Constructing a Noise Propagation Model to Assess Community Noise Levels Stemming From Road Traffic: The Case of Somerville, MA

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Abstract

This thesis explores the relationship between road traffic noise and sleep patterns, high blood pressure, and annoyance in Somerville, Massachusetts. Road traffic noise is assessed using a noise propagation model and predicted average day, night, and 24 hour noise decibel levels are calculated at the homes of participants in an ongoing NIH study of the health effects of exposure to traffic exhausts in the Somerville area (n=204). Using these modeled noise values, spearman correlations are calculated to assess the relationship between residents' sleeping patterns, high blood pressure diagnoses, and overall annoyance to road traffic noise. Modeled noise levels show that residents living closest to major roadways are subjected to noise levels that are 36% higher than WHO standards. Correlation results find a significant and positive correlation between the modeled noise levels and resident annoyance towards road traffic noise.

Introduction

Typing “noise” and any one or more of the following words --annoyance, stress, or quality of life--into a search engine will turn up an abundance of message boards, blogs, and YouTube videos detailing stories and actual footage of urban dwellers at their wits end when it comes to noise within and surrounding their living environments. From road traffic, train horns, and low flying airplanes, to construction projects, cries of domestic animals, and neighbors’ footsteps, the urban environment hosts a wide range of potential auditory nuisances. Both the Noise Control Act of 1972 and the Quiet Communities Act of 1978 define noise as any sound that may produce an undesired physiological or psychological effect in an individual or group (EPA 1977). At the time these two Acts were passed, the EPA estimated that well over half of the Nation’s population was exposed to noise on a daily basis (EPA 1977). Unfortunately, because of the many common assumptions our society has towards noise -- that it is the sacrifice we must make as we move towards a more technologically advanced society (Anthrop 1970); that significant adverse effects do not occur at decibels below noise levels deemed to be harmful (EPA 1977); or that individuals exposed to such noise adapt to it over time (Weinstein 1982) -- noise has become an often overlooked environmental health issue. Traffic noise is an increasing problem in our society and is the dominating source of noise in the urban environment (Ouis 1999).

The focus of this thesis is to model and describe the impact of noise generated by road traffic on residents living in Somerville, Massachusetts. The chosen region of analysis corresponds to an ongoing large-scale epidemiologic study of the Boston area known as the Community Assessment of Freeway Exposure and Health (CAFEH), which is a community-based participatory research project funded by the National Institutes of Health to assess the association between exposure to air pollutants emanating from highway traffic and cardiovascular health in the affected communities.

It is my hypothesis that noise represents a major confounding factor between any observed associations between air pollution and cardiovascular health. To test this hypothesis, I will construct a noise propagation model, which will give predicted levels of noise from nearby roads to the Somerville community. These noise values will be compared with available data from the CAFEH study to explore relationships between reported noise annoyance and health conditions in the study population.

This thesis is organized as follows: first, I provide a brief physical and biological background on sound that explores the nature of sound, how it is transmitted and propagated within a community, and how the human body processes sound. Second, I will examine the existing literature to describe the relationship between road traffic noise and cardiovascular health. Third, I will construct a noise propagation model to calculate predicted daytime and nighttime noise exposure levels of CAFEH Somerville area participants. Fourth, using these predicted values and CAFEH survey data, I will run a series of correlation tests to explore significant relationships between the predicted noise levels and sleep duration, reported annoyance to road traffic noise, and high blood pressure.

Literature Review

Existing epidemiological noise research assessing the links between environmental noise and human health has provided initial evidence to suggest that such noise exposure can be injurious to an individual's health. Table 1 provides an exhaustive list of the various health effects related to noise exposure and the level at which they may occur (Passchier-Vermeer and Passchier 2000).

Table 1: Environmental Noise Exposure Level and Corresponding Health Effects

Effect	Decibel Level (dB)
Hearing Impairment	70-75
Hypertension	70
Ischemic Heart Disease	70
Annoyance	42
Performance	70
Disturbance of Sleep Pattern	< 60
Awakening	55
Sleep Quality	40
Mood Next Day	< 60

Source: (Passchier-Vermeer and Passchier 2000)

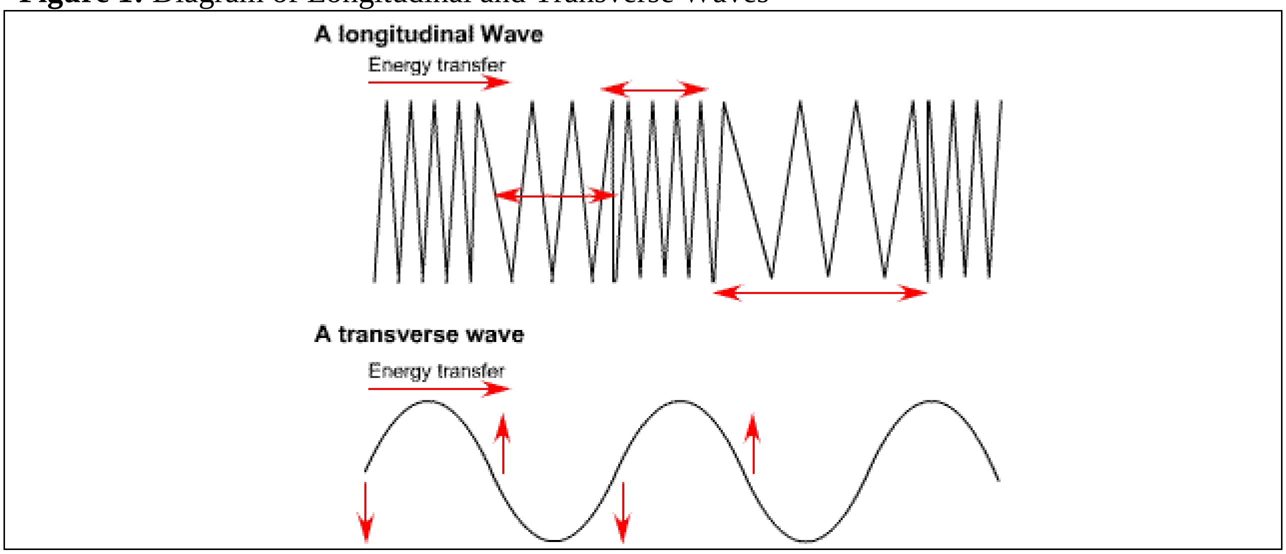
While this table aggregates all environmental noise exposures, of particular interest is the 70dB benchmark for negative cardiovascular health effects. However, to understand exactly what 70dB is or how it is experienced by the body, I will now briefly explore the scientific nature of sound.

THE SCIENCE OF SOUND AND SOUND PROPAGATION

What is Sound?

Sound is defined as mechanical waves emanating from a source, which can travel through a gas, liquid, or solid and have frequencies that fall in the audible range (Halliday and Resnick 2001). Sound is transmitted through two types of waves—longitudinal waves and transverse waves. Longitudinal waves occur when the oscillations are parallel to the direction of travel. Transverse waves occur when the oscillations are perpendicular to the direction in which the wave travels. Figure 1-1 illustrates these two types of waves.

Figure 1: Diagram of Longitudinal and Transverse Waves



Source: http://schools.look4.net.nz/science/physics/waves/characteristics

In a solid medium, sound is transmitted through both longitudinal and transverse waves. However, in gaseous or liquid mediums, only longitudinal waves can be transmitted. Additionally, sound waves are also characterized by their wavelength, frequency, and intensity.

Wavelength

Wavelength is defined as the horizontal distance between any two successive equivalent points on the wave (Halliday and Resnick 2001). With any group of sounds, the most notable distinction amongst them is that some sounds are higher in intensity or lower in intensity than other sounds. The varying distances between waves creates these differences (Halliday and Resnick 2001). Waves with longer wavelengths (long waves) don't arrive as often as waves with shorter lengths (short waves). Therefore, short waves sound high and long waves sound low. Short and long waves can be additionally defined by its frequency, which is described below.

Frequency

Mathematically, frequency f is defined by the following equation:

$$f = 1 / T$$

where T represents the time for completing one cycle (Halliday and Resnick 2001). The unit of frequency is the Hertz (Hz), and it refers to the number of vibrations per second of the air in which the sound is propagating (WHO 1999). Below is a table of sample frequencies with corresponding descriptions:

Table 2: Examples of Frequency Levels

Frequency (Hz)	Description
16 – 32 Hz	The human threshold of feeling, and the lowest pedal notes of a pipe organ.
< 20 Hz	Sound pulses
32 – 512 Hz	Rhythm frequencies, where the lower and upper bass notes lie.
1000 Hz	**Threshold of Hearing**
512 – 2048 Hz	Defines human speech intelligibility, gives a horn-like quality to sound.
2048 – 8192 Hz	Gives presence to speech, where labial and fricative sounds lie.
8192 – 16384 Hz	Brilliance, the sounds of bells and the ringing of cymbals. In speech, the sound of the letter "S" (8000-11000 Hz)
< 20,000	Upper limit of audibility

The range of frequencies audible to the human ear ranges between 20–20,000 Hz (WHO 1999). Within this range, however, the human ear does not equally hear at every frequency (Bilawchuk 2010). While the human ear is not very sensitive to low frequency sounds (which correspond to a high T), the human ear is very sensitive to high frequency sounds (a low T) (Bilawchuk 2010). Due to the large frequency range of human hearing, the complete spectrum is divided into 31 bands, each known as a 1/3 octave[1] band. (Bilawchuk 2010). An illustration for a center frequency of 2000 Hz is given in Table 3 below:

Table 3: Illustration of Whole Octave and 1/3 Octave Bands

Whole Octave			**1/3 Octave**		
Lower Band Limit (Hz)	Center Frequency (Hz)	Upper Band Limit (Hz)	Lower Band Limit (Hz)	Center Frequency (Hz)	Upper Band Limit (Hz)
1420	**2000**	2840	1778	**2000**	2239

[1] An octave is defined as a series of eight notes occupying the interval between (and including) two notes, one having twice or half the frequency of vibration of the other. Source: Halliday D, Resnick R. 2001. Physics. New York: Wiley.

Intensity

To deal with such a massive range of frequency values, the intensity of a sound is most commonly described in decibel levels. The most common decibel weighting measure used is "A-weighting". This measure converts frequencies into a sound pressure level, which is measured in decibels (dB) (Bilawchuk 2010). For example, applying an "A weight" to a frequency of 2000 Hz, gives you a decibel level of 0.

Using this A-weighting, a description of the experience associated with the decibel levels shown in Table 1 is provided in Table 4. As you can see, a decibel level of 70, which has been associated with Hypertension and Ischemic Heart Disease, can be categorized as "annoying" and is equivalent to the sound of a vacuum cleaner (Robinson 2010).

Table 4: Noise Makers and Corresponding Decibel Levels

Noise	Decibel Level	Sound Level
No Sound	0	Very Quiet
Breathing	10	
Soft Whisper	15	
Rustling Leaves	20	
Quiet Library	30	
Suburban Neighborhood	45	
Private Office	50	Quiet
Normal Conversation	60	
Vacuum Cleaner	70	Annoying
Telephone Dial Tone	80	Loud
Food Blender	90	
Subway Train (200 ft)	95	
Garbage Truck	100	Very Loud
Power Lawn Mower	105	
Chainsaw	110	
Jackhammer	115	
Live Rock Concert	120	Pain Threshold
Stock Car Race	130	
Gun Muzzle Blast	140	
Jet Engine (30 ft)	160	
Jet Engine (1 ft)	180	
Sonic Boom	212	Beyond Pain Threshold

Now, I will turn to sound propagation to describe how these various environmental noise sources travel throughout the environment.

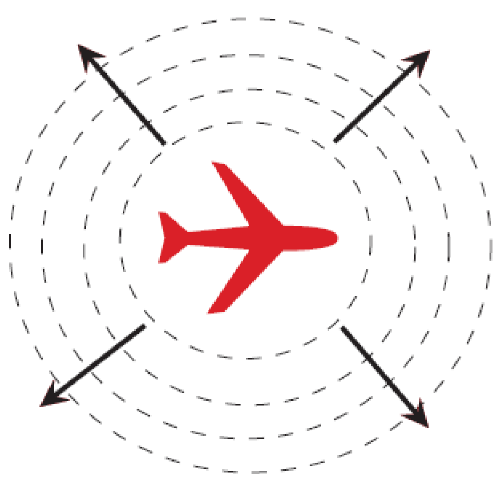
Sound Propagation

Sound propagation is the transmission of acoustic energy through a medium via a sound wave (Halliday and Resnick 2001). There are three important factors that affect the propagation of sound: geometric spreading, atmospheric effects, and surface effects (Halliday and Resnick 2001).

Geometric Spreading

Geometric spreading is the spreading of sound as a result of the expansion of the sound waves (Halliday and Resnick 2001). Depending on the sound source, either point or line, sound waves propagate as either a spherical or cylindrical wave fronts. Two examples are given below to illustrate this concept.

Figure 2: Point Source, Spherical Wave: Jet Engine Noise Propagation over a Community



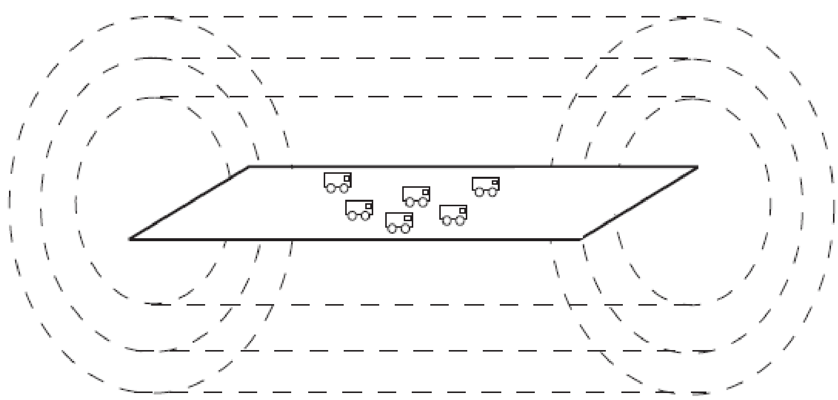
Source: Erica Walker

As sound radiates from a point source, it scatters through geometric spreading using the following relationship (Bilawchuk 2010):

$$\text{Sound Level}_{(\text{location 1})} - \text{Sound Level}_{(\text{location 2})} = 20\log_{10}(r_2/r_1)$$

Where r_1 is the distance from the source to location 1 and r_2 is the distance from the source to location 2. Therefore, as an example (with no atmospheric absorption): A point source measuring 50 dB at 100 meters will be 38 dB at 400 meters.

Figure 3: Line Source, Cylindrical Wave: Road Traffic Noise Propagation within a Community



Source: Erica Walker

A line source is equivalent to a long line of many point sources (Bilawchuk 2010). It scatters through geometric spreading with the following relationship (Bilawchuk 2010):

$$\text{Sound Level}_{(\text{location 1})} - \text{Sound Level}_{(\text{location 2})} = 10\log_{10}(r_2/r_1)$$

Therefore, as an example, a line source measuring 50 dB at 100 meters will be 34 dB at 400 meters.

Atmospheric Effects

The dissipation of sound energy in the atmosphere follows from rules of thumb below (Bilawchuk 2010):

- As frequency increases, absorption increases
- As relative humidity increases, absorption increases
- There is no direct relationship between absorption and temperature

Meteorological Effects

There are a number of meteorological factors that can affect how sound propagates over large distances (Bilawchuk 2010). These meteorological effects are wind, temperature, and rain. Depending on the direction, wind can significantly change the noise climate as you move away from the noise source. Such deviations fall within a range of 10 dB but depend on the severity of the wind and distance from the noise source (Bilawchuk 2010). Additionally, wind tends to generate its own noise, which can mask certain types of noise.

Temperature effects are similar to wind effects. Sound level differences of 10 dB are possible depending on gradient temperature and the distance from the noise source (Bilawchuk 2010). Rain does not affect sound propagation unless the rain is very heavy (Bilawchuk 2010).

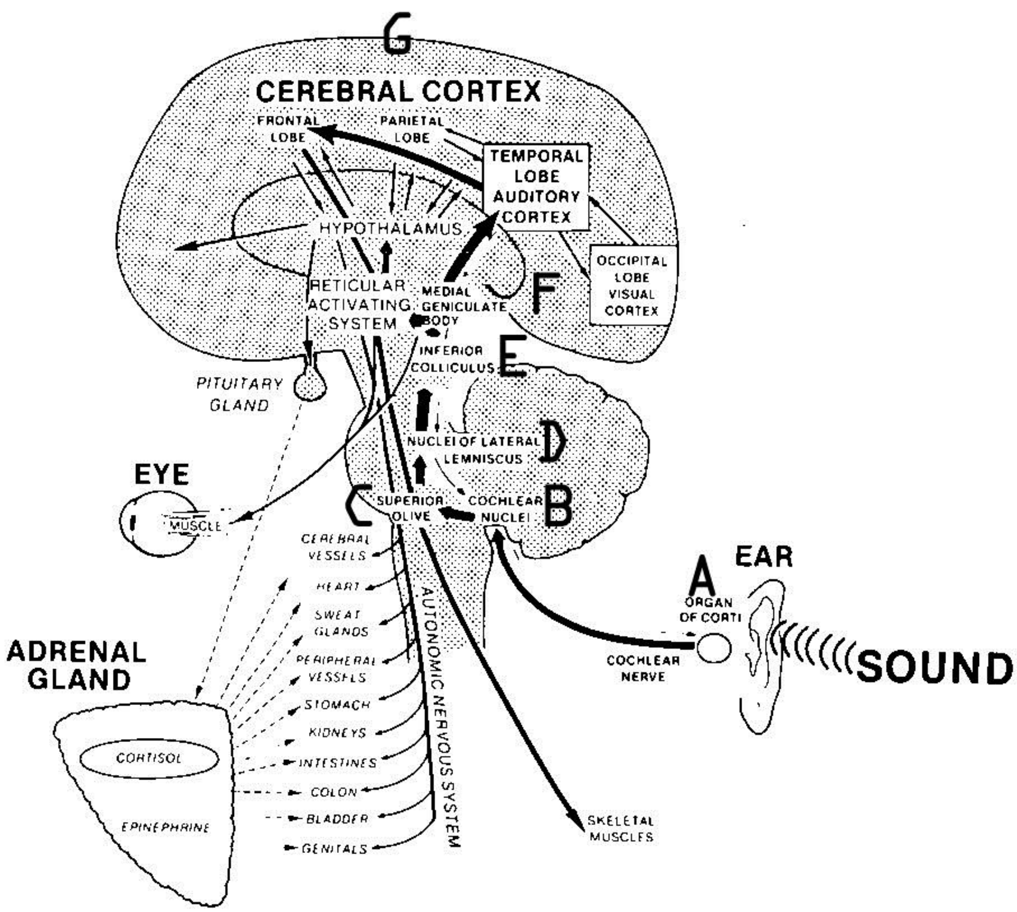
Topographical Effects

Sound propagation can also be greatly affected by the geographical and vegetative composition of a location. The main factors affecting propagation are topography, grass, trees, bodies of water, and snow. Topography is the most important factor and can be both a natural barrier and amplifier of noise (Bilawchuk 2010). Grass and trees can effectively absorb noise but only if they exist in large spans (Bilawchuk 2010). Bodies of water can provide the opposite effect to grass and trees (Bilawchuk 2010). Freshly fallen snow can be quite absorptive while snow which has been sitting for a while can reflect noise (Bilawchuk 2010).

Sound and the Human Body

A pictorial representation of the auditory system can be found in Figure 4 below.

Figure 4: Pictorial Representation of the Auditory System



Source: Westman and Walters 1981

The auditory system is continuously analyzing acoustic information (Babisch 2006). To do so, the auditory system uses a set of direct and indirect pathways. The direct pathway can be further broken down into ascending and descending pathways. Referring to Figure 4, ascending pathways consists of B, C, D, E, F to G. Sound penetrates the organ of corti (A), which sends impulses to the auditory system in the cerebral cortex. These impulses first travel through the ascending path along the auditory nerve and pass through the cochlear nuclei, the superior olivary complex, the inferior colliculus, the nuclei of the lateral lemniscus, and the geniculate body to a number of areas in the auditory cortex that are connected to other cortical areas which also receive inputs from other sensor organs (Westman and Walters 1981).

The descending pathway works in reverse to the ascending pathway. There are two descending pathways: G, E to B and F, E, D, to A. Generally, the descending pathway is regarded as exercising an inhibitory function by determining which ascending impulses are to be blocked and which are allowed to pass to other centers in the brain (Westman and Walters 1981).

Besides these direct pathways to and from the cerebral cortex, there are also a variety of indirect pathways, which stretch from the inner ear to the brain center and control the basic physiological, emotional, and behavioral responses of the body (Westman and Walters 1981).

Once noise is detected and processed through the auditory system, it may lead to the arousal of the sympathetic nervous system and finally, the arousal of endocrine system, which leads to changes in the physiological functions and metabolism of the individual exposed (Babisch 2006). These physiological changes includes changes in blood pressure, cardiac output, blood lipids (cholesterol, triglycerides, free fatty acids, phosphatides), carbohydrates (glucose), electrolytes (magnesium, calcium), blood clotting factors (thrombocyte aggregation, blood viscosity), leukocyte count and others (Babisch 2006). Given that these changes represent major risk factors for cardiovascular disease, over time chronic exposure to noise may increase the risk of cardiovascular disorders, in particular, hypertension, arteriosclerosis, and ischemic heart disease.

HEALTH EFFECTS OF NOISE

Over the last thirty years, a large number of studies have been conducted to determine if and to what extent exposure to noise negatively affects our health. However, it has only been within the past twenty years that studies have made strides towards understanding the relationship between noise exposure and cardiovascular health (Kluizenaar et al. 2002). While occupational noise studies have provided evidence linking workplace noise exposure to hypertension (Gan et al. 2011; Inoue et al. 2005), only within the past fifteen years, however, have epidemiological studies begun to center the discussion on *transportation noise* and cardiovascular health. This literature review will focus on more recent epidemiological studies on transportation noise exposure and cardiovascular health outcomes published during the past ten years, with special emphasis on the most recent studies.

Tobias, A., Julio, D., Saez, M., Alberdi, J.C., (2001)

Tobias et al.(2001), examined the short-term effects of environmental noise levels on the daily emergency admissions in Madrid, Spain between 1995-1997. All causes of emergency admissions and separately, circulatory and respiratory related admissions, were considered.

Descriptive statistics on community noise levels showed that under WHO guidelines, there were high noise levels (more than 65 dB) for more than 90% of the day. Eighty percent of the environmental noise originated from road traffic. Both Poisson regressions and Box-Jenkins methodology were used to assess the impact of 1 dB increments of increased noise levels on daily emergency admissions. Poisson results show that roughly 5% of all emergency admissions can be attributed to environmental noise levels over 65 dB. For circulatory specific cases, roughly 4% of all emergency admissions can be attributed to environmental noise levels over 65 dB.

Box-Jenkins results show that for all causes of emergency admissions, for each dB over the threshold of 65 dB, there was an increase of 3.3 emergency admissions per day, which implies a roughly 5% increase on the total of the emergency admissions for all causes. A similar discovery was made for circulatory-related emergency admissions, where each dB over the threshold of 65 dB prompted an increase of 0.58 emergency admissions per day, which translates into a 5% increase.

de Kluizenaar, Y., Gansevoort, R., Miedema, H., de Jong, P. (2002)

de Kluizenaar et al. (2002) assessed the relationship between road traffic noise exposure and the prevalence of hypertension in Groningen City, Netherlands, using a random sample of inhabitants of the city and individuals who were participating in the Prevention of Renal and Vascular End-Stage Disease (PREVEND) study. All participants were between the ages of 28 and 75 and completed a detailed questionnaire on demographics; cardiovascular, renal, and family medical history; use of anti-hypertensive medication; and smoking status. Hypertension was defined as systolic blood pressure ≥ 140 mm Hg, diastolic blood pressure ≥ 90 mm Hg, or use of anti-hypertensive medication based on pharmacy reports. Road traffic noise was calculated using a noise propagation model. A logistic regression model was used to determine the association between exposure to road traffic noise and hypertension.

In both the City of Groningen and individuals in the PREVEND cohort, subjects with hypertension were found to reside in areas with higher average noise levels -- 53.3 dB versus 54.6 dB in the City of Groningen sample and 52.8 dB versus 54.3 dB in the PREVEND cohort. Additionally, individuals with hypertension were more frequently exposed to noise levels greater than 55 dB.

Odds ratios (ORs) within the City of Groningen sample showed that noise levels greater than or equal to 55 dB had statistically significant associations with self-reported use of medication for hypertension. Specific odds ratios with 95% confidence intervals in parenthesis are 1.31 (1.25 – 1.37), 1.01 (0.96 – 1.06), 1.01 (0.96 – 1.06), and 1.03 (0.96 – 1.11) for an unadjusted, age and sex adjusted, full, and full plus PM_{10} models, respectively. For the PREVEND Cohort only in the unadjusted model did significant associations exist between hypertension and noise levels greater than 55 dB OR = 1.35 (1.27-1.45).

Babisch, W., Beule, B., Schust, M., Kersten, N., Ising, H. (2005)

Babisch et al. (2005) set out to determine the risk of road traffic noise for the incidence of myocardial infarction (MI) using a matched case-control study design within the city of Berlin, Germany. Eligible patients were enrolled over a period of three years from 1998 – 2001, and included those consecutively admitted to 32 major hospitals in Berlin with confirmed diagnosis of acute MI or survivors of sudden cardiac arrest (based on WHO diagnostic criteria) between the ages of 20 and 69.

Hospital controls were individually matched according to sex, age, and hospital. Additionally, controls such as the home environment, socio-demographics, family history of MI, smoking, educational level, marital status, employment status, working hours, and noise sensitivity were obtained using standardized interviews. Data on diagnoses of diabetes mellitus, hypertension, hyperlipidemia, and BMI was obtained from clinical records.

To assess traffic noise exposure, noise maps from the city were used. Noise levels for main roads with more than 6,000 vehicles per day were calculated using dosimeters, which are instruments used to assess noise levels within the environment. Subjective noise exposure was obtained from the survey. Noise group categories were as follows: ≤ 60 dB (side streets), 61-65 dB (side streets and main roads), 66-70 dB (main roads), and > 70 dB (main roads). Within the total study sample, there was minor increase in risk of MI for the men as the sound level intensifies (odds ratio: 1.01 (0.77-1.31), 1.13 (0.86-1.49), 1.27 (0.88-1.84) for noise groups 61-65 dB, 66-70 dB, >70 dB, respectively). However, within the total sample of women, there was no apparent risk. Within the subsample of individuals who had lived at least 10 years at their current address a similar story exists. For men, risk increased as noise levels increase (odds ratio: 1.17 (0.81-1.69), 1.31 (0.88-1.97), 1.81 (1.02-3.21) for noise groups 61-65 dB, 66-70 dB, >70 dB, respectively). For women, there was no noise effect.

When looking at the association between road traffic noise annoyance and MI, the risk of MI is elevated by road traffic noise annoyance at night in men only OR (1.10 (0.90-1.18)).

<u>Bluhm, G.L., Berglind, N., Nordling, E., Roselund, M. (2007)</u>

In 2007, Bluhm et al. studied the association between residential road traffic noise and hypertension in a municipality of 55,000 residents located 12 km from Stockholm, Sweden. A stratified random sample procedure was used to ensure a sufficient number of subjects were exposed to traffic noise, with two strata comprised of 500 residents each. The first stratum was the noise-exposed group, which was drawn from those individuals living within 100 meters on each side of the. The second stratum was drawn from the remaining part of the study area.

Hypertension was defined as a positive answer to the question "Have you been diagnosed with hypertension by a physician during the past five years?" Additional socioeconomic and health factors were controlled for in the model.

Individuals were classified into noise exposure categories of 5 dB(A) increments, from ≤ 45 dB(A) to > 65 dB(A), according to the noise level at their residence. A noise propagation model was constructed to assess noise levels.

A relationship between road traffic noise and hypertension was investigated using logistic regressions. Results show that the odds ratio (OR) for hypertension adjusted for age, smoking, occupational status and house type was 1.38 per 5 dB(A) increase. The association appeared to be stronger for women (OR: 1.71 (1.17 - 2.50)) and among those who had lived at their address for more than 10 years (OR: 1.93 (1.38 to 4.43)). The strongest association between road traffic noise exposure and hypertension was found amongst those who did not have triple-glazed windows (OR: 1.66 (1.17 - 2.34)), lived in an house built before 1976 (OR 1.83 (1.29 - 2.61)), and had a bedroom window facing a street (OR 1.82 (1.22 - 2.70)).

Belojevic, G., Jakovljevic, B., Stojanov, V., Paunovic, K., Ilic, J. (2008)

In 2008, Belojevic et al. investigated the effects of urban road traffic noise on children's blood pressure and heart rate. A cross sectional study was performed on 328 preschool children aged 3-7 years, who attended 10 public kindergartens in Belgrade, Serbia.

Children's blood pressure was measured using a mercury sphygmomanometer and their heart rate was counted by radial artery palpitation for 1 minute. Noise exposure was measured during the night using the front of the children's residence and during the day using the front of their schools. Resident noise was categorized as noisy if levels exceeded 45 dB(A) and quiet if levels were ≤ 45 dB(A). School noise was categorized as quiet if daily noise levels were ≤ 60 dB(A) and loud if daily noise levels were greater than 60 dB(A).

Study results showed that the prevalence of children with hypertensive values of blood pressure was 3.96% with higher prevalence in children from noisy residences (5.70%) compared to children from quiet residences (1.48%). The difference was borderline significant with a p-value equal to 0.054. Systolic pressure was significantly higher (5mm Hg on average) among children from noisy residences and kindergartens compared to children for both quiet environments ($p < 0.01$). Heart rate was significantly higher (2 beats/minute on average) in children from noisy residences compared to children from quiet residences ($p < 0.05$).

<u>Selander, J., Nilsson, M.E., Bluhm, G., Rosenlund, M., Lindqvist, M., Nise, G., Pershagen, G. (2009)</u>

More recently and unlike previous studies which only investigated exposure to road traffic risk of MI, in 2009, Selander et al. sought to simultaneously analyze the role of exposure to noise and air pollution from road traffic in the risk of MI. This study was based on the Stockholm Heart Epidemiology Program, which was conducted in Stockholm County, Sweden. In total, 3,666 study subjects were included, which consisted of 1,571 cases and 2,095 controls. Hypertension was defined as reported use of antihypertensive drugs, or as a systolic blood pressure of 170 mm Hg or higher, or a diastolic pressure of 95 mm Hg or higher.

The road traffic sound level was estimated using a noise propagation model. In 2003, a supplementary questionnaire was distributed to enhance the noise exposure assessment. This included questions on hearing impairment, window insulation, bedroom orientation, and noise annoyance.

Odds ratios and 95% confidence intervals were calculated using unconditional logistic regression analyses. For all cases of MI and a dichotomous categorization of noise levels, it was found that individuals exposed to road traffic noise levels greater than 50 dB had an odds ratio of 1.12 (0.95-1.33), which implies that they were 1.12 times more likely to have an MI as compared to those exposed to noise levels less than 50 dB. When comparing non-fatal cases of MI to fatal cases, increased risk occurred with road traffic decibel levels greater than or equal to 50.

For categorical analysis broken down in 5 dB(A) increments the following occurs: for decibel levels between 50 and 54 dB, individuals are more likely to develop MI than those exposed to less than 50 dB (OR: 1.15 (0.95-1.39)). However, between 55 and 59 dB, the risk decreases (OR: 1.05 (0.81-1.36)). For decibel levels greater than 60 dB, the odds of MI increase again (OR: 1.21 (0.83-1.77)).

Categorical analysis for both non-fatal and fatal cases shows a similar trend. For noise levels between 50 and 54 dB, the corresponding odds ratio was 1.20 (0.85-1.69) for non-fatal cases and 1.14 (0.93-1.39) for fatal cases. Between 55 and 59 dB, the odds ratios decreases for both non-fatal and fatal cases (OR: 1.12 (0.72-1.76) and 1.04 (0.79-1.36), respectively). For road traffic noise levels greater than or equal to 60 dB, there is an increase in risk for both cases (OR: 1.24 (0.64-2.42) for non-fatal cases and 1.21 (0.81-1.82) for fatal cases).

<u>Oftedal, B., Nafstad, P., Schware, P., Aasvang, G.M. (2011)</u>

Using participants in the Oslo Health Study these authors examined the relationship between road traffic noise and high blood pressure and hypertension. For this study, high blood pressure was defined as a systolic blood pressure above 140 mmHg, a diastolic blood pressure above 90 mmHg or self-reported use of antihypertensive medication. Road traffic noise was calculated using the Nordic Prediction Method[2] for road traffic noise.

Results showed that road traffic noise ≥ 60 dB was associated with an increase of 0.9 mmHg (95% CI: 0.0, 1.8) in systolic blood pressure compared to noise levels less than 50 dB. There were no associations found with diastolic blood pressure. Similarly, such a relationship was found with Ln noise levels.

Literature Review Summary

Table 5 includes a brief summary of the research presented in the literature review organized by study, cardiovascular outcome of interest, quantitative outcome, and conclusion.

[2] The Nordic prediction method for road traffic noise calculates noise exposures at the most exposed façade with a deviation of +/- 3-5 dB depending on the distance from the noise source. Combining the prediction method with a geographical information system is considered the best available method to assess residential noise exposure (Oftedal et al 2011).

Table 5: Summary of Literature Review

Study	Cardiovascular Outcome	DB Benchmark For Negative Cardiovascular Outcome	Conclusions
Tobias, A., Julio, D., Saez, M., Alberdi, J.C., (2001)	Association between environmental noise levels and daily emergency admissions	> 65 dB	Current levels of environmental noise have a statistically significant impact on emergency room admissions in Madrid. Around 5% of all emergency admissions can be attributed to high noise levels.
De Kluizenaar, Y., Gansevoort, R., Miedema, H., de Jong, P. (2002)	Association between road traffic noise and hypertension	> 55 dB	Exposure to road traffic noise may be associated with hypertension in subjects between the ages of 45 and 55. Associations appeared to be stronger at higher noise levels.
Babisch, W., Beule, B., Schust, M., Kersten, N., Ising, H. (2005)	Myocardial Infarction	61 – 65 dB 66-70 dB > 70	The results support the hypothesis that chronic exposure to high levels of traffic noise increases the risk for cardiovascular disease—especially for men.
Bluhm, G.L., Berglind, N., Nordling, E., Roselund, M. (2007)	Hypertension	45-50 dB 50-55 dB > 55 dB	There is an association between exposure to road traffic noise and hypertension.
Belojevic, G., Jakovljevic, B., Stojanov, V., Paunovic, K., Ilic, J. (2008)	Blood pressure and heart rate	> 45 dB > 60 dB	There is a significant correlation between urban road traffic noise and blood pressure and heart rates in preschool children.
Selander, J., Nilsson, M.E., Bluhm, G., Rosenlund, M., Lindqvist, M., Nise, G., Pershagen, G. (2009)	Myocardial Infarction	50-54 dB 55-59 dB ≥ 60 dB	The results lend some support to the hypothesis that long-term exposure to road traffic noise increases risk for MI.
Oftedal, B., Nafstad, P., Schware, P., Aasvang, G.M. (2011	High Blood Pressure, Hypertension	> 60 dB	Preliminary results showed that road traffic noise was associated with an increase in systolic blood pressure compared to noise levels less than 50 dB. There were no associations found with diastolic blood pressure.

Methodology

As previously mentioned, there are two main goals of this thesis. The first goal is to model the day and night time noise levels CAFEH participants are exposed to as a result of the proximity of their residence to major roadways. Using these predicted values along with CAFEH survey data, the second goal is to run a series of correlation tests to examine potential relationships between predicted noise levels and the CAFEH survey data.

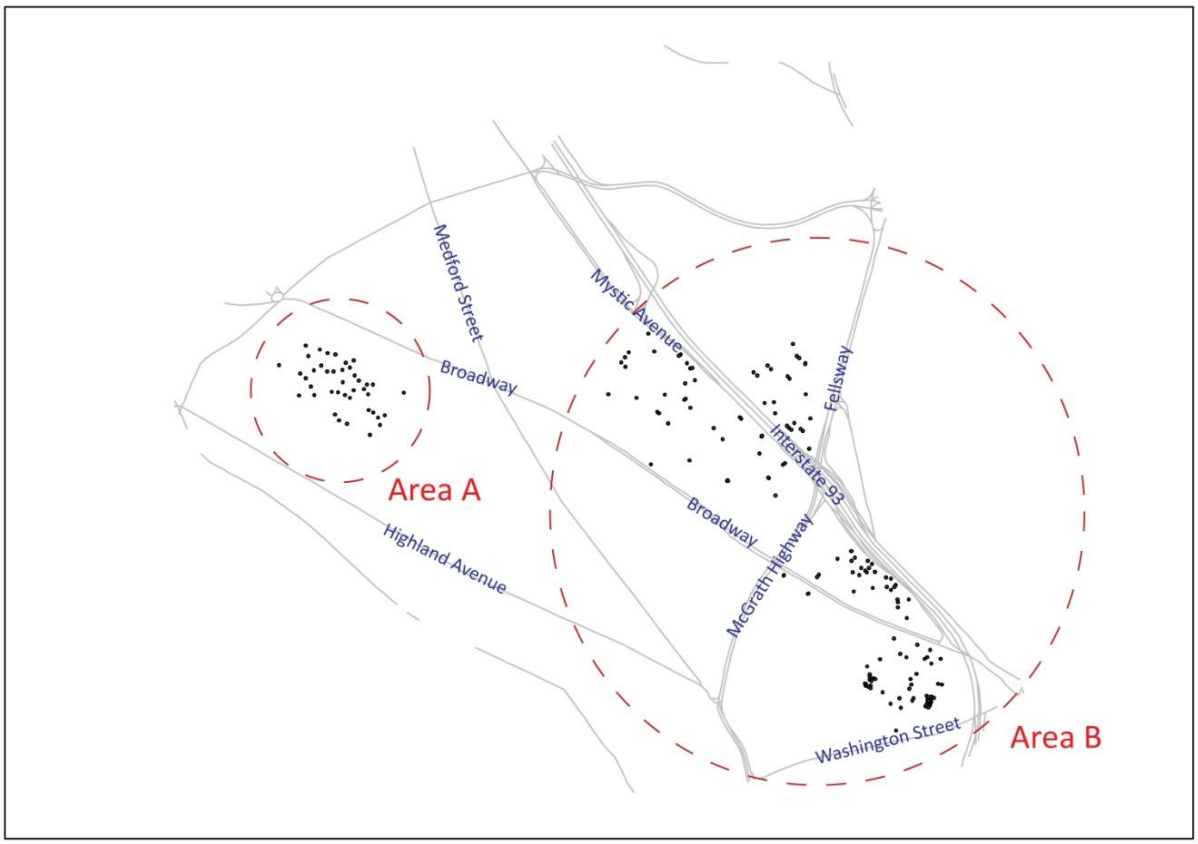
The methodology for achieving these goals is outlined in this section. I will begin with a discussion of the city of Somerville and the CAFEH study area. Next, I will define the components necessary to build a noise propagation model. Following, I will discuss the CAFEH survey and outline the subset of survey variables to be analyzed both independently and in conjunction with the predicted noise levels. Finally, I will discuss the statistical methods to be used in the results section of this thesis.

CAFEH STUDY AREA AND STUDY POPULATION

Somerville, MA is the most densely populated city in New England and the 17th most densely populated city in the United States, with a land area of only 4.2 square miles and population of 75,880 residents (U.S Census 2011). The CAFEH study area — the study area for this thesis — is shown in Appendix A. The CAFEH study area includes roughly 13,000 residence and commercial buildings nestled between 504 roads. These roads have an average daily traffic volume (ADT) ranging from 100 to 200,000 vehicles. The focus of this investigation will be on noise emanating from major roads, which are defined as any road with an ADT volume of 3,000 or more vehicles. Using this definition narrows down my analysis to 29 roads. A complete table of major roads can be found in Appendix B.

Within this study area, CAFEH conducted a random sample of residents, which yielded a total of 204 participants. Figure 6 shows the household location of the CAFEH sample. As you can see, study participants are scattered at varying distances from these major roads but fall into two distinct groups. I have labeled these groups A and B. Group A are those participants who reside the furthest away from the busiest major roads shown in Table 12 and Group B are those participants who reside the closest.

Figure 5: CAFEH Households



Source: MassGIS, CAFEH Study

NOISE PROPAGATION MODELING

To calculate a predicted level of noise propagating from a roadway and into the community, three important pieces of information is needed—the roadway characteristics, the spatial characteristics of the terrain between the roadway and the receiver, and a receiver's precise location. Here, the receiver is defined as a CAFEH participant's residence. Within this section, I will define this information and its source as well as how it will be used to build a noise model, which will give predicted noise levels emanating from these major roads.

Roadway Characteristics: Transportation Demand Model

The characteristics of the roadway complete with links and nodes are housed in a database called a transportation demand model. Links represent roadway segments and nodes represent intersections or changes in direction in a roadway (Kaliski 2005). With each link of a transportation demand model, there exists a database which houses information on a link's geometric information (road width and elevation), average travel speed, average daily traffic volume, type of roadway (collector, arterial, ramp, freeway), and vehicle mix (Kaliski 2005). Table 6 lists the data and data source for the roads used in the construction of the noise propagation model.

Table 6: Road Information—Transportation Demand Model

Type of Data	Source
Study area road geometric information	MassGIS EOTROADS LAYER
Average travel speed	MassGIS EOTROADS LAYER = Speed Limit
Average daily traffic volume	MassGIS EOTROADS
Type of roadway	MassGIS EOTROADS LAYER
Vehicle Mix	German RLS-90 Standard

The majority of this data was pulled from the MassGIS EOTROADS Layer (MassGIS 2011a). There were a few missing pieces of information for which proxy values were given. Specifically, the EOTROADS Layer did not contain vehicle mix and average travel speeds. Therefore, default values were given. For vehicle mix, the German RLS-90 Standard was applied. This option is available in CadnaA (DataKustik 2010), the noise propagation software used to calculate estimates. This software package will be discussed further in the next section. This standard gives default values to parameters such as vehicle flow, vehicle weight, and vehicle mix (percentage of heavy vehicles) based on German RLS-90 standard. This standard is widely used in traffic noise emission calculations (Calixto et al. 2003; Kaliski et al. 2007). For average travel speed, the road's speed limit, which was available in the EOTROADS layer, was used.

Spatial Characteristics

In addition to road characteristics, the study area's spatial characteristics are also needed. This information includes household locations, building geometry, terrain, orthophotography, and land cover. Table 7 details the spatial components used as well as the data source.

Table 7: Spatial Information

Type of Data	Source
Household/building information	MassGIS FOOTPRINTS LAYER and Somerville, MA Zoning ordinances
Terrain: Contour lines	MassGIS 1:5000 elevation points
Orthophotography	Google Earth, Inc.
Land Cover	Google Earth, Inc.

Spatial information was obtained from both MassGIS and Google Earth (Google Earth 2011). As was the case with road data, some data was missing and had to be assigned proxy values. The MassGIS building footprint layer (MassGIS 2011b) did not include building heights. As a result, I assigned value of 10.6 meters to all buildings and based this value on the maximum residential building height allowed under Somerville zoning codes.

Receiver Location

The study residents' locations are defined using the geographic coordinates supplied by the CAFEH study. All study participants are assigned an Ld, Ln, and Ldn noise measure calculated at the most exposed façade.

Choosing an appropriate noise prediction software package

Once the information in Tables 13 and 14 were gathered, a matrix of predicted noise levels can be calculated. To carry out these calculations, I used CadnaA, a noise propagation software package. The choice of CadnaA was advantageous for a number of reasons. From a review of literature of road traffic noise propagation modeling, it is the most widely used software package. Also, CadnaA has the capacity to handle a large volume of road and building data; finally, it works seamlessly with both Google Earth and ArcGIS. Appendix A gives a pictorial representation of how data looks as it is entered into CadnaA.

NOISE CALCULATIONS

The calculation method used for noise propagation follows directly from the International Standards Organization (ISO) 9613-2. This ISO series specifies an engineering method for calculating the attenuation of sound during propagation outdoors, in order to predict the level of environmental noise at varying distances from each roadway (ISO 1996). Specifically, these standards detail algorithms for geometrical divergence, atmospheric absorption, ground effects, reflection from surfaces, and screening by obstacles (ISO 1996). The computer noise modeling results were calculated using a 10m x 10m grid pattern within the entire study area where participant households were located. Using this approach, two noise levels were calculated:

1. Ld: The average day time noise level from 7 a.m. to 10 p.m.
2. Ln: The average night time noise level from 10 p.m. to 7 a.m.

Using the predicted Ld and Ln values obtained from CadnaA and the formula below, I calculated the Ldn, which is defined as the day-night average sound level. Ldn is the energy average sound level for a 24-hour day with a 10 decibel penalty applied to noise occurring during the nighttime period (WHO 1999). For example, noise levels occurring during the period from 10 p.m. one day until 7 a.m. the next day, are treated as though they were 10 dBA higher than they actually are.

The mathematical expression for Ldn (Bilawchuk 2010) is as follows:

$$Ldn = 10\log_{10}[\ (15/24)10^{Ld/10} + (9/24)10^{(Ln + 10)/10}]$$

CAFEH SURVEY DATA

The CAFEH survey is a 33-page document, which asks a wide range of questions regarding demographics, time activities during work and non-workdays, household/indoor exposure, outdoor exposure, smoking, noise, housing characteristics, occupational exposure, diet, physical activity, stress, health status, medications, risk perception, and income. For my analysis, a subset of this data was used and is shown in Table 8, and additional questions relevant to this thesis are provided in Appendix G.

Table 8: Thesis Data Obtained From CAFEH Survey

Variable	Description
Demographic Data	Age, gender, race, work status, marital status
Noise	Annoyance to traffic, aircraft, trains, sirens, music, alarms, and people
Sleep	Amount of sleep each night
Cardiovascular Health	Blood Pressure

Statistical Methods

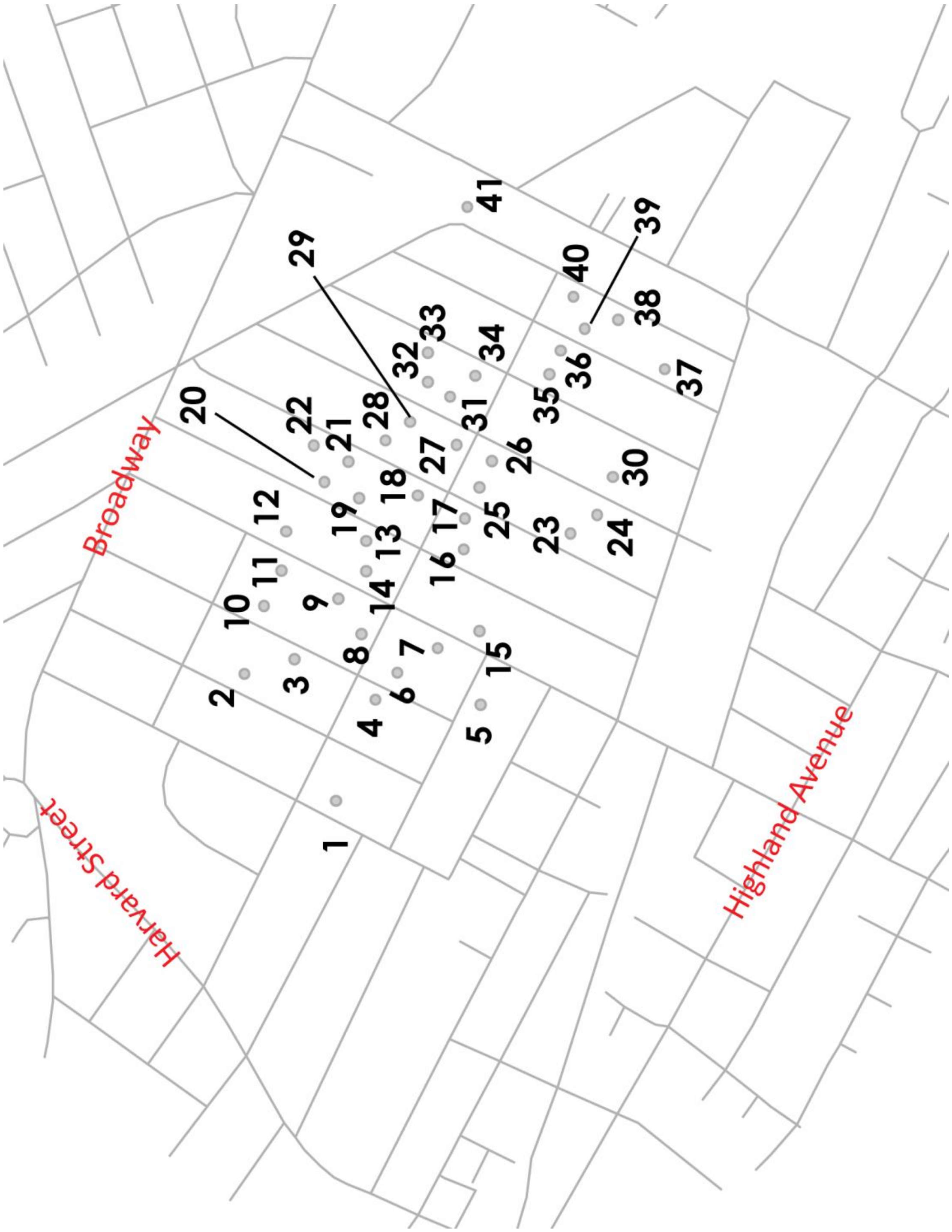
Basic descriptive statistics such as the mean, median, minimum value, maximum value, and percentages were calculated for the total sample as well as for each group A and B. Spearman correlations are used to test for a statistically significant relationship between predicted noise levels and hours of sleep. A Two-sample Wilcoxn Rank Sum test is conducted to test for statistically significant differences between predicted noise levels and the designation of high and low blood pressure status among residents. Kruskal-Wallis tests are conducted to test for a statistically significant relationship between predicted noise levels and residents' multiple response categories to annoyance from road traffic noise. Finally, chi-square tests are used to explore categorical differences in demographics across the two noise exposure groups. All of the statistical analyses were performed using STATA Version 11 (College Station, TX).

Results

NOISE MAP VALUES

Using the noise values obtained from CadnaA, MassGIS's EOTROADS layer and CAFEH's resident coordinates, I have designed a series of noise maps. Appendices C and D contain screenshots of how these data are presented in the CadnaA platform. As noted in the methodology, the CAFEH study area has been divided into a "less exposed" group and a "more exposed" group based on their proximity to major roads. These groups are labeled as groups A and B, respectively. Due to the massive size of the Group B image file and for pictorial representation only, I have further divided this group into three subsections: B1, B2, and B3. Noise maps for each group are presented as a set containing a numbered map of each CAFEH participant's residence and a corresponding table with the following values for each residence: average daytime noise level (Ld), the average night time noise level (Ln), and the day-to-night average noise level for a 24 hour period (Ldn). As mentioned earlier, each noise level value is calculated at a resident's most expose façade. Figure 7-8 are maps of the CAFEH participant residences within each grouping, and the modeled Ld, Ln, Ldn values for each of these residence are found in Appendix E-F.

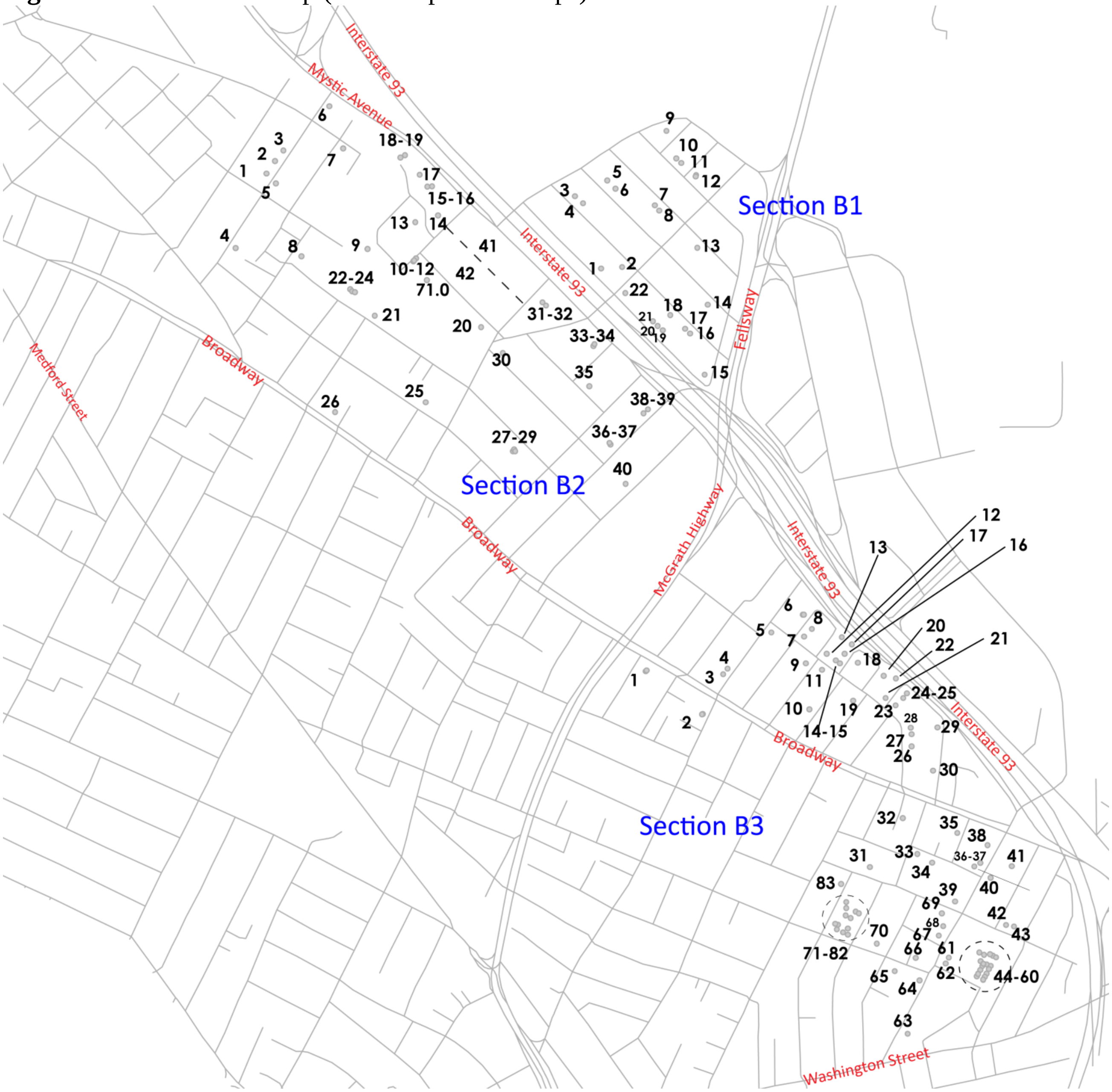
Figure 6: Area A (Less Exposed Group) Map[3]



Source: MassGIS, CAFEH Study

[3] Ld, Ln, Ldn values for each residence are found in Appendix E

Figure 7: Total Area B Map (More Exposed Groups)



Source: MassGIS, CAFEH Study

DESCRIPTIVE STATISTCS FOR NOISE MAP VALUES

The Distribution of Road Traffic Noise

For a pictorial representation of how noise levels are distributed across both groups, histograms are presented below. From these histograms, we can see that noise levels in Group A and Group B are roughly skewed to the right.

Figure 8: Histogram for Ld

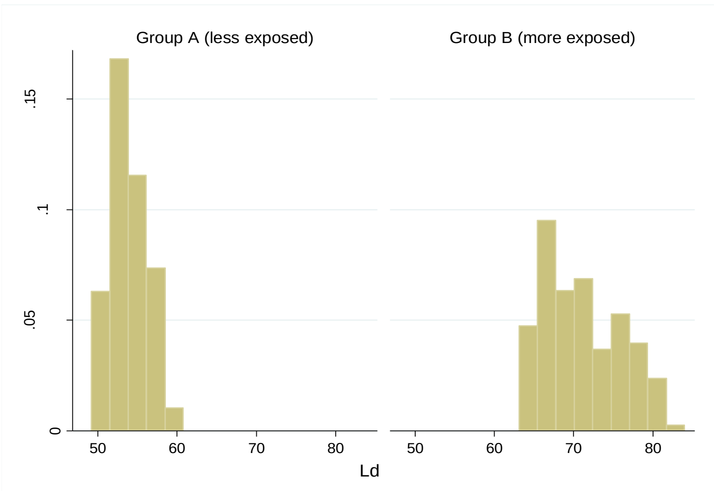


Figure 9: Histogram for Ln

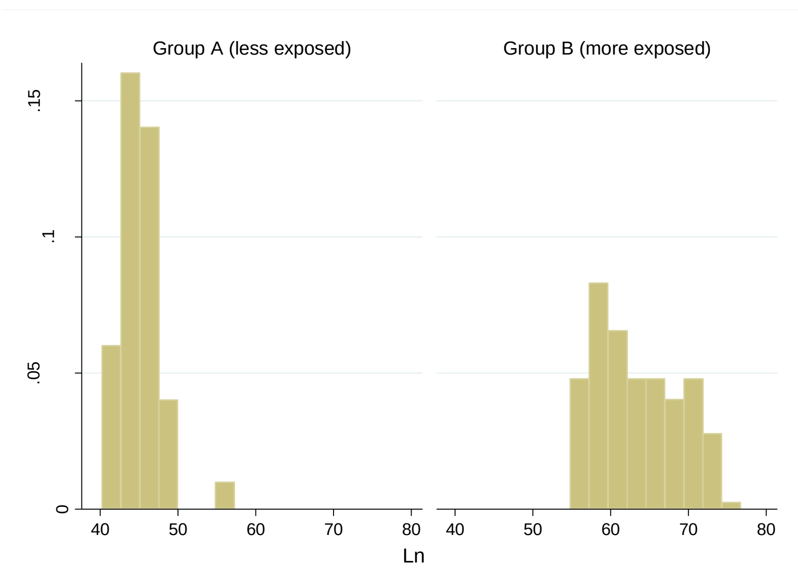
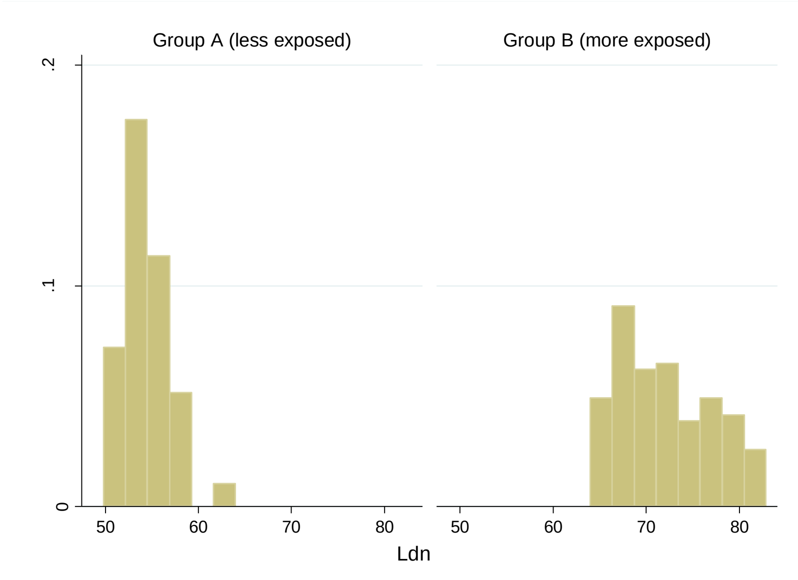


Figure 10: Histogram for Ldn



<u>Descriptive Statistics for Road Traffic Noise</u>

Tables 9-11 below describe the Ld, Ln, and Ldn for Group A and Group B.

Table 9: Ld—Day Time Average Sound Level: 7am to 10 pm (in decibels)

Ld	**Residents of Area A (less exposed)**	**Residents of Area B (more exposed)**
Mean (Standard Deviation)	53.8 (2.35)	71.1 (4.9)
Median	53.5	70.7
Min	49.2	63.7
Max	58.7	81.7
% above WHO criteria (>55 dB)	29.3%	100%

Table 10: Ln—Night Time Average Sound Level (in decibels)

Ln	Residents of Area A (less exposed)	Residents of Area B (more exposed)
Mean (Standard Deviation)	45.0 (2.75)	63.6 (5.02)
Median	44.8	63.1
Min	40.2	56.1
Max	55.6	74.3
% above WHO criteria (>45 dB)	46%	100%

Table 11: Ldn—Day-Night Average Sound Level (in decibels)

Ldn	Residents of Area A (less exposed)	Residents of Area B (more exposed)
Mean (Standard Deviation)	54.4 (2.5)	72.2 (4.95)
Median	53.9	71.9
Min	49.8	64.8
Max	62.4	82.9

Not surprisingly, residents living closer to major roadways experience higher noise levels. A Wilcoxon rank-sum (Mann-Whitney) test was used to test the null hypothesis, H_0 that the mean predicted Ld, Ln, and Ldn noise levels between the two areas are equal. The test results show that there is a statistically significant difference ($p<0.05$) for Ld, Ln, and Ldn between the two locations. Using World Health Organization's community noise level benchmarks,[4] fewer than half of residents in Group A are exposed to dB higher than WHO's benchmark, while 100% of residents in Group B are exposed to these levels.

[4] WHO community guidelines suggest that during the daytime, the sound pressure level at the outside façade of a dwelling should not exceed 55 dB and at night, the sound pressure level should not exceed 45 dB (WHO 2010).

Further, comparing the Ldn for groups A and B to more recent studies discussed within the literature review show that Group B exceeds every decibel level benchmark for negative cardiovascular disorders.

Table 12: Comparing Average Group Ldn to Previous Studies

Study	**Cardiovascular Outcome**	**dB Benchmark for negative cardiovascular disorders**	**Group A mean Ldn Less exposed (54.4 dB)**	**Group B mean Ldn More exposed (72.2 dB)**
Tobias, A., Julio, D., Saez, M., Alberdi, J.C., (2001)	Association between environmental noise levels and daily emergency admissions--all AND circulatory	> 65 dB	Does not exceed	Exceeds
De Kluizenaar, Y., Gansevoort, R., Miedema, H., de Jong, P. (2002)	Association between road traffic noise and hypertension	> 55 dB	Does not exceed	Exceeds
Babisch, W., Beule, B., Schust, M., Kersten, N., Ising, H. (2005)	Myocardial Infarction	61 – 65 dB	Does not exceed	Exceeds
		66 – 70 dB	Does not exceed	Exceeds
		> 70 dB	Does not exceed	Exceeds
Bluhm, G.L., Berglind, N., Nordling, E., Roselund, M. (2007).	Hypertension	45-50 dB	Exceeds	Exceeds
		50-55 dB	Exceeds	Exceeds
		>55 dB	Does not exceed	Exceeds
Belojevic, G., Jakovljevic, B., Stojanov, V., Paunovic, K., Ilic, J. (2008)	Blood pressure and heart rate	> 45 dB	Exceeds	Exceeds
		>6 0 dB	Does not exceed	Exceeds
Selander, J., Nilsson, M.E., Bluhm, G., Rosenlund, M., Lindqvist, M., Nise, G., Pershagen, G. (2009).	Myocardial Infarction	50 – 54 dB	Exceeds	Exceeds
		55- 59 dB	Does not exceed	Exceeds
		>/= 60 dB	Does not exceed	Exceeds
Oftedal, B., Nafstad, P., Schware, P., Aasvang, G.M. (2011	High Blood Pressure, Hypertension	> 60 dB	Does not exceed	Exceeds

SURVEY DATA ANALYSIS

Study Area Characteristics

Table 13: Study Area Characteristics

Variable	**Residents of Area A (less exposed)**	**Residents of Area B (more exposed)**	**All Residents**
Average Age	58.9	59.1	59.1
Gender	Female: 70.7% Male: 30.3%	Female: 64.4% Male: 35.6%	Female: 65.7% Male: 34.3%
Race	White:80% Asian: 7% Black:5% Hispanic: 5% Other: 3%	White:74% Asian: 2% Black: 10.5 % Hispanic: 13.5%	White: 75% Asian: 4% Black: 9% Hispanic: 11% Other: 1%
Work Status	Working: 50%	Working: 43.7%	Working: 46.5%
Currently Married	27%	33%	35%
Holds a Bachelor's Degree	46%	19%	24.5%
Average Amount of Sleep	7.2 hours	6.7	6.7
% with High Blood Pressure	36.6%	48.5%	46%

Survey data suggests that in aggregation, the majority of residents surveyed are white females around 60 years of age. A higher percentage of residents in Group A work and hold a bachelor's degree and a higher percentage of residents in Group B are married. When looking at sleep patterns and prevalence of high blood pressure, Group A sleeps more and has less cases of high blood pressure diagnoses. Chi-Square test results show that there is not a statistically significant difference in the number of individuals with high blood pressure between the two groups. Additionally, there is not a statistically significant difference in the average amount of sleep individuals get each night between the two groups.

Study Area Traffic Noise Annoyance

The CAFEH survey asked residents to rate their level of annoyance towards traffic noise both currently and in the past five years. Results are shown in Table 14 below.

Table 14: Traffic Noise Annoyance

Intensity	**Residents of Area A (less exposed)**	**Residents of Area B (more exposed)**	**All Residents**
Never	44%	41%	41.5%
Sometimes	44%	43%	43.5%
Often	7%	9%	8%
Always	5%	8%	7%

Annoyance levels across groups are roughly the same with higher percentages of Group B residents being at least sometimes annoyed by road traffic noise. Chi-square tests showed no significant differences between the two areas.

Predicted Noise Levels and Sleep Patterns, High Blood Pressure Status, and Overall Annoyance

Table 15: Correlations between Predicted Noise Levels and Hours of Sleep

Variable (p value) N = 204	Ldn		Ld		Ln	
Area	A	B	A	B	A	B
Hours of Sleep	-0.0205	-0.0773	0.0091	-0.0619	-0.0457	-0.0938

Table 16: Impact of Noise on High Blood Pressure Status

Variable (p value) N = 204	Ldn		Ld		Ln	
Area	A	B	A	B	A	B
High Blood Pressure Status (Yes/No)	Not statistically significant	Not statistically significant	Not statistically significant	Not statistically significant	Marginally significant ($p = .10$)	Statistically significant ($p < .05$)

Table 17: Impact of Noise on Traffic Annoyance

Variable (p value) N = 204	Ldn		Ld		Ln	
Area	A	B	A	B	A	B
Traffic Annoyance (Categorical: 1-4)	Not statistically significant	Statistically significant (p<.05)	Not statistically significant	Statistically significant (p<.05)	Not statistically significant	Statistically significant (p<.05)

Within Area A, Spearman correlation coefficients show that with the exception of daytime noise levels, there is a negative correlation between day and 24-hour average noise levels and hours of nightly sleep. For Area B, all noise levels had a negative impact on nightly hours of sleep. When comparing the relationship between predicted noise levels and the high blood pressure status, for residents of Area A, only night time noise levels showed a marginally statistically significant effect. For Area B, a similar story emerges—only night time noise levels showed a statistically significant effect on resident's blood pressure status. Finally, when comparing noise levels and residents' annoyance towards road traffic noise, there were no statistically significant effects for Area A. On the other hand, for Area B and across all predicted noise levels, there was a statistically significant effect on residents' level of annoyance to traffic noise.

However, I am only estimating noise stemming from road traffic. Within the urban matrix, there exists a wide range of noise sources, which may be equally or more annoying than road traffic noise. In fact, the CAFEH survey data suggests this. When study participants were asked about annoyance stemming from other environmental noise sources, aircraft noise and noise from car alarms and car horns ranked highest as additional sources of noise annoyance for residents. Table 18 details residents' responses.

Table 18: Annoyance from Other Environmental Noise Sources

Noise Source	**Residents of Area A (Rank overall)**	**Residents of Area B (Rank overall)**	**All Residents (Rank overall)**
Road traffic	32% (2)	26% (3)	27% (3)
Aircraft Noise	41.5% (1)	45% (1)	44% (1)
Trains	10% (6)	11% (5)	11% (6)
Emergency Vehicle Sirens	27% (4)	37% (2)	35% (2)
Loud Music	20% (5)	26% (3)	25% (5)
Car Alarms/Horns	29% (3)	25% (4)	26% (4)

Across both groups and in aggregation, the number one environmental noise annoyance was from aircraft noise, as close to half of the study population admitted to being annoyed by aircraft noise. For residents of the less exposed Group A, road traffic noise was the second most bothersome environmental noise source, followed by car alarms/horns. After aircraft annoyance, residents of group B were most bothered by emergency vehicle noise. Group B ranked road traffic noise and loud music, together with aircraft noise, as the three most troublesome environmental noise sources. However, these sources were not accounted for in my noise model and may elevate noise levels even further. Until such factors are incorporated into the analysis, it is difficult to accurately assess the impact of noise on cardiovascular health outcomes.

Conclusion

I set out with two goals for this thesis. The primary goal was to build a noise propagation model to estimate noise levels CAFEH residents are exposed to as a result of their proximity to major roadways in the Somerville area. The second goal was to use these predicted noise levels with CAFEH survey data to test for significant correlations between traffic noise annoyance, sleep duration, and high blood pressure. Within this thesis, I was able to achieve both goals. I was able to calculate predicted Ld, Ln, and Ldn noise measurements for all CAFEH study participants. In doing so, I was able to show that residents who live close to major roads pay a heavy price when it comes to noise levels. According to my research results, 100% of residents who live in Group B are exposed to day and night time noise levels far above the World Health Organization's guidelines. Additionally, 100% of Group B residents were exposed to noise levels that recent epidemiological studies suggested greatly increased the risk of developing negative cardiovascular outcomes.

To assess the relationships between predicted noise levels and residents' hours of nightly sleep, high blood pressure status, and annoyance towards road traffic noise, a series of non-parametric statistical tests are conducted. Spearman correlations are used to test the null hypothesis that predicted noise levels and hours of sleep are independent. A Two-sample Wilcoxn Rank Sum test is conducted to see if there are any statistically significant differences between predicted noise levels and a resident's high blood pressure status. Kruskal-Wallis tests are conducted to test for a statistically significant relationship between predicted noise levels and residents' annoyance towards road traffic noise. I believe that these test results are an informative and important first step, which opens the door for further investigation and set the framework for what needs to be done going forward.

Finally, survey results also showed that residents are bothered by other environmental noises—most notably aircraft noise, which CAFEH residents ranked as the most annoying noise source. Additionally, write-in responses showed that not only are residents annoyed by outdoor noise sources, they are also annoyed by noises within their homes.

Limitations

There are several limitations of the research presented in this thesis. Within this section, I have categorized these limitations into two main categories: noise modeling issues and exposure issues.

NOISE MODELING ISSUES

In constructing the noise propagation model, I had to make several assumptions due to data limitations. For road information, proxy variables had to be assigned for crucial pieces of information. Road speed limits served as the substitute for average daily speed. The German RLS-90 standard was used to account for vehicle mix, vehicle flow, and vehicle weight. For study area spatial information, data on building heights was unavailable so I had to assign a uniform height for all buildings. Finally, for study area elevation, I used elevation points instead the elevation contours. Elevation points only describe elevation at a particular spot and provide no information about the terrain beyond that point. Such data could underestimate the effects of the unaccounted for terrain on noise propagation. Therefore noise results may actually be higher than estimated here. Elevation contours, however, describe the elevation of a particular area, continuously. I believe that continuous contours may more accurately predict the noise levels at a residence's façade .

EXPOSURE ISSUES

For each CAFEH resident, I was able to calculate estimates of Ld, Ln, and Ldn. These values represented a static measure of the average noise level experienced during a specific time frame. I was unable to account for time variation within this thesis. In reality, noise is continuously volatile and is highly influenced by the time of day, the time of week, and the time of year. Having time-varying data will give a more accurate picture of how noise levels change throughout the day. Going forward, it would be interesting to examine how noise varies over time coupled with how an individual's blood pressure varies over time.

Additionally, noise levels are influenced by other noise sources such as aircraft noise, and this thesis limited its scope to roadway noise. After analyzing the survey results, I found that residents rated aircraft noise as the number one nuisance. Additionally, the second highest ranked noise annoyance was noise emanating from car alarms, car horns, emergency vehicle sirens, and loud music. Those surveyed were also bothered by noise from within their homes, such as appliance noise and noise from residents who live above or below them. The noise values presented in this thesis did not take into account any of these additional noise sources.

CONFOUNDING ISSUES

There are many potential confounders that have not been accounted for in this thesis. These confounders include environmental factors such as air pollution concentrations, socioeconomic factors such as income, and health factors such as smoking and dietary habits. Until I control for such factors, it is difficult to accurately assess the impact of noise on cardiovascular health outcomes.

Future Directions

The limitations of the research presented in this thesis greatly inform the direction I would like to take going forward. Within this section, I will list my intended steps moving forward.

UPDATE THE NOISE PROPAGATION MODEL FOR ROAD TRAFFIC

Updating the model constructed within this thesis involves filling in as much missing data as possible and accounting for temporal differences. First, I will need to obtain as much of the missing data as possible. I will need to find or measure precise values for average travel speed, vehicle mix, vehicle flow, and vehicle weights. I would also need to find this data for certain times of the day, week, month, and year. I will also need to obtain contour lines to fully capture the terrain of the study area.

OBTAIN REAL-TIME NOISE DATA TO CALIBRATE THE MODEL ESTIMATES

The noise level measures presented in this thesis are static measures. Going forward, I would like to add real-time noise data using a dosimeter. This data can be used to calibrate the noise propagation model. Additionally, real time data can be used to establish baseline noise levels, describe variances in noise levels, and provide measures for additional noise sources—all for certain times of the day, week, month, and year.

MODELING AND SAMPLING AIRCRAFT NOISE

A future goal of this thesis is to model additional noise sources and construct multi-leveled noise exposure models to more accurately assess the noise level residents are exposed to. Specifically, I would like to model aircraft noise as CAFEH participants found it to be the most bothersome noise source. Aircraft noise modeling will be carried out in a similar fashion to the road traffic noise modeling used in this thesis. Specifically, an Integrated Noise Model (INM) will be used. INM is a computer model which used Noise-Power-Distance (NPD) data to estimate noise accounting for specific operation mode, thrust setting, and source-receiver geometry, acoustic directivity and other environmental factors (FAA, 2012). The INM can output either noise contours for an area or noise level at pre-selected locations. The noise output can be either exposure-based, maximum-level-based, or time-based.

UNDERSTANDING THE INDOOR NOISE DYNAMIC-MODELING AND SAMPLING

There are two main ways to explore the indoor noise dynamic. The first way is to examine the infiltration of noise from the outdoor environment to the indoor environment. The second way is to examine the noise sources emanating from indoors. This includes noise generated from indoor appliances and between floors and walls if living in a shared space. Regardless of the focus, obtaining indoor noise measures further refines the noise exposure model.

UNDERSTANDING THE NOISE LEVEL OF THE “LIVING ENVIRONMENT”

Moving beyond the dichotomous indoor/outdoor noise exposure model and into a model of noise exposure within the “Living Environment” is another future goal. Dekonick et al. (2011) explain that the living environment is not limited to the house and yard. Rather, any subjective assessment of noise may also include a much wider neighborhood. It would be advantageous to assess the noise exposure levels experienced during an individual's daily activity and trip pattern, which may exist well beyond the resident's dwelling.

NOISE MODELING AND SAMPLING IN OTHER CAFEH AREAS

The overall CAFEH study is comprised of three communities—Somerville, MA; Dorchester, MA; and the China Town area of Boston, MA. I would like to construct a noise exposure model and sample within the remaining two areas of the study. With this holistic representation, it would be nice to compare and contrast areas.

FURTHER SURVEYING

I would also like to do additional surveying. This would include creating and disseminating a more detailed survey on a resident's noise experience.

FURTHER EXPLORE THE ISSUE OF NOISE ANNOYANCE

I would like to further explore the relationship between human responses to noise and increases (or decreases) in noise levels. Laszlo and Hansell (2011) detailed a framework for the types of human responses that may change as a result of noise level fluctuations. These human responses are: (1) changes in levels of annoyance; (2) activity disturbance; (3) physiological and psycho-social well being; and (4) use of living environment (Lazlo and Hansell 2011).

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Appendix A: Table of Major Roads

Table A-1: List of Major Roads within the CAFEH Study Area

Street Name	Average Daily Traffic Volume
BOW STREET	3000
BROADWAY	19500
CAMBRIDGE STREET	19900
COLLEGE AVENUE	7700
CONNECTOR MYSTIC VALLEY PARKWAY	20000
DAY STREET	3000
DOVER STREET	3000
ELM STREET	7700
FELLSWAY	45000
HARVARD STREET	7700
HIGHLAND AVENUE	7700
HOLLAND STREET	7700
INTERSTATE 93	171830
MAFFA WAY	19900
MAIN STREET	8900
MCGRATH HIGHWAY	50000
MEDFORD STREET	7700
MEDFORD VETERANS MEMORIAL HIGHWAY	40000
MIDDLESEX AVENUE	7700
MYSTIC AVENUE	8900
MYSTIC VALLEY PARKWAY	40000
POWDER HOUSE BOULEVARD	7700
POWDER HOUSE SQUARE	7700
REVERE BEACH PARKWAY	49000
RIVERSIDE AVENUE	7700
SULLIVAN SQUARE	19900
SUMMER STREET	3000
WARNER STREET	7700
WASHINGTON STREET	13600

Source: MassGIS

Appendix B: Data Presentation in Noise Software Package

Figure B-1: Road, building, and elevation data of the Ten Hills area as it is being entered into CadnaA

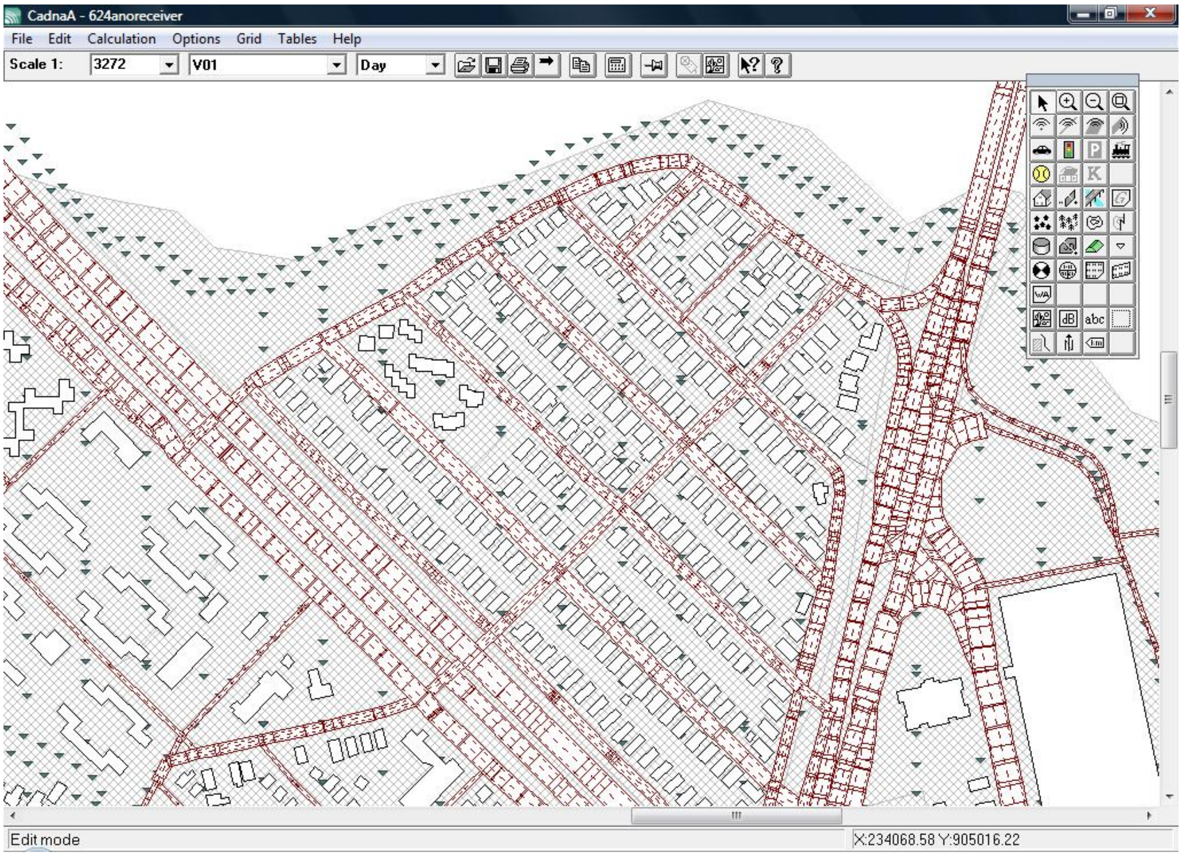


Figure B-2: A close-up of data as it is entered into CadnaA

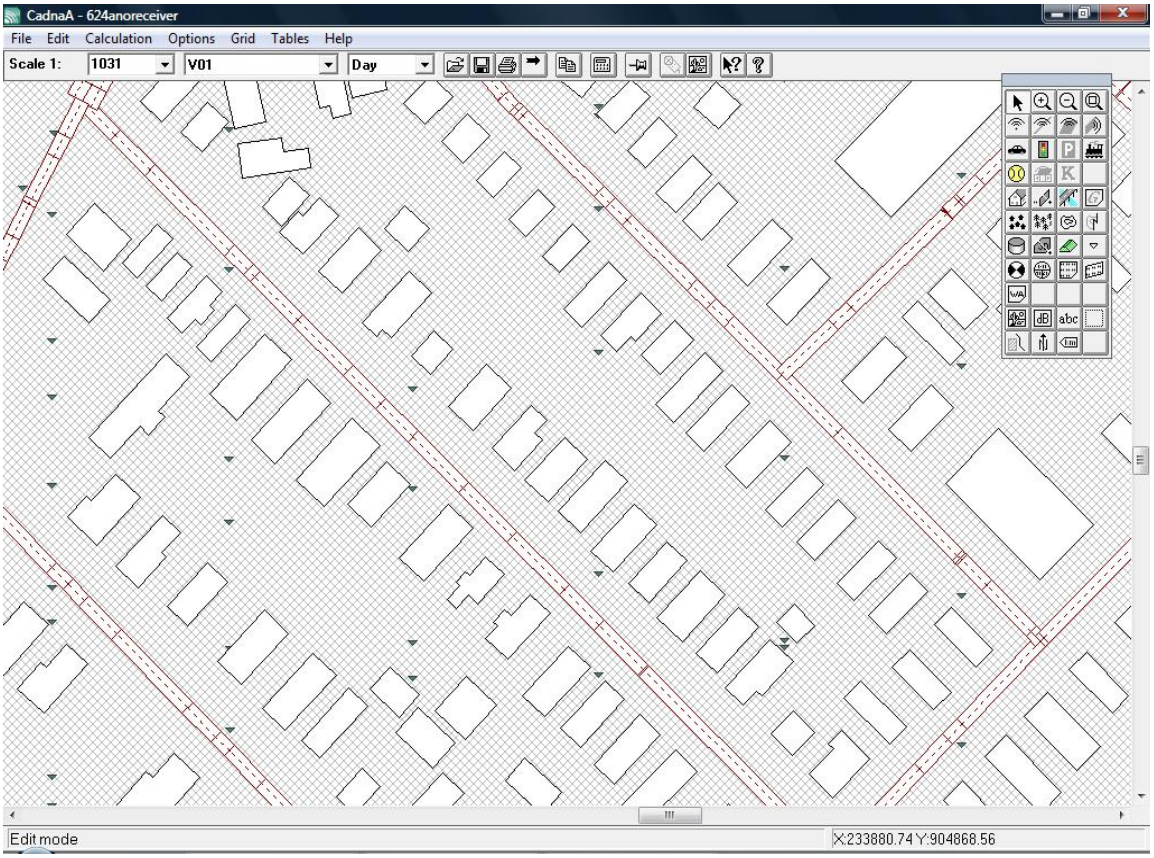
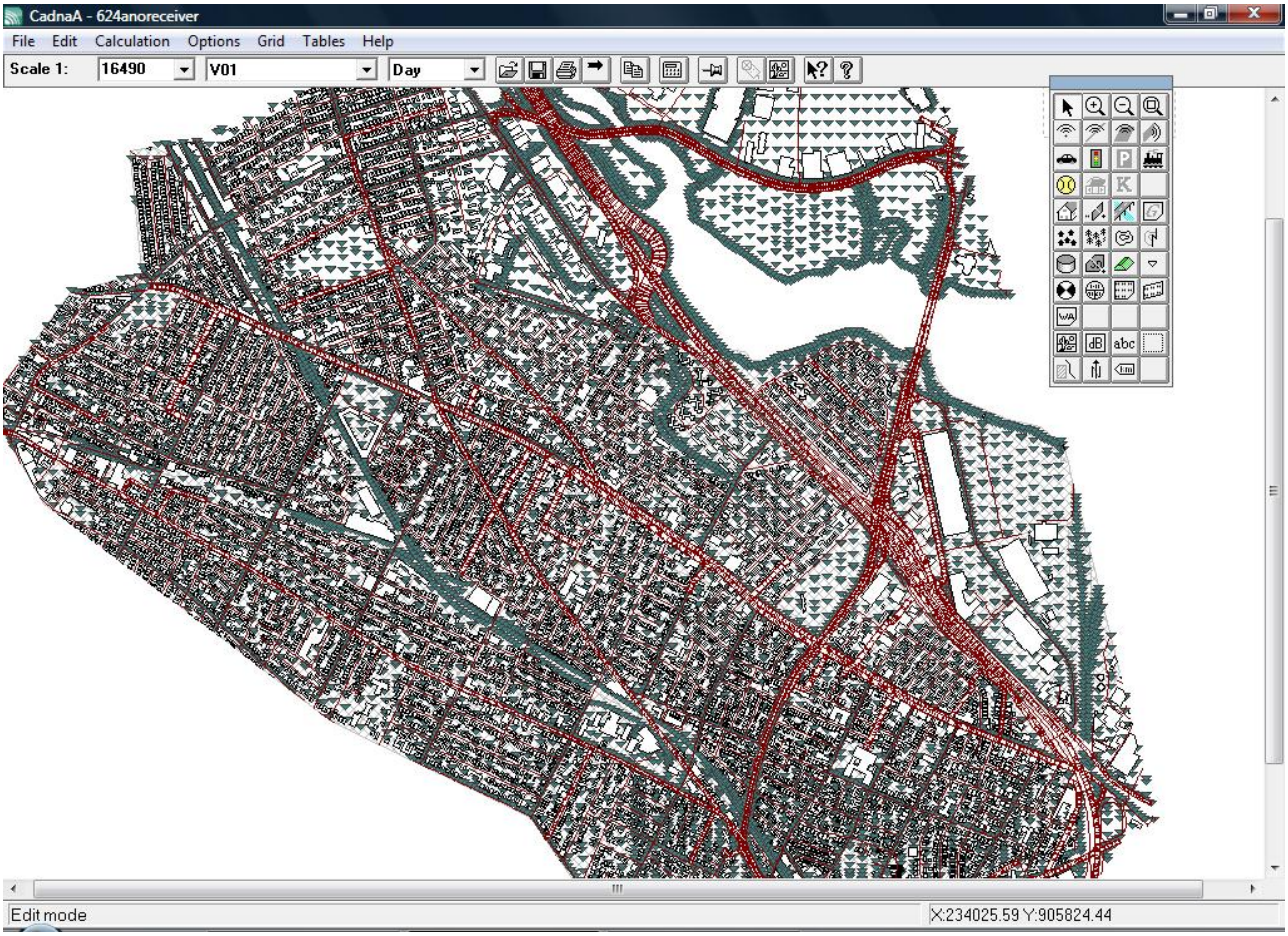


Figure B-3: Road, parcel, and elevation data entered into Cadna A



Appendix C: Noise Map Values in Noise Software Package

Figure C-1: A screen shot depicting how noise values for particular parcels are given in CadnaA This particular shot is for Ld noise values.

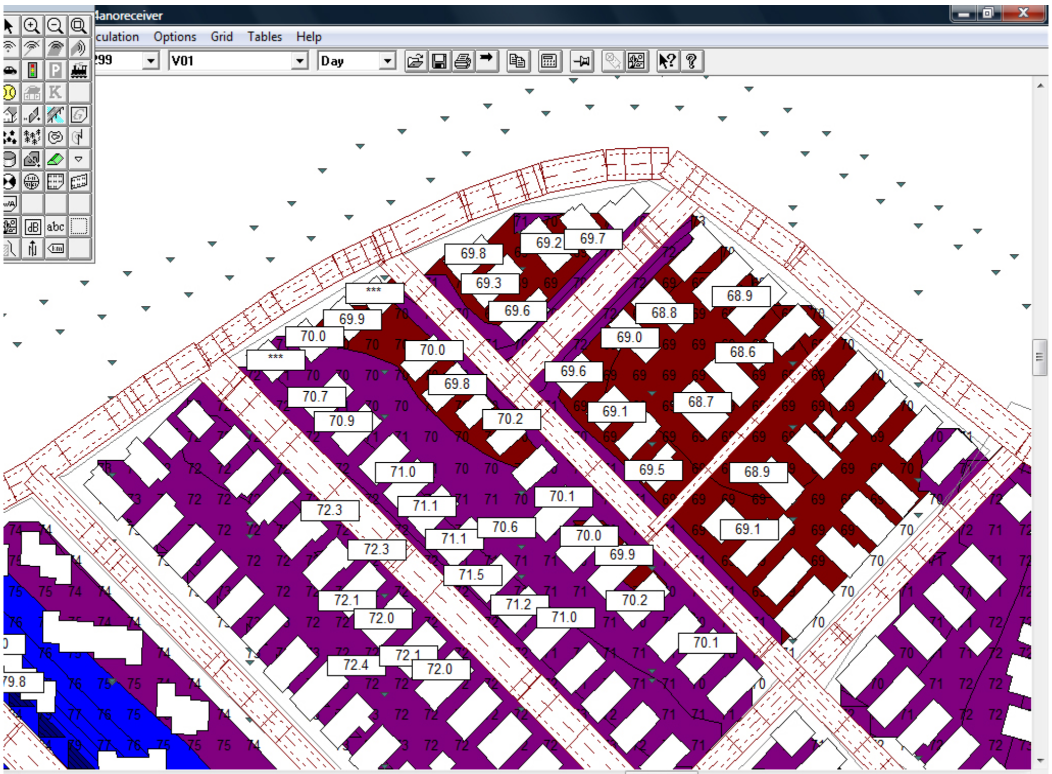
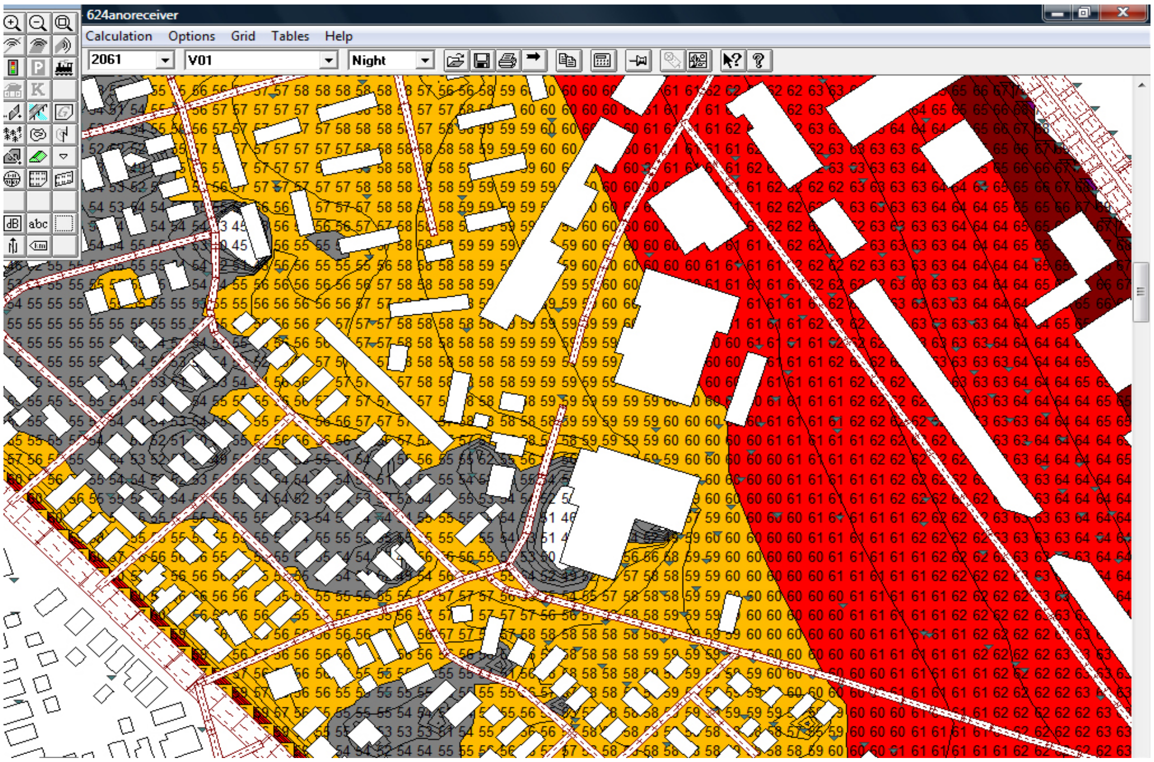


Figure C-2: A screenshot depicting how noise values for a particular area are shown in CadnaA. This particular shot is for Ln noise values.



Appendix D: Noise Level Values for Area A

Table D-1: Noise Values for Area A (Less Exposed Group)

Map Number	Ld	Ln	Ldn
1	55.0	45.8	55.3
2	58.7	49.6	59.1
3	58.2	48.0	58.1
4	56.5	46.4	56.5
5	56.5	46.4	56.4
6	55.4	40.2	54.1
7	50.9	40.9	50.9
8	52.3	42.3	52.3
9	57.1	47.2	57.1
10	55.6	45.6	55.6
11	57.7	55.6	62.4
12	57.0	48.5	57.6
13	54.3	45.6	54.8
14	56.1	47.0	56.4
15	58.2	48.1	58.2
16	54.0	45.3	54.5
17	53.3	44.7	53.9
18	53.2	44.8	53.8
19	52.9	43.9	53.3
20	54.6	45.9	55.1
21	54.0	45.5	54.6
22	55.2	46.9	55.9
23	53.0	44.0	53.4
24	51.6	42.8	52.0
25	52.5	44.1	53.2
26	53.5	45.3	54.2
27	49.5	40.6	49.9
28	52.1	43.6	52.7
29	50.7	42.3	51.3
30	52.7	44.2	53.3
31	51.4	42.9	52.0
32	52.3	44.2	53.1
33	52.9	44.8	53.7
34	52.3	44.0	53.0
35	54.2	46.1	55.0
36	52.5	44.3	53.3
37	49.2	40.6	49.8
38	53.7	43.7	53.7
39	51.3	42.8	51.9
40	54.2	46.2	55.0
41	53.0	44.7	53.7

Appendix E: Noise Level Values for Area B

Table E-1: Noise Map Values for Area B—Section B1

Map Number	Ld	Ln	Ldn
1	81.2	73.8	82.4
2	78.1	70.7	79.3
3	78.0	70.6	79.2
4	79.8	72.4	81.0
5	70.7	63.6	72.0
6	70.9	63.4	72.0
7	72.1	64.6	73.2
8	72.3	64.6	73.3
9	69.4	61.4	70.3
10	69.1	61.4	70.1
11	69.3	61.7	70.4
12	69.2	61.6	70.3
12	69.2	61.6	70.3
13	72.4	63.9	73.0
14	75.4	67.9	76.5
15	80.5	73.1	81.7
16	80.7	73.3	81.9
17	79.2	71.7	80.3
18	79.0	71.9	80.3
19	80.1	72.7	81.3
20	79.6	72.2	80.8
21	79.9	72.2	80.9
22	79.1	71.8	80.3

Table E-2: Noise Map Values for Area B—Section B2

Map Number	Ld	Ln	Ldn
1	68.0	60.5	69.1
2	68.4	60.9	69.5
3	68.6	61.1	69.7
4	66.4	58.8	67.5
5	68.0	60.5	69.1
6	78.4	70.8	79.5
7	73.2	65.7	74.3
8	67.4	59.9	68.5
9	68.0	60.6	69.2
10	71.0	63.5	72.1
11	71.0	63.5	72.1
12	71.0	63.5	72.1
13	73.1	65.7	74.3
14	75.7	68.3	76.9
15	75.7	68.3	76.9
16	78.1	70.6	79.2
17	76.7	69.1	77.8
18	71.0	68.3	75.2
19	77.0	69.5	78.1
20	71.5	64.0	72.6
21	68.4	60.9	69.5
22	68.3	60.8	69.4
23	68.3	60.8	69.4
24	68.3	60.8	69.4
25	67.7	60.0	68.7

26	68.8	60.0	69.3
27	69.0	61.4	70.1
28	69.0	61.4	70.1
29	69.0	61.4	70.1
30	71.8	64.3	72.9
31	72.2	64.8	73.4
32	72.2	64.8	73.4
33	78.6	70.2	79.3
34	78.6	70.2	79.3
35	73.7	66.3	74.9
36	73.0	65.6	74.2
37	73.0	65.6	74.2
38	78.0	70.6	79.2
39	78.0	70.6	79.2
40	72.2	64.8	73.4
41	79.5	72.0	80.6
42	75.0	67.6	76.2

Table E-3: Noise Map Values for Area B—Section B3

Map Number	Ld	Ln	Ldn
1	73.3	65.1	74.1
1	73.3	65.1	74.1
2	70.0	61.8	70.8
2	70.0	61.8	70.8
3	71.4	63.4	72.2
4	71.4	63.4	72.2
5	73.7	65.7	74.5
6	77.0	69.5	78.1
6	77.0	69.5	78.1
7	74.6	67.1	75.7
8	75.7	68.2	76.8
9	73.8	66.2	74.8
10	70.9	63.1	71.9
11	73.5	66.1	74.6
12	75.1	67.7	76.3
13	78.9	72.1	80.4
14	75.2	67.4	76.2
15	75.2	67.4	76.2
16	76.9	71.5	79.2
17	78.9	71.5	80.1
18	74.8	69.5	77.2
19	73.5	66.0	74.6
20	80.6	73.2	81.8
20	75.9	68.5	77.1
21	75.9	68.5	77.1

22	81.7	74.3	82.9
23	75.9	68.5	77.1
24	76.0	68.4	77.1
25	76.0	68.4	77.1
26	72.5	65.0	73.6
27	72.5	65.0	73.6
28	72.5	65.0	73.6
29	79.1	71.6	80.2
30	71.3	63.1	72.1
31	65.7	58.0	66.7
32	68.7	60.6	69.5
33	67.1	59.5	68.2
34	67.1	59.3	68.1
35	69.1	61.0	69.9
36	70.7	62.9	71.7
37	70.1	62.4	71.1
38	70.9	64.0	72.3
39	63.7	56.1	64.8
40	70.7	63.0	71.7
41	70.5	63.5	71.9
42	69.3	61.8	70.4
43	69.2	61.6	70.3
44-60	67.5	59.6	68.4
61	66.0	58.3	67.0
62	65.7	58.0	66.7
63	65.8	56.7	66.2
64	65.7	58.0	66.7

65	64.0	57.2	65.5
66	64.0	57.2	65.5
67	65.9	58.0	66.8
68	65.7	58.0	66.7
69	66.4	58.8	67.5
70	64.3	56.7	65.4
71-82	64.4	56.8	65.5
83	64.9	57.2	65.9

Appendix F: Relevant CAFEH Survey Questions

A2_age: **How old are you today?**
A continuous variable. All values are >= 40.

A3_gender**: What is your sex or gender?**
A nominal variable ranging from 1-3.
1 – Males
2 – Female
3 – Transgender

A9_white
Binary Variable range 0-1
0 – No
1 – Yes

A9_asian
See a9_white

A9_black
See a9_white

A10_hispanic: **Are you Hispanic/Latino?**
Nominal Variable
1 – Yes, I am Latino/Hispanic
2 – No, I am not Spanish/Hispanic/Latino

a15_workstatus: **What is your work status?**
A nominal variable that ranged from 1-8.
1 – Working Full Time
2 – Working Part Time
3 – Unemployed, looking for work
4 – Unemployed, not looking for work
5 – Retired
6 – Disabled
7 – A homemaker, not looking for work
8 – A full time student, not looking for work.

a16_maritalstatus: **What is your marital status?**
A nominal variable that ranged from 1-6.
1 – Married
2 – Widowed, living alone
3 – Divorced
4 – Separated, living alone
5 – Never married, living alone
6 – Living with partner

a20_hs – a20_othertxt:
are binary variables (0 or 1) that represent the various degrees a participant has attained. The degrees are High School, Jr. College, Bachelors, Graduate School, Vocational degree, Professional License, and Other. Variables that end in the letters "txt" are string variables that specify the type of professional, vocational, or other degree the individual attained.
a20_norespnse = 999 when no a20 questions were answered.

e1_trafficsound: **How much does sound from traffic bother you currently when you are at this address?**
An ordinal variable that ranges from 1-4
1 – Never
2 – Sometimes
3 – Often
4 – Always
e3_aircraft-e3_othertxt**: are binary variables that represent what noises bother the participant. The range in numbers are 0 – no and 1 – yes. These variables measure sound sources from street traffic, aircraft, trains, emergency vehicle sirens, loud music, car alarms, other.**
h7_sleep: **How much sleep do you usually get at night on weekdays or workdays?**
A continuous variable that represents hours.
j1-j18:
All odd number variables **j1, j3, j5, etc.** are binary variables that indicate whether a doctor has told the participant if he/she has x disease, where x is (in order of how they appear in the table) Congestive Heart Failure, Heart Attack, Angina, Diabetes, High Blood Pressure, Cholesterol, Arthritis, Asthma, and Stroke.
All even number variables **j2, j4, j6, etc.** are ordinal variables that have a range of 1-5:
1 – within the past 12 months
2 – 1-4 years ago
3 – 5-9 years ago
4 – 10-20 years ago
5 - >20 years ago
The even j's are only answered if the corresponding j (the odd j preceding the even j) has a code = 1.
TerminalDegree**: The highest degree attained by the participant**
(This variable was coded from the variables a19_education and the a20's degree variables)
An Ordinal Variable
1 – Less than High School
2 – Some High School
3 – Completed High School
4 – Completed Jr. College
5 – Completed College
6 – Completed Graduate School