Vehicle-pedestrian Accidents at Signalized Intersections in Montreal

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ABSTRACT

Pedestrian safety is a topic of growing concern. To better understand pedestrian safety and the variables that affect it, this thesis had four main objectives. The first objective was to build a database to be used for the analysis of pedestrian safety. The database built consisted of 1,875 signalized intersections (75% of all signalized intersections on the island), randomly distributed throughout the island of Montreal. Manual vehicular and pedestrian counts were provided by local authorities for these intersections, but they also needed to be visited individually, so that geometric data could be recorded for each intersection. This is the largest data set that has ever been assembled for a pedestrian safety analysis. The second objective was to use automatic counters to extrapolate manual pedestrian counts taken during peak periods, to full 24 hour average daily counts through the use of expansion factors. By placing automatic counters at six different locations throughout the city of Montreal for one full year, various expansion factors were generated (monthly, daily and hourly). The third objective was to investigate the effect of traffic exposure measures, geometric designs and traffic controls on vehicle-pedestrian collision occurrence at signalized intersections. To investigate the impact of vehicle movements on pedestrian accidents, three separate definitions of risk exposure were used: completely aggregated flows, motor-vehicle flows aggregated by movement type (left, right and through movements) and disaggregated flows analyzing potential conflicts between motor vehicles and pedestrians. Various negative binomial (NB) models were fitted to the data with and without geometric design characteristics. Among other findings, vehicular traffic is found to be the main contributing factor in accordance with previous works. Significant geometric properties included pedestrian phasing, exclusive left turn lanes, commercial entrances and exits, total crossing distance, curb extension and number of lanes. Exclusive left turn lanes, pedestrian phasing and curb extensions were found to decrease pedestrian accidents, whereas longer crossing distances, number of lanes and more commercial entrances and exits were found to increase pedestrian-vehicular accidents after controlling for vehicular and pedestrian flows. The final objective was to estimate pedestrian activity at signalized intersections based on built environment attributes. Using both a log-linear and negative binomial regression, it was found that pedestrian activity could be estimated by several land-use, transit, demographic and weather variables; including: population, commercial space, open space, subway presence, bus stations, schools, percent major arterials, number of street segments, presence of a 4-way intersections, presence of precipitation and presence of windy conditions. These findings support other studies done in this field.

RÉSUMÉ

La sécurité des piétons est un sujet de plus en plus préoccupant. Pour mieux comprendre la sécurité des piétons et les facteurs qui l'affectent, cette thèse avait quatre principaux objectifs. Le premier objectif était de mettre en place une base de données pour analyser la sécurité des piétons. Cette base de données était constituée de 1 875 intersections signalisées (75% des intersections signalisées sur l'île), distribuées au hasard à travers l'île de Montréal. Les données sur les véhicules et les piétons comptées manuellement étaient fournies par les autorités locales pour ces intersections, mais il a aussi fallu les visiter individuellement, afin que les données géométriques soient enregistrées pour chaque intersection. Cette base de données est le plus grand ensemble de données jamais assemblé pour l'analyse de la sécurité des piétons. Le second objectif était d'utiliser des compteurs automatiques pour extrapoler les données sur les piétons obtenues manuellement durant les heures de pointe aux données moyennes durant 24 heures à travers l'utilisation de facteurs d'expansion. En plaçant des compteurs automatiques à six endroits différents à travers la ville de Montréal durant un an, différents facteurs d'expansion ont été générés (mensuellement, quotidiennement et à toutes les heures). Le troisième objectif était d'étudier l'effet des mesures d'exposition du trafic, des désigns géométriques et des contrôles du trafic sur les possibilités de collision entre les véhicules et les piétons aux intersections signalisées. Pour étudier l'impact des mouvements des véhicules sur les accidents chez les piétons, trois définitions différentes des risques d'exposition étaient utilisées : les flux entièrement regroupés, les flux de véhicules automobiles regroupés par type de mouvement (mouvements vers la gauche, vers la droite et vers l'avant) et les flux dispersés analysant les conflits potentiels entre les véhicules automobiles et les piétons. Différents modèles binomiaux négatifs (NB) ont été insérés dans les données avec et sans les caractéristiques des désigns géométriques. Parmi les autres résultats, la circulation des véhicules a été établie comme étant le principal facteur en conformité avec les travaux précédents. Les propriétés géométriques significatives incluaient la phasage des piétons, des voies réservées pour le virage à gauche, des entrées et sorties commerciales, le total de la distance pour traverser la rue, l'étendue du freinage et le nombre de voies. Les voies réservées pour le virage à gauche, le retrait des piétons et l'étendue du freinage diminueraient les accidents de piétons, alors que les plus longues distances de traverse, le nombre de voies et le plus grand nombre d'entrées et sorties commerciales augmenteraient les accidents entre les véhicules et les piétons suite au contrôle des flux d'automobiles et de piétons. Le dernier objectif était d'estimer l'activité des piétons aux intersections signalisées en se basant sur les attributs d'un environnement contrôlé. Utilisant à la fois une régression log-linéaire et une régression binomiale négative, il a été constaté que l'activité des piétons pouvait être estimée par plusieurs variables sur l'utilisation de l'espace, les mouvements démographiques et les conditions météorologiques; incluant : la population, l'espace commercial, l'espace ouvert, la présence de métro, les arrêts d'autobus, les écoles, le pourcentage des grandes artères, le nombre de segments de rue, la présence d'intersections à quatre sens, la présence de précipitations et de vent. Ces résultats supportent d'autres études faites dans cet domaine.

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1. INTRODUCTION

1.1 Problem statement

Sustainable transport cannot be achieved without non-motorized forms of transportation such as walking. Despite the health and environmental benefits, walking can also impose some road safety risks. In Canada, between 2002 and 2006, 1,829 pedestrians were killed while another 23,920 were seriously injured (43). As part of the pedestrian safety problem, intersections are critical elements. In Montreal, about 60% of pedestrian injuries occur at intersections. In response to this issue, transportation agencies are looking for efficient engineering countermeasures and better road designs related to road geometry, traffic controls and traffic conditions that reduce injury risk faced by pedestrians at intersections. By understanding which designs and traffic factors are the most/least dangerous, engineers and urban planners can implement safety interventions to help make roads safer for pedestrians.

Pedestrian safety in urban areas, particularly at intersections, has attracted attention in the last few years. Various works have been published dealing mainly with the link between pedestrian and motor-vehicle traffic flows and pedestrian crash risk (safety in numbers). Most studies have looked at vehicular and pedestrian activity at intersections, but are limited to a relatively small number of intersections or have not distinguished vehicle movements or have not included measures of intersection geometry. Very few studies have looked at the impact of geometric designs, traffic controls and the built environment on pedestrian safety. Some exceptions are the recent works of Schneider et al. (4), Miranda-Moreno et al. (3), and Pulugurtha (5). Very few studies have looked at disaggregate proxies of traffic exposure, such as the iteration of vehicles and pedestrians during short periods of time while considering the different turning movements (right, left and through movements). Moreover, past studies have involved a relatively small sample of intersections, which may affect the quality of the results. Another important issue when studying pedestrian safety in urban areas is the lack of data, including pedestrian and vehicular traffic flows as well an inventory of geometric design, traffic controls and built environment characteristics.

Due to lack of data collected, or in large areas where widespread data collection by manual counts would be very time consuming and expensive, various methods for estimating pedestrian activity at intersections has been proposed. In this regard, an important body of research has been in the identification of pedestrian activity determinants such as the relationships between built environment, road designs and weather on pedestrian activity levels. Some research has also been done on accurate adjustment factors to extrapolate hourly measures of pedestrians into full daily, weekly, monthly or yearly pedestrian volumes by using automatic pedestrian count data (6). Accurate adjustment factors are needed to compare pedestrian counts that are taken for different lengths of time, at different times of day, in different locations and under different weather conditions. Other factors such as land use and weather patterns and their effect on pedestrian activity is also explored in detail in (6).

Different pedestrian activity methods have been proposed in the literature – for a comprehensive study on that, we refer to (6). Among those, we can mention regional traffic volume models, trip generation models using the classical 4-step travel demand modeling approach using block-sized pedestrian analysis zones, space syntax models using regression techniques to link pedestrian flows to street and pedestrian network characteristics (connectivity measures), models based on land-use patterns, among others.

In particular, the land-use and urban form (LU & UF) regression approach has recently attracted some attention. This basically consists of the development of built-environment models based on a set of sites (e.g., intersections or sidewalks). For instance, we can refer to Pulugurtha and Repaka *(7)*; Schneider, Arnold et al. *(8)* and Miranda-Moreno et al. *(9)*. The goal is to estimate pedestrian activity based on built-environment attributes in close proximity to an intersection, a crosswalk or a block.

This thesis will look at all these topics and how they relate and influence pedestrian safety at 1,875 signalized intersections on the island of Montreal.

1.2 Objectives

The main objective of this research is to look in-depth at the effects of geometric designs and the built environment on pedestrian activity and crash frequency at the city level. According to the issues identified in the previous section, this thesis has the following particular objectives:

- Objective 1: Build an extensive inventory for the majority (~75%) of signalized intersections on the island of Montreal. The inventory consists of pedestrian and vehicular volumes, several geometric design variables, built environment properties and traffic control attributes for each intersection. The pedestrian and vehicular volumes are compiled from manual counts obtained from the local transportation authorities. The geometric and traffic control data were manually collected for each of the 1,875 intersections. Each of the 1,875 intersections was visited individually to collect this data. The data collection and inventory will be explained in detail in Chapter 2.

- Objective 2: Obtain expansion factors to extrapolate hourly short-term manual counts. These are obtained from a set of six different automatic pedestrian counters, each with a years worth of automatic count data. These factors help expand short-term manual counts to full 24 hour average daily counts. This is done in order to correct for hourly, daily and monthly variations in manual counts between signalized intersections, where data was recorded at different times throughout the year. The expansion factors and 24 hour volumes will be covered in Chapter 2.

- Objective 3: Investigate the effect of traffic exposure measures, geometric designs and traffic controls on vehicle-pedestrian collision occurrence at signalized intersections. For this purpose, a statistical modeling approach is implemented to assess the relationships between these variables. This will be covered in detail in Chapter 3.

- Objective 4: Propose a method to estimate pedestrian activity at signalized intersections based on built environment attributes. This method is expected to help estimate pedestrian activity at intersections with missing data. This will be covered in Chapter 4.

As part of the outcome of this research work, some recommendations are provided for practitioners on how to build a large scale intersection inventory for pedestrian safety studies, as well as how to improve safety at signalized intersections. Pedestrian injury risk estimates can be used for the identification of the most dangerous sites. This is expected to help identify and prioritize which intersections should be considered for safety inspections and potential engineering improvements.

1.3 Literature review

There has been a fair amount of research done on pedestrian safety and their associated factors. Some recent work has also investigated some associated issues such as:

i) The estimation of average annual daily traffic based on pedestrian manual counts and expansion factors obtained from automatic pedestrian counters.

ii) The lack of geometry and traffic control intersection inventories at the city level,

iii) The development of pedestrian activity methods to integrate the role of built environment on pedestrian safety analysis, as well as to estimate pedestrian flows at facilities with missing data.

The following sub-sections present some of the research that has been previously conducted.

1.3.1 Pedestrian-vehicular crash occurrence at intersections

Pedestrian safety is a topic well documented. Many studies have looked at pedestrian-vehicular crash occurrence at different spatial levels. These studies can use either aggregated data (ex: using census tracts or postal/ZIP codes) or disaggregated data (ex: intersection or roadway sections). The role of the built environment and socio-demographics on crash frequency has been investigated mainly in aggregate studies. Few studies have looked at the link between vehicular traffic and pedestrian flows with crash occurrence at intersections (disaggregate studies). Most past studies have also only used a relatively small sample size of intersections.

Among the works looking at pedestrian-vehicle crash risk at intersections, we can refer to Cameron (16), Brüde and Larsson (17), Lyon and Persaud (18), Shankar et al. (19), Lee and Abdel-Aty (20), Harwood et al. (2) and Miranda-Moreno & Morency et al. (3). Most of these studies have focused on the effect of aggregate (total) motor-vehicle traffic and pedestrian flows only, for pedestrian crash frequency. Lee and Abdel-Aty (20) also looked at the effects of the drivers and pedestrians age, gender and alcohol levels on pedestrian-vehicular accidents. A comprehensive literature review has been produced by Elvik (1). In general, previous works show that daily traffic volume (measured usually as average annual daily traffic, AADT), is the main determinant of pedestrian collision frequency. Moreover, the literature agrees that the risk faced by pedestrians with respect to traffic volume is non-linear, and that individual pedestrian risk increases as the number of motor vehicles goes up (1). The elasticity’s reported in previous studies range between 0.2 and 1.2 (1, 2 and 21). This means that for a 100% increase in motor vehicles, there have been reports ranging from a 20% to 120% increase in pedestrian risk. Pedestrian flows have also been found to be one of the main contributing factors to pedestrian-vehicle collision frequency. Papers (2, 3, 4, 18, and 21) have found a statistically significant and positive relationship between pedestrian activity and collision frequency at different types of intersections. As for motor-vehicle traffic, past studies also suggest that the individual risk faced by a pedestrian changes in a non-linear way with respect to pedestrian volumes - this is referred to as the safety in numbers effect (22 and 23). The literature reports elasticity estimates between 0.3 (22) and 0.54 (23) for the pedestrian volume and collision frequency relationship. This shows that an increase in pedestrian volume seems to evoke a change a driver behaviour which decreases individual pedestrian risk to pedestrian-vehicular accidents.

From these works, we can see that pedestrian injury frequency increases as the number of motor vehicles and pedestrians increase. However, individual pedestrian risk (crash rates) decreases as pedestrian volume increases (the safety in numbers effect).
In addition to vehicular traffic and pedestrian activity, variables such as street geometry, the built environment and traffic controls, also play an important role in pedestrian safety at intersections. Street geometry contains variables such as road width, the number of lanes, presence of marked pedestrian crosswalks, median presence, types of turn restrictions, curb extension, etc... These factors can all affect pedestrian safety. A summary of the literature in this domain has been explored by Schneider et al (4), Harwood et al (1) and Miranda-Moreno et al. (3). Various findings are listed in the following paragraphs.

Zegeer et al. (24) found that after controlling for pedestrian and traffic volumes, the number of lanes and raised medians had significant effects on collision frequency. Zegeer also makes a number of suggestions and recommendations for traffic calming and safety considerations for pedestrians not at intersections, which is also important but a different topic entirely. A study by King et al. (25) showed similar results. In this study, the inclusion of raised medians, narrowed lanes and timed signals all contributed to increases in pedestrian safety. In another study, Bowman et al. (26) looked at the effect of different types of medians on pedestrian crashes. They suggested that medians not only block vehicle interactions in different directions, but also provide a safe refuge area for pedestrians. In their recent work, Schneider et al (4) also found that raised medians on both intersecting streets were associated with lower numbers of pedestrian crashes.

Other studies have looked at speed limits and operating speeds (24, 27 and 28). Higher operating speeds or speed limits have been found to be associated with a greater risk of pedestrian-vehicle crashes, as well as greater injury severity at intersections. One study suggests that vehicular volumes determine crash frequency, whereas operating speeds determine crash severity (28).

The effect of curb parking was also documented by Box (29). Box's study showed that on street parking was involved in 20% of all accidents on urban street surfaces. The study also demonstrated that angled parking caused 2 to 3 times more accidents per mile than parallel parking. On-street parking also greatly increases the risk of accidents for children (30). This is consistent with children running into the street playing, where parked cards obstructed their view of traffic.

The effect of traffic controls and operations have only been investigated using subrogate measurements (violations). Longer traffic signal phases and pedestrian wait times tend to be associated with lower levels of comfort and more pedestrian violations at signalized intersections, De Lavalette et al. (31) and Tiwari (32). The presence of a narrow one way street or a two-way street with a central island/median also increased the chance of pedestrian violations (31). From a study in Delhi, India, females were found to wait 27% longer than males to cross a street. It was also found that up to 90% of pedestrians would attempt to make an unsafe crossing at a signalized intersection (32).

Some studies have looked at the effect of the Built Environment (BE) such as (2, 3 and 20). For instance, in their recent work, Schneider et al (4) showed that significantly more pedestrian crashes occurred at intersections with more right-turn-only lanes, more non-residential driveways within 50 ft (15 m) of an intersection, more commercial properties within 0.1 mi (161 m), and a greater percentage of residents within 0.25 mi (402 m) who were younger than 18 years of age. It is important to note that the effect of Built Environment and geometric variables on pedestrian safety has been mostly studied at the area-wide level using census-tract data. We can refer to the works of Graham and Glaister (33) and Wier et al. (34). The study in London showed that pedestrian-vehicular accidents were most likely to occur in wards of higher population density and in residential areas. Areas with very high population and congestion showed fewer pedestrian-vehicle accidents than expected, which again shows the safety in numbers concept (33). A study in San Francisco related vehicle-pedestrian collisions to traffic volumes and a number of built environment factors, such as: arterial streets without public transit, proportion of land area zoned for neighbourhood commercial use and residential-neighbourhood commercial use, land area, employee population, resident population, proportion of people living in poverty, and proportion of people aged 65 and over. The Built Environment is then used as a surrogate of pedestrian volumes in absence of pedestrian volume data (34).

Some area-wide studies have also looked at other factors such as children (35 and 37). Injuries in pedestrian-vehicle collisions were most likely to occur in areas of the city with greater population density, a greater proportion of males, a lower proportion of children aged 0–15, a greater proportion of unemployment and a lower proportion of well educated residents (high school degree or better). In addition, injuries in pedestrian collisions were more frequent in areas of the city with larger traffic flows. In the case of injuries in which alcohol use by the pedestrian was implicated, injuries occurred most frequently at locations where bar density was high (36). A study in Baltimore, Maryland looked directly at pedestrian collision risk for school children and the factors associated with these collisions (37).

Some past studies have had some limitations and drawbacks, which are listed below:

-Few studies have looked at the effect of the factors explored in section 1.4.1 using a large sample of intersections (city-level studies).

-Most of these studies have looked at the effect of aggregate (total) motor-vehicle traffic and pedestrian flows on both collision frequency and pedestrian crash frequency. Aggregate measures of traffic are less informative. For instance, the effect of vehicular movements by type (left vs. right turns flows,) can help identify vehicular-pedestrian flow interactions. These disaggregate measures of traffic exposure have not been attempted in the pedestrian safety context, but have been attempted for vehicular-cyclist interactions (40).

-Few geometric and pedestrian traffic controls factors have been included in most past studies, with some exceptions, such as Schneider et al. (4). This study did collect and include a rich set of variables in the analysis.

-Very few studies have normalized and expanded manual pedestrian counts to obtain average daily pedestrian flows. Some modeling issues such as potential presence of endogeneity and spatial correlation have not been addressed.

1.3.2 Pedestrian activity at intersections

As seen before, pedestrian activity or pedestrian volume in each of the facilities of analysis is an important component of the traffic exposure in a road safety study. In addition to the link between pedestrian activity and pedestrian injury frequency, there is a growing interest to indentify the determinants of pedestrian activity and more specifically to develop pedestrian activity models based on built environment variables.

Among one of the first works that has tried to develop a pedestrian activity model, is the one done by Benham and Patel (10*),* who developed a noon-hour pedestrian activity model from land use data in the core of Milwaukee, Wisconsin. The dependent variable used was the pedestrian volume per hour per block, and it was linked to the total square footage of commercial, office, cultural & entertainment and storage & maintenance uses on adjacent block faces. These factors explained approximately 60% of the pedestrian activity variability. Among the limitations in this study, we can mention that it focused on dense central business districts (CBDs) and specific hours of the day.

Another study, is the one of Pulugurtha and Repaka *(7)*. These authors developed a model to measure pedestrian activity, using data collected for a moderate sample of 176 signalized intersections in the city of Charlotte, North Carolina. Based on a standard regression analysis, they found that population, total employment, urban residential area and the number of transit stops had a statistically significant effect on pedestrian activity. However, the study was conducted in a midsized North American city with a relatively low population density, and used a smaller sample of intersections than the one presented in this thesis.

A more recent study is the one by Schneider et al. *(8)*. In this study, 50 intersections from Alameda County, California were used to develop a regression model in determining pedestrian intersection crossing volumes. The intersections were selected representatively from a stratified group of intersections labelled with low, medium or high levels of population density, median income and commercial retail space. Authors linked pedestrian activity at intersections to a variety of surrounding land uses, transportation system attributes and neighbourhood socioeconomic characteristics. In a similar way, some significant variables included total population, employment, number of commercial retail properties, and the presence of a regional transit station in close proximity to an intersection. As one of the contributions of this work, pedestrian count data was extrapolated to weekly volume estimates by combining manual and automatic counts. Despite the important contributions of these two previous works, they did not validate the predictive capacity of developed models.

Another study linked to this research was performed recently by Miranda-Moreno et al. *(9)*. This work involved 509 signalized intersections in Montreal that were analyzed and used to develop pedestrian activity and accident prediction models. The approach to calculating pedestrian activity is the same as what will be done in this thesis. Pedestrian activity was modelled as a function of land use, density, transit supply and road connectivity measures.

Other studies have also looked at pedestrian exposure. The main problem with some of these studies is that they use only density to approximate pedestrian activity at intersections, because pedestrian count data is either not available or too expensive. In one study in Connecticut, pedestrian exposure was related to factors such as population density, median income, sidewalk presence, etc… (11). None of these studies have looked at the simultaneous effects of land use and urban form patterns, intersection spatial location, weather conditions and short and long-term trends.

Despite these important and recent efforts, previous research presents some limitations. This includes the fact that previous studies have used relatively small sample sizes of intersections**.** This is due in part to the fact that pedestrian counts for a large sample of intersections are not constantly collected by a public agency during a short period of time. In addition, few studies have developed pedestrian activity models for intersections during different periods of the day, e.g., see Pulugurtha and Repaka *(7).* Although recent studies have investigated the link between pedestrian activity and land use and urban form, they concern US urban medium-sized areas. Transferability of the few US evidences to large cities in the Canadian context may not be adequate given socio-cultural, urban form and mobility pattern differences. For example, participation in transit and non-motorized modes is often higher in urban Canada. Differences in climate also affect transferability of models between Canada and the USA (*12*). Furthermore, no study has looked at temporal-spatial patterns and the impact of traffic intensity and weather on pedestrian activity.

1.3.3 Expanding pedestrian counts to average annual daily volume

The use of AADT (Average Annual Daily Traffic) is fairly common, and a necessity when evaluating data with counts. AADT allows researchers to compare counts taken from different intersections, at different times, to one another, through the use of expansion factors. Some of the research done in this field is presented in the following paragraphs.

One study (13) looked at computing AADT from automatic counts along low-volume, rural roads in Alberta, Canada. Automatic counts from various sites were compiled from May to September. They then used 48 hour counts from various sites and expansion factors to see how accurately their estimated AADT was to the actual AADT. The study concluded that the estimated AADT would be off by a maximum of 30% with a confidence interval of 95%. The difference between the Alberta study and the one presented in this paper, is that automatic counts were done for pedestrians (instead of vehicles) over an entire year, rather than only four months, allowing to fully capture the temporal and seasonal variations in pedestrian volumes. The methodology presented in the study by Sharma et al.(13) however, could be applicable to collecting vehicular volumes and AADT distributions in more remote areas of the city.

A more relevant study was the one done in Montpelier, Vermont from November 2006 to November 2007 (14). This study placed an Automatic counter in a downtown area of Montpelier for an entire year, to measure the hourly, daily and monthly shifts in pedestrian activity. This is exactly the approach that will be used in this thesis, except data from multiple sites in Montreal will be used instead of only one site. The Montpelier study shows a particular pattern, which may vary by site and land use. In the Montpelier case, pedestrian activity would peak in summer months as well as around 1 o'clock pm, suggesting higher activity during lunch time and in warmer weather. The automatic counts were verified with manual counts, and were revealed to be 98% accurate. As a side to the topic of AADT and count expansion, the various types of automatic counters along with their cost and performance can be seen in (15). There are many different types of counters, each with their own pros and cons. The one being used in this study is similar to the one being used in the Montpelier study, which is the passive infra-red sensor.

1.4 Conceptual framework for pedestrian safety analysis

A conceptual framework for analyzing pedestrian safety at signalized intersections is presented in **Figure 1**. This framework shows the links between the built environment, street design, the weather, exposure and pedestrian safety. The overall goal is to improve pedestrian safety. This can be achieved by reducing both the severity and frequency of collisions. All pedestrian accidents are primarily influenced by the risk exposure factors: pedestrian activity, traffic volume and operating speeds. As seen in the literature, traffic volumes (AADT) have the strongest impact on pedestrian accidents, followed by pedestrian volumes. The safety in numbers effect can also be observed. The individual risk of a pedestrian incurring an accident decreases, as the amount of pedestrian activity increases. The operating speeds of the vehicles primarily influence the severity of the accidents but also the frequency as well.

Risk exposure factors are in turn influenced directly at the macro level by the Built Environment (BE). The Built Environment is made up of: land-use characteristics (industrial, commercial, residential, parks, number of schools, etc…), demographics (population density, children, senior population, etc…), transit supply (kilometers of bus lanes, number of transit stops, the presence of metro stations, etc…) and connectivity, (kilometres of streets and major roads, number of intersections, speed limits, etc…) all within the vicinity of an intersection (usually a 50 to 150 metre buffer around the intersection).

At the micro level, street and intersection design also play an important role on exposure and pedestrian safety. Traffic controls will affect traffic movements (left, right or thru) at intersections. Signal timing at intersections influence vehicular flow rates over the intersection, as well as crossing times for pedestrians. Geometric properties of roads and intersections also play a role in determining vehicular/pedestrian volumes, speeds and behaviour. Pedestrian facilities such as crosswalks, all-red phasing, curb extensions etc…also play a role on exposure and pedestrian safety and need to be taken into consideration.

The weather also has an effect on pedestrian activity and pedestrian safety. Rain, extreme temperatures and wind can affect the amount of pedestrian activity directly. Adverse weather conditions also influence pedestrian safety as vehicles tend to have lower visibility and longer stopping distances in rain, snow and ice. Quantifying how much the weather affects vehicles is difficult, but this thesis looks at the effects of weather on pedestrian activity patterns.

Policies and interventions can be made to improve intersections at the micro level. This thesis aims to find interventions that can be applied to help improve pedestrian safety.

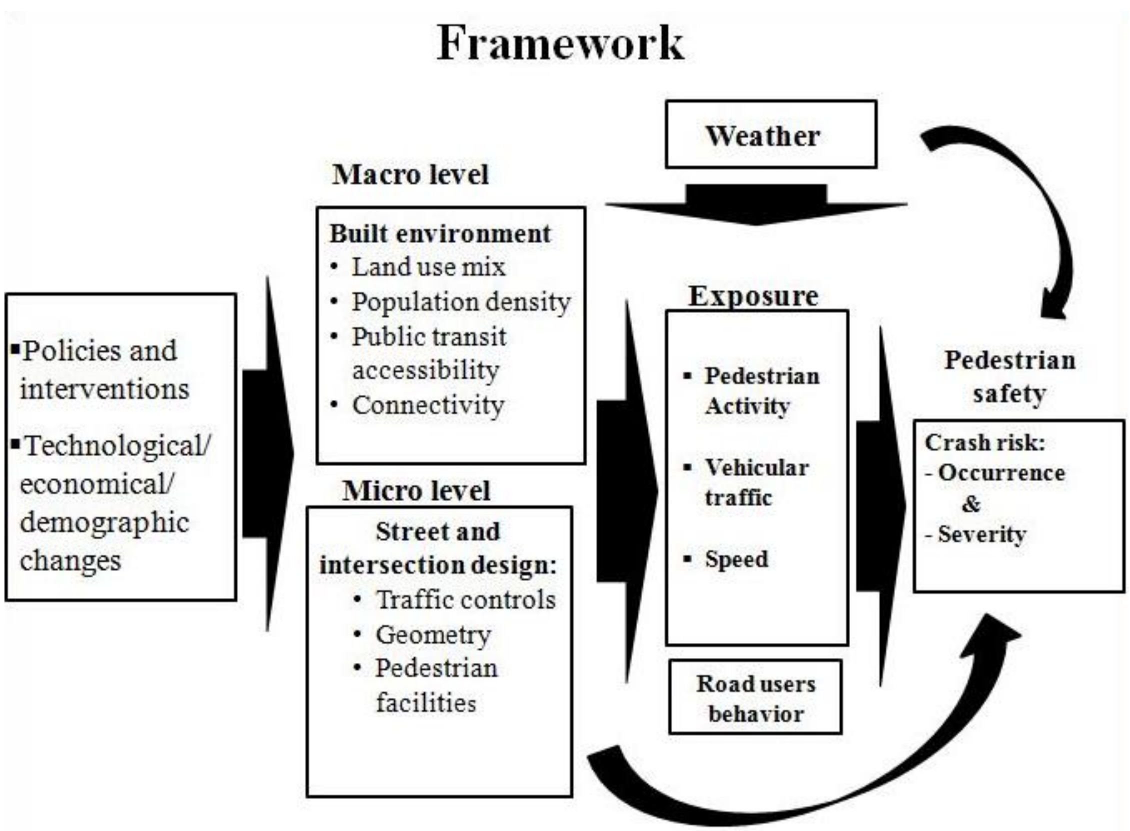


Figure 1 - Conceptual Framework for Pedestrian Safety (3)

We can make a mathematical model to represent the relationships between the variables in **Figure 1**, as can be seen in **Equations 1 and 2**. These equations are the main focus points of this research. In **Equation 1**, we attempt to predict pedestrian activity by modeling it as a function of land-use, density, transit and road networks. This equation is useful for practitioners to implement in areas where pedestrian data is either too time consuming, costly or remote to collect. Instead, using GIS and a spreadsheet, pedestrian activity at signalized intersections can be approximated by a function of several variables. Pedestrian-vehicular accidents can be modelled in a similar way. We can hypothesize that pedestrian-vehicular accidents are a function of several variables as well, including: vehicular volume, pedestrian volume and geometric layout of intersections. This model can be seen in **Equation 2**. This equation can then be used to find out how much each variable contributes to pedestrian-vehicular accidents. Areas with the highest accident rates and most dangerous geometric configurations can be flagged and treated first. Determining the safest geometric configurations for particular pedestrian and vehicular volumes, can help engineers and urban planners design intersections and neighbourhoods which are safer for everyone.

$$P = f(L,D,T,R) \qquad \textbf{Equation 1}$$

P: Pedestrian activity at signalized intersections, measured as a function of L, D, T and R. The equation can be used to predict pedestrians per hour or per day.

L: Land-use type (Commercial, Residential, Industrial, Parks/Recreation etc…)

D: Density of the area within the buffer zone of the intersection.

T: The types of transit offered within the buffer zone of the intersections. This includes variables such as the number of bus stops and the presence of a metro line.

R: This evaluates the types and length of road segments within the buffer zone. Road types include: highways, expressways, arterial, local and collector.

$$A = f(V,P,G) \qquad \textbf{Equation 2}$$

A: Pedestrian-vehicular accidents at signalized intersections, measured as a function of V, P and G. The equation can be used to predict the amount of pedestrian-vehicular accidents at a particular signalized intersection in a year.

V: The average annual daily traffic (AADT) passing through the signalized intersection in a day. This is measured in vehicles per day.

P: The average annual daily pedestrian volume (AADP) crossing a signalized intersection in a day. This is measured in pedestrians per day.

G: The geometric properties of a signalized intersection. Such properties include: median presence, median width, road width, crosswalk width, parking availability, presence of commercial spaces, pedestrian crossing phasing, number of lanes, curb extensions, type of traffic light, left turn lanes etc…

CHAPTER 2

INTERSECTION DATA INVENTORY

2.1 Study area

The city of Montreal is located in the province of Quebec in Canada. From the 2008 OD survey, it was determined that non-motorized trips represented 10.6% (542,365) of all trips made across the greater Montreal area. The island of Montreal has a population of roughly 2 million people. There are an additional 1.5 million people around the island of Montreal, for a total population of roughly 3.5 million in the greater Montreal area. When looking specifically at downtown, the importance of non-motorized transportation is evident. 50,000 non-motorized trips are made within the downtown district every day. This number represents one-third of all trips produced within the downtown core. This number represents non-motorized trips as the primary transit mode only. If you take into consideration how many people park and walk, or use transit then walk, the number of pedestrians grows considerably. In the downtown core, pedestrians represent 40% or more of the traffic volume at the majority of signalized intersections. Between 1999 and

2008 there were 4,150 accidents reported at the 1,875 signalized intersections analyzed. This works out to 415 reported accidents per year over the study area, at signalized intersections only. **Figure 2,** demonstrates the total pedestrian accidents reported in Montreal and the province of Quebec. This includes all pedestrian accidents, not just at signalized intersections. The numbers remain stable from year to year, and the importance of safety at signalized intersections can be emphasized by the fact that they represent over 60% of all pedestrian accidents. This chapter discusses all the data needs and the various sources of data that were required to complete this thesis.

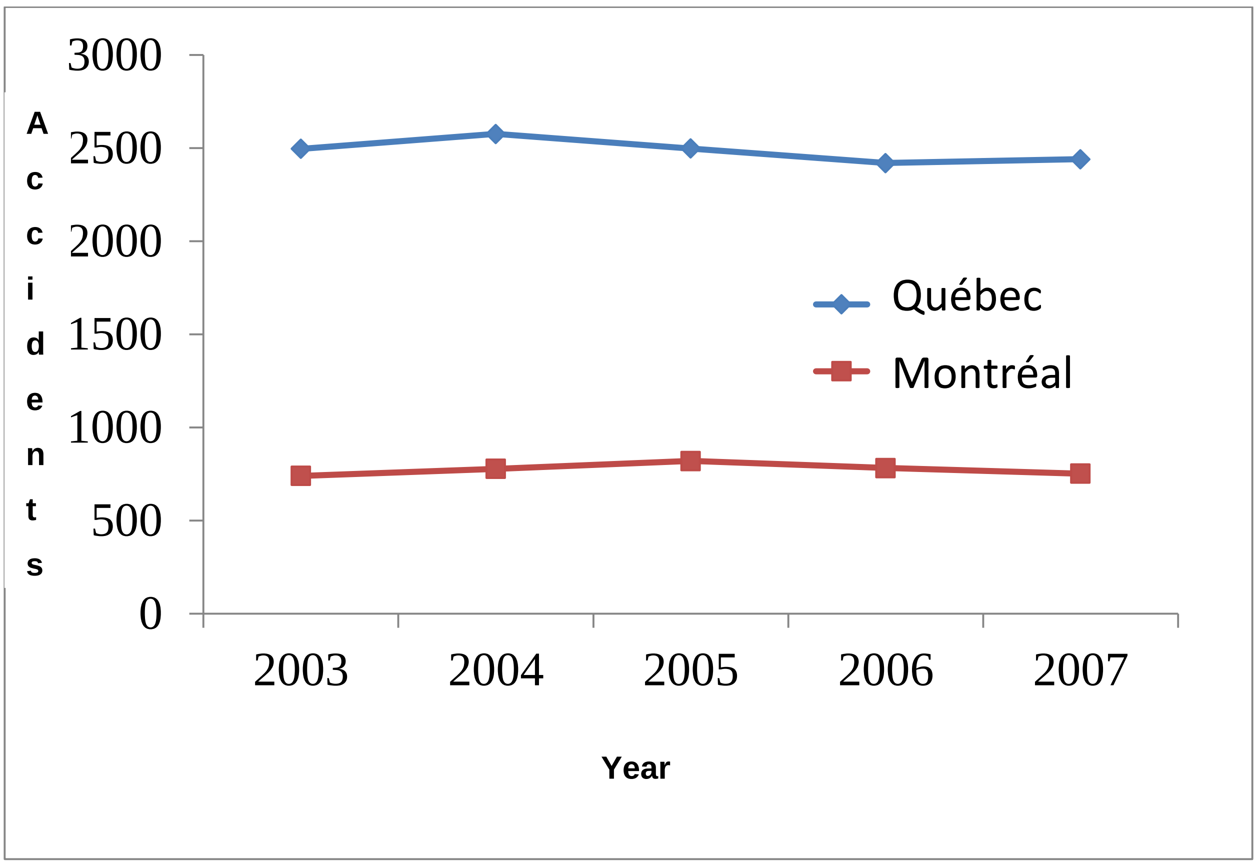


Figure 2 – Pedestrian Accidents in the city of Montreal and province of Quebec (41 & 42)

2.1 Data needs and integration

This study involves analyzing a large and unique sample of 1,875 signalized intersections on the island of Montreal, which is roughly 77% of the total population of signalized intersections on the island. The intersections analyzed come from most of the boroughs across the island of Montreal, as can be visualized in **Figure 3**. These intersections represent a mix of arterial, collector and local streets. In order evaluate pedestrian-vehicular accidents at signalized intersections, a database needed to be built with all 1,875 intersections. For each intersection, vehicular counts, pedestrian counts and full geometric properties needed to be collected. Vehicular and pedestrian counts were performed by private companies for the City of Montreal, but needed to be compiled into a database format from individual count sheets. Furthermore, all pedestrian and vehicular counts were only collected over peak hour periods, and needed to be expanded to full 24 hour volumes. Geometric data for each intersection was manually collected, which took close to 2,000 hours to complete. Each of the 1,875 intersections had to be visited in person to obtain this geometric data.

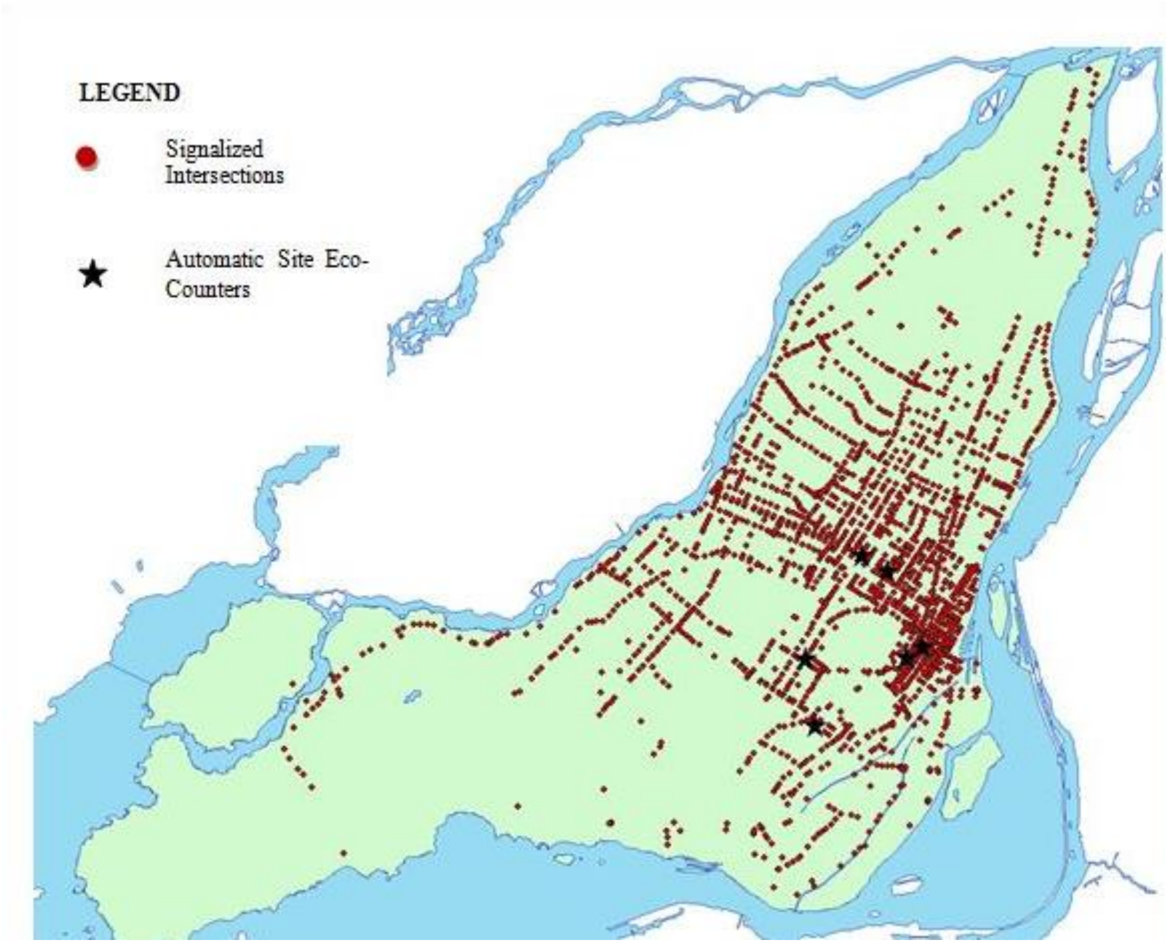


Figure 3 - Spatial distribution of 1,875 studied intersections and of 6 locations with automatic Eco-counters.

The entire process of collecting, treating and analyzing the data can be visualized in **Figure 4.** Each step within the data integration process is explained further in this chapter. The analysis and modelling of the data is covered in **Chapters 3 and 4**.

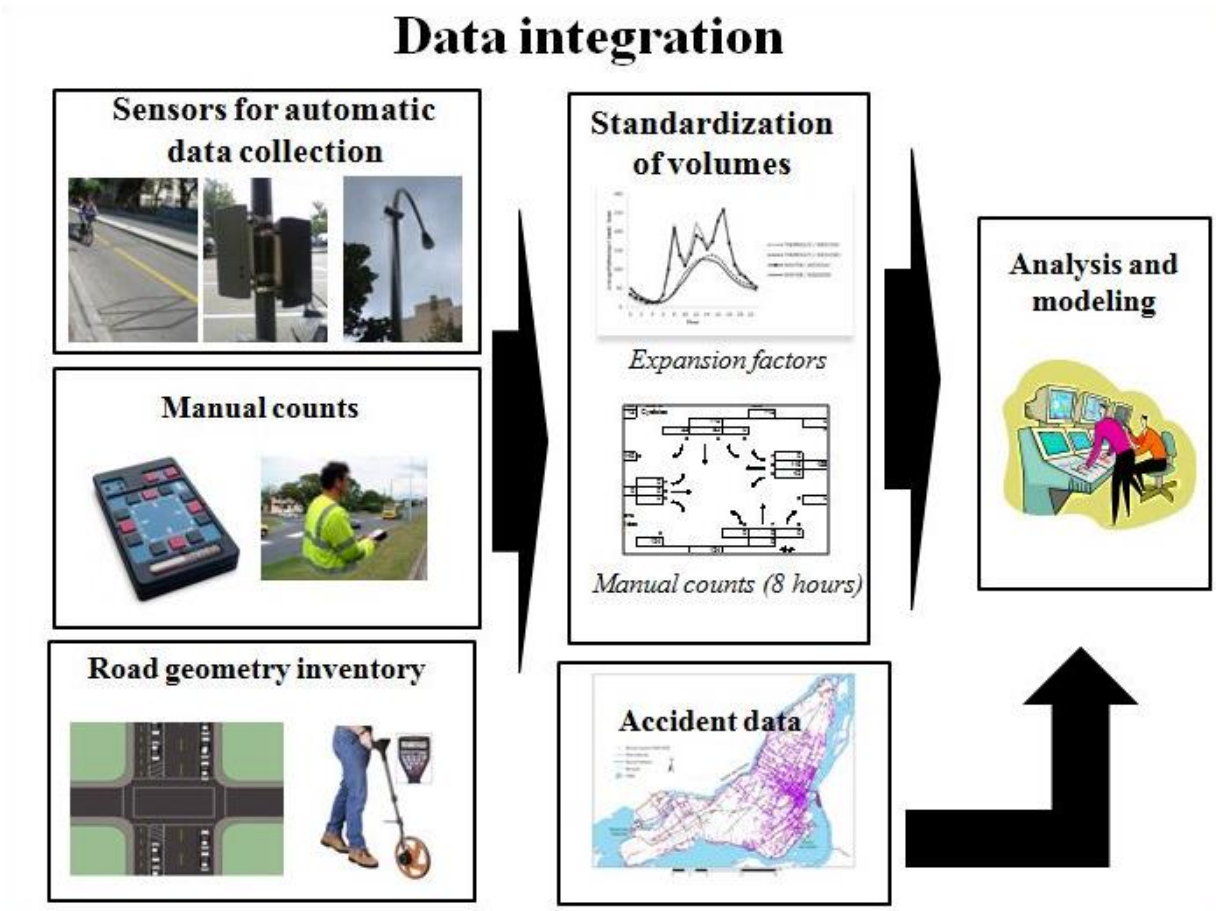


Figure 4 – Data integration flow chart.

2.2 Collecting of vehicular and pedestrian count data

Each of the 1,875 studied signalized intersections (as seen in **Figure 3**) needed both vehicular and pedestrian data provided, in order to evaluate pedestrian safety at each intersection.

Both pedestrian and vehicular counts for these intersections were obtained from Montreal's Transportation Authority. The counts were collected by private engineering companies, hired by the City of Montreal. The counts were collected in groups of 3 to 8 hourly counts done throughout the day (on weekdays). The 3 to 8 hours of counts were spread into AM/NOON/PM peak periods. Each peak period had counts lasting 1 to 3 hours, depending on the company. The hourly counts were disaggregated into 15 minute intervals and were recorded by approach and movement type for each intersection. For vehicles, each intersection could have up to four approaches: Northbound, Southbound, Eastbound & Westbound. Each approach could have up to three movements: left turning, thru & right turning. Each movement also had separate counts for movements based on vehicle size. Trucks and heavy vehicles were counted separately from cars and motorcycles. For pedestrians, each pedestrian could be crossing one of the four approaches regardless of direction. For example: a pedestrian crossing the North side of the intersection would be counted as 1 pedestrian crossing the North side, regardless of whether the pedestrian was travelling Eastbound or Westbound. If a pedestrian crossed multiple sides, they would be tallied for each crossing they made. For example: if a pedestrian crossed the North side of an intersection (from West to East), then crossed the East side of the intersection (from North to South), they would be counted once for each movement (North side and East side crossings), resulting in two pedestrian movements for the whole intersection in total. A schematic for the vehicular and pedestrian movements at signalized intersections can be seen in **Figure 5**.

Different companies counted over different peak hour periods. It was therefore important that all data be expanded to 24 hours, in order for all the data collected to be compatible with one another. The first step of this study was to compile all the pedestrian and vehicular counts into excel. Every intersection had a unique id and was geocoded with X and Y co-ordinates, then imported into ArcGIS. These intersections had counts taken between 2004 and 2009. Data was collected over three peak periods of the day (on a weekday). For the 2009 data, the AM peak period was defined from 06:00-09:00, the noon period from 11:00-13:00 and the PM peak period from 15:30-18:30. For data prior to 2009, the AM period was defined from 07:30-08:30, the noon period from 12:00-13:00 and the PM period from 16:30-17:30.

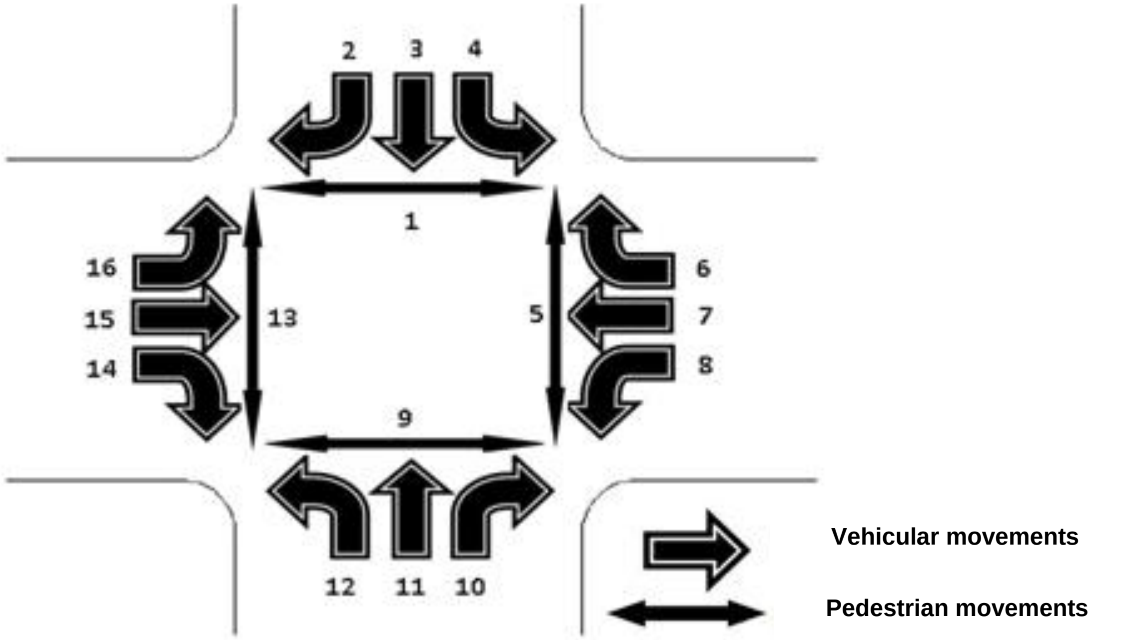


Figure 5 – Vehicular and pedestrian movements and signalized intersections

Pedestrian counts were taken during different months of the year and different days of the week during relatively stable weather conditions. In order to standardize these counts for the hour, day and month of data collection, expansion factors were used to convert hourly values to 24-hour average annual daily pedestrian (AADP) counts. This was done using the same approach that is usually done for normalizing manual motor-vehicle counts and similar to the one proposed by Schneider et al [6]. This process is explained in detail in **section 2.3**. As the counts were done by a third party, the tolerance of how close the pedestrians had to be to the intersection crosswalks to count as a pedestrian crossing is unspecified. This could be a potential source for error; however, if present, this error would be consistent for every intersection. A summary of all the 24-hour pedestrian and vehicular movements can be seen in **Table 1.** The pedestrian-accident data will be described in further detail in **section 2.5**.

	Total Pedestrian Flows AADP (per intersection, per day)	Vehicular flows AADT (per intersection, per day)				Pedestrian-Vehicular Accidents (per intersection over 10 years)
		Total	Left turn movements	Through movements	Right turn movements	
Total counts	1,875 intersections	1,875 intersections	1,875 intersections	1,875 intersections	1,875 intersections	4 150 accidents
Mean	2,883	26,541	2,607	21,149	2,785	2.21
Std. Dev	5,036	14,165	3,214	11,477	3,423	3.17
Minimum	0	1,695	0	0	0	0
Maximum	77,736	154,656	47,783	76,525	46,526	29

Table 1 – Summary of 24-hour vehicular and pedestrian counts and 10-year pedestrian-vehicular accident counts per intersection

2.2.1 Processing of vehicular and pedestrian data

Several different companies collected pedestrian and vehicular count data for the city of Montreal at each of the 1,875 signalized intersections. Each company had its own style of count sheet for collecting pedestrian and vehicular data. Furthermore, the companies collected data at different times depending on the day. These conditions posed some challenges. The first challenge was how we could take count data from 1,875 intersections, each with multiple sheets of data, and merge it into one database file that had all the counts for each movement at a given intersection. This was not an easy task, because this required going through 1,875 different files, each with counts taken during different hours of the day. In order to be able to go through all these files macros needed to be created in order to copy the data that was needed from each company count sheet and then paste that data into a giant database.

Since different companies had different style count sheets, a different macro was needed for each company. On top of this, counts were taken at different times of day depending on the year. For example, in the year 2009, Company A took counts between 06:00 AM and 09:00 AM, 11:30 AM and 13:30 PM & 15:30 PM and 18:30 PM. In the year 2008 however, Company A took counts only between 07:00 AM and 09:00 AM & 16:00 PM and 18:00 PM. The fact that Company A took counts at different times during different years meant that even for the same company, multiple macros had to be made to adjust for the different times. Therefore, **a macro had to me made for each company for each unique set of hours.** When dealing with 1,875 intersections, this meant a lot of different macros had to be created.

A second challenge with the data was how it would be possible to evaluate pedestrian-vehicular accident rates at intersections, as a function of pedestrian and vehicular counts, when the counts were taken for different lengths of time during different days/months of the year? The answer to this challenge was to use expansion factors to adjust for these differences in hours and dates, by converting hourly counts to average annual daily values. This whole process is described in detail in **section 2.3.**

A third challenge with the pedestrian and vehicular data was that one company provided only pdf's of the counts for roughly 400 intersections. This was quite the problem because macro's could not be used to process this data. In order to get around this, various pdf to excel software's were tested, and finally Nitro pdf was selected as the best one, as it consistently converted the pdf's into exact excel cell locations every time, which was crucial for a macro to function correctly. The macros that were written, were designed to expect a certain value in a certain cell. For example, a macro created for Company B expects the 11:00 to 11:15 AM right turn movements to be in cell C76. In order for this to work, the pdf to excel converter must always paste the pdf data for the right turn movements from 11:00 AM to 11:15 AM into cell C76. Some pdf to excel data converters had trouble consistently pasting to exact locations. Sometimes the converter would paste to C76, other times it may have pasted to C75 or D76 which would lead to errors. Nitro pdf always pasted a cell destined for C76 to C76 every time.

After a copy of Nitro pdf was obtained, the 400 intersections with only pdf data were all converted to excel spreadsheets. Next, all the remaining sheets were grouped by time periods. All intersections with 3 peak hour counts (06:00-09:00, 11:00-13:00 & 15:30-18:30) were grouped into one folder. Intersections with 2 peak hour counts (06:00-09:00 & 15:30-18:30) were grouped into a separate folder etc…There were 4 different folders in total.

Each folder had several hundred intersections, all with counts taken during the same hourly periods (but on different dates and by different companies). For each folder, unique macros were created for each company in order to export the hourly data from the company count files to a yearly database. Each year had its own database (2004, 2005, 2008 and 2009). Each macro was run manually, intersection by intersection, until each had been completed.

Once each year had its own database, all the years needed to be combined into one large database. Because different years had different hourly counts done, the challenge was how to combine all these intersection into one database, if the counts weren't all taken over the same hour? The answer is by the use of expansion factors (further explained in section 2.3). These factors allowed all hourly counts to be converted to 24-hour values. Once all counts were converted within excel to 24-hour values, a final macro was created to import the 24-hour volumes from each yearly database into one master database consisting of all 1 875 intersections with 24-hour volumes for each pedestrian and vehicular movement.

2.3 Automatic count data and expansion factors

Since pedestrian and vehicular counts were taken on different weekdays throughout the year, expansion factors needed to be generated to obtain AADP (Average Annual Daily Pedestrian) and AADT (Average Annual Daily Traffic) volumes. For pedestrians, expansion factors for peak hours, days and months were generated using automatic pedestrian counts from permanent counting stations. To achieve this, six counters (University & de Maisonneuve, Sherbrooke & Drummond, Monkland & Girouard, Cote-Sainte-Catherine & Descelles, Laurier & Saint-Hubert and Saint-Hubert & Bellechasse), were placed along sidewalks within close proximity to the intersections listed. One full year of data (from summer 2010 to 2011) was collected for each of these locations. These locations can be visualized in **Figure 3** as black stars. The counters were made by Eco-Counter and made use of infrared technology to detect pedestrian movement and direction of travel, while continuously recording counts 24 hours a day. These counts were used to generate hourly, daily and monthly totals of pedestrians. By continuously counting pedestrians at these locations for an entire year, the temporal distribution of pedestrian volumes was measured. Hourly, daily and monthly expansion factors were developed to compensate for pedestrian volume fluctuations according to the hour of the day, the day of the week and the month of the year. With these expansion factors, manual pedestrian counts performed at an intersection at a specific hour and weekday could be standardized and compared to pedestrian counts performed during any other hour or any other day. The peak hourly, daily and monthly expansion factors for pedestrians are presented in **Tables 2 and 3**. Note that expansion factors can be generated for different types of environments and weather – e.g., see Schneider et al. (6). Since only six counting sites were available and hourly patterns were similar across sites, a unique set of expansion factors was produced by averaging out the factors across all sites.

Expansion factors are used to convert manual hourly pedestrian counts made over a few hours, into 24 hour average daily pedestrian volumes. In order to expand the peak hour counts to average annual daily pedestrian (AADP) volumes, the averages of the daily and peak hourly factors from all six sites were used. Converting counts to average daily volumes is a relatively simple process. All that is needed is the total number of pedestrians counted, as well as the hour, day, month and length of time during which the count was performed. With this information, the expansion factors can be applied to convert these counts to 24 hour average daily volumes. Using expansion factors can be highlighted through the following example: Say at a given signalized intersection, 1,000 pedestrians total were counted during the AM, Noon and PM peak periods, on a Wednesday in December. The AM period runs from 06:00-09:00, Noon from 11:00-13:00 and PM from 15:00-18:00. In order to convert this to an AADP, the daily, hourly and monthly factors need to be looked up from **Tables 2 and 3**. First the daily and monthly factors are needed, from **Table 2**. For a Wednesday, the daily value is 1.1308, while the monthly factor for December is 0.8481. Next, the hourly factors are needed from **Table 3**. Since the counts took place during 8 hours, the factors for each of these hours are aggregated. Under Wednesday at 06:00 we find a value of 0.2445. The values for 07:00, 08:00, 11:00, 12:00, 15:00, 16:00 and 17:00 need to be looked up as well and summed together. The sum of all these values (underlined in **Table 3**) represents the hourly adjustment factor, which in this case is 12.252. To convert 1,000 pedestrians counted during the peak AM, noon and PM peak periods on a Wednesday in December to an AADP, the following equation can be applied: AADP = 1000 (pedestrians) x 24 (hours/day) ÷ 1.131 ÷ 12.252 ÷ 0.848 = 2,043 pedestrian on average per day.

The process to convert vehicular counts to AADT volumes is identical, however the factors are different from those presented in **Tables 2 and 3.** Vehicular expansion factors were provided by the City of Montreal and did not have to be expanded from the Eco-counter data.

This method of obtaining AADP and AADT was used in the yearly databases of all the intersections (as mentioned in **section 2.2.1**). For each intersection, various functions in excel were used to determine the day of the week, the month and the hours the counts were done in. Lookup functions were then used to obtain the expansion factors given the day, month and hours the counts were done in. The AADP equation was then used to get the 24-hour volumes for each movement. The 24 hour volumes for both pedestrians and vehicular traffic can be visualized in **Figures 6 and 7.**

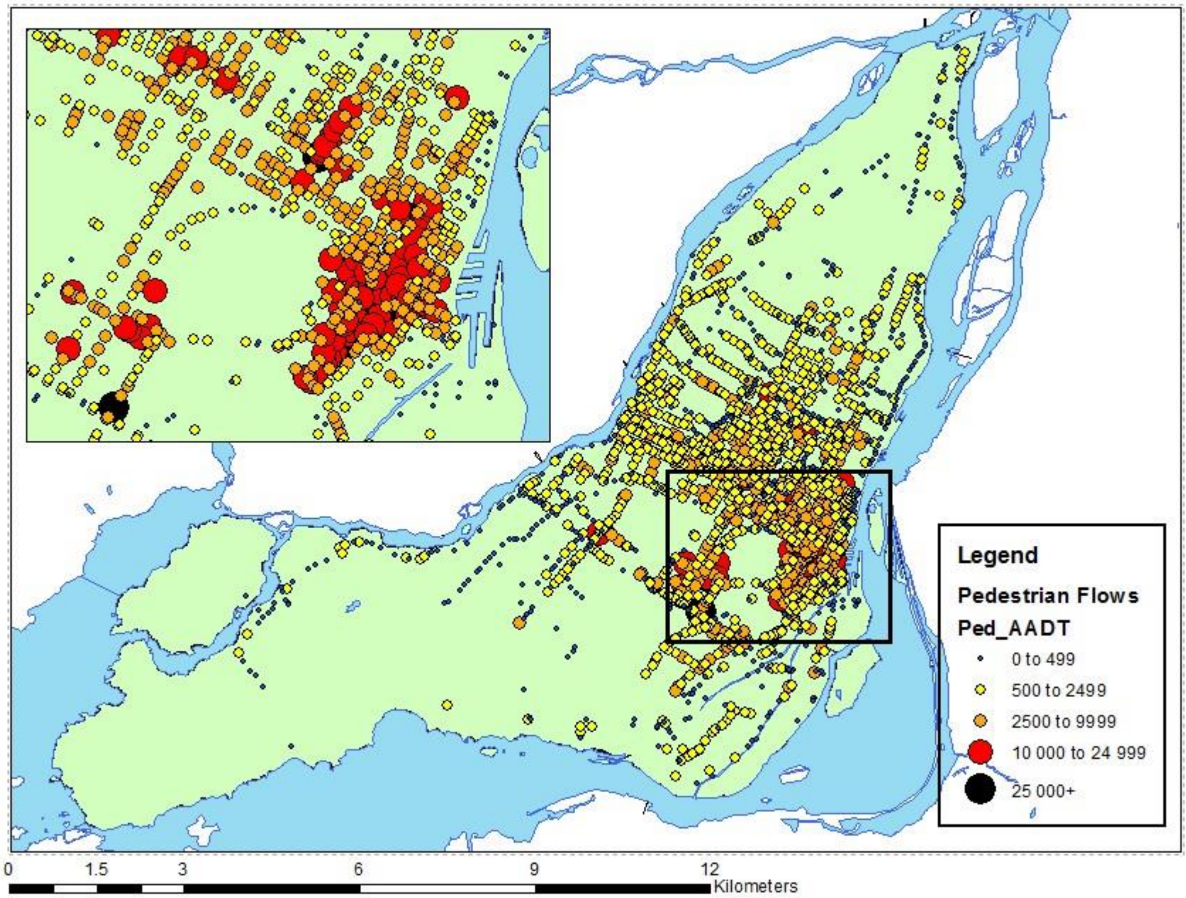


Figure 6 – Pedestrian Average Annual Daily Pedestrian Volume (AADP)

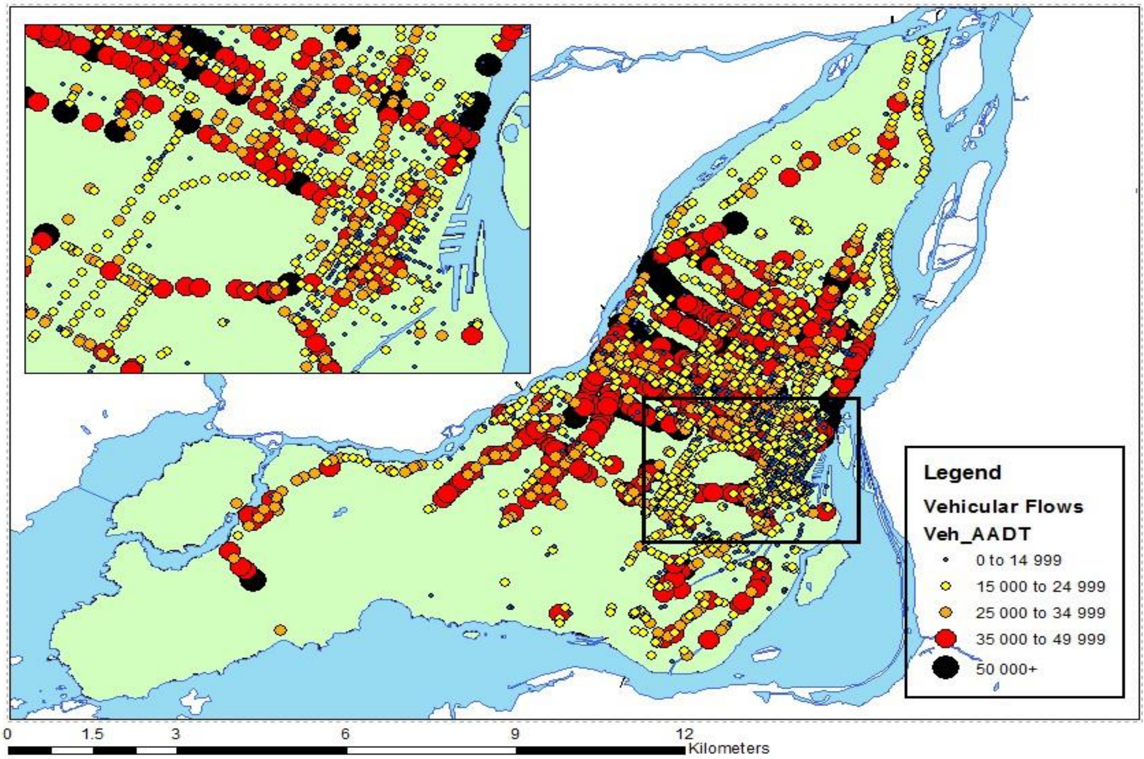


Figure 7 – Vehicular Average Annual Daily Traffic (AADT)

DAY	DAILY FACTOR
Sunday	0.656
Monday	0.992
Tuesday	1.122
Wednesday	1.130
Thursday	1.149
Friday	1.152
Saturday	0.796
TOTAL	**7.000**

MONTH	MONTHLY FACTOR
January	0.915
February	0.872
March	1.023
April	1.051
May	1.134
June	1.025
July	0.954
August	1.030
September	1.086
October	1.017
November	1.041
December	0.848
TOTAL	**12.00**

Table 2 – Daily and Monthly expansion factors from automatic counters

Time	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
12:00:00 AM	0.687	0.233	0.187	0.274	0.224	0.275	0.573
1:00:00 AM	0.474	0.142	0.098	0.126	0.128	0.157	0.374
2:00:00 AM	0.302	0.079	0.072	0.076	0.086	0.117	0.272
3:00:00 AM	0.271	0.069	0.050	0.053	0.058	0.078	0.222
4:00:00 AM	0.141	0.057	0.046	0.046	0.047	0.058	0.111
5:00:00 AM	0.126	0.101	0.085	0.086	0.087	0.088	0.100
6:00:00 AM	0.150	0.262	0.238	**0.245**	0.268	0.234	0.160
7:00:00 AM	0.249	0.879	0.909	**0.888**	0.881	0.836	0.334
8:00:00 AM	0.480	1.680	1.709	**1.717**	1.670	1.567	0.638
9:00:00 AM	0.939	1.283	1.247	1.215	1.212	1.232	1.095
10:00:00 AM	1.301	1.166	1.113	1.128	1.111	1.139	1.379
11:00:00 AM	1.517	1.413	1.403	**1.413**	1.401	1.452	1.618
12:00:00 PM	1.904	1.888	1.896	**1.918**	1.890	1.923	1.822
1:00:00 PM	2.082	1.789	1.754	1.774	1.742	1.815	1.938
2:00:00 PM	2.178	1.537	1.507	1.497	1.439	1.634	1.953
3:00:00 PM	2.134	1.788	1.742	**1.641**	1.689	1.736	2.012
4:00:00 PM	2.019	2.244	2.187	**2.108**	2.115	2.099	1.901
5:00:00 PM	1.703	2.419	2.370	**2.323**	2.293	2.023	1.639
6:00:00 PM	1.347	1.575	1.596	1.676	1.675	1.492	1.348
7:00:00 PM	1.169	1.055	1.142	1.194	1.228	1.151	1.151
8:00:00 PM	0.918	0.804	0.917	0.920	0.954	0.912	0.970
9:00:00 PM	0.818	0.679	0.790	0.775	0.763	0.793	0.865
10:00:00 PM	0.633	0.513	0.542	0.537	0.602	0.661	0.803
11:00:00 PM	0.458	0.345	0.399	0.372	0.438	0.529	0.724

Table 3 – Hourly expansion factors from automatic counters

2.4 Intersection geometric design

As part of this research, a major effort has been carried out to initiate a geometric design inventory of signalized intersections on the island of Montreal. For every intersection, several variables were collected such as; crosswalk distance, number of lanes, type of traffic signal, pedestrian phasing, parking restrictions, left turn lanes, median presence/width etc... Measuring wheels were used to obtain crosswalk distance and road width. All variables were recorded on paper and later transferred to computer. To reduce the duration of data collection, intersections were grouped by proximity and inventoried in one session. When including the time it takes to get to the intersections, collect the data, move to the next intersection, then upload the data to a computer file and process it, it would take roughly one hour of work per intersection to collect the data. Over a year’s worth of effort was required to inventory all 1,875 signalized intersections.

To facilitate the collection of geometric data, various teams of students were formed. Teams of 2 (sometimes 3) would be assigned a route of anywhere from 10 to 25 intersections to inventory. Depending on the route size, location and spacing between intersections, teams would use different modes of transportation to collect the data. In the downtown core, teams would typically take a metro and then walk from intersection to intersection. In the more residential areas around downtown, teams would typically take a metro and then use a bixi (Montreal’s bike-sharing program) to travel from intersection to intersection. For the intersections far from the downtown core on the extremes of the island, cars were used to move between intersections. For students who had a license but no access to a car, communauto (Montreal’s ride sharing program) was made available.

Each intersection had its own distinct geometric data sheet. Each data sheet was manually uploaded to excel by each team. Once all files were manually uploaded, a macro was created to transfer the data collected from each sheet to the master database. A sample data collection sheet can be found in the Appendix.

2.5 Pedestrian accident data

Ambulance service reports for pedestrian injuries across the island of Montreal were compiled in ArcGIS. These injuries covered all reported accidents for which there was an ambulance intervention from January 1st, 1999 to July 31st, 2008 inclusively. In order to calculate how many accidents had taken place at each of the 1,875 signalized intersections, a 20 metre buffer was created around each intersection. For this study, it was assumed that pedestrian-vehicular injuries at intersections would occur within this buffer. Intersection sizes vary across the island of Montreal; however no intersection crosswalks were further than 20 metres from the centre of the intersection. It was therefore assumed that every pedestrian vehicle collision that occurred within a 20 metre radius of the centre of an intersection, was a pedestrian-vehicular accident at a signalized intersection. The accident data provided was intersected with each 20 metre buffer and summarized to calculate how many accidents had occurred at each of the intersections. **Figure 8** shows the amount of pedestrian-vehicular accidents that have occurred at the 1,875 signalized intersections from 1999 to 2008. This accident data will be used in conjunction with pedestrian and vehicular volume exposures at these intersections, in order to develop pedestrian injury models.

It is interesting to note the effects the built environment, street geometry and pedestrian awareness have on pedestrian safety. In **Figure 9,** two signalized intersections from the island of Montreal can be seen. Des Sources and Pierrefonds is an intersection of two major boulevards in the suburban West Island, whereas Sainte-Catherine and Peel is located in the heart of downtown Montreal. When looking at the two different pictures what can you notice?

As can be seen, both intersections are very different. Downtown Montreal has a much more commercial/retail/pedestrian oriented layout, whereas the west island is more car/residentially oriented. Des Sources and Pierrefonds has an AADP (Average Annual Pedestrian Volume) of 650 and a vehicular AADT (Average Annual Daily Traffic) of 40,775. Contrast this with Sainte-Catherine and Peel, which has an AADP of 56,050 and an AADT of 23,350. Why is this interesting? Well, Sainte Catherine and Peel has had 13 vehicular-pedestrian accidents (from 1999 to 2008), while Des Sources and Pierrefonds has had 11 pedestrian accidents (from 1999 to 2008). Considering there are 90 times less pedestrians per day at the West Island intersection and only twice the number of vehicles, it is a little shocking to see that the number of pedestrian-vehicular accidents at both locations is roughly the same. **Equation 3**, demonstrates that although Sainte-Catherine and Peel have 2 more accidents than Des Sources and Pierrefonds, a pedestrian is **42 times** less likely to be injured at the downtown location. This is referred to as the “safety in numbers” effect.

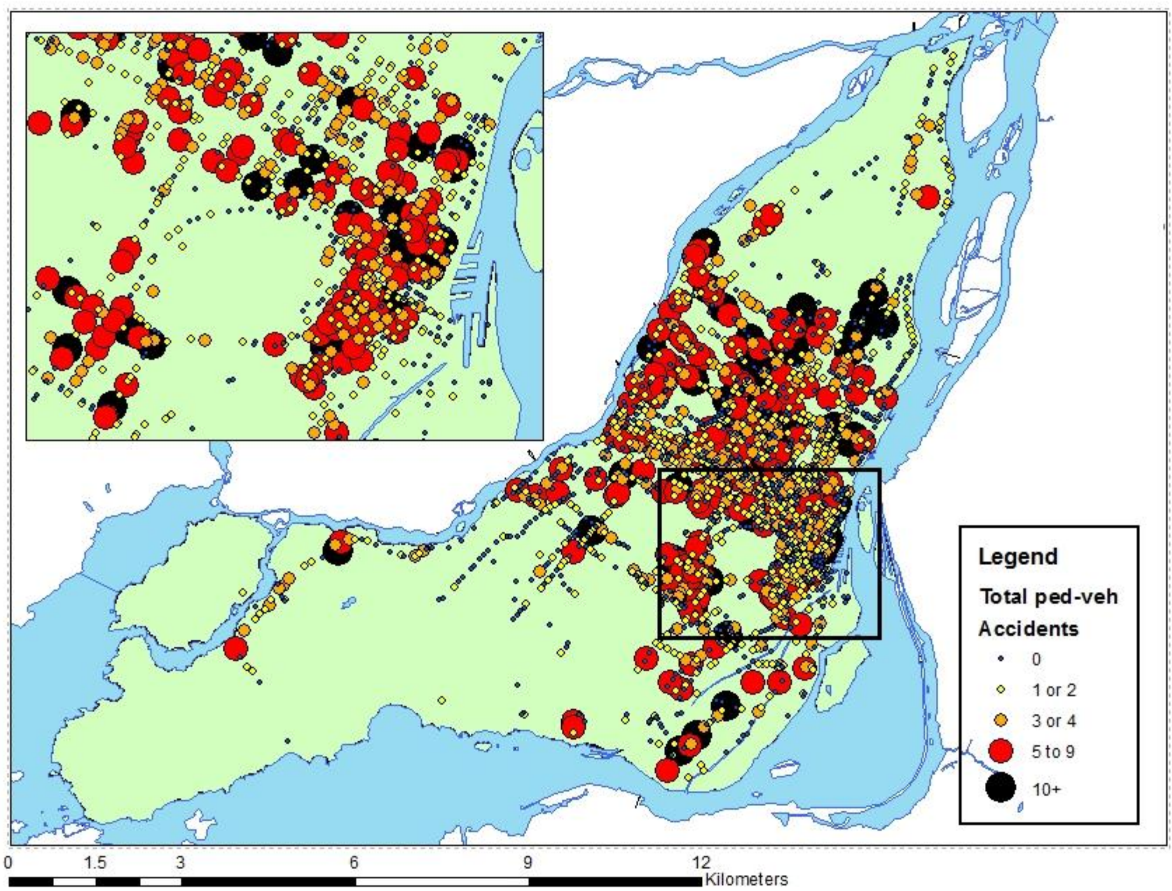


Figure 8- Pedestrian-Vehicular accidents for the island of Montreal classified by total amount per intersection, from 1999 to 2008.

Figure 9 – Suburban vs. Downtown

R = $(\mathbf{A} \times \mathbf{10^6}) \div (\mathbf{365} \times \mathbf{V} \times \mathbf{P} \times \mathbf{Y})$ **Equation 3**

R = Pedestrian risk per million vehicle-pedestrian interactions.

A = Number of accidents that have taken place at the intersection over a time period Y.

V = Vehicular AADT (Average Annual Daily Traffic) volume.

Y = Time period of the analysis in years.

P = Pedestrian AADP (Average Annual Daily Pedestrian volume).

Sainte-Catherine and Peel:

R = $(\mathbf{13} \times \mathbf{10^6}) \div (\mathbf{365} \times \mathbf{23\ 350} \times \mathbf{56\ 050} \times \mathbf{10})$**=** $\mathbf{2.72} \times \mathbf{10^{-6}}$

Des Sources and Pierrefonds:

R = $(\mathbf{11} \times \mathbf{10^6}) \div (\mathbf{365} \times \mathbf{40,775} \times \mathbf{650} \times \mathbf{10})$**=** $\mathbf{1.14} \times \mathbf{10^{-4}}$

CHAPTER 3

PEDESTRIAN ACCIDENTS AT SIGNALIZED INTERSECTIONS

One objective of this research, was to quantify pedestrian accidents as a function of several variables. By identifying the variables that influence pedestrian accidents, it can be determined which of those variables are statistically significantly, and to what degree they affect pedestrian accidents. Identifying and determining which variables are most important to pedestrian safety, is the first step in being able to better plan and design existing and future intersections. Intersections can be classified by accident rates and prioritized for treatment accordingly, in order to improve pedestrian safety.

3.1 Methodology

To investigate the contributing factors associated with pedestrian injury occurrence, regression models were tested. This included the standard negative binomial and the generalized negative binomial models. These models produced similar results, therefore, only the results of the standard negative binomial model were reported. In this model setting, the number of pedestrian-vehicular accidents (Y_i) at intersection i is Poisson distributed, with mean Θ_i and can be seen in **Equation 4.** The difference between these two models is that in the first one (NB), the dispersion parameter is assumed to be fixed across sites. In the second model, heterogeneity in the dispersion parameter is allowed. This is done by allowing this parameter to vary as a function of site-specific variables such as flows and geometry characteristics. The second model is a more flexible model that in some cases can improve the goodness of fit of the model to the data.

$$\theta_i = \lambda_i \, exp(\beta \tilde{x}_i + \varepsilon_i) \qquad \textbf{Equation 4}$$

Θ_i: Mean pedestrian-vehicular accident count.
λ_j: A measure of risk exposure as defined in **Equations 5 to 8.**
β: (β_0,...,β_k) is a vector of regression parameters to be estimated from the data.
$\tilde{x}_i$: Geometric or built environment site-specific attributes.
ε_i: Multiplicative random effect of the model - which is assumed to follow a Gamma distribution with both parameters equal to $1/\kappa$, where κ is the dispersion parameter, which is fixed in the standard negative binomial model and varies according to intersection factors in the generalized negative binomial model

3.2 Definition of risk exposure measures

To estimate the specific impact of each movement type (left, right and through movements) on the mean number of pedestrian injuries, alternative proxies of risk exposure are used, as proposed first by Miranda-Moreno et al. (40). These include the common measures using total pedestrian/traffic flows and exposure measures using disaggregate data. Vehicular and pedestrian movements described in this section can be visualized in **Figure 5.**

a. Total pedestrian and vehicular flows

This simple measure takes into account daily volumes of pedestrian and vehicular movements, regardless of direction. This can be seen in **Equation 5** where P_i and F_i are average annual daily flows (for pedestrians and vehicles respectively) and α_o. α_1 and α_2 are parameters to be estimated from the data.

$$\mu_i = \alpha_0 P_i^{\alpha_1} F_i^{\alpha_2} \qquad \textbf{Equation 5}$$

b. Vehicular flows by movement type: Left turn, Right turn and Through movements.

With this measure, the aim is to observe the impact of each particular vehicle movement. It is very possible that left and right movements are a greater danger to pedestrians than through movements. This model can be represented by **Equation 6**.

α_o, β_1, β_2, β_3 & β_4 are parameters to be estimated from the data. F_{li}, F_{ri} and F_{ti} represent left, right and through vehicular movements respectively.

$$\mu_i = \alpha_0 P_i^{\beta_1} F_{li}^{\ \beta_2} F_{ri}^{\ \beta_3} F_{ti}^{\ \beta_4} \qquad \textbf{Equation 6}$$

c. Pedestrian-vehicle potential conflicts by movement type: Left turn, Right turn and Through potential conflicts

This method is used to evaluate pedestrian and vehicular movements conflicting with each other at an intersection. The hypothesis behind this is that the greater number of potential conflicts between pedestrians and vehicles, the greater the likelihood of an accident. The model for this type of setting is given in **Equation 7**. The C terms represent the potential conflicts and γ_1, γ_2, γ_3 are parameters estimated from the regression.

$$\boldsymbol{\mu_i = \gamma_o C_{li}^{\gamma 1} C_{ri}^{\gamma 2} C_{ti}^{\gamma 3}} \qquad \textbf{Equation 7}$$

Where C_{li} = left turning potential conflicts between pedestrians and vehicles, C_{ri} = right turning potential conflicts between pedestrians and vehicles and C_{ti} = through conflicts, which may occur if either a pedestrian or vehicle illegally crosses on a red light. Each of these conflict types is obtained by summing the products per movement type in **Equation 8.**

$$\boldsymbol{C_{li} = \sum_{p=1}^{P} P_{lip} * V_{lip}}, \qquad \boldsymbol{C_{ri} = \sum_{p=1}^{P} P_{rip} * V_{rip}} \qquad \boldsymbol{C_{ti} = \sum_{p=1}^{P} P_{tip} * V_{tip}}$$

Equation 8

Where, V_{lip}, V_{rip} and V_{tip} are motor-vehicle left turn, right turn and through flows in each 15 minute interval and P_{lip}, P_{rip} and P_{tip} are the conflicting pedestrian flows in the same 15 minute interval, respectively. Although the interaction of pedestrian and motor-vehicle flows can be analysed using shorter periods than 15 minutes, flows for shorter time frames do not exist.

3.3 Model results

For **Equations 5 to 7** described in section 3.2, two separate models were used to predict accident rates at signalized intersections. One set of models was tested with geometric variables (**section 3.5**) and one set without (**section 3.4**).

3.3.1 Model results for vehicle and pedestrian exposure only

According to the modeling approach and measures of risk exposure defined in **section 3.2**, standard Negative Binomial models were used to fit data for each exposure equation, yielding **Models 1 to 3** as presented in **Table 4**. The models are described in detail below.

Model 1: In this model, risk exposure is represented by the traditional manner using the total flows as defined in **Equation 5**. In this case, the total pedestrian and motor-vehicle flows are represented by average annual daily values (AADP and AADT). The pedestrian and vehicular volumes both have a significant effect on pedestrian injury frequency. A 100% increase in pedestrian and vehicular volumes leads to a 42.6% and 79.2% increase in pedestrian-vehicular accidents respectively. These are the impact elasticity's of pedestrian and vehicular volumes on pedestrian-vehicular accidents. The values are in the range of those reported in the literature. The results also highlight the importance of vehicular exposure which is the main pedestrian injury risk determinant. The only drawback of this model is that it aggregates all vehicular movements together.

Model 2: This model makes use of **Equation 6**, which looks at traffic exposure according to vehicular movements and total pedestrian volumes. Left, right and through values for vehicular traffic, along with total pedestrian volumes are all significant. Surprisingly, through vehicular traffic seems to have the highest effect on accident rates. A 100% increase in through traffic, produces a 45.9% increase in accidents. This seems counterintuitive; however it could be true for two reasons. Firstly, we have seen through Model 1, that an increase in vehicular traffic (while keeping pedestrian volumes constant), increases pedestrian-vehicular accidents. It therefore makes sense that through movements, which represent the vast majority of vehicular traffic at intersections, would naturally also have the highest correlation with pedestrian-vehicular accidents. The second reason through movements produce more accidents is that there might be more red violations on through vehicle movements than right and left turn movements, leading to more pedestrian-vehicular accidents.

Model 3: This model makes use of **Equation 7**, which looks at exposure in terms of vehicular-pedestrian potential conflicts (interaction of vehicle and pedestrian flows). This makes the most intuitive sense as to where accidents would happen. Left and right turns would naturally conflict with pedestrians wanting to cross. Although through conflicts are technically never supposed to occur, (at least when there is a pedestrian signal and a sufficient period of time to allow pedestrian crossing), vehicles running reds and pedestrians crossing on reds make them an issue. The results are all significant, and once again like in Model 2, the through conflicts have the greatest impact on pedestrian-accident accident occurrences. Estimated elasticity's are 5.2% for right turn conflicts, 11.3% for left conflicts and 13% for through conflicts. Once again, elasticity's measure the percentage increase in pedestrian vehicular accidents, for a 100% increase in the variable in question.

Comparing Models 2 and 3, Model 2 is preferable given the lower AIC value and the fact it is easier to understand and calculate than Model 3. Comparing Models 1 and 2, the AIC value for Model 2 is lower. Model 2 also disaggregates movements and makes more logical sense, thus making Model 2 the selected model. All variables were tested for collinearity. The results showed that all variables in Models 1 and 2 had correlations of less than 0.4 with one other, making multi collinearity a non issue. Model 3 experienced a considerable amount of multi-correlation issues between some of the movements. In terms of goodness of fit, models 1 and 2 are similar and both outperform model 3.

Variables	Model 1			Model 2			Model 3		
	Coef.	Elasticity	p-value	Coef.	Elasticity	p-value	Coef.	Elasticity	p-value
Ln total pedestrian flows	0.426	42.6%	0.000	0.410	37.2%	0.000	N/A	N/A	N/A
Ln total traffic flows	0.792	79.2%	0.000	N/A	N/A	N/A	N/A	N/A	N/A
Ln total right turn traffic	N/A	N/A	N/A	0.074	7.4%	0.003	N/A	N/A	N/A
Ln total through traffic	N/A	N/A	N/A	0.459	45.9%	0.000	N/A	N/A	N/A
Ln total left turn traffic	N/A	N/A	N/A	0.187	18.7%	0.000	N/A	N/A	N/A
Ln total right turn conflicts	N/A	N/A	N/A	N/A	N/A	N/A	0.052	5.2%	0.001
Ln total through conflicts	N/A	N/A	N/A	N/A	N/A	N/A	0.130	13.0%	0.000
Ln total left turn conflicts	N/A	N/A	N/A	N/A	N/A	N/A	0.113	11.3%	0.000
Constant	-10.43	N/A	0.000	-8.78	N/A	0.000	-3.589	N/A	0.000
Log-likelihood	3,397.6	N/A	N/A	-3,382.7	N/A	N/A	3,506.6	N/A	N/A
AIC	6,801.1	N/A	N/A	6,777.3	N/A	N/A	7,023.2	N/A	N/A
Observations	1,875	N/A	N/A	1,875	N/A	N/A	1,875	N/A	N/A

Table 4 – Model results for pedestrian and vehicular exposure only

*Coef.: Is the coefficient as calculated from the model.

*Elasticity: For a 100% increase in the variable being described, the elasticity will indicate the associated percentage increase in pedestrian-vehicular accidents.

*p-value: The formula for this is 1-significance value. A p-value of 0.05 denotes 95% significance, 0.10 denotes 90% significance etc...

Variables	Model 4 – with crosswalk			Model 5 – with proxy of curb extension			Model 6 – with number of lanes		
	Coef.	Elasticity	p-value	Coef.	Elasticity	p-value	Coef.	Elasticity	p-value
Ln total pedestrian flows	0.439	43.9%	0.000	0.432	43.2%	0.000	0.454	45.4%	0.000
Ln total traffic flows	0.619	61.9%	0.000	0.762	76.2%	0.000	0.593	59.3%	0.000
Phase_1	-0.505	-39.6%	0.000	-0.530	-41.1%	0.000	-0.544	-42.0%	0.000
Phase_2	-0.330	-28.1%	0.000	-0.344	-29.1%	0.000	-0.372	-31.1%	0.000
Commercial	0.085	7.8%	0.000	0.100	9.2%	0.000	0.087	8.0%	0.000
Length_walk	0.0077	52.7%	0.000						
Curb extension proxy				-0.399	-39.9%	0.000			
Total_lanes							0.086	58.7%	0.000
Constant	-8.227			-10.165			-9.031		
Log-likelihood	-3,337.2			-3,346.7			-3,344.0		
AIC	6,690.4			6,709.4			6,704.0		
Observations	1,875			1,875			1,875		

Table 5 – Model results for pedestrian and vehicular exposure, including geometric variables

*Coef.: Is the coefficient as calculated from the model.
*Elasticity: For a 100% increase in the variable being described, the elasticity will indicate the associated percentage increase in pedestrian-vehicular accidents.
*p-value: The formula for this is 1-significance value. A p-value of 0.05 denotes 95% significance, 0.10 denotes 90% significance etc...

4.3.2 Model results for vehicle and pedestrian exposure including geometric variables

Table 5 presents models for pedestrian exposure including several geometric variables. The models differs slightly than what was found in the previous section, as a model considering total pedestrian and vehicular flows produced the best results for explaining pedestrian accidents.

Phase_1: This is a binary variable that indicates whether or not there is an "all red pedestrian" phase at the intersection. An all red fully protected pedestrian phase stops traffic on all approaches and allows pedestrians to cross in any and every direction (North, South, East, West and diagonally). As expected, the presence of a pedestrian all red phase significantly reduces the pedestrian injury risk, with an elasticity of -39.6% to -42.0%. Once again, this elasticity implies that the presence of this type of phasing will reduce accidents from 39.6% to 42.0%. This type of phasing is found at 6.2% of all studied signalized intersections.

Phase_2*:* This is another binary variable which indicates whether or not the intersection has an approach with a half red pedestrian phase. A "half red phase" is a semi protected pedestrian phase. This phase allows pedestrians on either the North and South side, or East and West side of an intersection, to start crossing before a green opens up for traffic on those same approaches. The red phase lasts for roughly 8 seconds and pedestrians are shown a white man for crossing. Unlike the all red pedestrian phase, the half red pedestrian phase does not last as long and is only intended for the two opposing movements to begin to cross, not movements on all of the approaches. The purpose of the half red phase is to increase pedestrian awareness to drivers and protect pedestrians from turning vehicles. This variable has a negative effect on pedestrian accidents, with elasticity's ranging from -28.1% to -31.1%. This type of phasing is present at 20.8% of all studied signalized intersections.

Commercial*:* This variable records the amount of entrance/exits to commercial properties (Gas stations, shopping malls etc…) in close proximity (within 25 metres) to a signalized intersection. For a four legged approach, there can be a maximum of 8 entrances and exits to commercial spaces, 2 at every corner. It was believed that the greater the number of entrances and exits to commercial spaces, the greater the number of pedestrian-vehicular accidents, based on the increase in conflicts. The results show that there is a positive correlation between commercial entrances and exits and pedestrian-vehicular accidents, with elasticity's ranging from 7.8% to 9.2%. The average for the studied intersections is 0.92 commercial entrances/exits.

It is important to note that the aforementioned variables were tested in all three models (4, 5 and 6). The **length_walk**, **Curb Extension proxy** and **Total_lanes** variables were then each tested separately in models 4, 5 and 6 respectively, along with the other geometric variables. They could not be tested together, due to the strong correlations with one another.

Length_walk*:* This variable is featured in Model 4. It sums the total length from sidewalk to sidewalk (crosswalk) for all four approaches. These results confirm intuition, that the longer the crossing distances, the more likely the accident. A 100% increase in the length of crosswalks, produces a 52.7% increase in pedestrian-vehicular accidents. The average total crosswalk distance (sum of all approaches) for the studied intersections is 66.7 metres.

Curb Extension proxy*:* This is a binary variable in Model 5, which measures the difference between crosswalk width and the road width. Road with is measured 50 meters or more, upstream of the crosswalk. If the difference is negative, it means that the crossing distance is reduced at intersections (curb extensions present) and therefore this binary variable is 1, otherwise it's 0. The elasticity of this variable is -40%.

Total_lanes*:* This variable in Model 6, sums up the number of lanes with **traffic moving in that direction** on all approaches. For example, if the Northbound movement is one way with 4 lanes and the East/West movements are 2-way with 2 lanes in each direction, the total_lanes for this intersection would be 8. If there are 4 lanes on the Southbound approach for this intersection, they would not be counted because it is a one way street for the Northbound movements. The greater the number of lanes, the greater the chance of pedestrian-vehicular accidents, with an elasticity of 58.7%.

All variables in each model were tested with a correlation matrix, and all variables had a correlation of less than 0.3 in most of the cases, with very few correlations between 0.3 and 0.4, thus making multi-collinearity a non-issue. Other variables such as medians, parking restrictions, bicycle paths and types of traffic signals were also tested, but they were not statistically significant and thus did not appear to be associated with pedestrian accidents in this sample of Montreal intersections. In terms of goodness-of-fit, models with geometric characteristics perform better than those without geometric data. Model 6 performs slightly better than model 5, but is very similar to Model 4, as presented in **Table 5**. Model 4 was selected as being better than model 6 based on the lower AIC value.

Utilizing the model setting from model 4, **Figures 10** and **11** show the difference in the expected number of accidents for intersections with all red pedestrian phases and different crosswalk sizes respectively. These figures show the effect of these treatments for pedestrian safety at signalized intersections. These figures are obtained by evaluating the impact of a single variable with respect to daily pedestrian volume, while keeping constant all other factors. For example, **Figure 10** demonstrates how solely adding a fully red pedestrian phase to an intersection, without changing anything else, lowers the amount of pedestrian vehicular accidents at signalized intersections. Similarly, **Figure 11** demonstrates how intersections with smaller crosswalk distances, tend to have lower accident rates than intersections with larger crosswalk distances.

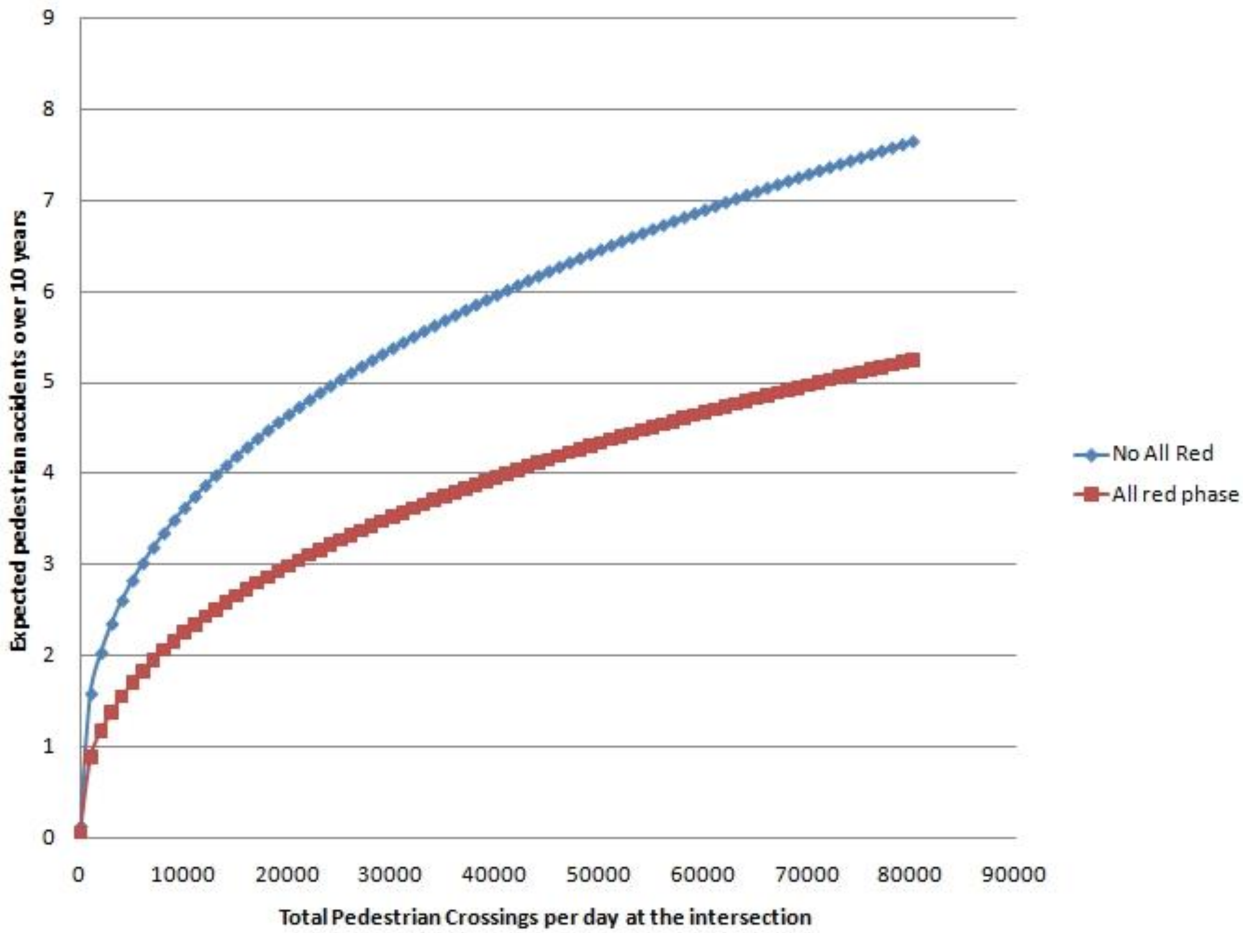


Figure 10- Expected pedestrian accidents in 10 years for "All Red pedestrian phasing" treatment

Note: this is based on Model 4, taking into account risk exposure and controlling for other geometric characteristics; model input variables use mean values from the 1,875 study intersections**.** In this graph, signalized intersections with all red pedestrian phasing (red) are compared to intersections with no all red phasing (blue). While holding all other variables constant, it can be seen that intersections with all red phasing are expected to have fewer pedestrian accidents.

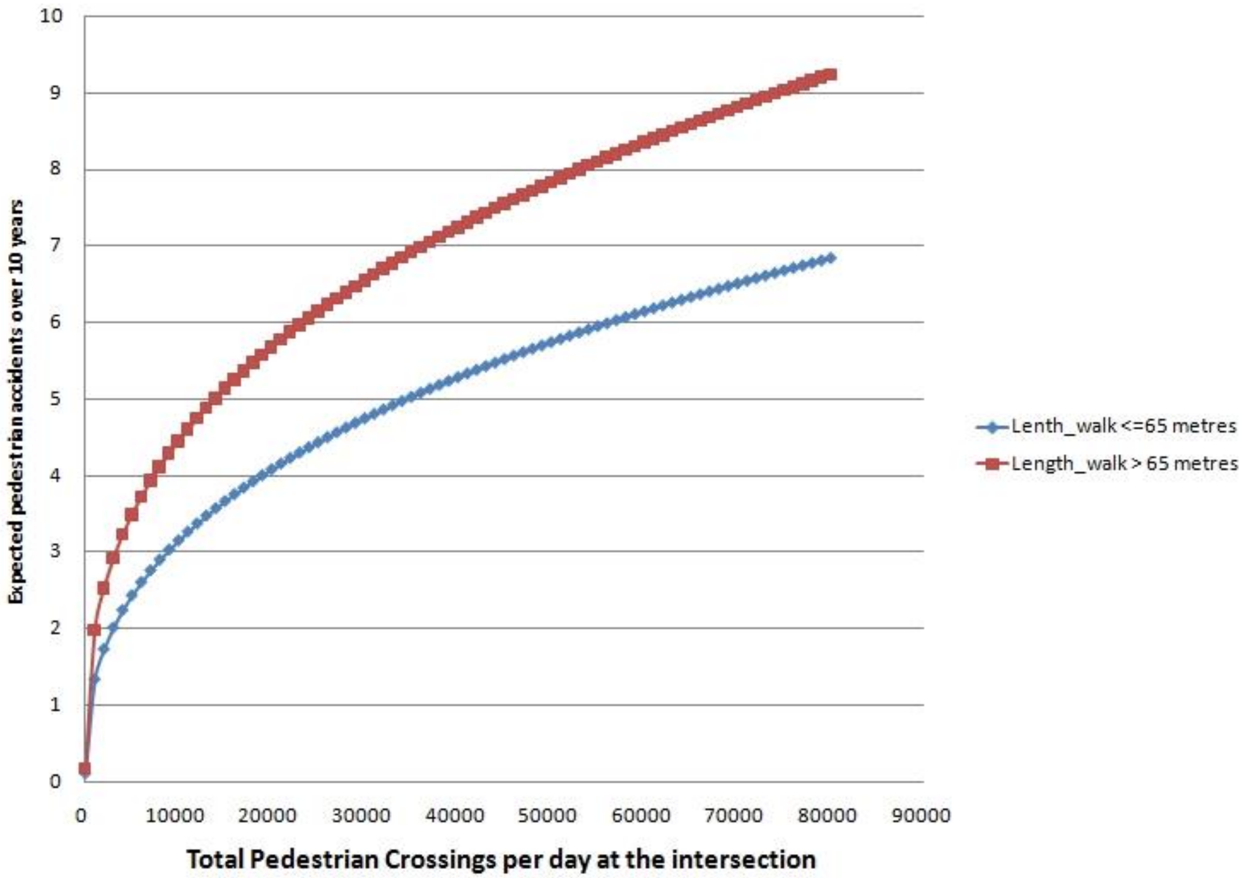


Figure 11 - Expected pedestrian accidents in 10 years for different crosswalk lengths

Note: This is based on Model 4, taking into account risk exposure and controlling for other geometric characteristics; model input variables use mean values from the 1,875 study intersections; length_walk stands for the sum of the crosswalk distances of all approaches. The average crosswalk distance for a signalized intersection is 66.7 metres. Total crosswalk distances (Sum of crosswalk lengths of all approaches) of 65 metres or less for an intersection are denoted in blue. Total crosswalk distances of over 65 metres are denoted in red on the graph in **Figure 11**. As can be seen, by holding all other variables constant, shorter crosswalk lengths are expected to have fewer accidents.

CHAPTER 4

PEDESTRIAN ACTIVITY AT SIGNALIZED INTERSECTIONS

This section focuses on using GIS techniques to generate pedestrian activity volumes at signalized intersections. This technique is useful for estimating pedestrian volumes for hundreds or even thousands of intersections without having to spend the hundreds or thousands of hours collecting manual counts. There have been studies in the past that have successfully found strong correlations between the Built Environment and pedestrian volumes, but have been limited by their sample size. As part of this research, this study has looked at using a very large sample size of 1,875 intersections in order to validate past research and establish a model that is specific to the city of Montreal. For each of these 1,875 intersections, GIS techniques will be used to identify which elements of the Built Environment are specific to each intersection. Once all the attributes of each intersection are determined, a log-linear regression can be performed to see how closely the Built Environment factors can predict the pedestrian volumes expected at each of the 1,875 intersections. The expected and actual numbers of pedestrians for each intersection can then be compared, to give an idea of the overall accuracy of using the GIS method of predicting pedestrian activity at signalized intersections. With regards of applying the model to more remote areas of the city, census tract data along with data from the geographically closest weather station can be used to estimate pedestrian flows on a given day.

4.1 Pedestrian activity modeling framework

Modeling pedestrian activity is a function of several variables. There exists a log-linear relationship between pedestrian activity and Built Environment factors. **Equation 9** explains the variables that will be used to predict pedestrian activity at signalized intersections.

$$\ln(P_{i,t}) = \alpha + \beta\, LU_i + \gamma\, TN_i + \rho\, W_{i,t} + \gamma\, S_i + \delta_t + \varepsilon_{i,t}$$ **Equation 9**

***i**:* stands for the intersection i (i=1,...,n);

t: stands for the observation time (one day);

LU_i: Land use and socio-demographic patterns around intersection i. For example: commercial/retail space (‘000 m^2), the presence of schools (# of schools), general population (‘000), children (‘000), seniors (‘000) etc.

TN_i: Urban form, road and transit network patterns. This includes transit supply with the following variables: total bus lanes (km), transit stops (# of stops) and subway station presence (0/1 binary indicator). Road network characteristics also include the following: intersection density (number of intersections within the given buffer), average street length (number of street segments divided by total road length), road class type (km), proportion of major arterials (Class 1 to 5 roads in km divide by total road length in km) and intersection type, 3 way vs. 4 way (0/1 binary indicator).

$W_{i,t}$: Daily weather conditions (precipitation, wind and temperature). This also includes extreme weather conditions or interaction effects among variables. Note that the same weather conditions are assigned for all the paths;

S_i: Spatial location of intersection i.

δ_t: Effect parameters for daily or seasonal trends.

$\varepsilon_{i,t}$: Independent error term representing unobserved heterogeneities.

α,β,γ,ρ,η: Parameters to be estimated from the data.

To represent pedestrian activity different model settings can be tested such as the log-linear and negative binomial regression models for count data. This corresponds to the fact that pedestrian activity is a count variable positively skewed.

4.2 Pedestrian activity data and weather

The pedestrian data for the 1,875 intersections was collected as described in section 2.2. The intersections analyzed are drawn from several boroughs across the island of Montreal and represent a mix of arterial, collector and local streets. The intersections are drawn from areas of various Built Environments. All intersection counts were compiled in Excel, geocoded with X and Y coordinates and then imported into ArcGIS. Variables for the land use and urban form were generated by creating buffers of varying width around the 1,875 signalized intersections using ArcGIS. Buffers of 50, 150 and 400 metres around intersections were used for the analysis – See **Figure 12**. A 50 metre buffer is in eyesight distance of an intersection. A 150 metre buffer is within a 2 minute walking distance of an intersection. A 400 metre buffer is within a 5 minute walk of an intersection. The buffers were all independent of one another and intersection buffers were not dissolved together. The data on the Land use and urban form was made available through Statistics Canada and DMTI Spatial Inc. The 50 metre buffers were used to see how the immediate surroundings of intersections affected pedestrian activity. The 150 metre buffers take into account land use and urban form features within close proximity to an intersection. The 400 metre buffers are used to evaluate neighbourhoods at a higher level, as well as features within walking distance of intersections. In order to generate data within buffers; census tract, demographic, road and transit data were intersected with buffers and compiled into tables. This approach is similar compared to the work done by Pulugurtha and Repaka (7) and Schneider et al (8). There are 878 census tracts for the island of Montreal. In general, acceptable results were obtained in other studies using the same data, as is the case in (39). Shorter buffers were explored, given the fact that the areas under study (central neighbourhoods in Montreal) are located in a relatively denser area, with a rich mix of land uses and high transit accessibility due to an extensive public transport system. The intersections analyzed in this study have a range of built environments. The downtown core is highly commercial and features services with many restaurants and retail outlets, many schools and access to subway (metro) and buses within close proximity. Pedestrian activity is naturally quite high in this area. However, central neighbourhoods close to the downtown core feature a high mix of residential and commercial activity with good transit accessibility. Neighbourhoods further away from the central core are less mixed, having less transit accessibility. This would be represented by the Eastern and Western part of the island, which are suburban and tend to be highly residential. **Table 6** provides a list of all variables analyzed along with their corresponding units. To extract demographic data, census tract data was intersected with each buffer generated around the intersections. To classify intersections according to the number of approaches (three-legged versus four-legged intersections), a dummy variable was generated. A three-legged approach counted only pedestrians exposed to traffic on the three legs, not on the un-exposed leg.

After all pertinent information was imported into ArcGIS, it was intersected with the buffers created around each intersection. For each buffer the land use and urban form variables within the buffer were summarized. In order to obtain the population and employment within buffers, formulas were used. **Equation 10** illustrates for example how employment within buffers is calculated.

$$E_i = \sum_j \frac{A_{j,i}}{A_j} * E_j \qquad \textbf{Equation 10}$$

E_i: Jobs inside buffer zone i,

E_j: Jobs of census tract j,

A_{ji}: Area of census tract inside buffer zone i

A_j: Area of census tract j.

A similar process can be used to calculate land use data as well. **Figure 12** shows the buffers and land use and urban form analysis of one of the intersections in the study. As can be seen, there are several bus stops and a rich land use mix within the buffers.

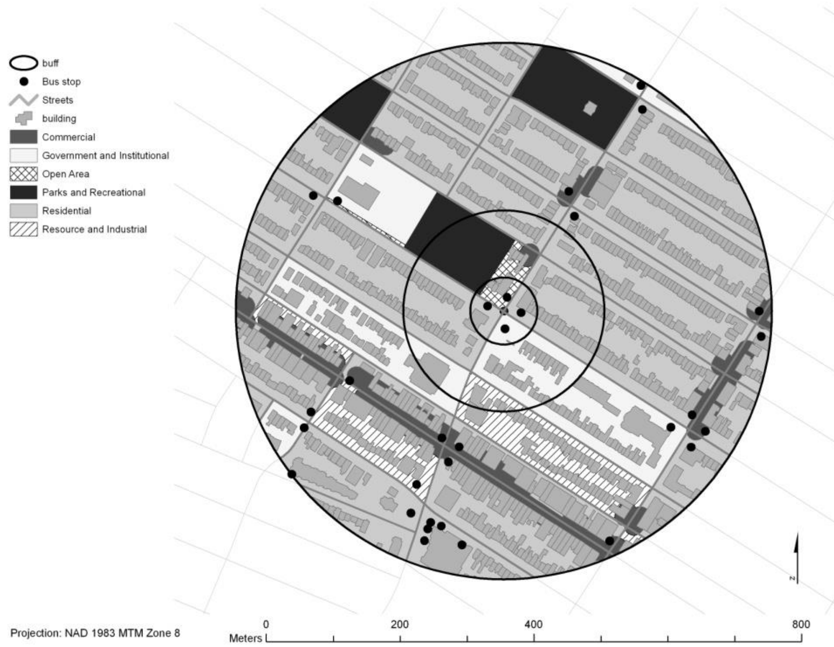


Figure 12– Schematic of a typical buffer with Land use and Transit Network

Based on the date associated to each intersection count; weather daily data was matched to the pedestrian flows. These variables included mean/max/min daily temperatures, daily precipitation (mm) and if windy conditions were present. It is important to notice that counts were done in relatively good weather conditions, therefore, the impact of weather is somewhat hidden and its impact was expected to be low as the results will show later. However, despite this, weather variables still show important variations. Once all variables were intersected with the buffers, the results were exported into STATA for a statistical analysis. **Table 6** shows a summary statistics of all the land use and urban form variables used in this analysis. The majority of variables are self explanatory. The land use measures land area in square metres within a given buffer. The proportion of major roads measures the ratio of major roads to all roads. The hypothesis behind this is that a higher proportion of major roads should discourage walking. Average street length is a measure of connectivity. This variable is the sum of total road length in the buffer, divided by the number of streets in the buffer. If average street lengths are smaller, streets are better connected with shorter block distances, encouraging walking trips. High average street lengths on the other hand should discourage walking because of the lack of connectivity.

4.3 Pedestrian activity model results

According to the model specifications presented in **Equation 9**, a regression modeling analysis was developed using manual pedestrian counts, in order to investigate the relationship between pedestrian activity, land use and urban form (UF), adverse weather conditions and spatial patterns at signalized intersections. As a first step, a multi-correlation analysis was conducted, in order to identify high correlations between the different UF variables. A correlation matrix for each buffer size is generated (50, 150 and 400 meters). This exercise is also useful to identify the potential factors related to pedestrian activity. Correlation matrices are not reported in this thesis given the lack of space. Aggregated and disaggregated pedestrian activity models are then developed to account for the different modeling issues discussed before – unobserved heterogeneities, clustering and correlation between random effects.

After trying different combinations of the land-use and urban form (LU & UF) variables listed in **Table 6**, the best models for explaining pedestrian activity (P) are selected. The criteria for selecting the variables for each model consisted of three aspects. First, all variables had to be statistically significant to the 95th percentile (t-value greater than 1.96). Secondly, all the variables used within the model could not be highly correlated with other variables used in the same model (correlation less than 0.4). Finally, the variables which satisfied the first two conditions and outputted the highest adjusted R^2 values (a measure of how much variance is explained by the model) were used. In addition, intuitive sense on the coefficients and variables was used for model selection. For example, it would not make sense for rain to increase walking.

Table 6 – Land use and Urban Form Variables

Category	Variable	Units	Buffer: 50 m		Buffer: 150 m		Buffer: 400 m	
			Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Land Use	Commercial	m^2 (1000s)	0.85	1.38	4.82	8.38	28.15	41.98
	Residential	m^2 (1000s)	3.69	2.28	37.19	18.66	263.46	102.55
	Industrial	m^2 (1000s)	1.23	1.76	12.58	15.79	94.21	96.67
	Park	m^2 (1000s)	0.36	1.02	3.72	8.68	32.60	49.20
	Open space	m^2 (1000s)	1.10	1.61	6.08	10.10	32.75	46.94
	Government	m^2 (1000s)	0.60	1.20	6.15	10.02	45.94	50.32
	Number of jobs	Counts	83.6	187.8	753.8	1,650	5,159	9,970
	No. of schools	Counts	0.02	0.15	0.17	0.47	1.14	1.22
Demographic	Population	Count (1000s)	0.03	0.02	0.25	0.18	1.15	1.15
	Median income	Dollars ($'000)	40.50	18.98	40.37	17.90	40.12	15.65
	Average income	Dollars ($'000)	54.84	32.30	54.59	29.81	54.33	26.65
Transit System	Presence of subway station	0/1	0.01	0.11	0.07	0.26	0.27	0.45
	No. of bus stops	Counts	1.77	1.39	3.56	2.28	16.91	7.05
	Km of bus route	Km	0.46	0.37	1.66	1.23	7.52	4.04
Road Network	Road length (km)	Km	0.25	0.09	1.36	0.45	8.51	2.22
	No. street segments	Counts	7.1	4.7	31.1	21.7	282.2	223.9
	Number of intersections	Counts	2.08	1.68	8.04	5.32	47.78	21.98
	Portion of major Roads	%	15.87	26.57	12.23	19.44	9.61	11.45
	Average Street length*	Km	0.042	0.013	0.055	0.023	0.043	0.023
	3-way/4-way intersection**	0/1	0.78	0.41	0.78	0.41	0.78	0.41
Weather variables	Windy (>30 km/hr)	0/1	0.26	9.9	*Weather variables are the same across buffers and are average daily values			
	Moderate precipitation (>5 mm/day)	0/1	0.18	0.44				

* Total road length divided by the number of street segments

** 0 if 3-leg intersection, 1 if 4 or more leg intersection.

Tables 7 and 8 provide a summary of the pedestrian activity models. Both models have identical variables, except that in **Table 7**, street segments are used to predict pedestrian activity, whereas the distance to downtown variable is used in **Table 8.** These two variables each had a high correlation with one another, and were thus split into two different models. These tables include the parameter estimates, p-values and elasticity's estimated at the mean values of the variables. A description of each variable is provided below.

400m Population ('000): This variable measures the amount of people (in thousands), living within a 400 metre radius of an intersection. The greater the population living in the vicinity of an intersection, the more likely it will be that pedestrians will use it. A 100% increase in population yields a 9.4% to 22.8% increase in pedestrian activity at signalized intersections, varying between the street segments and distance to downtown models.

50m Commercial Space ('000 m^2): This variable measures the amount of commercial activity within a 50 metre radius of an intersection. It makes logical sense that high amounts of commercial activity (i.e.: shopping centres) would naturally attract a large number of pedestrians to nearby intersections. The elasticity's of this variable range from 16.3% to 18.4%.

150m Open Space ('000 m^2): This variable measures the amount of open space within a 150 metre radius of an intersection. If there is a lot of open space nearby an intersection, there's less reason for there to be people nearby, and therefore fewer pedestrians would be using the intersection. The elasticity's of this range from -13.3% to -18.7%. This confirms the expectation that large areas of open space decrease pedestrian activity.

150m Subway: This is a binary variable that indicates whether or not a subway station is present within a 150 metre radius of an intersection. The importance of this variable is highlighted through its elasticity. A metro station increases pedestrian activity by 105.8% to 129.7%.

150m Bus Stations: This variable measures the amount of bus stations within 150 metres of a signalized intersection. Intersections that are highly accessible by bus should have higher levels of pedestrian activity. The elasticity's range from 27.3% to 37.3%.

400m Schools: This variable counts the number of schools within a 400 metre radius of an intersection. The greater the number of schools, the more likely there will be pedestrian activity in the form of students walking to and from school. The schools have a positive effect on pedestrian activity, with elasticity's ranging from 13.8% to 24.9%.

400m % Major Arterials: The presence of major arterials with heavy vehicular traffic should naturally discourage pedestrian activity implicitly. This variable calculates the percentage of roads within a 400 metre radius of an intersection that are major arterials. A 100% increase in major arterials decreases pedestrian activity by 3.3% to 11.6%.

400m Street Segments ('000): This variable is a measure of street connectivity. It measures the number of street segments within a 400 metre radius of a signalized intersection. The greater the number of segments, the easier it is for pedestrians to move around. This variable had a high correlation with the distance to downtown variable, they are therefore tested separately. This makes intuitive sense, since streets downtown tend to be more connected then streets in the suburbs, where walking is a less used mode of transportation. A 100% increase in street segments, yields a 70.9% to 77.0% increase in pedestrian activity.

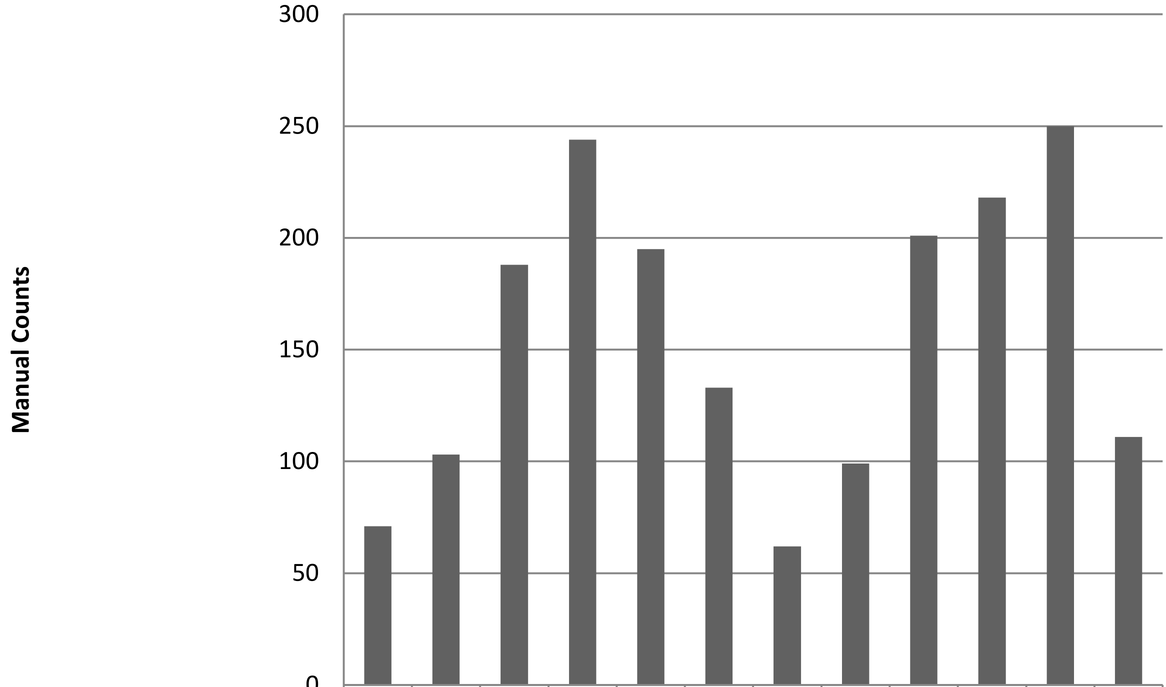
Ln distance to downtown (m): This variable measures the natural logarithm of the distance between a signalized intersection and its linear distance to downtown (bird's eye). The further the distance from downtown, the fewer the amount of pedestrians was expected. For calculation purposes, downtown Montreal was assumed to be at the intersection of McGill College and Sainte-Catherine. The distance to downtown variable was tested separately from the street segment variable. A 100% increase in the distance from downtown produced a 54.8% to 64.4% decrease in pedestrian activity.

4 way intersection: This is a binary variable to indicate whether or not the signalized intersection is 4 way. The models predict a 27.6% to 80.2% increase in pedestrian activity with the presence of a 4 way intersection.

Moderate precipitation (>5mm/day): It makes intuitive sense that adverse weather conditions would reduce pedestrian activity. The moderate precipitation variable is a binary variable that indicates if 5mm or more of precipitation occurred on the day the counts were done. This variable makes sense in the log-linear models, but not in the negative binomial ones. In the log-linear models, precipitation resulted in a 15.4% to 16.6% decrease in pedestrian activity.

Windy: This is a binary variable which measures if strong wind (>30 km/hr) was present on days the counts were done. If it is windy, fewer pedestrians should be walking. This variable reduces pedestrian activity by 3.0% to 9.3%. This variable is significant only in the log-linear model with street segments.

Other weather variables were tested as well, such as very hot and cold conditions, but they were not significant. This is certainly not absolute, as the impact of weather from the counts is somewhat hidden, due to the fact that counts were taken during periods of relatively good weather conditions. Although some counts occurred during extreme temperatures and rain, the majority of counts were taken on relatively nicer days – for instance, about 20% of days with manual counts had some form of precipitation present. Data was collected throughout all 12 months; the monthly distribution can be seen in **Figure 13**. Most variables are statistically significant with very low p-values – with a few exceptions depending on the model. The weather variables are poorly predicted (low p-values) and even have counter-intuitive signs (positive for rain) in the negative binomial model.This is true because the negative binomial model is used for parameters which have over-dispersion. The windy and moderate precipitation variables both have variances lower than their means and are not over-dispersed. The log-linear model explains about 50% of the variance and the Negative Binomial model also detects the presence of over-dispersion associated to unobserved heterogeneities across sites. These results are in accordance with previous studies (7) and (8). Overall the log-linear model with street segments is the best model. It contains the greatest number of significant parameters as well as making the most intuitive sense. All variables were tested for multi-collinearity. Values were below 0.4 for all variables, except street segments and distance to downtown, hence why they were tested separately in their own models.



	1	2	3	4	5	6	7	8	9	10	11	12
Count frequency by month	71	103	188	244	195	133	62	99	201	218	250	111

Figure 13– Monthly distribution of counts

Variables	Negative bin. Coef.	Negative bin. p-value	Log-Linear Coef.	Log-Linear p-value	Impact (elasticity) Neg. Bin	Impact (elasticity) Log-lin
400m Population ('000)	0.082	0	0.141	0	9.4%	16.2%
50m Commercial Space ('000 m^2)	0.190	0	0.198	0	16.3%	17.0%
150m Open Space ('000 m^2)	-0.023	0	-0.031	0	-14.2%	-18.7%
150m Subway	0.831	0	0.722	0	129.7%	105.8%
150m Bus Stations	0.077	0	0.095	0	27.3%	33.8%
400m Schools	0.189	0	0.219	0	21.5%	24.9%
400m % Major Arterials	-1.209	0	-1.103	0	-11.6%	-10.6%
400m Street Segments ('000)	2.513	0	2.732	0	70.9%	77.0%
4 way intersection	0.244	0	0.464	0	27.6%	59.0%
Moderate precipitation (>5mm/day)	0.050	0.377	-0.168	0.024	5.1%	-15.4%
Windy	-0.032	0.516	-0.098	0.135	-3.2%	-9.3%
Constant	5.978	0	5.189	0	N/A	N/A
R-square	Dispersion = 0.803		R-Square = 0.498			

Table 7 – Pedestrian Activity Model with street segments

Variables	Negative bin. Coef.	Negative bin. p-value	Log-Linear Coef.	Log-Linear p-value	Impact (elasticity) Neg. Bin	Impact (elasticity) Log-lin
400m Population (‘000)	0.090	0	0.198	0	10.4%	22.8%
50m Commercial Space (‘000 m^2)	0.191	0	0.215	0	16.3%	18.4%
150m Open Space (‘000 m^2)	-0.022	0	-0.028	0	-13.3%	-17.3%
150m Subway	0.814	0	0.798	0	125.6%	122.1%
150m Bus Stations	0.089	0	0.105	0	31.8%	37.3%
400m Schools	0.122	0	0.182	0	13.8%	20.7%
400m % Major Arterials	-0.480	0.023	-0.345	0.223	-4.6%	-3.3%
Ln distance to downtown (m)	-0.644	0	-0.548	0	-64.4%	-54.8%
4 way intersection	0.323	0	0.589	0	38.1%	80.2%
Moderate precipitation (>5mm/day)	0.048	0.392	-0.182	0.017	4.9%	-16.6%
Windy	-0.031	0.532	-0.091	0.177	-3.0%	-8.7%
Constant	12.048	0	10.370	0	N/A	N/A
R-square	Dispersion = 0.803		R-Square = 0.498			

Table 8 – Pedestrian Activity with distance to downtown

Conclusion

This thesis presents an analysis of pedestrian safety at signalized intersections. The following contributions can be highlighted:

- A large and rich sample of intersections was involved in this study. About 75% of the total number of signalized intersections in the city of Montreal are included. This is one of the first studies that has used such a large sample.
- For all intersections analyzed, geometric data was manually collected for each intersection in order to test the correlation between certain geometric properties and pedestrian crash risk.
- Average daily values for pedestrian volumes were extrapolated based on the data collected from automatic counters from six different locations throughout the city. The counters recorded pedestrian movements 24 hours a day for an entire year, which made it possible to determine the hourly, daily and monthly variations in pedestrian activity. This allowed all intersections to then have an average annual daily volume for pedestrians. A similar approach was used to obtain vehicular average annual daily volumes.
- -A regression was used to determine the contributing factors to pedestrian-vehicular accidents. It was found that vehicles were the most important contributor to pedestrian accidents, followed by number of pedestrians.
- -New findings for this study include the role that geometric properties of intersections play. Features such as fully/semi-protected pedestrian phasing, crosswalk distance, presence of commercial entrances/exits, the number of lanes and curb extension proxies all have an effect on pedestrian accidents.
- In remote areas, or if wide scale pedestrian activity needs to be predicted at intersections, it can be approximated by taking into account landuse, demographic, transit and weather details (from the nearest weather station). Within a vicinity of an intersection, variables such as: population, commercial space, open space, subway presence, bus stops, schools, % major arterials, street segments, 4-way intersection, distance to downtown, windy conditions and precipitation can all be used together to estimate the number of pedestrians at a given location.

- Considering this study, there are some recommendations for improving pedestrian safety. If possible, discourage the use of automobiles and promote alternative forms of transportation. Since vehicle presence has the greatest impact on pedestrian safety, the fewer vehicles there are, the less accidents that will occur. The city of Montreal already does this once a year downtown, where cars are not allowed. This is a great way to promote walking and pedestrian awareness. From an engineering standpoint, pedestrian safety could also be improved by reducing crosswalk distances, including semi-protect/fully protected pedestrian phases and by avoiding commercial entrances and exits in close proximity to intersections.
- Some limitations of this study are the ambulance reports. If an accident occurred and an ambulance wasn't called, this study would not know about it. This could lead to underreporting, especially for more minor accidents. In the future it would also be good to know the exact details of each accident (did the driver run a red, did he turn left etc…) and the weather conditions for that day. It would be interesting to see how all the factors leading up to the accident played out to be able to better design and account for these factors. The other limitation of this study was that counts were taken on days with relatively good weather conditions, therefore hiding some of the weather effects. It would be better to have more counts done on days of poorer weather conditions to fully capture the effects of bad weather on pedestrian activity.

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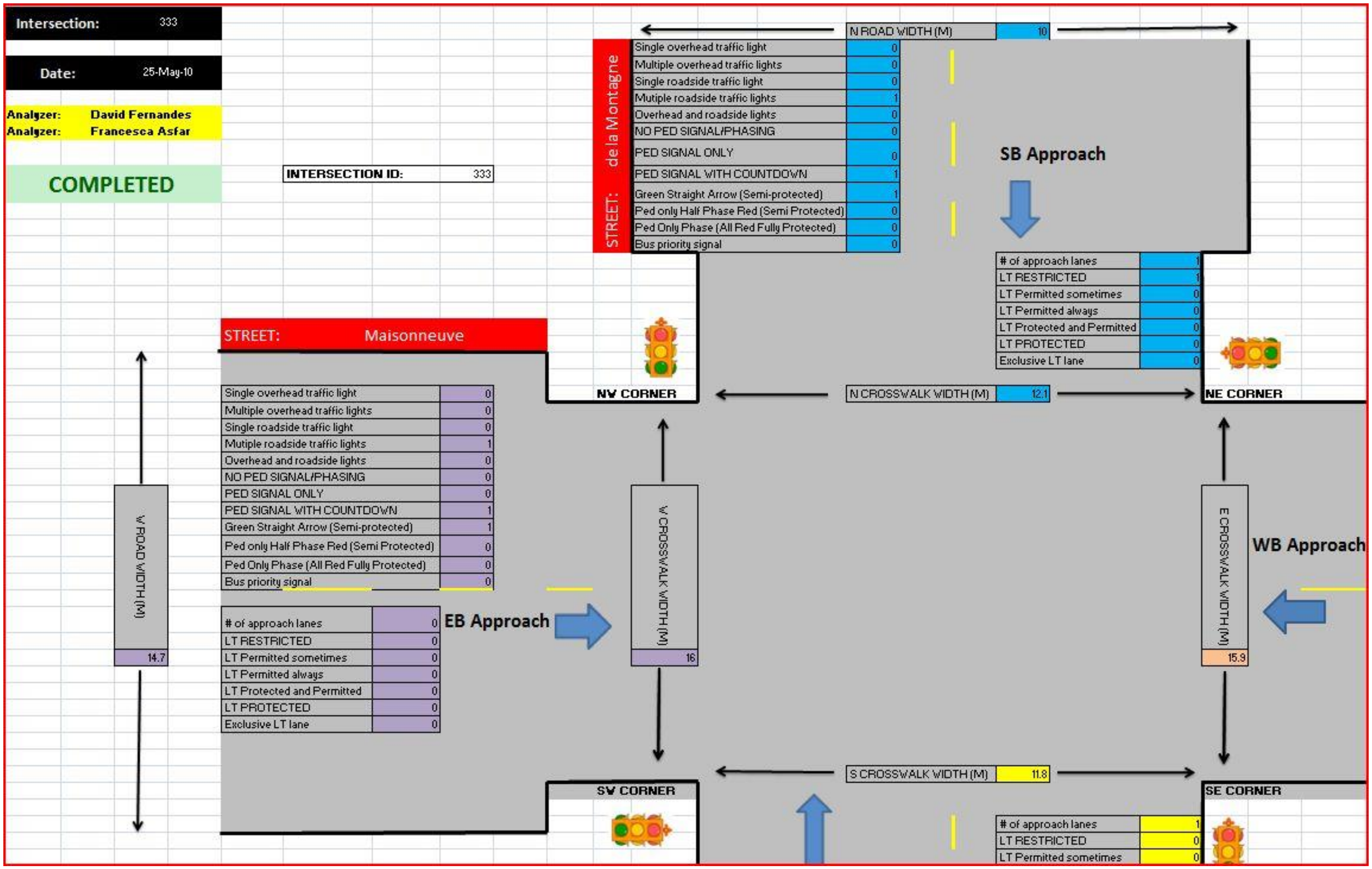
Appendix – Geometry Collection Sheets



Intersection: 333

Date: 25-May-10

Analyzer: David Fernandes
Analyzer: Francesca Asfar

COMPLETED

INTERSECTION ID: 333

STREET: de la Montagne

N ROAD WIDTH (M)	10
Single overhead traffic light	0
Multiple overhead traffic lights	0
Single roadside traffic light	0
Mutiple roadside traffic lights	1
Overhead and roadside lights	0
NO PED SIGNAL/PHASING	0
PED SIGNAL ONLY	0
PED SIGNAL WITH COUNTDOWN	1
Green Straight Arrow (Semi-protected)	1
Ped only Half Phase Red (Semi Protected)	0
Ped Only Phase (All Red Fully Protected)	0
Bus priority signal	0

SB Approach

# of approach lanes	1
LT RESTRICTED	1
LT Permitted sometimes	0
LT Permitted always	0
LT Protected and Permitted	0
LT PROTECTED	0
Exclusive LT lane	0

STREET: Maisonneuve

Single overhead traffic light	0
Multiple overhead traffic lights	0
Single roadside traffic light	0
Mutiple roadside traffic lights	1
Overhead and roadside lights	0
NO PED SIGNAL/PHASING	0
PED SIGNAL ONLY	0
PED SIGNAL WITH COUNTDOWN	1
Green Straight Arrow (Semi-protected)	1
Ped only Half Phase Red (Semi Protected)	0
Ped Only Phase (All Red Fully Protected)	0
Bus priority signal	0

EB Approach

# of approach lanes	0
LT RESTRICTED	0
LT Permitted sometimes	0
LT Permitted always	0
LT Protected and Permitted	0
LT PROTECTED	0
Exclusive LT lane	0

NW CORNER

NE CORNER

N CROSSWALK WIDTH (M): 12.1

W ROAD WIDTH (M): 14.7

W CROSSWALK WIDTH (M): 16

E CROSSWALK WIDTH (M): 15.9

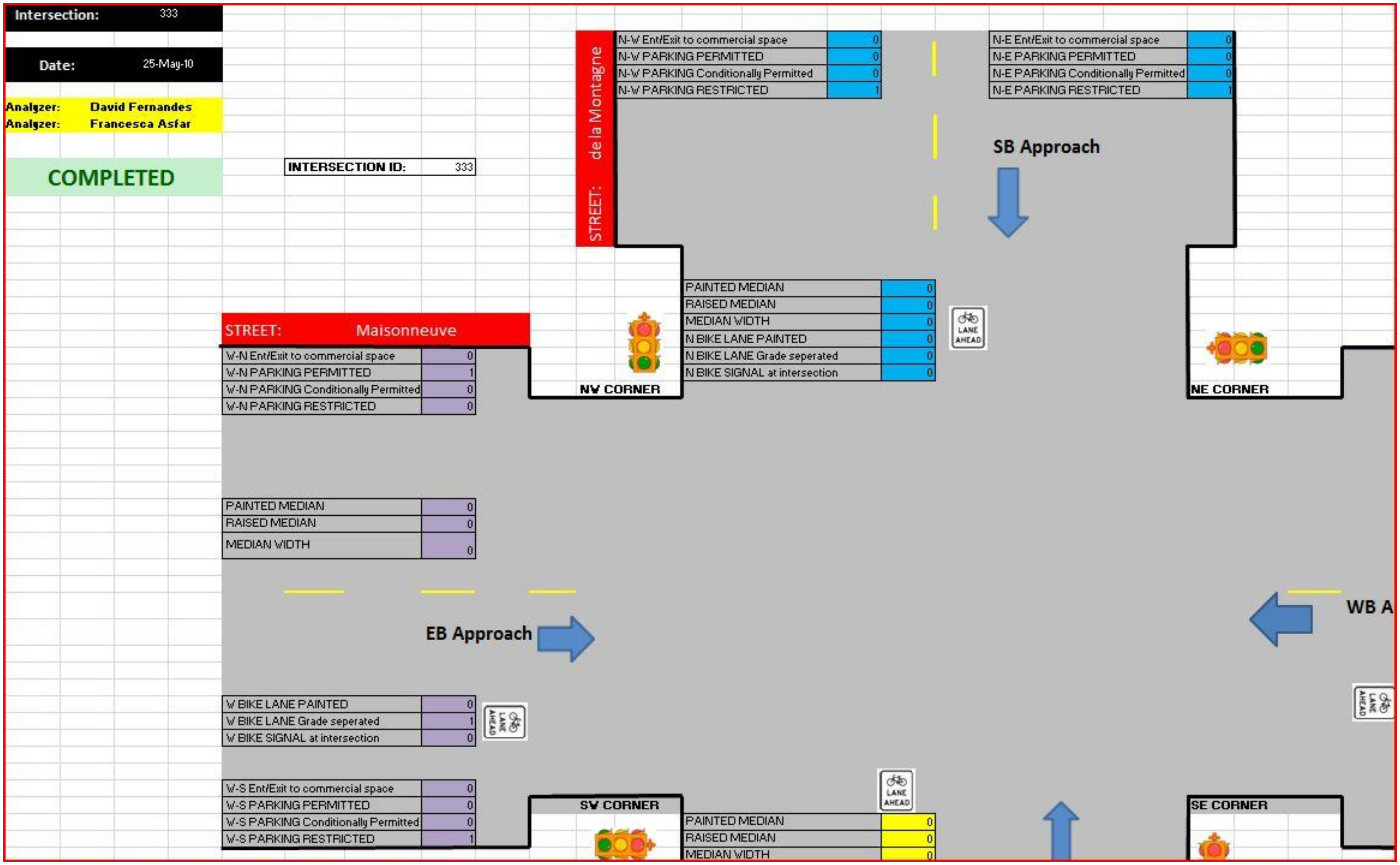
WB Approach

S CROSSWALK WIDTH (M): 11.8

SW CORNER

SE CORNER

# of approach lanes	1
LT RESTRICTED	0
LT Permitted sometimes	0


Intersection: 333
Date: 25-May-10
Analyzer: David Fernandes
Analyzer: Francesca Asfar
COMPLETED
INTERSECTION ID: 333
STREET: de la Montagne
N-W Ent/Exit to commercial space 0
N-W PARKING PERMITTED 0
N-W PARKING Conditionally Permitted 0
N-W PARKING RESTRICTED 1
N-E Ent/Exit to commercial space 0
N-E PARKING PERMITTED 0
N-E PARKING Conditionally Permitted 0
N-E PARKING RESTRICTED 1
SB Approach
PAINTED MEDIAN 0
RAISED MEDIAN 0
MEDIAN WIDTH 0
N BIKE LANE PAINTED 0
N BIKE LANE Grade seperated 0
N BIKE SIGNAL at intersection 0
LANE AHEAD
STREET: Maisonneuve
W-N Ent/Exit to commercial space 0
W-N PARKING PERMITTED 1
W-N PARKING Conditionally Permitted 0
W-N PARKING RESTRICTED 0
NW CORNER
NE CORNER
PAINTED MEDIAN 0
RAISED MEDIAN 0
MEDIAN WIDTH 0
EB Approach
WB A
W BIKE LANE PAINTED 0
W BIKE LANE Grade seperated 1
W BIKE SIGNAL at intersection 0
LANE AHEAD
W-S Ent/Exit to commercial space 0
W-S PARKING PERMITTED 0
W-S PARKING Conditionally Permitted 0
W-S PARKING RESTRICTED 1
SW CORNER
SE CORNER
PAINTED MEDIAN 0
RAISED MEDIAN 0
MEDIAN WIDTH 0