Assessing the Effect of the King Street Transit Pilot on Residential Traffic Noise Exposure

by

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Abstract

The noise in urban environments continues to grow as more of the world's population transitions to cities. Vehicular noise is one of the main factors of noise pollution in cities. Toronto recently introduced a Transit Priority Corridor which reduced the total traffic flow along one major road. High levels of noise can have serious health impacts on city residents who work and live in dense urban cores. This study aims to model the noise on the façades of buildings in the City of Toronto. Two models were created using traffic flow data modelled from measured vehicle counts. SoundPlan a noise modelling software, was used to create façade level noise maps and to estimate the residential exposure. In the study area surrounding King Street, over 90% of the population in the study area was found to be exposed to levels described by the World Health Organization as dangerous. In the study area, 91.66% of the population based on the modelled results was exposed to levels above 45 db(A) before the pilot and 92.45% were exposed after the pilot. Noise disturbance at this level is associated with many long-term health impacts that can be mitigated by reducing source noise. Transit efficiency management systems like the King Street Pilot program can be used to reduce source noise although programs along only one stretch or road are unlikely to significantly reduce noise levels.

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List of Acoustic Terms and Abbreviations:

WHO: World Health Organisation

AADT: Average Annual Daily Traffic

dB: Sound pressure measure in decibels, a logarithmic unit used to describe the ratio between the measured level and a reference or threshold level of 0 db.

dB(A): Measure of relative loudness while low frequencies are reduced. This corrects for the insensitive nature of the human ear to low frequencies. Is also referred to as A-weighted decibels.

EU: The European Union, a political and economic union of 28 member states.

FHWA: The Federal Highway Administration run under the United States Department of Transportation.

Lden: Day-evening-night-weighted sound pressure level as defined in section 3.6.4 of ISO 1996-1:2016.

Lday: Day weighted sound pressure levels, also referred to as the day noise indicator.

Ln: Night weighted sound pressure levels.

Le: Evening weighted sound pressure levels.

Leq: Equivalent continuous sound level in decibels measured over a stated period of time.

GIS: Geographic information systems.

DGM: Digital Ground Model, is also referred to as a Digital Elevation Model

TNM 2.5: A specific version of traffic noise model developed by the Federal Highway Administration.

1. Introduction

Most people living today do so in an urban environment and this will continue to grow as time goes on. Urbanization as a movement has both positive and negative effects on human health and wellbeing. Increased access to health services or basic needs like clean water, and shelter are some ways in which the urban form has benefit its residents. There are always caveats to the benefits of any living environment and dense urban cities like Toronto experience higher exposures to pollution in the air and water unlike that of rural towns. The problem after taking into account this relationship with the urban form and pollution has led to a quantification of its dangers in scientific literature (Kang, 2006). Noise pollution is one example and it has a large influence on human health in cities. City residents have been complaining of noise before cities were well established. In the United States, complaints increase year over year (Staples, 1997). Traffic is often cited as the major source of chronic noise levels in cities and is therefore important to study and understand (Oiamo, et al, 2018). Although noise can be measured physically in the environment by sound pressure monitors, models have become a tool of modern science to help understand the effects of specific noise sources more accurately. This research aims to create such a model that can help describe the effects that alterations to network traffic flows on downtown streets will have on traffic noise levels and as a result, those who live there.

This research comes as a direct response to the changing traffic flow of one of Toronto's downtown streets. Specifically, the King Street Pilot as originally named, now known as the King Street Transit Priority Corridor. This report will refer to the Pilot by its original name. The goal of this pilot program when it was initiated in November of 2017 was to decrease the private vehicle traffic along King Street in downtown Toronto, while improving transit reliability (City of Toronto, 2019). The Pilot along King Street resulted in a reduction in the amount of private vehicles on the road after it was made illegal to proceed along the street without turning at the first available intersection. Streetcars are the main transit available on the street and saw a general increase in their frequency. The corridor design also included an upgrade in sidewalk design with a focus on improving the public spaces parallel to the sidewalks. More access to seating for cafes, art installations, and loading zones were some of the features that King Street saw in the time since its inception.

There are several goals this research will endeavour to address. The first question is how the traffic flow on Toronto's downtown streets changes after the introduction of the road restrictions along King Street. The models that were created in part to address this relies on traffic volumes downtown and it was therefore hypothesized that the effect of vehicle restrictions should result in the vehicles moving to adjacent streets. The second question aimed to address the change in traffic noise for buildings whose façades are along King Street and the adjacent streets. Buildings whose facades face the roads should see high levels of noise while facades that are sheltered from the roads should see low levels of noise. The third question is whether exposure levels could then be estimated based on the model. Residents of any urban environment are subject to chronic traffic noise and therefore this research hypothesized that the number of residents who could be exposed to levels dangerous will be extreme.

1.1 Study Area

The study area of the calculated traffic model was based around the King Street Pilot, though extended out by several city blocks in all directions. Figure 1.1 shows the extent of the study area in relation to all the streets within Toronto. On the northern border is Queen Street that travels parallel to King Street, which is likely to have increased vehicle numbers as those who cannot drive along King must now move somewhere else. On the southern border is Front Street which also travels parallel to King while also having some points at which it is one-way only. Front is not the only one-way street in the study area as both Richmond Street and Adelaide Street are full width downtown streets where traffic flows in one direction. Wellington that is just south of King is the final major road to run east to west. The interior streets like Adelaide and Wellington streets were especially important to include in the study area as they would have most of the traffic that has now been diverted from King Street.

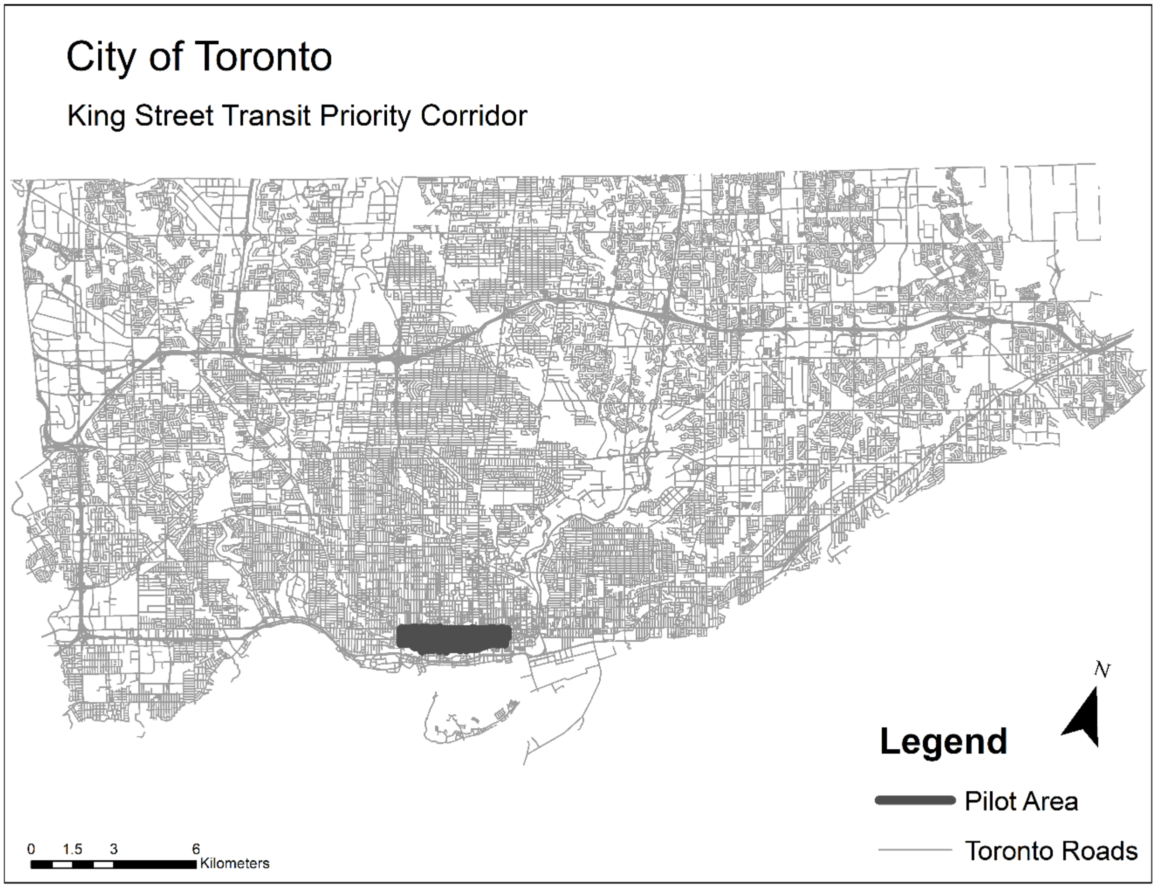

Figure 1.1- City of Toronto Roadways with the Highlighted Transit Corridor

Although the Pilot was run along King Street alone, the traffic it has an effect on runs throughout the city. This is why the streets running parallel to King Street as well as several perpendicular streets were included and taken into consideration in the model. The pilot runs between Bathurst Street and Jarvis Street while the study area extends several roads west of Bathurst to Strachan. On the east end, Sherbourne Street which is several blocks east of Jarvis marks the study area boundary. Most of the major downtown streets and avenues are similar in size and traffic while all maintain 40km/h speed limits. Both Bathurst and Spadina Avenues are exceptions to the size and include more lanes and therefore more vehicles than most other streets in the study area. There are many local roads and laneways visible although, they are only used as visual guides and have no traffic data associated with them.

The King Street Pilot study area also contains some of the tallest buildings in Toronto. This is one of the reasons a façade calculation was done on this area. Façade calculations can take into account the height of these buildings which include both office space as well as condominiums and many businesses. Buildings like these that have as many as 62 floors in this case, provide an interesting example of how traffic noise travels upwards as well as outwards. Figure 1.2 shows a three-dimensional representation of the buildings in the study area.

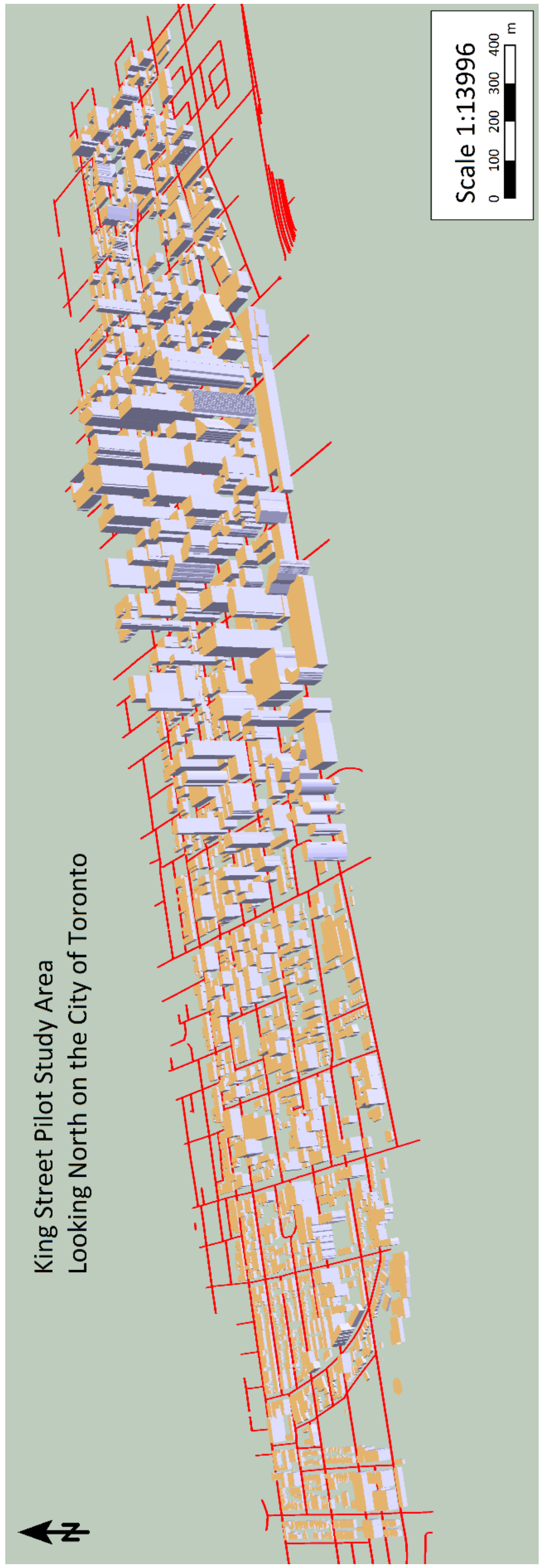

Figure 1.2 – Overview of traffic noise modelling area including road network from the City of Toronto Centreline data and building massing data from the City of Toronto (Open Data Catalogue)

2. Literature Review

2.1 Public Health Risk of Noise Pollution

The health of the public in urban areas encompasses more issues than just noise. Joel Tarr's book "The Search for the Ultimate Sink: Urban Pollution in Historical Perspective" (1996) discusses the emerging problem of pollution that has plagued American cities since their inception. Different types of pollution are common in urban environments and because of the high population levels more residents will be exposed. Where air, ground and light pollution are found noise pollution will follow in urban environments. Noise overexposure at its highest levels can cause physical injuries to the ear and cause temporary or permanent hearing loss (Kujawa & Liberman, 2009). Excessive noise exposure can take place in many settings, occupational and otherwise. Nelson et al. (2005) discussed the morbidity and the effect caused by occupational noise pollution globally. Excessive occupational noise is described in this research as noise levels at 85-90 decibels (db) and higher than 90 db. Noise at this level could be experienced while inside subway cars or emitted from a food processor. The effects of exposure of noise will also depend on the duration of the exposure over time. Lang et al. (1992) described the overexposure of occupational noise and its connection with higher levels of blood pressure when exposed for longer than 25 years. These longer exposure times were linked with higher blood pressure and an increased likelihood of hypertension among the study subjects. While the subjects body mass index and job characteristics did account for blood pressure levels being higher in short term time scales (less than 25 years), they did not explain the levels after long periods of exposure to noise above 85 A-weighted decibel limit (db(A)).

The relationship of higher levels of occupational noise and hearing loss are well studied and less controversial. Talbott et al. (1985) described the strong relationship between the high levels of occupational noise and induced hearing loss with noise over 65 db(A). For reference air conditioners are likely to emit noise at 60 db(A). This research also found a connection with older workers (above 56), and their increased likelihood to show signs of hearing loss meaning this population is at risk. While occupational noise is very dangerous not all city residents are exposed to these levels of noise.

The health effects associated with traffic noise are somewhat different than occupational noise. Sleep disturbance, annoyance, hypertension, and cardiac related problems can all stem from traffic noise in urban environments (Perron et al, 2016; Standsfeld & Matheson, 2003). These problems have been studied for the last 30 years and the effects can apply to both auditory and non-auditory conditions (Basner et al., 2014). Babisch et al. (2005) has published research over the last ten years that mostly focuses on traffic noise and its effect on human health (Babisch et al, 2002, 2008, 2011). The author discusses that non-auditory noise is not perceived consciously. This heightens the danger of lower frequencies of noise that were once thought to not have much of an effect on sleep disturbance. The unconscious detection of traffic noise can now be studied in greater detail to show exposures and help determine the extent of those affected by the previously understudied chronic traffic noise.

Although there are many studies dedicated to the subject of noise exposure and its health related issues, several review papers aptly point out that studies based on individual perceptions often fail to reach any statistical significance when noise and health are the topic (Ising & Kruppa, 2004). Noise disturbance is difficult to properly define individually because of the complicated nature of perception, when the measurements are taken and specifically how the disturbance is affecting the human body. The increased risk of cardiovascular diseases as they relate to stress for example is described by Münzel et al. (2014). This study focused on demonstrating the increased risk of arterial hypertension, myocardial infarction and stroke from the exposure to high levels of noise at night. The relationship between night time disturbance and noise related health issues is common in epidemiologic studies related to noise. Spreng (2000) discussed the relationship between increased stress hormones and sleep disturbance. Both aircraft and traffic noise were shown to trigger higher levels of stress related hormones among animals with a focus on their increased cortisol levels.

The complicated nature of both defining and then testing whether in the lab or otherwise makes these types of studies lack some of the statistical consistency which makes the scientific consensus far from unanimous. Ising & Kruppa (2000) still argue that these studies show a consistent trend and that the traffic noise studies should prompt at the very least preventative measures for protecting residents against noise-induced risk of cardiovascular disease.

Noise annoyance and sleep disturbance are therefore just as important as cardiovascular risk because of the ability to detect and predict them (Michaud et al, 2008). While health effects related to biological function can be difficult to quantify, sleep disturbance and annoyance can be more easily reported and are therefore better understood.

2.2 History of Strategic Noise Mapping in Canada

Although originating and mainly being practiced in Europe, strategic noise mapping has been utilized in Canada in the past. Canada unlike the European Union (EU) is not a part of large multi-country agreements to study and report noise and as such, depending on the organization and the location on the study can approach reporting differently. Europe has conveniently provided the framework in which noise mapping can be carried out regardless of the location in which it is being measured or modelled and as such provides the robust groundwork that can be used in Canada. Beginning in the early 2000s, Vancouver based researchers were modelling noise using linear transportation sources. Gan et al. (2012) used both road and rail traffic noise to model the community noise levels in conjunction with air pollution to estimate the risk of coronary heart disease for Vancouver's urban area. The Vancouver based study followed much of the same methodology that Babisch et al. (2002) used when measuring the same effects for Europe using the European Noise Directive guidelines in 2011 and otherwise (Babisch et at., 2008, 2009, 2011, 2014). Gan et al. (2012) used road traffic to estimate noise exposure at the individual residence level over a 5-year period. The study used CadnaA, which is a German noise modelling program similar to SoundPlan to estimate the noise exposure of Vancouver's residents. Road traffic data including the speed of the vehicles, traffic volume, road width and fleet composition were all taken into account. The study found that annual average noise levels were 64 db(A) for the region using daytime A-weighted continuous noise levels as comparison. The study concluded that community noise and traffic related air pollution could be used to assess adverse long-term cardiovascular effects.

More recently, another study was conducted in which land use regression models (LUR) were used to determine the spatial variability in environmental noise levels in Montreal (Ragettli et al., 2016). Similar to the Vancouver study, road, rail and air traffic were taken into account. The data in this study came from noise samples taken over a five day period with continuous two minute noise measurements from sites across the city. Ragettli et al. (2016), also distinguishes between noise levels at different times in the day referencing both rush hour and non-rush hour time frames. This is important as the time of day will determine the number of vehicles on the road as during rush hour the traffic on roads will peak. Modelling using measured noise levels is a common practice in noise models in North America and models derived from LUR models, although used mainly in air pollution modelling, work reasonably well for noise estimation. LUR modelling for both air and noise both come from the measured levels and therefore are subject to the sample type and durations of the measurements taken. Distinguishing the studies that focus on measured noise level versus the estimated or modelled traffic levels is important in the context of this research. While taking noise samples from the sound pressure levels in a particular study area like Ragettli et al. (2016) in Montreal or Oiamo et al. (2018) in Toronto can provide good evidence for noise levels overall, but they cannot fully account from where the noise comes from. Monitored sound pressure levels take into account all noise whether from traffic, construction or emergency vehicles this can overlook the acute versus the chronic noise, the latter being the bigger health concern as previously discussed.

In Toronto, Oiamo et al. (2018) used a hybrid approach to monitor and model the noise for the entire City of Toronto. By using both multi-criteria analysis and location-allocation GIS methods, 220 monitoring sites were chosen out of over 8000 candidate sites. These included sites in residential, commercial and industrial locations across Toronto. Most sites were determined solely from the mentioned methods while others were handpicked as they were of specific concern for being near common noise emitting venues. This study prioritized traffic noise as it is the main cause for noise pollution across the city. The modelling done by Oiamo et al. (2018) used SoundPlan with inputs similar to the ones used in this research.

2.3 Strategic Mapping of Environmental Noise in the EU Noise Directive

Strategic noise mapping in Europe has been a large and growing part of noise related research and literature for decades (Aguilera et al., 2015; Gulliver et al., 2015; Kurakula et al., 2007; Murphy & King, 2011; Quartieri et al., 2009). Europe has been at the forefront of the development of strategic noise mapping to assess the potential risks that all major roads, airports and, railways so that action plans can be drawn up to curb high noise levels. Research has included the growing community of GIS applications for noise modelling as well as the health and impact of noise on the general population. Both the European Commission and The World Health Organisation (WHO) have been critical to the growing literature surrounding the detrimental effects of noise exposure (Kephalopoulos et al., 2014). These organisations are also responsible for the development of action plans to curb noise as well as the development of guidelines to measure it (Hurtley, 2009; Murphey & King, 2011). The accelerated pace of determining the best ways to go about noise mapping make these organisations a key part and basis for this paper.

In Europe, the European Commission based on WHO guidelines have created the Environmental Noise Directive. The goal of this document is to 'properly identify noise pollution and create a necessary action plan at Member State and EU levels' (European Commission, 2002). The identification of excess noise and the transparency in reporting to the public are made priority by the directive. The member states of the EU are all required by this directive to report every 5 years both noise maps and how they plan to address and manage the noise. The size of the populations, number of vehicles, trains and aircraft are all taken into consideration when deciding when to report noise levels. The methodology for reporting, calculating traffic, air and, rail noise has been decided by several bodies. The methods for modelling air transportation noise in the environment for example was decided in 1999 while traffic in multiple occasions, first in 1970 and most recently in 2000.

The sensitivity of noise on residents is described in these documents as 'built-up, in public parks, schools and, hospitals'. A 1996 directive describes what environmental noise means in the context of its negative effects on human health and otherwise (Council Directive 96/61/EC, 1996). "L_{den}" is one such definition where it’s defined as a day-evening-night noise indicator which can describe the overall annoyance caused by traffic. 'Noise mapping' is defined as "the presentation of data on an existing or predicted noise situation in terms of a noise indicator, indicating breaches of any relevant limit value in force, the number of people affected in a certain area, or the number of dwellings exposed to certain values of a noise indicator in a certain area" (European Commission, 2002). Action plans are a large part of the directive where member states must create plans to 'manage issues of noise including noise reduction if necessary'. The locations where this is necessary as set out in Article 8 are areas where populations exceed 250000, roads see over 6 million travellers per year and train and air passengers exceed 60000 (European Commission, 2002). The City of Toronto would easily meet the requirements for this type of reporting if it was under the jurisdiction of this directive.

It is clear that the EU is well ahead of Canada in terms of its development of plans to report, and curb noise in member states. The guidelines are therefore a constructive for Canada to adopt so that all urban residents are informed and protected from noise levels exceeding known health damaging limits. WHO states that night time noise should not exceed 30 db(A) for continuous background noise for sleep disturbance (World Health Organisation, 2018). Individual noise of 45 db(A) should be avoided. Noise in office environments and classrooms should not exceed 35 db(A) based on the perception of casual speech. Day time noise should be limited to L_{eq} values below 55 db(A) for high levels of annoyance, and 50 db(A) for moderate amount of annoyance. Sound levels for the night should generally be 5-10 dB lower to curb annoyance levels.

3. Methods

The methodological approach taken in this research involves multiple parts: (1) Gathering and preparing data in Shapefile format to be input into SoundPlan, including a road layer with the Annual Average Daily Traffic (AADT), a building layer with heights and number of inhabitants as well as a Digital Elevation Model generated within SoundPlan; (2) Inputting the data and linking Soundplan's known attributes in Geo-files to the needed attributes from the imported Shapefiles; and (3) creating a calculation area and running the model to simulate the noise generated by the vehicles and their reverberations off of the built urban environment.

3.1 Network Traffic Flow Predictions and Data

The University of Toronto was responsible for the acquisition and processing of the traffic flow prediction data used in this study. The development of the Traffic Emissions Prediction Scheme (TEPs) was the basis of the creation of point observations to link volumes. Within this framework, the Autoregressive Fraction Moving Average time series model was also developed. This was necessary in order process the temporal based traffic counts where the data were numerous enough to be processed for parameter estimation. The City of Toronto provided the traffic data collected from 324 stations across the cities major arterial and highway systems. The TEP scheme involved the creation of three different databases to cover several traffic stations. Long-term, medium range, and short-term databases were created and combined with pattern recognition software which then was split with two methods. First a regression in the form of Kriging was performed along with a local machine learning algorithm to form the AADT database. This AADT database described the Average Annual Daily Traffic for the entirety of Toronto.

The City of Toronto used a manual approach to measuring traffic volumes along King Street during the day with 15-minute measurements taken (City of Toronto, 2017). While these measurements clearly show a decrease in traffic volume on King, combining the data with the TEPs modelled volumes was proven problematic as they differed in how they were presented. The City of Toronto used Peak A.M and P.M hours while the TEPs model estimated 24hr traffic volumes. Because of the large scale nature of the predictions for daily traffic across the city using the TEPs model and the different definition of traffic volume data, the difference along King Street could not be adequately explained in this model.

3.2 Description of SoundPlan (8.0)

SoundPlan (8.0) is a sound modelling software used for estimating road vehicle, train, and industrial noise by using the geospatial physical environment. The SoundPlan software was originally created in 1986 and is used across the world (Hadzi-Nikolova et al, 2012; Karantonis et al, 2010; Oiamo et al, 2018). SoundPlan has the functionality to model noise created by a multitude of sources (in this case road vehicle noise), and simulate them interacting with the physical space around them. The calculations the program can run take into consideration the laws of physics and can use a number of different acoustic standards from across the world. The industry standard used in this study is defined as 'ISO 9613-2: 1996'. This general method of calculation is an international standard of acoustic attenuation of sound during propagation outdoors (World Health Organisation, 1996). SoundPlan has several levels of calculation that the analyst must decide upon when running a model. There are Single Receiver, Grid level and Façade level calculations which all provided different detail levels of output.

Upon running a successful façade model, the program can output result tables which provide very detailed information surrounding the estimated dB(A) at multiple source points across a study area and more specifically across all buildings in a study area. SoundPlan also conveniently provides a three-dimensional model of the study area where the source points can be easily interpreted across the façades of the buildings calculated. The SoundPlan manual is provided online which makes it easier to set up the necessary files and run a successful calculation. SoundPlan also has the functionality to be run as a network program meaning it can be used across multiple computers at once. This made the 'Distributed Computing' functionality available which significantly decreases the calculation times. Acoustic modelling can be done in several ways while following the ISO 9613-2: 1996 standard. The Traffic Noise Model 2.5 (TNM 2.5) was used in the calculation run in SoundPlan. Originally released in 1998 there have been many changes to the model as the Federal Highway Administration has updated the way that predicted sound levels are calculated (Lau et al, 2004). SoundPlan has many of these types of models built into the program and as such it is simple to select and use the TNM model. This was done in the global settings so that when a model was run to calculate the façade level noise, the program would automatically use the TNM 2.5 method. The importance of selecting the right acoustic model will have an impact on how the sound is propagated from its source point. The TNM method best describes the types of vehicles used in North America as discussed in Section 3.4 in more detail.

3.3 Creating a Road Network Shapefile

The creation of road network files was one of the most important imports into the SoundPlan software. There were several key attributes that needed to be included so the model could run properly. Firstly, the Annual Average Daily Traffic needed to be included. These data were gathered jointly by the University of Toronto, Ryerson University, and the City of Toronto as discussed previously. Gathering traffic data was performed by using specialized 'MIOvision' cameras which could be uploaded directly to Miovision's servers for processing. The City of Toronto Department of Transportation conducted field evaluations of many traffic collection methods and discussed the MIOvision Scout camera in detail (Marti et al., 2014). The road network files also included several other variables related to traffic speeds and road type. The road speed limits were derived partially from the City of Toronto Guidelines, on the city's website and from using Google Street View. Most major roads in Toronto's downtown core are 40km/h, although local and laneways were 30km/h and 20km/h respectively. Whether the road was one-way (or not) was another attribute included in the data to help better understand the acoustic profile of each street. The noise attributed to vehicles in a one-way environment can change the way noise is produced and is therefore important to consider (Ragettli et al., 2016).

3.4 Use of Traffic Volume Histograms and TNM 2.5

Commercial and private traffic caused noise pollution accounts for most of the chronic noise in urban environments (Moudon, 2009). This is why the Federal Highway Administration (FHWA) in the United States who are responsible for the regulation of noise on roadways in the U.S have developed their own model. The TNM 2.5 model as described by the FHWA differs from other models in the way it interprets the noise created by vehicles. TNM 2.5 uses noise level curve changes and includes tailpipe, engine and tire noise whereas some of the models discussed later will only include the speed of the vehicles. There are many traffic modelling standards such as the Common Noise Assessment Methods in Europe (CNOSSOS-EU) used by those closely following the European Commission guidelines (Kephalopoulos et al., 2012). Several others including; Richtlinien für den Lärmschutz an Straben (RSL 90, Germany)), Calculation of Road Traffic Noise (CoRTN, United Kingdom), as described by Steele in 2001. The difference in standards comes in the way the vehicles noise is interpreted. The differing vehicle types in Europe and North America in their size and emissions is one example of the need to differentiate in the use of standards.

The road attribute Shapefile had a lot of important information that is used by SoundPlan's 'Road Day Histograms'. These libraries hold information about the frequency of each vehicle type as they travel along the roads. SoundPlan has many default options that include the use of several models as discussed above. The TNM model was used to initially generate the histogram for the façade calculation with key several changes. Some of the difference in the model before and after the pilot can be explained by the use of different histograms. The City of Toronto previously released the percent change in private vehicle use (King Street Annual Dashboard, 2017-2018) along the new transportation corridor and therefore this was applied directly to the histograms. The road file used the new histograms each created for specific areas of Toronto to best represent the change in the number of vehicles. The first was used to represent all Toronto streets apart from King Street while two others were used to describe the East and then West portions of King Street. The City of Toronto released data based on the Peak A.M. and P.M. times which were described as from 7-10 am and 4-7 pm respectively. This was key as the histograms could be adjusted for those times specifically making the model as accurate as possible to the real life scenario.

3.5 Creating a Building Shapefile

Buildings are important in a façade calculation to help the Software model the propagation of sound off the built environment. The nature of the study area in that it is highly urban and dense means the reverberation of sound on these surfaces will be high. The heights, elevation of the buildings and, the number of floors are all included in the import into SoundPlan. Included in the building Shapefile were also the number estimated number of inhabitants.

To estimate the number of inhabitants, several steps were taken in SoundPlan's geodatabase. First the buildings were 'prepared' which fixes any issues the program has with interpreting the buildings physical construction. Then, a tool called 'define inhabitants' was used. This uses a simply engineering equation that takes into account the total area of a building and then assigns a population based on the users input. For both models 1 inhabitant per 35 metres squared was used. This is slightly less than the default and was used to have a proportional representation of people by residence area. Another way the population could be estimated was by using the Canadian census at the Dissemination Block level. The dissemination block area could be downloaded and combined with the census data. These attributes could then be spatially joined with the 3D massing file found on the Toronto Open Data portal. To assign the number of people in the dissemination block to individual buildings, a simple calculation could be made where:

*Building (ID) population=[building volume/total DB building volume]*DB population* (1)

Unfortunately using the Dissemination Block area data could not be used in this research as the assignment of a population from the pre-defined blocks to individual buildings proved to be difficult within the allotted time frame.

3.6 Generation of a Digital Elevation Model

Due to the nature of the Geographic Information Systems (GIS) based program like SoundPlan, several GIS related files did not have to be input into the geodatabase for them to be used. A digital elevation model (DEM) was an example of this which is necessary for the model to run correctly. An elevation model is important to acoustic calculations because of the various inclines and declines of roads and buildings as they relate to vehicles travelling along them. Toronto and more specifically the King Street Pilot study area, do not have a large gradient and therefore the DEM within SoundPlan can calculate it based on the terrain that is imported into the geodatabase. The imported road network file which used the Ontario Ministry of Natural Resources point elevation data to derive the DEM (Ministry of Natural Resources and Forestry, 2019).

3.7 Other SoundPlan Tools and Calculation Settings

Several other tools within SoundPlan were used to further prepare the imported shapefiles. Firstly the ‘Generate DEM’ tool was used to create a Digital Elevation Model for the study area. This tool works by essentially using the Thiessen Polygon method to filter elevation data points across the city. This method reduces the overall size of the files which is necessary with such large calculations. The ‘Prepare buildings’ function fixes any issues with how SoundPlan interprets the X and Y coordinates when drawing the buildings. The ‘Place receivers’ function is necessary in order to create and assign the receivers to which the weighted sound will be associated with. The estimated sound based on traffic volumes will be calculated at each receiver which are located on each side of a building façade and on every floor. Over the entire study area 114,335 receivers were calculated for each model.

Several measures were taken in the calculation kernel of SoundPlan in order to reduce the calculation time of the models. The minimum length of a façade of 2 metres was decided on for the calculation of receivers. This meant that façades whose length was less than 2 metres was not considered in the calculation. The reflection order of noise on façades in the calculation area was also reduced from 2 to 1. This meant only one reflection would be calculated. Another setting that reduced calculation time was the change in the maximum reflection distance. This is 200 metres originally and reduced to 100 metres. The allowed tolerance was the final setting used in the calculation kernel to reduce total calculation time where the default tolerance of 0.1 dB was changed to 0.2 dB. With the specifications presented below, each model finished calculations after roughly 90 hours. The computer hardware relevant to the calculation were two Intel(R) Xeon(R) CPU E5-2620 v4 @ 2.10GHz, 2101 MHz, 8 Cores, 16 Logical Processors and 64 GB of installed random access memory (RAM). These were the same on both servers used to make the final models.

4. Results

4.1 Network Traffic Flows

The change in traffic volume on major roads in the study area is clearly shown in Figure 4.1. Using Quantile classification method in ArcMap to derive the categories the change in volume is shown along multiple segments of roads. Traffic along King Street can be seen as mostly between 13044 through 55339 vehicles before the pilot was put into place. After the pilot, several sections of the road have decreased to the 8345-13044 category. Queen Street which is the northern most road in Figure 4.1 can be seen to absorb the excess traffic as several sections have moved up in volume demonstrated by first the yellow road links through to red. All roads adjacent King Street saw increased traffic volumes following the Pilot. Table 4.1 shows the change in traffic along King Street from before and after in more detail.

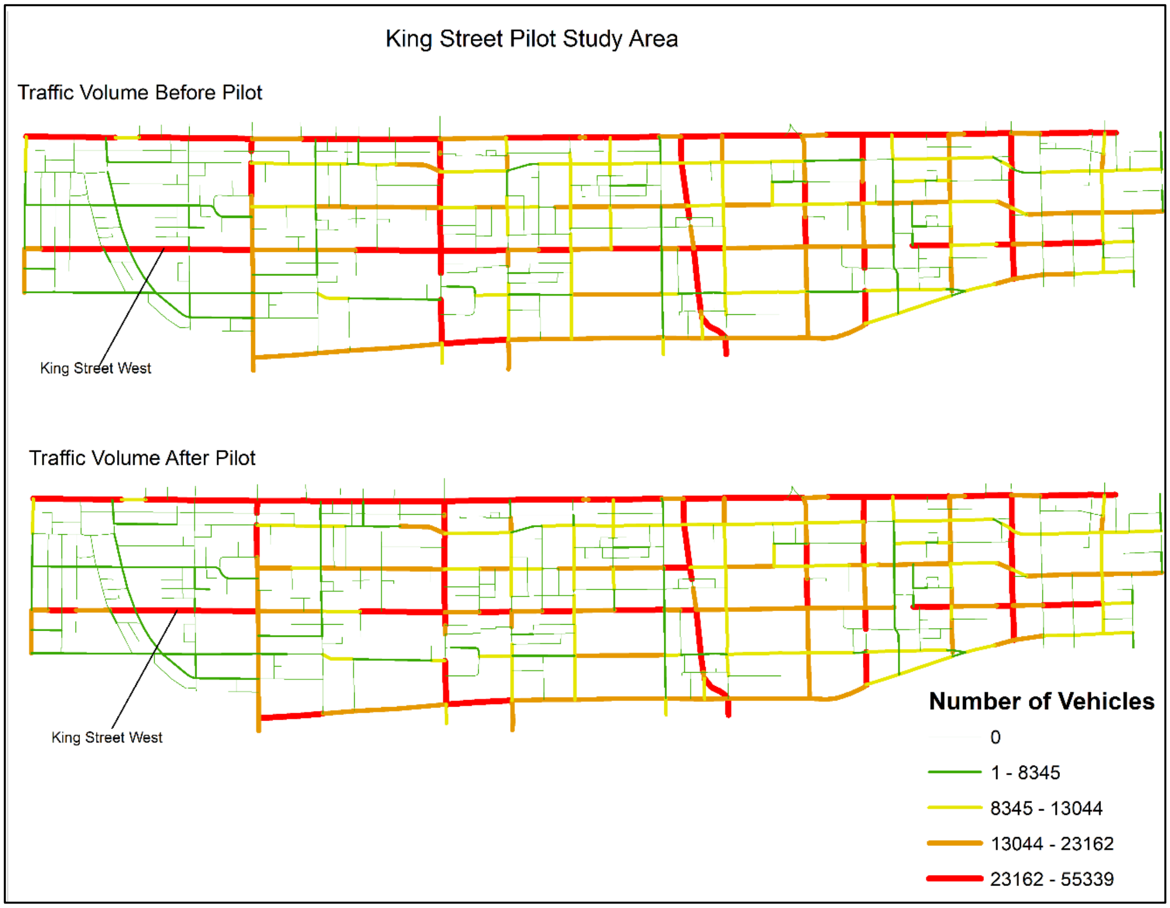

Figure 4.1 Comparison of the different traffic flow rates in the King Street Pilot Study Area from the University of Toronto Modelled Traffic Flow Data

Table 4.1: Traffic flow along King Street as segmented in the shapefile using the University of Toronto modelled traffic flow data

Road Segment	AADT Before	AADT After
50-70 King St E	25394	25742
70-92 King St E	25350	25811
106-130 King St E	12772	16783
210-222 King St E	23177	24014
230-250 King St E	9788	11437
120-144 King St E	24622	25249
150-172 King St E	16829	19714
200-204 King St E	23568	24359
901-982 King St W	15921	15255
881-880 King St W	24493	24283
855- 879 King St W	24350	24137
845-834 King St W	23553	21058
833-797 King St W	23922	23690

4.2 Traffic Sound Level Predictions

The pre- and post-pilot noise models ran from the 17th of August to the 26th of August, each having run for three days. The unaccounted for days were used to ensure the models were running correctly and to ensure their proper setup for re-runs if necessary. The maximum simulated noise levels occurred in the core of the city before the pilot was put into place was 69.9 db(A). This was the L_{den} or the day, evening, and night level. The highest noise on the façades of buildings was found adjacent to the major arterial roads in Toronto's downtown core. This is where the buildings are highest, traffic levels were at their peak and the reverberation was very high. Figures 4.2 through 4.6 show that buildings nearest to the major roads had the highest noise while the façades of buildings where they either faced inwards or were next to laneways had low levels of noise. The lowest level of simulated traffic noise was 17.4 decibels. This occurred in the downtown in the less dense areas of the study area as shown in figures 4.5 and 4.6.

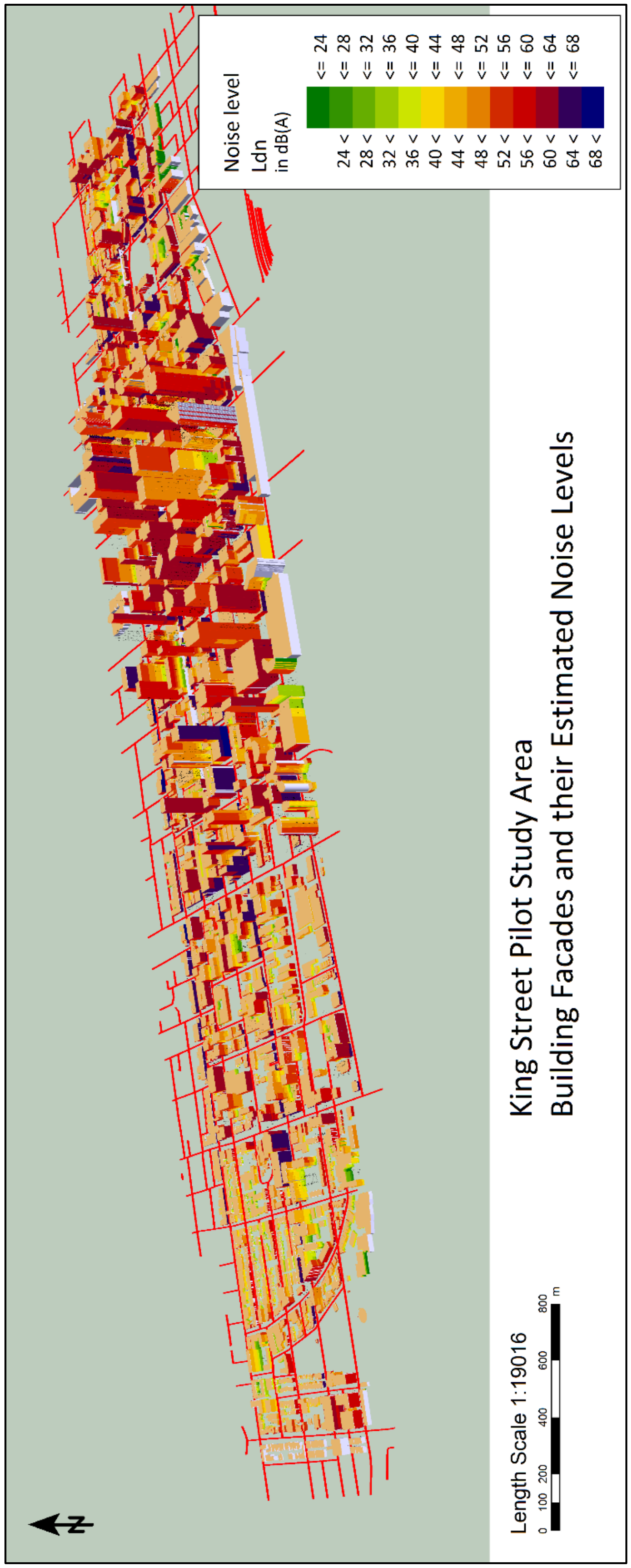

Figure 4.2- The King Street Pilot study area with the modelled noise levels before the pilot was put into place, displayed on the façades of buildings

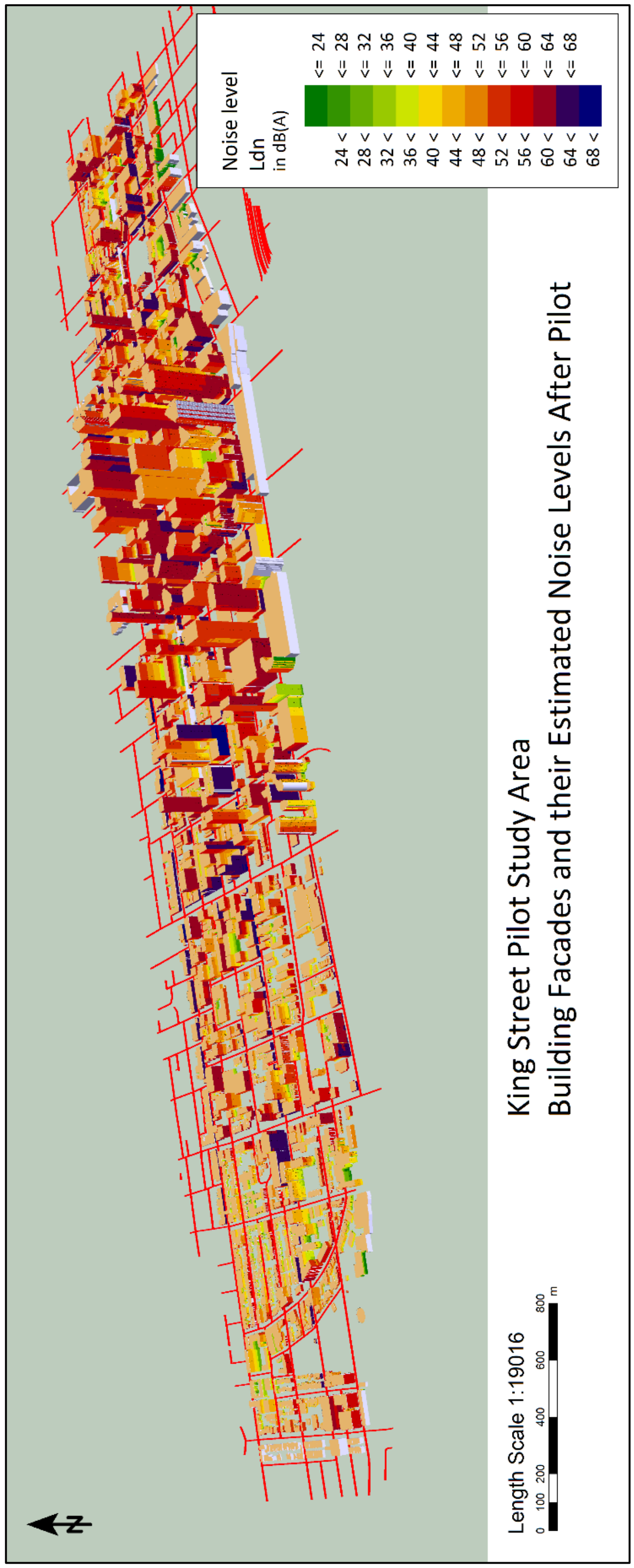

Figure 4.3- The modelled noise on the façades of buildings after the King Street Pilot was put into place

Figure 4.4 shows the extreme levels of noise in the highest density area of the pilot study. The estimated noise can be seen to change depending on building height. While façades that face roadways are higher in noise, façades that face inwards are generally low in noise. The height of the buildings also has an effect on how loud estimated noise is. In most cases, buildings see less noise as they get higher but there are several circumstances where this is reversed in the downtown area. The dense clustering of buildings that are more than 20 floors can cause unique circumstances where the reverberations and reflections off the façades of buildings can actually increase the overall noise.

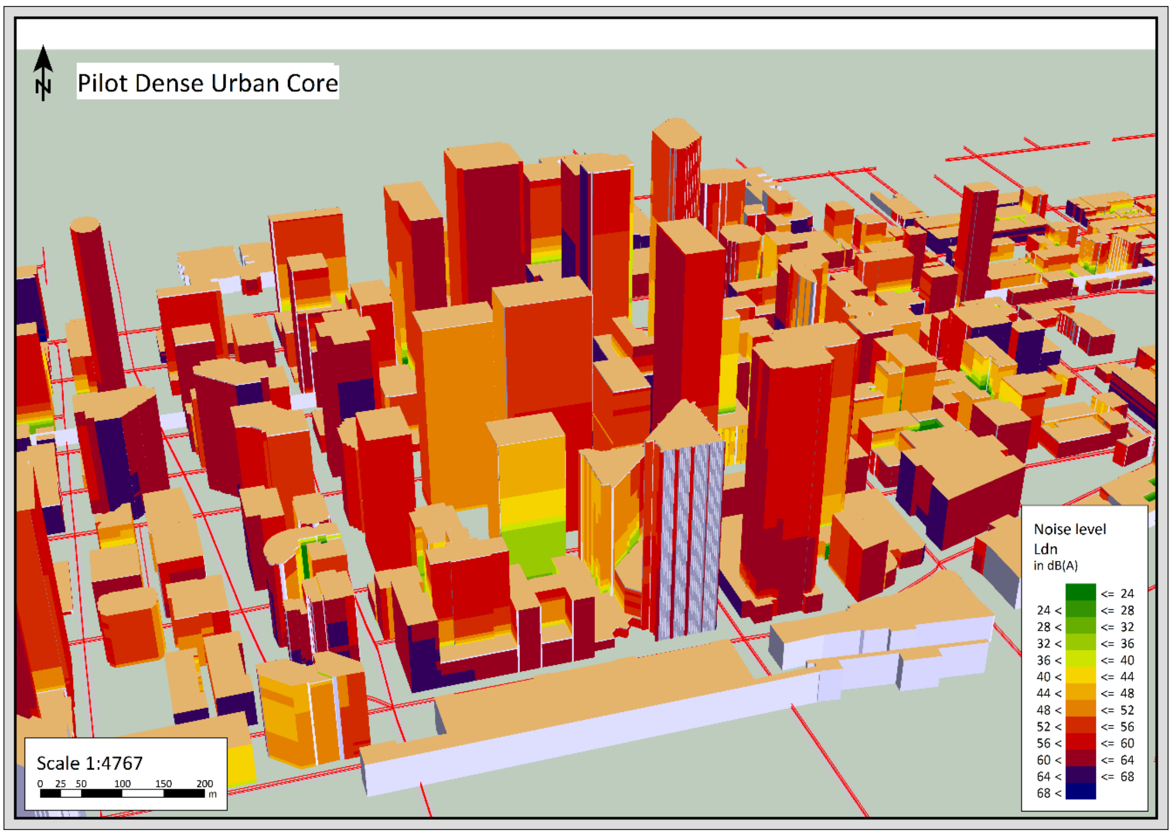

Figure 4.4 - The modelled noise on the façades of buildings with each dot representing a receiver.

Figure 4.5 shows an even less dense urban area of the pilot. Similar to the core of the city several buildings can be seen to have lower noise on the ground floors while being noisier up top. In this case, the lower height of some buildings along the roadways blocks noise from the lower floors while letting it travel to the higher floors of buildings behind them. This is true for both the eastern and western parts of the city. The noise levels along the streets are demonstrated once more in Figures 4.5 and 4.6 where noise is in the upper categories (64-68 db(A)) along major roads while sheltered enclaves see very low noise in the lowest categories. Although as seen in Figure 4.6 there are many buildings that appear to be low in estimated noise, these buildings hold very few people when compared to the larger buildings downtown.

Figure 4.5 - Modelled noise levels on the façades of buildings in the eastern area of the study area

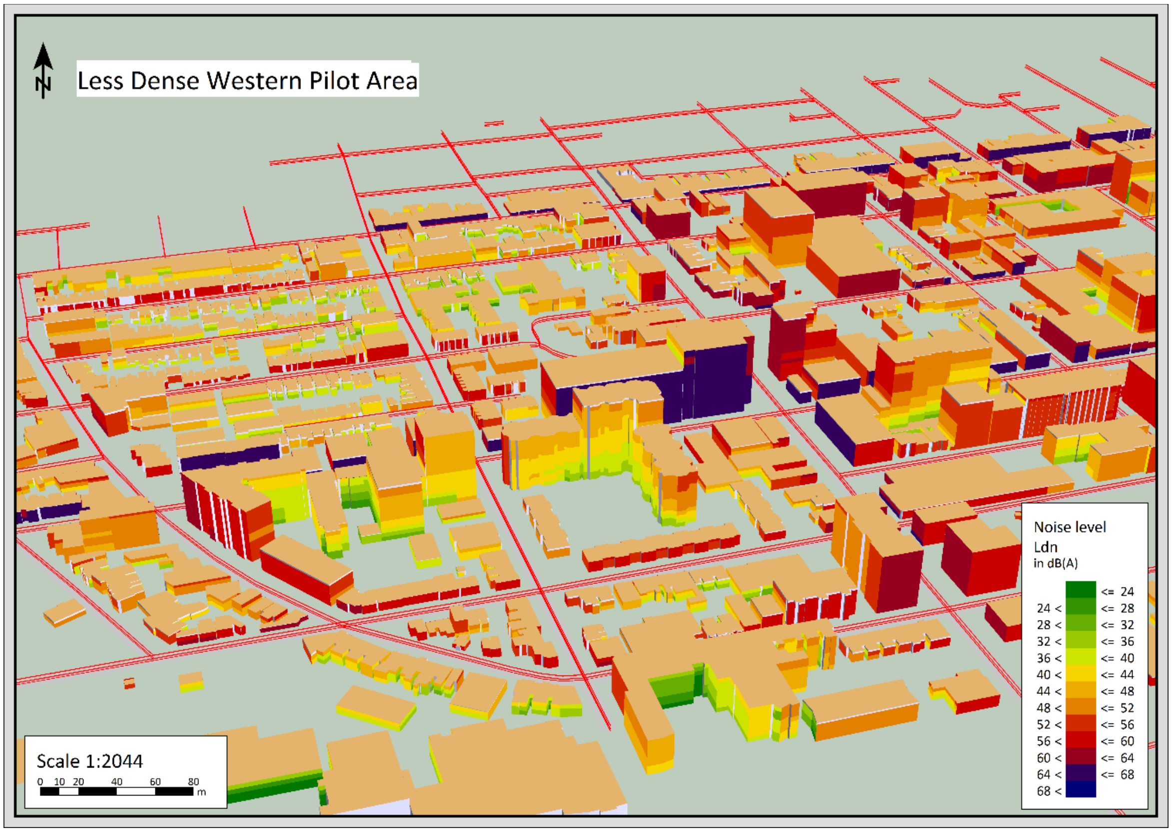

Figure 4.6 - Modelled noise levels on the façades of buildings in the western area of the study area

4.3 Traffic Noise Exposure Changes

Of the 114,335 simulated façade receivers the average estimated noise levels were 61.5 db(A) before the pilot and 61.6 db(A) after. Table 4.2 shows the largest category of those exposed to high levels of noise occurred between the 55 db(A) and 70db(A) where 92% of the population was included. At the highest levels measured (65-70) 27% of the population was estimated to be exposed. After the pilot was put into place the maximum noise level increased slightly to 70.2 db(A) and the lower limit was 17.5 db(A). The difference in the estimated exposure of residents came from the 60-65 db(A) category where originally 53% of residents were estimated to be exposed before the pilot while only 51% were after it was put into place. Before the pilot was put into place, 1.24% of all residents were exposed to noise under 45 db(A) and 8.34% of the total residents before the pilot were exposed to noise under 55 db(A). This meant that in total, 98.76% of residents were exposed to noise over 45 db(A) while 91.66% were exposed to noise over 55 db(A). After the pilot was put into place, slightly more residents overall were exposed to noise over 45 db(A) at 98.94% while 92.45% were exposed to levels above 55 db(A).

Table 4.2: Estimated noise levels in 5 db categories and the percentage of modelled exposure to residents in Toronto

Noise levels	Percent of Residents Exposed (%)	
Measured in db(A)	Before Pilot	After Pilot
<20 or less	0	0
20-25	0.12	0.13
30-35	0.05	0.05
35-40	0.14	0.12
40-45	0.93	0.76
45-50	3.06	2.58
50-55	4.04	3.91
55-60	11.04	11.25
60-65	52.89	51.16
65-70	27.73	30.04

5. Discussion and Conclusion

This research demonstrates the effectiveness of estimating urban noise pollution through multistep noise modelling. By combining several traffic related variables while estimating the residential population density, SoundPlan was able to assign an estimated noise level to specific building façades and therefore the residents that potentially occupy the buildings. Modelling the downtown core of a city took the distributed network of computers several days to calculate over 100,000 receivers on the façades of buildings. These buildings saw high levels of noise where traffic was heaviest while noise low noise levels when traffic was lessened. The difference in noise was estimated to be along the major roads where the pilot took place. While the noise overall in the city did not change much, this was not surprising as the goal of the pilot was not to decrease overall traffic in the city. Where the traffic was lowered along King, it migrated to the streets adjacent. This association can be taken to mean that similar pilots can be implemented along downtown streets and where the traffic decreases so will the amount of those exposed to the dangerous levels of noise.

The noise from vehicle engines at lower speeds and eventually with higher speeds the noise from tires on the pavement has effects on both perceived and unperceived noise annoyance and public health. The steep increase in population of urban environments coupled with the built urban form creates situations where reverberation is high and exposures levels follow. Tang & Wang (2007) discussed this where they modelled the effects of the urban built environment on both noise and air pollution. The increase in the population of cities also comes with an increase in the amount of vehicles on the road. Anywhere there are people, vehicles follow and so does noise exposure. Levy et al. (2010) discussed the growth of congestion in urban spaces and how this growth leads to the inevitable over exposure of city dwellers.

By evaluating the built form of urban environments with higher spatial resolution than the discussed 'mesoscale model systems' (Tang & Wang, 2007) they could more accurately model buildings on individual levels. This paper used a similar spatial resolution to develop a model that can accurately simulate noise propagation in Toronto and more specifically in the urban core. This study found, that although noise did not increase significantly, the overexposure of residents living in the study area is extreme.

The estimated noise levels modelled in this study have several implications of the observed changes in noise exposures of residents in urban areas. When residents are exposed to levels of noise higher than 45 db(A) negative health effects begin. Over 98% of residents in Toronto are exposed to this level while over 91% are exposed to levels above 55 db(A). WHO recommends traffic noise levels for urban residents remain under 45 db(A) in the day and under 35 db(A) at night. Noise annoyance begins at 55 db(A) as defined by WHO. This means for Toronto residents most of the population is overexposed to dangerous levels of noise. Most of the residents in the study area will see annoyance and sleep disturbance as well as health related issues at chronic levels.

The limitations of this model come mainly from the estimated traffic flow volumes. These volumes did not accurately estimate the traffic levels along King Street specifically which led to noise levels have little change in the SoundPlan model and overall in the study area. The restrictions that would have been necessary in order to produce accurate results along

King Street would have changed the fundamental nature of the calculations making the model more unreliable with restrictions than without. The City of Toronto have published documentation stating that the traffic at peak times was reduced by 80% after the pilot was put into place (City of Toronto, 2018). This is a major reduction of traffic but the difficulty of translating peak volumes to 24 hour averages that were used in this study was evident when running these models. Although the King Street Pilot reduced traffic along King Street and potentially the noise, the nature of traffic flow means the vehicles must move elsewhere in the city.

WHO has many recommendations and intervention plans to help curb noise and potentially change exposure related negative health outcomes. Reducing the exposure at source level is one of those recommendations and the King Street Pilot is one way of addressing this issue. The volume of traffic along King Street after the Pilot was put into place as reported by the City of Toronto would normally be the most effective way to curb noise. The change in traffic flow on existing roadways as a prevention measure is discussed in great detail in the systematic review of Transport Noise Interventions and Their Impacts on Health published by WHO (Brown & Van Kamp, 2017). The measureable change in both noise and resident exposure is a large part of the framework intended to intervene when estimated noise levels are as high as they are in Toronto.

The negative health impacts of traffic noise are serious and can have long-term effects if continuously exposed. Putting traffic noise measures in place like the King Street Pilot can curb noise and therefore help prevent unnecessary health problems for residents living along King Street. More of these types of projects must therefore be considered in Toronto to help curb noise in the city as a whole to benefit the most amount of people. Downtown streets are the priority as this is where the highest density of the population live and the King Street Pilot is a good first step in addressing chronic noise in Toronto.

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