses are especially vulnerable. The analysis also shows that areas characterized by lower incomes are more likely to experience excessive noise levels. This confirms findings of previous studies, such as a recent assessment in Montreal (Carrier et al., 2016).

Observed noise levels among the sites of interest varied depending on the category. Some sites were targeted because of public concern. This includes sites assumed to be characterized by high levels of amplified sound. These sites highlighted a challenge in noise assessment, regulation and mitigation in general. Average sound pressure levels over extended periods of time correspond relatively well to levels of annoyance. On the contrary, metrics that capture the proportion of shorter term noise nuisances or events are available and reported in this document, but there is much less information available about how such events influence people's annoyance levels. One reason is that such noise nuisances need to be considered in the context of the particular soundscape within which they occur. Shomer et al. (2012) argues that a soundscape does not only depend on physical characteristics of sound at a certain point in time, but additionally depend on socioeconomic and cultural variables among sensitive receptors (i.e., residential areas).

Another category of sites identified as proximal to construction activities also exhibit higher levels of noise compared to overall noise levels. This is exacerbated by the common occurrence of construction activities during the summer and fall. Monitoring of the remaining categories of special interest sites produced results much as expected. This included high noise levels near busy TTC facilities and an EMS station. Monitors in proximity to large gatherings of people also indicated high noise exposures (BMO Field and CNE).

The Toronto noise by-law prioritizes the mitigation of noise near certain land uses through 'quiet zones,' which in the current study were represented by hospitals and long-term care facilities. These zones seek to limit noise levels during the night and on weekends. This study did not find any effect of such policies. This is likely due to their placement near or on major or minor arterial roads, and possibly related to emergency vehicles. Other sensitive areas monitored included community housing sites, and these were characterized by temporal variations and levels of noise very similar to hospitals and long-term care facilities.

In addition to monitoring a set of representative sites of interest, a major objective of the study was to assess noise exposures in sensitive areas throughout the city. In this case, sensitive areas refer to residential areas more generally. This was assessed with a subset of sites characterized by different types of zoning. Observed noise levels in these sites were higher during the weekday, measurements which corresponds to the high influence of traffic noise, and areas zoned solely for residential use are notably quieter than mixed land uses. However, the relatively low population densities in these areas means that many reside in areas characterized by mixed types of land use, where noise levels are higher.

b. Canadian and international comparisons

There are relatively few examples of studies with a similar scope for comparison in the literature, in particular for Canadian or North American cities where one would expect similar acoustic environments as a result of common building forms and linear source distributions. In the Canadian context, three previous studies in Toronto Vancouver and Montreal provide good comparisons. The most recent monitoring and modelling project was conducted in Montreal in 2014 (Ragettli et al., 2016). This study did not report differences between weekday and weekend levels, but with reference to common metrics (Lden, LAeq,Night, LAeq,24h) the patterns and overall levels were very similar, although all were slightly lower in Montreal. This may be due to a positive bias correction applied to observed levels in Montreal. This study also utilized a form of LUR modelling using additive general models, but did not include propagation model estimates for any linear sources. The models reported for Montreal explained a similar level of variance among monitored sites, which also included the explanatory predictors NDVI, air traffic, railways, transit and residential density.

Zuo et al. (2014) conducted large scale monitoring and modelling study in Toronto in 2012-2013. Their approach was different with respect to monitoring and modelling. A large number of sites (554) were selected for short-term monitoring (30 minutes). A sub-selection of these included repeated measurements and long-term (1-week) measurements for validation. Based on 10 1-week measurements this study also observed a similar pattern of higher levels during the day compared to night. This previous study in Toronto also built LUR models (referred to as geostatistical models), which explained similar levels of variance with traffic volume, arterial roads and industrial land use. These results are confirmed in the current study, although a different approach to assessing traffic emissions was utilized. Much like the current study, Zuo et al. (2015) concluded that noise exposures almost ubiquitously exceed guidelines set by the Province of Ontario.

Gan et al. (2012) utilized an approach to assess noise levels throughout Vancouver based on monitoring and modelling of linear transportation sources. Their study employed a propagation model for road and rail traffic in combination with noise exposure forecasts from the Vancouver airport authority. In other words, this model was based on using only emissions based modelling techniques. The results showed a similar average noise level for the daytime (64.3 dBA), but a slightly lower average level for nighttime noise. Field measurements in Vancouver were actually lower than predicted noise levels, and they observed a lower correlation between these values (0.62 compared to 0.76 for LAeq,Day in Toronto).

Other studies provide less value as means for comparison because of their differing geographic contexts and/or use of short-term noise measurements. This includes a study of the relationship between traffic counts, measured and modelled noise in three US cities (Lee et al., 2014). The study identified a moderate association between traffic counts and measured noise, but only observed a weak association between measured noise and emission (not propagation) model results. Aguilera et al. (2015) compared the performance of LUR models to emission and propagation based models in three European cities. The LUR models provided explained similar levels of variance as this study and the Montreal study.

c. Limitations

One of the most significant challenges to noise modelling is data requirements. This includes geospatial data to evaluate the influence of the environment on propagation, but to a larger extent information about noise sources. First and foremost, as demonstrated by previous research, reliable road traffic data is crucial. This refers to both spatially and temporally resolved information. Traffic surveying programs such as maintained by the City of Toronto provide a good estimate of spatial variability, while temporal variability can be acquired through transportation forecasting models and more detailed small-scale traffic surveys. To combine these sources of information is ideal, but this was not an opportunity in the current study. In addition to limitations posed by lack of detailed road traffic data, estimating rail and air traffic noise equally depends on access to detailed data. Resources for this study did not permit assessment of air and rail traffic through propagation modelling. The LUR correction model indicated that these two noise sources explained approximately 5% of the variation observed in sound level measurements. Although the final noise surfaces take this into account, the employed methodology is limited in terms of differentiating noise exposures from air traffic in particular in Toronto neighbourhoods.

Another limitation in environmental noise studies of this scale is instrumentation. Costs precluded the use of Type 1 sound level meters, which have a smaller degree of imprecision than type 2 meters utilized in the current study. At the reference frequency of 1 kHz, the error tolerance limit for a Type 2 meter is 0.3 dB. This difference is larger (3-4 dB) at the lower and upper extremities of the frequency range, however, road traffic noise normally has a frequency close to 1 kHz. The sound level meters employed in the current study are also limited to integrating dBA and dBC levels. Although this is the industry standard for noise assessment, there are shortcomings of this approach as certain frequency ranges can be misrepresented in terms of perceived loudness (Kjellberg and Goldstein, 1985). Other potential limitations in the form of uncertainty in measurements arise from surface reflections. The ISO standard for noise assessment suggests a small correction for reflections bias (3-6 dBA) if monitors are placed on a perfectly reflecting and infinite surface. While this was not the case in this study as meters were attached to round utility poles, there is potentially a small positive bias in measurement results. However, the results are consistent with other studies in similar environments. A final limitation with respect to monitoring is the 1-week measurement conducted during a single season. Capturing temporal variability with some level of certainty depends on the duration of measurement. The measurement period chosen in this study was based on conforming to standards set in similar studies (e.g., Montreal) and to maximise the spatial coverage within resource constraints for the study.

One of the main objectives of the study was to assess population exposures to noise. This not only depends on an accurate assessment of local noise levels, but on the methodology used to link such information to population measures. The current study utilized a standardized approach to assess sound levels at the most exposed façade, but a limitation exists as this was assessed at a height of 4m. The result of this is a limited ability to make conclusions about indoor noise for residents in Toronto as this needs to take into account dispersion of noise in the vertical dimension for mid- and high-rise buildings commonly found in areas with high population densities.

7. Conclusion and Recommendations

The current study provides a comprehensive assessment of environmental noise in the City of Toronto. This assessment was designed to meet objectives to understand general and specific noise exposures in the city. The results show that residents near major roads, in commercial residential land uses, and within lower income dissemination areas are particularly vulnerable to high noise exposures. The levels of noise observed in these areas are concerning as they exceed thresholds for negative effects on health observed in population-based studies. The study found that over 60% of residents in Toronto are exposed to traffic noise levels above 55 dBA during the day, and more than 90% of residents are exposure to nighttime total noise levels exceeding 45 dBA. For sites of interest the results were mixed, but a number of these sites exhibited excessive noise levels. This includes areas designated as quiet zones as well as residential areas near major construction projects, in proximity to amplified sound and other sites noted in the report.

Based on these results, it is the recommendation of this study team that any noise management plan that seeks to improve the acoustic environment in Toronto is complemented by performance-based goals to reduce noise exposures. Performance-based goals in this context means setting long-term targets for reducing the proportion of people exposed to excessive noise levels, in particular among vulnerable groups and in sensitive areas identified in this report. Specific targets as defined by noise levels and/or population exposures should be identified through a collaborative process that includes stakeholders from multiple levels of government, industry and community organizations. By utilizing the extensive body of evidence currently available as well as identifying knowledge gaps of relevance to Toronto, outcomes in the form of a strategic action plan can support and complement the instrumental role of a revised noise by-law. This may require regular noise assessments such as required under the European Noise Directive. It is also the recommendation of this study team to build on this report with a detailed study of population perceptions to noise to gain a better understanding of the spatial and temporal distribution of noise annoyance and potential impacts on health and wellbeing in Toronto.

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9. Appendices

a. Noise indicator definitions

Noise Indicators	Definition
LAeq, 24h	A-weighted equivalent sound pressure level in dB measured over 24 hours
LAeq, 16h	A-weighted equivalent sound pressure level in dB measured from 7 am to 11 pm
LAeq, 8h	A-weighted equivalent sound pressure level in dB measured from 11 pm to 7 am
Lden	Day-evening-night equivalent sound pressure level in dB with 5 dB penalty added to evening hours (7 pm to 11 am) and 10 dB penalty added to nighttime hours (11 pm to 7 am)
Lmax	The maximum observed 1-second dBA level
L1, L5, L10, L50, L90, L95	The sound pressure level exceeded X percent of the time over a 24 hour period
Exceedances	
24h: 55 dB(A), 65 dB(A)	The proportion of time during 24 hour measurement period when sound pressure level exceeds 55 or 65 dB(A)
Day: 55 dB(A), 65 dB(A), 70 dB(A)	The proportion of time during daytime hours (7 am to 11 pm) measurement period when sound pressure level exceeds 55, 65 or 70 dB(A)
Night: 40 dB(A), 50 dB(A), 55 dB(A)	The proportion of time during nighttime hours (11 pm to 7 am) measurement period when sound pressure level exceeds 40, 50 or 55 dB(A)

b. Land use regression candidate predictor variables

Category	Indicators	Measurement *
Transportation	Length of major roads	Length of expressways and arteries
	Length of all roads	Length of all roads
	Distance to railways	Linear and exponential Euclidian distance to major or minor railways
	Length of railways	Total length of minor and major railways
	Streetcars	Total length of streetcar routes in operation
	Bus routes	Total length of bus routes in operation
	Nighttime bus routes	Total length of nighttime bus routes in operation
	Distance to Pearson Airport	Linear and exponential Euclidian distance
Land use	Commercial	Total and proportional area
	Government and institutional	Total and proportional area
	Open area	Total and proportional area
	Parks and recreation	Total and proportional area
	Residential	Total and proportional area
	Resource and industrial	Total and proportional area
	Waterbody	Total and proportional area
	Land use entropy	Shannon's and Simpson's Diversity Indices
Land cover	Tree canopy	Total and proportional area
	Grass/Shrub	Total and proportional area
	Bare earth	Total and proportional area
	Water	Total and proportional area
	Buildings	Total and proportional area
	Roads	Total and proportional area
	Other paved surfaces	Total and proportional area
	Agriculture	Total and proportional area
Vegetation	Normalized Difference Vegetation Index (NDVI)	Normalized greenery for Toronto based on remote sensing
Demographic	Population density	Mean, median and standard deviation of census block derived populations

*All variables except distance based measures were computed for buffer zones around monitoring sites at the following intervals: 50;100;150;200;250;300;350;400;450;500;600;700;800;900;1000

c. Sites of Interest

SITEID	Site Description	Location
40006	Amplified sound	St. James Park
40010	Amplified sound	Cherry Beach/Clarke Beach
40013	Amplified sound	Toronto Music Garden
40014	Amplified sound	Village of Yorkville Park
40015	Amplified sound	Yonge-Dundas Square
40016	Amplified sound	Ashbridge's Bay Park
40020	Amplified sound	Woodbine Park
40021	Amplified sound	Harbourfront + Island residents
40022	Amplified sound	155/119 Yorkville
40023	Amplified sound	Echo Beach / Molson Amphitheatre
40026	Amplified sound	toronto Music Garden
40051	Amplified sound	David Pecaut Square
40063	Amplified sound	Dundas and Ossignton
40064	Amplified sound	Liberty Village
40065	Amplified sound	King West
40080	Amplified sound	540 Queen st E dBA
40008	BMO Field	BMO Field
40001	CNE	Exhibition Place
40046	Community housing	Community housing building 4096
40047	Community housing	Community housing building 4036
40048	Community housing	Community housing building 5610
10006	Construction	Bridlewood Crcl construction
10046	Construction	Rexdale Blvd construction traffic
40025	Construction	99 blue jays way
40030	Construction	Construction near allen road and eglinton
40050	Construction	555 Adelaide St West (new condo construction)
40054	Construction	Bayview/Eglinton-construction deliveries
40055	Construction	Yonge/Eglinton-construction deliveries
41023	dBC	Corresponding dBC to 400xx)
41051	dBC	Corresponding dBC to 400xx)
41063	dBC	Corresponding dBC to 400xx)
41065	dBC	Corresponding dBC to 400xx)
41080	dBC	Corresponding dBC to 400xx)
61001	dBC	Ward's Island Wk1 dBC
61002	dBC	Algonquin Island Wk1 dBC
40070	EMS	Bendale Acres
40002	Historic or cultural site	Fort York National Historic Site
40004	Historic or cultural site	Riverdale Park West
40005	Historic or cultural site	Royal Ontario Museum
40007	Historic or cultural site	St. Lawrence Market & Market Gallery

40009	Historic or cultural site	Casa Loma
40011	Historic or cultural site	Todmorden Mills Heritage Site
40017	Historic or cultural site	High Park
40019	Historic or cultural site	The Distillery Historic District
40049	Historic or cultural site	Christie Pitts.
40059	Historic or cultural site	Near golf courses
40031	Long term care or hospital	Toronto East General Hospital
40032	Long term care or hospital	North York General Hospital
40071	Long term care or hospital	Carefree Lodge
40072	Long term care or hospital	Castleview Wychwood Towers
40073	Long term care or hospital	Cummer Lodge
40074	Long term care or hospital	Fudger House
40075	Long term care or hospital	Kipling Acres
40077	Long term care or hospital	True Davidson Acres
40079	Long term care or hospital	Seven Oaks
10001	School	Fundy Bay Blvd elementary school
40036	School	CEDARBRAE COLLEGIATE INSTITUTE
40037	School	MILNE VALLEY MIDDLE SCHOOL
40038	School	CHURCH STREET JUNIOR PUBLIC SCHOOL
40039	School	OSSINGTON OLD ORCHARD JUNIOR PUBLIC SCHOOL
40040	School	NORTHERN SECONDARY SCHOOL
40041	School	DON VALLEY JUNIOR HIGH SCHOOL
40042	School	ST MARIA GORETTI CATHOLIC ELEMENTARY SCHOOL
40043	School	ST LUKE CATHOLIC ELEMENTARY SCHOOL
40044	School	AVALON CHILDREN'S MONTESSORI
60001	Toronto Island	Ward's Island Wk1
60002	Toronto Island	Algonquin Island Wk1
62001	Toronto Island	Ward's Island Wk2
62002	Toronto Island	Algonquin Island Wk2
40060	TTC Yards	Leslie TTC Barns