Optimizing the built environment for pedestrian safety in an ageing society: Toward an inclusive approach

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Abstract

With the longstanding overrepresentation of seniors in pedestrian injuries and fatalities, added to the prevalence of North-American ageing population, there is a sense of urgency for public health and transport planners to better understand the conditions surrounding senior injury risk. However, planners and practitioners are still challenged by a North-American built environment often optimized for vehicles rather than active and ageing road users. Researchers, on the other hand, still do not fully understand the nuances between younger and older injury factors, and particularly the effect of senior pedestrian exposure on their injury risk.

The primary research question in this thesis seeks to determine if senior injury factors at signalized intersections differ from those of the younger and to what extent? In a secondary fashion, this thesis explores the definition of an optimal built environment for pedestrian safety in an ageing society. In addition, it explores determining whether or not subpopulation models are more inclusive. Chapter 4 presents an injury regression analysis comparing 479 younger and 107 older pedestrian injuries that occurred at 191 signalized intersections in Montreal, a study deemed “practice ready” that was presented at the 2015 Transportation Research Board (TRB) annual meeting.

Among other results, the center median refuge was found to reduce injury probability in seniors by 70%, implying that it has the potential to be a strong countermeasure in an ageing society. Results of this research revealed nuances between younger and older injury factors, and suggest that the optimal built environment for pedestrian safety of an older society may indeed differ from one optimized for the younger. In addition to being more inclusive, findings suggest that without subpopulation models, safety or health performance indicators of senior pedestrians may be overlooked.

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I also wish to recognize the influence of my initial supervisor, Dr Zacharias, whom although having left Concordia for a new career path in China in my first year, his keen understanding of pedestrian behavior and empiricism played a role in triggering my interest in pedestrian safety.

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Chapter 1 Introduction

Senior pedestrians are arguably the most at risk pedestrian subpopulation given their longstanding overrepresentation in injuries and fatalities (Oxley, Charlton, Corben, & Fildes, 2006); (Fontaine & Gourlet, 1997). Meanwhile, ageing population is creating an increasing source of urgency for researchers and planners given that the effect of senior exposure on their risk is still unknown (SWOV, 2002). In order to ensure that the built environment and its design do not exclude older adults in an ageing society, some planners may contend that safety models ought to be built for the most vulnerable, as captured in the text of Bernard Isaacs: "Design for the young… you exclude the old – but if you design for the old you include the young." (ALGA, 2010, p. 1). As such, there is research interest in determining what built environment design attributes are safer for senior pedestrians and how planners can adopt a pedestrian safety vision that is more inclusive for an ageing society.

Planners and researchers have increasingly taken interest in the field known as Vulnerable Road User (VRU) safety, namely to address the safety of more active transport modes such as pedestrians and cyclists. This interest is largely fueled by the growing importance of sustainability, public health and providing access to safety to more vulnerable transport users. North-America's performance in VRU safety is said to be lacking in policy and the built environment, particularly compared to Europe (Pucher & Dijkstra, 2000). Furthermore, although road injuries have declined since the 1970's in countries that are members of the Organization for Economic Cooperation and Development (OECD) (IRTAD, 2009), North-America is still poorly ranked according to Transport Canada (Transport Canada, 2011). As such, researchers and planners have incentive to seek improving the situation albeit in the context of an ageing or a younger society.

Overview of the Thesis

This thesis is organized using both chapters and sub-headings. Chapter 1 presents a portrait of the problem and the conceptual framework, followed by thesis research questions and objectives. The first part of Chapter 2 extends the conceptual framework of this to situate pedestrian safety within the evolution of sustainable transport to then transition into a broad review of the pedestrian injury literature. Chapter 3 presents an overview of methods used while Chapter 4 is the case-study in the form of a pedestrian injury study submitted as a paper at the 94th annual Transportation Research Board (TRB) conference. The paper was accepted in their Pedestrian Safety Policy, Planning, and Design Issues poster session as a "practice-ready" study. Given that the literature review and methodology in this article are more detailed, other chapters of this thesis are kept to a broader scope to tie results back into implications of health and transport planning. Chapter 5 presents overall implications of results, including weaknesses and future work, and concluding remarks.

1.1 Senior Pedestrian Safety: A longstanding Problem and Future Concerns

Recent road safety research is increasingly focused on injury prevention of VRUs and determining built environment attributes associated with their injury factors in order to optimize the built environment for active road users. One could argue that seniors are the most vulnerable subpopulation solely based on their longstanding overrepresentation, let alone the additional future exposure concerns associated with ageing population and prolonged life expectancy. This problem justifies research seeking to better understand their injury involvement. The safety problem faced by older adult pedestrians to be covered next includes their longstanding overrepresentation in pedestrian injuries and fatalities and future concerns due to ageing society.

1.1.1 A Longstanding Overrepresentation

Seniors have been overrepresented in fatal (Sklar, Demarest, & McFeeley, 1989) and non-fatal (Oxley et al. (2006)) pedestrian injuries for quite some time; and their involvement is fairly localized at intersections in urban areas (Siram, Sonaike, Bolorunduro, Greene, Gerald, Chang, Cornwell & Oyetunji, (2010)). For example, between 2003 and 2009 on the Island of Montreal, seniors or older adults, heron defined as adults aged 65 and older (65+), represented nearly 50% (72 of 148) of pedestrian fatalities (SAAQ [Unpublished data], 2011). However, they only represented 15.4% of the population (Statistics Canada, 2010a). Figure 1 illustrates this overrepresentation using the same period data but showing only fatalities according to population, age-group and gender. The proportions of fatal pedestrian injuries are the red outlined bars and population is represented by the blue filled bars. Figure 1 evokes some interesting trends to link to past studies. For example, the figure shows the heightened risk of the "older old" (defined as people over 75 years-old (DoT London, 2004)), and the gender injustice experienced by women, perhaps given that they tend to drive less than their male counterparts (SAAQ, 2007). On the other hand, the lower death rates of younger females could perhaps be hypothesized by the fact that their parents tend to drive them to school more than their male counterparts? Although interesting, objective of Figure 1 is to illustrate the most pronounced finding – which is the heightened vulnerability of senior pedestrians.

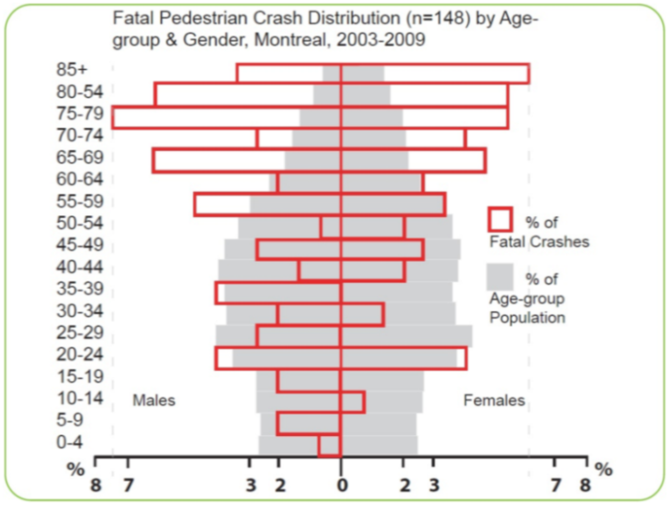

Figure 1: Percentage Distribution of Fatal Pedestrian Crashes & According to Population Age-group and Gender, Montreal 2003-2009

Adapted from Auger (2011) using SAAQ pedestrian crash data for the 2003-2009 [unpublished data]; 2006 Montreal Census population was also used.

A nuance between pedestrian injuries and fatalities is appropriate to discuss before embarking on the more elaborate elements of injury analysis in this thesis. Although some past studies have emphasized fatality and senior frailty as a key factor as the senior pedestrian safety problem (Siram, et al., 2010), this thesis will nuance this slightly and contend that injury analysis (involvement) is also important. It is assumed here that a better understanding of senior injury involvement is the first step towards then solving the factors that lead to their fatal involvement. It is worth remembering that succumbing to an injury (fatality) first begins with their involvement (injury). The next section presents a portrait of ageing trends which is a key concern for researchers and planners.

1.2 Future concerns: A question of exposure

There is concern among health and transport planners and researchers that the already longstanding senior pedestrian risk problem will be further impacted by ageing population. Although many factors can influence pedestrian injuries, a key factor of concern is the effect of exposure, whether due to more senior walking trips in an area or because of active ageing policy implemented by planners. More importantly, researchers still do not fully understand the relationship between exposure and senior pedestrian injuries (SWOV, 2002).

1.2.1 Ageing Trends

Ageing population trends are increasingly becoming a concern as it will likely translate into a greater numbers of retirees or seniors walking, and thus a potential for more senior pedestrian injuries. Figure 2 (below) shows the senior population percentage in both its current and forecasted state, according to the specified number of years and different geographies. In a span ranging from 25 to 44 years, the percentage increase of seniors is expected to be 58% in Canada (Statistics Canada, 2010), 57% in the U.S. (AoA-US-DoHHS, 2010), 73% for Europe (U.S. Census Bureau, 2009) and 100% worldwide (WEF, 2012). See Figure 2 for details. With an expected growth of 83% in just 25 years, the province of Quebec has one of the heaviest growths in their older population. In the city of Montreal, on the other hand, the 65+ age-group is expected to grow from 15% to 22% over the course of 25 years (from 2006 to 2031), or a 47% growth (ISQ, 2009). This more modest growth is largely offset by higher rates of younger immigration compared to regional areas of the province of Quebec (ISQ, 2009). In addition to ageing trends there is evidence that seniors tend to live increasingly in urban areas when they age, therein creating a concern of a, so to speak, ‘urbanization of ageing’.

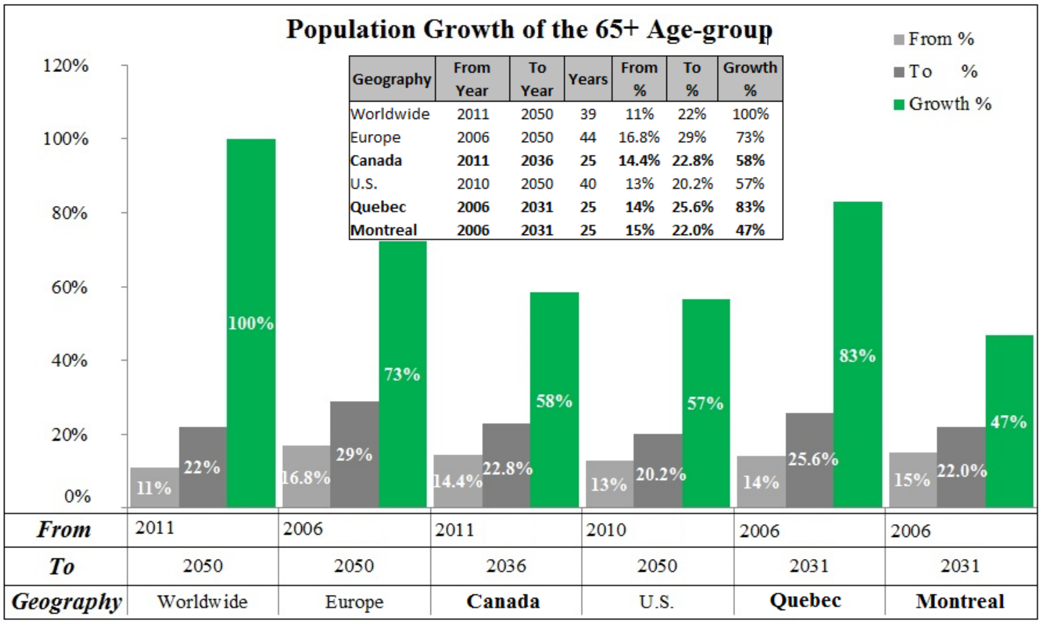

Figure 2: Population Growth of the Older Age-group Across Different Geographies

Sources for Figure 2 for geographies left to right include (WEF, 2012); (U.S. Census Bureau, 2009); Statistics Canada (2010b); (AoA-US-DoHHS, 2010); (ISQ, 2009)

1.2.2 The Urbanization of Ageing

In Canada there is clear evidence of the urbanization of ageing since 78% of those aged 55+ already lived in urban areas in 2006 (CMHC, 2015). Further, those living in urban areas increases when looking at the proportions of age-groups 55-64, 65-74 and 75+ which increase respectively from 77% to 78.2 to 83% (based on 2006 data (CMHC, 2015)). Globally, a similar trend is apparent, where from 2000 to 2025 adults aged 60+ living in urban areas are expected to grow from 51% to 62% (Mirkin & Weinberger, 2000).

Other potential indirect exposure factors raise additional concerns, for example, the effect of growing life-expectancy, active ageing policy (WHO-NMH-NPH, 2002) and the tendency for walking and transit use once seniors can no longer drive (Statistics Canada, 2012). These are factors for which injury models have had difficulty accounting for.

These facets discussed revolve around the assumption of a relationship between seniors (exposure) and their injury risk. This relationship cannot be assumed without discussing the nuance presented by some recent studies based on the existence of a “safety in numbers” phenomenon. To sketch out the conceptual framework of this thesis, the following section includes a discussion of this and other key concepts such as ‘injury incidence risk’ versus ‘individual risk’, optimizing of the built environment for prevention, Vision Zero and the prevention paradox.

1.3 Research Objectives

Most researchers and planners studying or practicing from a context VRU safety have focused or relied on approaches using the overall pedestrian population to measure the effect or understand injury factors. Although it is also necessary to include overall majority subpopulations, there is also a need to better understand senior injury factors, especially considering that countermeasures tailored for this subpopulation may be more inclusive. To address this research question, this thesis proposes specifying subpopulation regression models for both the younger and older. The primary research question seeks to:

i. Determine if and to what extent senior pedestrians are influenced by different injury factors compared to the younger and?

Two secondary research questions are tangentially addressed:

i. Explore the question of defining a built environment that is optimal for pedestrian safety in an ageing society.

ii. Determine if subpopulation models offer a more inclusive approach?

The objective in this thesis is imply to seek a better understanding of senior pedestrian injury factors at signalized intersections and hopefully planners will use these results to apply them in the form of built environment countermeasures and taking advantage of potential prevention opportunities.

Given that Chapter 4 has a more detailed literature review targeting senior pedestrian safety injury factors, below is meant to further outline the conceptual foundation of this thesis and how it relates current transport planning and sustainability.

1.4 Conceptual Framework

In order to situate older adult pedestrian safety within the current state of practice and provide a preamble for the literature review, the following points are discussed:

- Safety in numbers",
- Vision Zero,
- The "prevention paradox", opportunities for prevention and inclusivity.

1.4.2 Safety in Numbers Versus Vision Zero?

The problem surrounding senior pedestrian safety suggested in the introduction is largely due to the expected increase in risk given the expected spike in seniors. This implies a hypothesized relationship between senior pedestrian injury incidence and exposure. Broadly speaking, individual injury risk is the probability that the individual (i.e. pedestrian) is subjected whereas injury incidence probability is defined as the probability of incidence or occurrence. However, some recent studies in the literature have showed evidence of what is referred to as a "safety in numbers" phenomenon. Rather, the phenomenon shows an opposite effect between (individual) injury risk and exposure (i.e. pedestrians and cyclists) (Elvik et al. (2009)). Although a number of studies have indeed provided evidence for safety in numbers (Feng Wei & Lovegrove, 2012) it should be noted that in nearly all cases an increase in injury incidence usually occurs (Miranda-Moreno, Morency,

& El-Geneidy, 2011). It is unknown if and how exposure affects the senior pedestrian subpopulation, and whether or not safety in numbers applies to seniors (SWOV, 2002). However, the nuance presented in response to safety in numbers is provided by the Vision Zero initiative, to be discussed below.

1.4.3 The Link between the Built Environment, Prevention and Vision Zero

Inextricably linked to this paradigm of prevention is the importance of Vision Zero, a road safety planning initiative originating in Sweden. Two primary orientations of Vision Zero are worth highlighting as captured by Elvik et al. (2009):

i. *...proponents of Vision Zero argue that vehicles and traffic systems must be designed in such a way that no one is killed or seriously injured when they travel...* (p. 131)

ii. *...Vision Zero states that the responsibility for accidents is shared by the system designers and the road user...* (p. 131)

Vision Zero is largely a proactive and preventive planning approach[1] that condemns a *laissez-faire* approach and encourages planners to continuously seek to improve (hence optimize) road safety. In response to safety in numbers, Vision Zero advocates would condemn satisfaction with only a reduction in individual risk, and contend that a rise in incidence is not only a justification for intervention but an opportunity for prevention. As such, Vision Zero encourages planners and

[1] A complimentary element to Vision Zero is the multidisciplinary approach referred to as the three E's: Education, Enforcement and Engineering.

researchers to continue seeking to better understand injury factors[2] and to be proactive, especially for VRUs. However, excessive focus on vulnerable subpopulations, such as seniors, has been critiqued in the health literature for overlooking preventative opportunities among the majority (albeit lower risk), also known as the “prevention paradox”.

1.4.4 The Prevention Paradox and the Question of Inclusivity

The prevention paradox makes reference to a renowned white paper by Geoffrey Rose where he argued the concept of a population based approach for ‘preventative medicine’. The prevention paradox critiques targeted risk modelling[3] of high risk subgroups, because despite being “high risk” or more *vulnerable*, because they only represent a minority which, it is contended, there is a prevention opportunity lost from larger majority population (Charlton, 1995). However, one could argue that Rose’s expertise was not necessarily accustomed to the nuances of road safety. Rather, his interest was mainly focused on predisposed or co-occurring illnesses, such as the link between cholesterol and coronary heart disease, hence prevention opportunity lost. However, given that an individual is rarely predisposed to a traffic injury in the way that cholesterol related to coronary disease. The prevention paradox must nevertheless be addressed because the state-of-the-art research is increasingly focused on this subpopulation (Fuller & Morency, 2013), which raises concern: However, it is contended in this thesis that, on the contrary, the objective of subpopulation models specified for both seniors and the younger have the objective to seek for

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[2] As noted previously, the relationship between exposure and senior injury risk is largely still unknown (SWOV, 2002).

[3] Modelling, spelled with two l’s, makes reference to the renowned publication entitled “Modelling Transport” (Ortuzar & Willumsen, 2011), the objective being to distinguish between the traditional meaning.

prevention opportunities. As such, this thesis adopted a more nuanced position regarding the prevention paradox and includes subpopulation models of the majority population (the younger).

However, in the context of pedestrian safety it appears that optimizing the built environment for senior risk factors may be more inclusive for the younger. Take for example a practitioner whom decides to add 4-5 seconds of crossing time to the pedestrian WALK phase because she or he observed that older pedestrians had difficulty crossing in time. If there is no evidence of this being a risk factor in the younger, yet it having a protective effect on seniors, this is a more inclusive countermeasure – not only for the older but also the younger.

Chapter 2 Literature Review

2.1 A Cultural Shift in Transport Planning

In order to elucidate why VRU safety has become increasingly important in North-America, a brief step back is helpful. A cultural shift happened in transport planning near the end of the twentieth century that was characterized by measures that sought to counter problems of an automobile oriented culture (Transport Canada, 2010). Modern planning approaches tended to focus on large scales such as grandiose buildings and the automobile, typical of a modernist design style of *Le Corbusier's* which often overlooked the human scale. On the other hand, more contemporary planning sought to bring back the human scale, more in the styles of Jane Jacobs, Kewis Mumford, William Whyte and Kunstler (1994). As such, transport planning too sought to bring back the human (pedestrian) scale. This shift sought to (re)introduce walking, cycling and transit (Transport Canada, 2010). Although earlier forms of mass urban transport existed, such as "…horse-drawn buses, first used in Bordeaux in 1812." (Lay, 1992, p. 129), sustainable transport planning is more formally dated to have begun at the end of the twentieth century (Wolf, 1996);

(Transport Canada, 2010).[4] The result of this cultural shift in transport planning characterized by a multidisciplinary approach and global environmental awareness that sought to encourage health, access to safety for active or vulnerable road users (Pucher & Dijkstra, 2000) and lower greenhouse gas (GHG) emissions (Environment Canada, 2012). These elements are what Gehl (2013) refers to as "green mobility" (p. 7). Sustainable transport planning is multifaceted and multidisciplinary – the nuances and extent of which cannot be exhaustively covered in this thesis. Suffice to underline that the shift away from a modern approach to that of a more contemporary approach is herein defined as a more sustainable transport planning approach. Readers should note that the objective of juxtaposing the planning characteristics of modernity and the automobile to that of a more sustainable one is intended to map the development of pedestrian safety and the importance of the notion of access to safety therein.

2.1.1 Twentieth Century Transport Planning, Modernity and the Automobile

Before the advent of the automobile, it is said that richer horse-carriage owners were already causing fatalities among lower class pedestrians (Lay, 1992) and justified their priority due to their higher social status (Muhlrad, 2007). This class priority is still troubling for some planners given that poorer neighborhoods today still face an overrepresentation in road injuries and fatalities (Morency P. , Gauvin, Plante, Fournier, & Morency, 2011). As such, the notion of access to safety has been a key driving force behind safety in sustainable transport. Convincing decision makers

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[4] Although cycling and rail transport (Wolf, 1996) was omnipresent as a means of transport as early as the nineteenth century, to speak of a contemporary global awareness and effort to counter modern-automobile oriented problems, the advent of sustainable transport planning is more formally assigned to the 1990's (Transport Canada, 2010) (DoT London, 2007).

against an automobile oriented planning model was difficult both then and arguably is still the case today given that transport planning and modernity seem to have a strong relationship with job creation and economic growth (Ben-Joseph, 1995); (see *"The Great Car Economy"* in Wolf (1996)). Twentieth century automobile demand was fulfilled by modern 'travel-demand forecasting' approaches, also known as the four-step model, characterized by fulfilling overgrowing automobile demand with less consideration for other modes of transport. The built environment therefore was optimized for automobile users rather than for VRUs. However, evidence shows that Europe as further ahead in terms of policy favoring VRU safety (Pucher & Dijkstra, 2000). Two primary examples are outlined next in order to highlight the importance of access to safety in sustainable transport: The Buchanan Report (1963) and the *Woonerf* (Ben-Joseph, 1995).

2.1.2 The Buchanan Report and the Woonerf

The Buchanan Report was a set of recommendations put forward by Colin Buchanan to address the problem of the congested roads of Britain in the 1960's, as mandated to him by the British government (Ben-Joseph, 1995). Buchanan's recommendations leaned towards the human scale by providing access to safety for pedestrians, which was not well accepted by his interlocutors of the time. His recommendations were initially said to be rejected because they were incompatible with the post-war modern economic development culture of the time (Ben-Joseph, 1995); (Wolf, 1996). The Buchanan report would however later influence sustainable transport culture by virtue of its later influence to planners in Europe.

Influenced by the Buchanan Report, Niek De Boer was an early planner whom is credited with pioneering one of the first *Woonerfs* implemented in Europe. A street design based on principles of shared-space and access to safety for pedestrians, the *Woonerf* is said to have been first implemented in the Netherlands in 1970 (Gehl, 2013) and was largely recommended by early planners inspired by the Buchanan Report (Ben-Joseph, 1995). The importance of the *Woonerf* cannot be overstated here since it demonstrates an early example of sustainable transport that highlights reoccurring themes in this thesis: The importance of a more optimal built environment for VRUs, access to safety for pedestrians (inclusivity) and the importance of the human scale (pedestrians). However, the facets that encompass sustainable transport values can still be a challenge in North-America today, especially compared to Europe (Pucher & Dijkstra, 2000).

2.1.3 North-American Sustainability: Delayed Shift or Illusory?

To be clear, automobile oriented transport planning was still a challenge in many places throughout Europe in the 1970's and 80's; they were not impervious the "Roads to Prosperity" phenomenon. However, it appears that North-America had struggled in its ability to go beyond "statements of exhortation of sustainable policy (Wellar, 2006). For example, it is suggested in the literature that a large factor in the early trend of reducing traffic fatalities in the U.S. was due to the 1973 Oil Crisis/Embargo, specifically when the U.S. government introduced the National Maximum Speed Law (NMSL) (IIHS, 2014). Although other factors contributed, such as fewer people driving, it is well known today that limiting speeds had the effect of reducing fatalities (NHTSA-FHA-US-DoT, 1998) (Farmer, Retting, & Lund, 1999) (Johnston, 2004). During this era of limited energy resources, a sense of governmental awareness arose among transport and land-use planners, leading to efforts to encourage mass transit, cycling and walking (Wellar, 2006). New schools of planning surfaced, such as New Urbanism, Smart-Growth, Complete Streets and Transit Oriented Development (TOD). While exhaustive coverage of these schools of planning and practice is beyond the scope of this thesis, suffice to state that improving transport planning towards a "greener mobility" (Gehl, 2013, p. 7) was primordial in defining the sustainable cultural shift.

2.2 Pedestrian and Vulnerable Road User (VRU) Safety Literature

Pedestrian safety studies can loosely be categorized among three broad study types:

- Surveys,
- Descriptive or empirical, and
- Regression based injury analysis.

Surveys generally measure *perceived* injury probability while empirical or descriptive studies analyze *observed* or *descriptive* conflict situations or injury. Injury regression analysis studies are typically regression based and have a stronger inferential capacity and measure actual injury risk. However, obtaining crash or injury data can be difficult or costly.

2.2.1 Terminology and Types of Studies

A pedestrian injury, sometimes referred to as a crash, accident or collision, is an impact occurring between a vehicle and a pedestrian resulting in injury or death (WHO, 2013). Although some have used the terms crash and injury in a synonymous fashion, the term 'crash' here is used in reference to the broader study of crash or collision analysis. To be clear, a *pedestrian injury* is defined here as a vehicle-pedestrian crash regardless of severity or outcome (slightly, severely and fatal injuries). The journal article presented in Chapter 4 omitted cases where there was only property damage. The primary reason for this is not only related to the fact that data reliability is poorer for more casual crashes (Austin, THE IDENTIFICATION OF MISTAKES IN ROAD

ACCIDENT RECORDS: PART 2, CASUALTY VARIABLES, 1995), but also because these are mostly reported for drivers' vehicle insurance purposes.[5]

2.2.2 Crash or Injury Analysis Studies

Appreciation of the spatial scale in crash modelling is necessary because there is an inextricable link between the scale of the study area, the response variable, research objectives and type of model to be used (Thomas, 1996). Two loosely defined types of injury studies are aggregate and disaggregate types. Injury count, frequency or incidence studies, are more commonly aggregate and therefore usually involve a spatial dimension, such as by census tracts or zip-codes (Ukkusuri, Miranda-Moreno, Ramadurai, & Isa-Tavarez, 2012). More commonly, injury count models are specified by intersection (Miranda-Moreno et al. (2011)) and commonly use either the Poisson or Negative Binomial (NB) distribution assumptions. The Poisson distribution has been a foundational probability distribution equation used for early studies, given by the following function:

$$P(y_i) = \frac{e^{-\lambda i}\ \lambda_i^{\ y_i}}{y_i!}$$

Equation 1

where $P(y_i)$ is the probability of intersection i having y_i injuries, whereas λ_i is the Poisson parameter for the expected number of injuries. The limitation of holding the mean and the variance constant has been identified as a shortcoming of the Poisson distribution when the variance and mean in fact vary in the data (Posh & Mannering, 1996). As such, the NB distribution is increasingly preferred in injury analysis because it accounts for overdispersion in the data

[5] In SAAQ dataset, these crash types are defined as Domage matériel seulement (DMS).

distribution, implying that the variance is larger than the mean. The NB model is favorable for this and, extended from the Poisson model, it is rewritten as follows:

$$\boldsymbol{\lambda}_i = EXP\ (\beta X_i + \ \varepsilon_i)$$

Equation 2

where $EXP\ (\varepsilon_i)$ is the gamma-distributed error term with mean 1 and variance α^2 (Washington, Karlaftis, & Mannering, 2011). The NB probability distribution function is written as follows:

$$P(X = x\,) = \binom{x-1}{r-1}\ p^r(1-p)^{x-r}$$

Equation 3

where X is the random variable in the model, x is the number of injuries, r is the number of intersections. As such, the NB model is commonly appropriate for intersection analysis.

On the other hand, disaggregate studies do not necessarily relate to a spatial scale. For example, disaggregate studies can be found at highly fine scales, such as time-series models of injuries by hour of the day (Usman, Fu, & Miranda-Moreno, 2012). More commonly, disaggregate studies are found at the individual level and employ a logistic regression model because of the binary nature of the response variable. For example, the objective can be to determine factors predicting the fatality of individuals involved in crashes (1 = fatal injury, 0 = non-fatal injury) (Al-Ghamdi, 2002) or can combine one or more severity types such as fatal and severely injured (1 = fatal or severe, 0 = slight or no injury) (Sze & Wong, 2007). Alternatively, studies seeking to exploit the ordinal or nominal nature of the injury severity data have employed multinomial (Rifaat, Tay, & De Barros, 2011) or ordered logit or probit models (Mohamed, Saunier, Miranda-Moreno, & Ukkusuri, 2013) (Lee & Abdel-Aty, 2005). Although some studies have showed the benefit of disaggregate scales, aggregate scale studies can be important for measuring the efficacy of policy according to larger administrative or political boundaries (Aziz, Ukkusuri, & Hasan, 2013) (Schuurman, Hameed, Fiedler, Bell, & Simons, 2008).

As is the case in this thesis, more novel studies and particularly those with a focus on VRU safety, have increasingly showed interest in built environment predictors as a means, either indirectly or directly, to optimize the urban environment surrounding roads or intersections for safety.

2.2.3 Built Environment Predictors and Urban Intersections

The Public Health Agency of Canada (PHAC) defines the built environment as:

> *"...part of our physical surroundings and includes the buildings, parks, schools, road systems, and other infrastructure that we encounter in our daily live."* (PHAC, 2015)

Pedestrian safety research focusing on the built environment seeks to determine injury predictors in association with the built environment. As shown in Figure 3 (below), this can include physical infrastructure immediately surrounding intersections, such as pedestrian crossing signals (PCS) attributes (crossing characteristics), road, geometry and design characteristics, but can also include some area-wide attributes such as different land-use types. However, as shown in Figure 3, it is important to remember that built environment attributes more commonly have an indirect effect on injuries (Miranda-Moreno et al. (2011)). As such, certain variables should be assigned higher importance when calibrating injury models. For example, traffic and exposure have first order importance as direct injury predictors given that an injury cannot happen without either of these, although there are some indirect ways to estimate exposure and traffic.

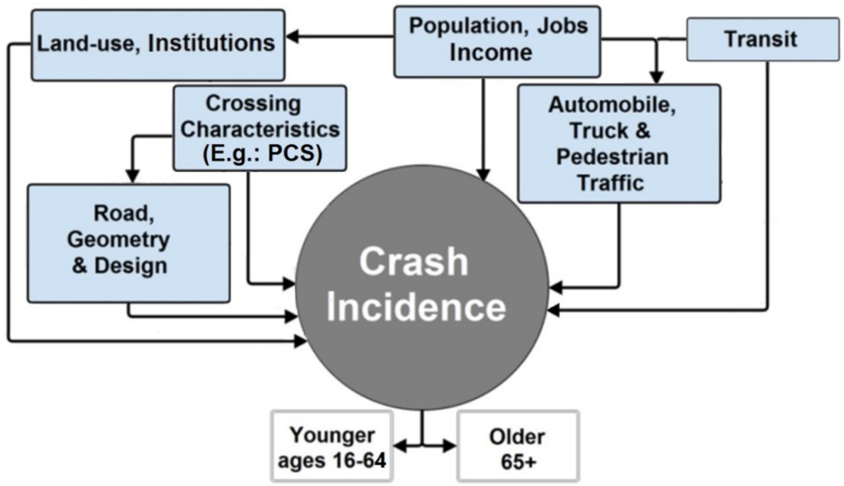

Figure 3: Variable Categories and Their Link to Pedestrian Injury Incidence

The built environment is also closely associated with intersections. The urban intersection is an appropriate spatial scale to study pedestrian injuries not only because most overall pedestrian injuries happen there (Cloutier, Tremblay, & Morency, 2014), but because this is particularly the case for senior pedestrians (Oxley & Fildes, 1999). In fact, a spatial query on the Island of Montreal for the period between 2003 and 2009 revealed that 85% of senior (65+) injuries happened at intersections using a 30-meter buffer (SAAQ [Unpublished data], 2011).

On the other hand, Geurrier & Jolibois (1998) provided evidence that older pedestrians (defined as 65 and older) had trouble at certain types of intersections. Their study, which used a videotaping observational approach at five intersections in Florida, United States, concluded that future countermeasures should seek to improve the surrounding 'engineering design' of intersections to better suit older pedestrians. Implicitly, authors are referring to the built environment. The following section covers data derivation, methodology of variables or sources that were not justified in the article of Chapter 4 – given the word limit requirements of the journal.

Chapter 3 Methodology

3.1.1 Overview of Data Sources

Pedestrian crash data used in the regression analysis in Chapter 4 derives from the Société de l'assurance automobile du Québec (SAAQ). This data was provided by the city of Montreal Department of Transport. The study area, comprising of the 191 signalized intersections, derive from a collaboration between the Institut national de recherche scientifique (INRS), Direction de la santé publique (DSP), and the Centre d'écologie urbaine de Montréal (CEUM). Partial results from this collaboration, can be found in some recently published studies (DSP, 2013); (Cloutier, Tremblay, & Morency, 2014). To make future reference to this collaboration in this thesis, the "DSP (2013) collaboration" will be cited. Transit data derived from the Société de Transport de Montreal: STM dataset (STM, 2010). Population data derived from the Canadian Census Profile (Statistics Canada, 2010a). For the complex intersection variable, field observation and consultation of Google Street View of the built environment was performed during research activities in the years of 2013-14. Data on traffic counts and intersection cycles and phases were derived from the city Montreal Department of transport (DoT Montreal [b], 2013) and were retrieved by collecting and collating data from the their physical archives in December of 2013.

3.1.2 The Study Area in Chapter 4 and Sampling of the 191 Signalized Intersections

The study area appearing in the regression analysis of Chapter 4 comprises of only signalized intersections because the city of Montreal only provided vehicle and pedestrian traffic data for these intersections. These signalized intersections (n=191) were taken from the 512 intersections appearing in the DSP (2013) collaboration. The DSP (2013) collaboration selected their sample at random using a stratified methodology according to the six different intersection types found in the 8756 intersections that make up central Montreal boroughs (DSP, 2013). As shown in Table 1, the different types of intersections are defined by the different combinations based on the two main roads that connect the intersection: Arterial/Arterial, Collector/Collector, Arterial/Collector, Collector/Local, Arterial/Local and Local/Local. A minimum of 5% of each type of intersection was also a condition used for selecting the stratified sample in the DSP (2013) collaboration. However, given that the regression analysis in Chapter 4 consists of only signalized intersections, the proportions of intersection types shown in Table 1 underline two important characteristics of the study area. First, it shows that the majority of intersections are major roads such as the arterial types: in fact, 97% of 191 signalized intersections in the study area have minimally either one connecting arterial or one collector road type. As such, the regression analysis in Chapter 4 does not maintain a stratification methodology as did the DSP (2013) collaboration but rather a focus on major urban road types.

Table 1: Derivation of the Study Area from Central Montreal Borough Intersection Types

As Defined in DSP (2013)					*Selection of Signalized Intersections in Chapter 4 from DSP's (2013) Original Stratified Sample*	
Intersection Type Based on Connecting Roads	**Intersection Category**	**No. of Intersections in Central Montreal Boroughs (n=8817)**	**No. of Intersections in Stratified Sample (n=512)**	**% of 512**	**No. of Signalized Intersections (n=191)**	**% of 191**
Arterial/Arterial	Major	181	53	10.4%	47	25%
Collector/Collector	Major	127	51	10%	35	18%
Arterial/Collector	Major	343	60	11.7%	55	29%
Collector/Local	Mixed	1987	91	17.8%	21	11%
Arterial/Local	Mixed	1773	80	15.6%	27	14%
Local/Local	Local	4406	177	34.6%	6	3%
Total Intersections		8817	512	100%	191	100%

3.1.3 Crash and Injury Data

In the province of Quebec, crash or injury data can derive either from police reports standardized by the SAAQ or ambulance/hospital reported data by Urgences Santé. In this thesis, police reported crash data from the SAAQ was used (SAAQ [Unpublished data], 2011). This data was provided by the city of Montreal Department of Transport, Safety and Planning Division (DoT Montreal [a], 2011). Permission was granted by them following my initial work in what was a post-undergraduate internship position I held there in 2010-11 (Auger, 2011). The crash period used in the regression analysis in Chapter 4 totals to seven years using data from 2003 to 2009, which represents a total of 11,515 pedestrian-vehicle crashes (Auger, 2011). It is important to note that this number represents crashes before filtering for property-damage-only crashes (i.e. no injuries) or crashes occurring in private or parking lots (see Figure 5). A more explicit discussion of how injury counts were derived from SAAQ crash data is discussed next.

3.1.4 Deriving Injuries from SAAQ Crash Data

As shown in Figure 4, SAAQ crash data is composed of three linked tables, with the central event being the crash table. This table contains several attributes pertaining to the event (e.g. intersection, road condition, location, type, number of users involved, etc.). Connected in a *one-to-many* relationship, there are two additional tables: Vehicle/Driver and the Victims (injuries) tables. The Vehicles/Driver table contains attributes about both the vehicles and drivers involved, such as the type of vehicle involved, its make and weight, the age and gender of the driver. On the other hand, the victims table contains attributes on the victims involved, such as their age, gender, the severity of their outcome, etc.

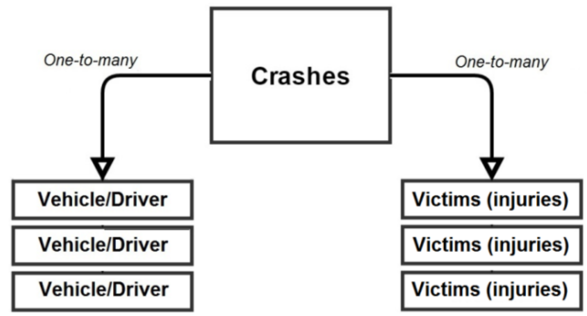

Figure 4: SAAQ Accident Tables

For example, a vehicle crashing and injuring three pedestrians and then hitting another vehicle will record one observation in the crash table, three observations in the Victims (injuries) table and two observations in the Vehicle/Driver table. As such, observations in the sub-tables can have more than one event assigned the same crash. Crashes can be victimless when the pedestrian involved does not report any injuries and if vehicle owners still call upon a police officer to fill-out a police report for insurance purposes. These are referred to as property damage only (or “DMS: Domage matériel seulement” in SAAQ variable coding). A victim is defined as either being slightly, seriously or fatally injured. This implies that crash incidents involving yet not injuring pedestrians were not considered in the regression models in Chapter 4.

3.1.5 Data Preparation and Spatial Joins to the Study Area

The study area was populated using pedestrian injuries (victims) falling within 30 meters of the 191 signalized intersections comprising of the study area. The buffer distance was defined as 30 meters based on the standard used by the Montreal Department of Transport in 2010-11 (DoT Montreal [a], 2011). Figure 5 illustrates the different steps used to derive and merge the disaggregate SAAQ crash data to the study area found in the regression analysis in Chapter 4. These steps started with the initial disaggregate dataset comprising of 11,515 crashes, which initially included property-damage-only and crashes occurring in parking or private lots. The geolocation of crash points were joined to the victim data in order to later perform spatial joins to the study area. This resulted in 10,488 victims or injuries (in association with 9,929 crashes) (see Figure 5). After filtering injuries occurring on private or parking lots, age not reported and children aged 0-15, a total of 9,726 injuries remained, representing 6,830 younger (ages 16-64) and 1,528 older (65+). With these points geolocated and geocoded, a spatial join was performed between the disaggregate SAAQ injuries and the 191 signalized intersections comprising of the study area. Using ArcMap 10.1 this was done using a 30-m *within match option* to aggregate the injury counts using the 'count' *merge rule* (ESRI, 2014).

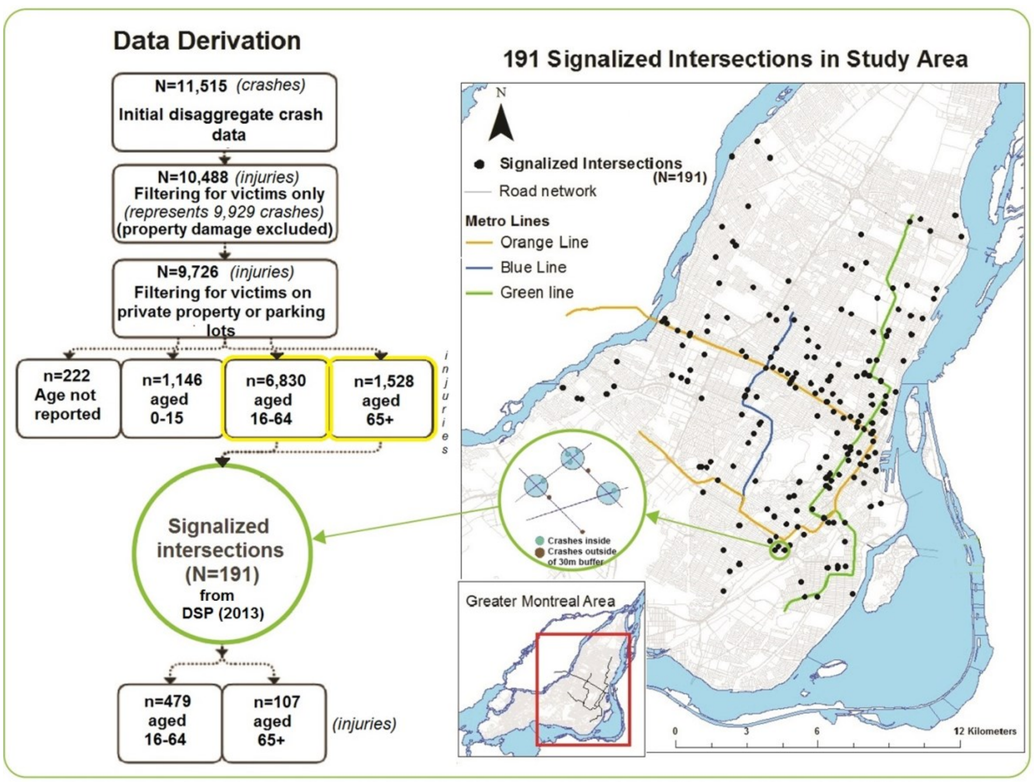

Figure 5: Derivation of Injury Counts That Occurred in the Study area of 191 Signalized Intersections

The result of this operation led to 586 injured pedestrians for which the subpopulation regression models of Chapter 4 were created, namely 479 younger (aged 16-64) and 107 older (65+). In the regression analysis in Chapter 4, age-groups are defined conceptually as the younger and older. Categorically, these age-cohorts represent ages 16 to 64 and 65 and older, respectively. The next section takes a step back to outline the work done to improve the accuracy of the geolocated SAQ crash data. This work was done in 2010-11 during the previously mentioned internship at the Montreal Department of Transport, Safety and Planning Division, the work of which can be found in Auger (2011).

3.1.6 Geocoding and Accuracy Improvement of Crash Points

The accuracy of the geolocation of police reported crash points has been cited as a problem in the literature (Austin, 1995). A procedure was developed in order to improve the accuracy of SAAQ crash data provided to the Montreal Department of Transport at the end of the aforementioned internship. The main focus of this procedure aimed to standardize and clean the location attribute appearing in the SAAQ dataset. The main location attribute used to geolocate and geocode crashes was the Address attribute. This attribute is commonly reported by police officers by using a civic number followed by the street name or, in the case of intersections, two cross-streets. In both these cases common batch processing geolocators and geocoders can assign latitude and longitude coordinates using either of the two formats. However, given that all written information appearing on the original police reports are indiscriminately transcribed into the SAAQ datasets, the address field often times has non conformities preventing a geolocator to properly assign latitude and longitude coordinates. For example, police officers would often add specification notes, such as if the crash occurred on the opposite side of a visible civic address. In such cases, they would denote abbreviations for “opposite” or “facing” (e.g.: “opp” or “face”). As such, a comprehensive cleaning procedure had to be developed to standardize the Address information for geolocation, of which was done using batchgeo (batchgeo, 2015), an online application that uses Google's Application Program Interface (API). Once crashes were assigned geolocation coordinates, they were then geocoded into map points into Geographic Information Systems (GIS). See Auger (2011) for more details.

An additional procedure was developed to improve the accuracy of geolocated crash points using an iterative approach with the use of GIS by querying crash points using the categorical attribute for the borough code. Given that it was unlikely for a police officer to mistaken the borough in which the crash occurred, it was deemed to be an effective validation procedure. In GIS software, crash points were selected using the borough attribute. Those crash points that were in fact not inside the intended borough boundaries was isolated and corrected manually by first searching the proper address in Google Maps and then using the "*what is here*" tool. This tool provides the latitude and longitude coordinates which was then copied and collated manually into the database to correct the geolocation of the crash point. In some rare cases the wrongly geolocated points were caused by missing Address information. In such cases, the original scanned police report was consulted, access of which was possible during my internship. This method was often successful given that police officers would generally complement the location of the crash with the use of a sketch diagram in the section of the police report meant for this, also known as the "croquis"[6]. For more information on the geolocation of crash data, see Auger (2011).

[6] "Croquis" is the French term used on police reports. Translated, it implies a sketch diagram to characterize the crash.

3.2 Origination of Selected Explanatory Variables Modeled in Chapter 4

This section details the methodology and pays particular attention to explanatory variables for which an explicit definition was not provided in Chapter 4, given the word length regulation of the academic journal for which the paper which represents Chapter 4 was submitted to. Other explanatory variables are therefore detailed in the regression analysis study in Chapter 4.

3.2.1 Traffic Sample Counts

Explanatory variables based on traffic seen in the regression analysis of Chapter 4 derive from vehicle and pedestrian traffic sample counts entering an intersection. This data was provided by the city of Montreal, Department of Transport, Traffic Light Division (DoT Montreal [b], 2013). This data comprised of samples that generally ranged from three to seven hours and were collected on a typical weekday from 6:00AM to 8:59AM, from 11:00AM to 12:59PM and from 4:00PM to 17:59PM. These samples were converted into Average Annual Daily Traffic (AADT) for vehicles and Annual Average Daily Pedestrians (AADP) for pedestrian exposure (Miranda-Moreno & Fernandes, 2011). Expansion factors for vehicles (AutoAADT) were obtained from the World Road Association (Association internationale permanente des Congrès de la Route : AIPCR) (AIPCR: Road Safety Manual, 2004). On the other hand, expansion factors for pedestrian exposure (PedAADP) were obtained from Miranda-Moreno & Fernandes (2011).

To obtain AADT, the sample counts for available hours are summed and first divided by the daily and monthly expansion factor and then divided by the sum of expansion factors corresponding to each hour of available sample counts (Equation 5).

AADT = (Sum of sample counts for available hours / month & day exp. fact.) / Sum of hourly exp. factors	Equation 4

Pedestrian sample counts (PedAADP) were expanded to using the following function derived from Miranda-Moreno & Fernandes (2011):

PedAADP = (Sum of sample (ped.) counts X 24 (hrs) / monthly exp. fact + daily exp. fact.) / sum of hourly exp. Fact.	Equation 5

Furthermore, each intersection had a different sample size and varying times for which the data was collected; double entries were also a problem in the dataset cautioned to me by the staff at the Department of Transport. As such, each of the 191 signalized intersections had to be isolated manually in Excel to first remove double entries to then apply the above functions to derive the respective average daily traffic.

3.2.2 Complex (Non-standard) Intersection Geometry

Complex (non-standard) intersection geometry is a variable sparsely covered in past regression based studies. Most past studies in the literature focus on specific intersection geometry, such as horizontal curvature or intersection skew (DoT-FHWA, 2009). Complex or non-standard intersection geometry here is operationalized to include these, but also includes other types such as misaligned or more than four approaches (see Figure 6). This variable was identified in a binary fashion as whether or not the intersection could be identified as complex or not (1/0) according to the created scheme shown in Figure 6. To derive these data for all 191 intersections, a combination of site visits and Google Street View imagery were consulted and, after an empirical assessment, the data (1/0) was coded and entered manually into the dataset.

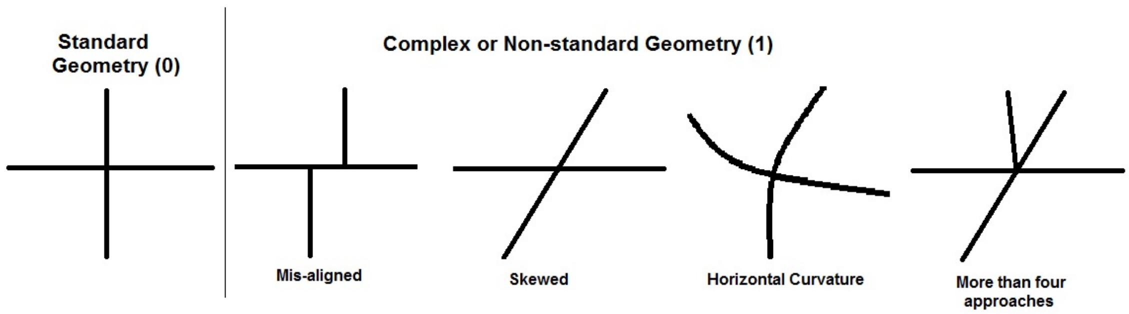

Figure 6: Non-standard (complex) Intersection Geometry Coding Scheme

3.2.3 Pedestrian Crossing Signals (PCS)

A total of 56% (n=107) of the 191 signalized intersections appearing in the study area in Chapter 4 were equipped with a PCS device. PCS characteristics were derived from the Department of Transport, Traffic Light Division (DoT Montreal [b], 2013). These data were collected by consulting their archives in December of 2013 as part of a graduate course assignment. Given that this data was not readily available, the head of department, Ms Vizioli, had arranged to provide me with office space for the duration of a work week in December of 2013 where I manually consulted and photocopied their archival traffic light plans for the study area in Chapter 4. These plans are referred to electronic programing plans (commonly abbreviated to “plans PE” in the French language). The data available on these plans include cycle and phase times and types.

To collect and collate the necessary data in the form of explanatory variables, data such as total cycle time, different phase times and types were entered directly into the dataset comprising of the study area appearing in Chapter 4. This variable was eventually omitted from the version of the regression analysis appearing in Chapter 4 because of uncertainty regarding data reliability. This was primarily motivated by the fact that it was brought to our attention that the city of Montreal underwent a major standardization operation over the past 10 years (also known as “mise aux norms 1 et 2” [MAN1 et MAN 2]) which implies that the data appearing in the electronic programming plans may not reflect the crash period modeled. As such, the data was deemed unreliable for including in the regression models.

3.2.4 Area-wide Data and the Use of Geographic Information Systems

Certain explanatory variables included in the regression analysis in Chapter 4 were on a wider spatial scale than the response variable, sometimes referred to as area wide or zonal variables in the literature. Population and the low income indicator were obtained from Statistics Canada Census Tract Profiles (Statistics Canada, 2010a). Figure 7 provides an illustration of how an intersection was spatially joined to a wider geographic scale for obtaining area-wide data. For the respective population explanatory variables, the in census-tract average within a 500-m of the signalized intersection was the methodology applied. For the low-income indicator the data was derived in two steps. First, a binary variable was created and assigned to each census tract based on whether or not it could be considered having a low-income. This was defined using the 1992 low-income cut-off (LICO) value, namely an income lower than $21,359 (Placeholder2)[7]. Subsequently, a

[7] This could be considered a conservative estimate of low-income given inflation. The year 2006 was used for median income.

spatial query was performed to identify whether or not (1/0) the signalized intersection was touching at least one census tract having a low-income.

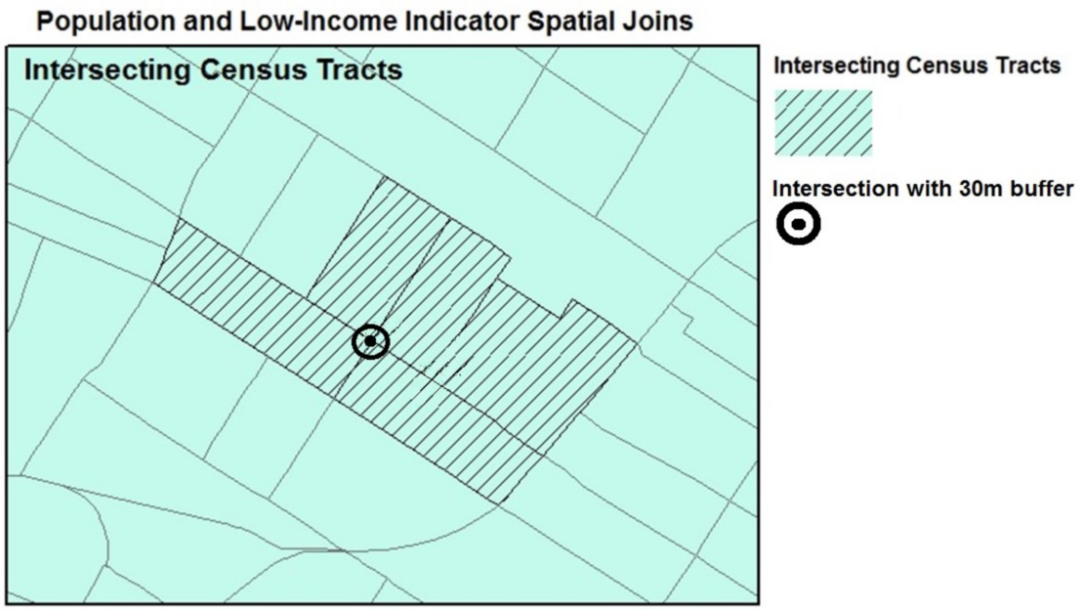

Figure 7: Methodology for Deriving Population, Low-income and Jobs

Before presenting the article (Chapter 4) which consists of the regression analysis study in this thesis, Table 2 shows a recap of research questions, variables, methods and sources.

Table 2: Recap of Thesis Research Questions, Variables, Methodology and Sources

<table>
<tr><th>Research Questions</th><th>Variable</th><th>Variable Type and Method Derived</th><th>Sources</th></tr>
<tr><td rowspan="11">Primary Research Questions
• Are senior pedestrian injuries influenced by different characteristics compared to the younger and to what extent?
Secondary Thesis Research Questions
• Explore the question of defining an optimal built environment for pedestrian safety in an ageing society, and if the optimal model of a younger model differs from the older.
• Determine if subpopulations models are more inclusive?
Secondary Journal Paper Question
• Is there credence to the slow walking speed hypothesis</td><td>Crashes and Injuries</td><td>Dependent Count Variable: From a disaggregate crash to injuries (victims) geocoded in GIS.</td><td>(DoT Montreal [a], 2011); (SAAQ [Unpublished data], 2011)</td></tr>
<tr><td>Intersections</td><td>Spatial Scale of Dependent Variable: Disaggregate injury data joined to the study area (intersections) using GIS.</td><td>(DSP, 2013)</td></tr>
<tr><td>Traffic and pedestrian counts</td><td>Count data samples ranged from 3 to 7 hours were converted to AADT or AADP (continuous).</td><td>(DoT Montreal [b], 2013)</td></tr>
<tr><td>Buses & Metro Stations</td><td>Count: Spatial join of number of bus stops within 50m and 500m for metro stations.</td><td>(STM, 2010)</td></tr>
<tr><td>Population</td><td>Continuous: Average population in census tracts within a 500m buffer ArcMap 10.1.</td><td>(Statistics Canada, 2010a)</td></tr>
<tr><td>Jobs</td><td>Continuous: Total jobs within a 1km buffer.</td><td>(Cloutier, Tremblay, & Morency, 2014); (DSP, 2013) a collaboration between INRS, DSP & CEUM</td></tr>
<tr><td>Low-income</td><td>Binary (1/0): Based on 1992 LICO, whether or not CT is has a 2006 median income of lower than $21,359.</td><td>(Statistics Canada, 2013)</td></tr>
<tr><td>Land-use</td><td>Binary (1/0): If intersection is within or connecting land-use type.</td><td>(Statistics Canada, 2010a) Census Tract Profiles</td></tr>
<tr><td>Pedestrian Crossing Signal</td><td>Cycle & phase time (continuous) & cycle and phase types & the LPI phase (binary).</td><td>(DoT Montreal [b], 2013)</td></tr>
<tr><td>Center median refuge</td><td>Binary: Whether or not the intersection had at least one center median refuge on any of the approaches.</td><td>(DSP, 2013)</td></tr>
</table>

Note: TWO regression models are specified: one for injured pedestrians 16-64 years-old, one for 65+

Chapter 4 A Regression Analysis Study in Montreal, Canada

A subpopulation modelling approach for pedestrian injuries at signalized intersections: Toward an inclusive approach for an ageing society

The following chapter contains the main study regression analysis of this thesis, a version of which submitted and accepted for presentation at the 2015 Transportation Research Board (TRB) conference (paper no. 15-4619). The study applies a subpopulation comparative regression modelling approach of pedestrian injuries that occurred at 191 signalized intersections in Montreal, Canada. The version of the paper appearing in this thesis was revised from the TRB submittal, and significantly shortened to conform to the shorter word length regulations of its intended journal of submission: Journal of Transport & Health. The initial TRB paper was 9200 words while the following paper was shortened to 7500 words. For this article, I was the lead author while Dr Marie-Soleil Cloutier and Dr Patrick Morency were co-authors.

Dr Marie-Soleil Cloutier acted as my primary thesis supervisor while Dr Patrick Morency is a medical doctor and a leading researcher at the provincially mandated Public Health Department (DSP: Direction de la santé publique) that oversees the Montreal region. Both have not only authored or co-authored several Montreal-based studies, but they have also worked on a number of academic-governmental collaborations. The notion of an academic-government collaboration is important for them, but also for myself given that I also worked full-time as a transportation analyst for the duration of this thesis and paper trying to make the link from research results to application in practice. As such I am pleased that this study was also deemed “practice ready” by TRB reviewers (Auger, Cloutier, & Morency, 2015).

A subpopulation modelling approach for pedestrian injuries at signalized intersections: Toward an inclusive approach for an ageing society

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Abstract

The safety of Vulnerable Road Users (VRU), which includes pedestrians, cyclists and two-wheelers, is a subfield research that has been growing in recent years. Older pedestrians are arguably the most sensitive subpopulation of these VRUs if we consider their longstanding overrepresentation in pedestrian injuries and fatalities. Given ageing population and the urbanization of ageing, there is an even greater sense of urgency for planners to be proactive. It is therefore timely for research that seeks to better understand senior pedestrian injury factors and to explore the question of how to define an optimal built environment for safety in an ageing society. Although the VRU safety literature has grown to abundant levels in recent years, most studies have specified predictive regression models that confound all age-groups. In this paper we propose a subpopulation approach and focus on specifying two regression models to compare 479 younger and 107 older pedestrian injuries that occurred at 191 signalized intersections in Montreal, Canada. For injury predictors that were common in both age-groups, results show that older adults were on average 150% more likely to be injured compared to the younger. Among other findings, the center median refuge was found to have the potential to reduce the likelihood of injury by 70% for senior pedestrians. Results suggest that the optimal built environment for older pedestrian safety may indeed differ from one that is optimal for younger pedestrians. This finding and others in the paper suggest that a subpopulation modelling approach may provide planners with a better understanding of pedestrian injury factors allowing them to select more inclusive countermeasures.

Key words: pedestrians, injury risk, seniors, built environment, negative binomial, center median refuge.

4.1 Introduction

Although road injuries have declined since the 1970's in countries that are members of the Organization for Economic Cooperation and Development (OECD) (IRTAD, 2009), North-America is still poorly ranked according to Transport Canada (Transport Canada, 2011). Meanwhile, seniors arguably make up the most vulnerable subpopulation given their longstanding overrepresentation in pedestrian injuries and fatalities (Oxley, Charlton, Corben, & Fildes, 2006); (Fontaine & Gourlet, 1997). Ageing population has researchers and planners increasingly concerned as they still do not know how direct or indirect measures of exposure will affect this overrepresentation (SWOV, 2002). This concern for older adult safety has thus prompted some planners to focus building safety models on seniors, as captured in the text of Bernard Isaacs: "Design for the young and you exclude the old – but if you design for the old you include the young." (ALGA, 2010, p. 1)". While several descriptive and empirically oriented health studies have looked at seniors, fewer have proposed a comprehensive approach for include both younger and older. In this paper we propose a subpopulation regression modelling of pedestrian injuries at signalized intersections and seek to better understand injury factors of the younger and the older.

4.1.1 Urban road intersections and pedestrian safety: A localized problem

Ageing North-American population and the tendency for urban living with old age are important sources of concern for planners and researchers, as it will likely translate into a greater number of seniors living in urban areas and walking through intersections (CMHC, 2015); (Mirkin & Weinberger, 2000). In urban areas, senior pedestrian injuries are more often localized at intersections than other pedestrians (Siram, Sonaike, Bolorunduro, Greene, Gerald, Chang, Cornwell & Oyetunji (2010). In fact, a query of older pedestrian injury involvement (aged 65+) in Montreal, Canada between 2003 and 2009 shows that 85% occurred within 30 meters of an intersection (SAAQ [Unpublished data], 2011). For overall pedestrians this figure is 60% (Cloutier, Tremblay, & Morency, 2014). One must ask why senior pedestrians are overrepresented in injuries or fatalities and why more so at intersections? On one hand, some have suggested that older adult pedestrians risk can largely be explained by the existence of a link between “risky street crossing decisions” due to their diminished cognitive abilities (Dommes & Cavallo, 2011, p. 293); (Oxley et al. (2006)). On the other hand, we may postulate on the existence of an association between the slower walking speed of seniors and their injury risk (Asher, Aresu, Falashetti, & Mindelli, 2012) (Romero-Ortuno, Cogan, Cunningham, & Kenny, 2010). Dunbar (2012) refers to this phenomenon as the ‘slow walking speed hypothesis’. In the context of crash or injury analysis, this begs the question whether or not seniors are more sensitive to what may be operationalized as “crossing characteristics” at intersections, namely attributes that are associated with crossing at intersections?

4.2 Research questions

While several descriptive or empirically based studies have dealt with senior pedestrian safety in the context of road crossing (Asher, Aresu, Falashetti, & Mindelli, 2012), the built environment (ALGA, 2010) or perception of walkability (Michael, Green, & Farquhar, 2006), fewer have inferentially measured actual senior injury likelihood in a comparative fashion to the younger (Ward et al. (1994); (Dunbar, 2012); (Lee & Abdel-Aty, 2005). In attempt to fill this void while seeking to bridge a disciplinary gap, this paper specifies subpopulation regression models for older and younger injury incidence at signalized intersections. A focus on built environment attributes is underlined, yet other common variable categories are also measured in association with injury incidence, such as traffic, transit, land-use and population.

In exploring the definition of a built environment that is optimal and more inclusive for an ageing society, we seek to determine if and to what extend injury factors in the older differ to those of the younger and how this can translate into prevention opportunities or potential countermeasures that can be applied by planners.

4.3 Vulnerable road user (VRU) safety and prevention

Vulnerable Road User (VRU) safety, which is the focus on the safety of active road users such as pedestrians and cyclists, is intricately linked to sustainable and active transport. Namely, VRU safety contains an intrinsic link to global awareness culture that seeks to improve public health and reduce green-house gas emissions (Environment Canada, 2012). Gehl (2013) refers to this culture as "green mobility" (p. 7). VRU safety is especially important in North-America given that policy and the built environment could be improve to accommodate for pedestrians and cyclists, particularly compared to Europe (Pucher & Dijkstra, 2000). For example, in selected European countries the risk of being fatally injured for pedestrians and cyclists compared to car occupants is nine and seven times greater, respectively. On the other hand, in the United States pedestrians and cyclists are 23 and 12 times more at risk compared to car occupants, respectively (Pucher & Dijkstra, 2000). Furthermore, researchers and planners are increasingly investing significant resources VRU safety and in encouraging active transport, which should inevitably result in greater numbers of active road users.

However, prominent epidemiologist Geoffrey Rose has coined the term "prevention paradox" in a paper entitled "The Strategy of Preventive Medicine", which has been presented as a nuance to strictly focusing on a subpopulation approach. The prevention paradox contends that a focus on vulnerable minorities may overlook the opportunity for "preventive medicine", thereby presenting a nuance to the subpopulation analysis such as VRU modelling. However, Geoffrey Rose has not been without critique (Charlton, 1995). Rather, it is not known to what extent the prevention paradox applies to road safety research. Although seniors make up a minority of the population, they constitute a significant proportion of those fatally injured (Siram, et al., 2010).

4.3.1 Built environment characteristics influencing pedestrian crashes

Figure 1 below illustrates variables (injury factors) while Table 1 presents their associated relationship found in past pedestrian crash analysis studies. As shown, variables such as traffic and road geometry have a more direct influence on injuries while population and job density have an indirect influence, because their affect is on exposure rather (Miranda-Moreno et al. (2011)). It should also be noted that some hypotheses were formulated with the intention of validating certain results shown from past overall pedestrian studies and whether or not they still apply to seniors.

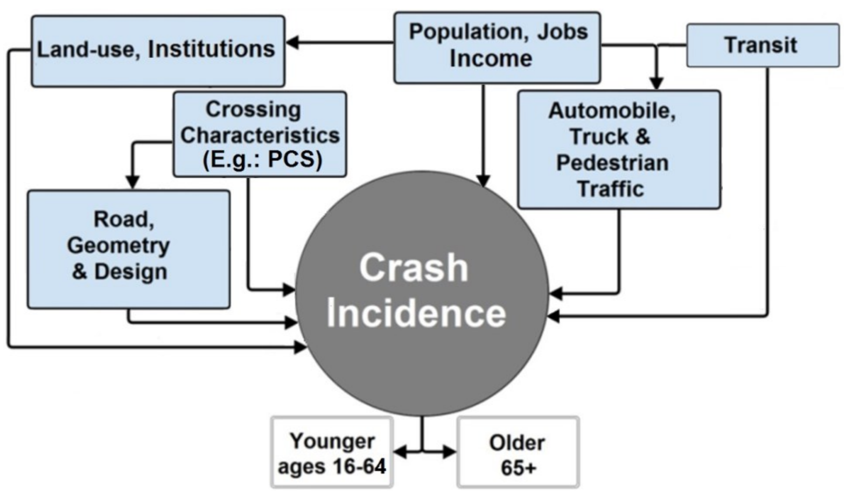

Figure 8: Variable Categories and Link to Pedestrian Injury Incidence

Source: Adapted from Auger, Cloutier, & Morency (2015)

Table 3: Variables influencing pedestrian injury risk based on the literature

Variable Category	Variable	Found Relationship in Past Studies for Overall Injuries or Conflicts	Sources
Traffic & Transit	Auto AADT	+ Automobiles + Injuries (Positive)	(Lee & Abdel-Aty, 2005); (Pulugurtha & Sambhara, 2011); Miranda-Moreno et al. (2011);
	Pedestrian volume (AADP)	+ Exposure + Injuries (Positive)	(SWOV, 2002); (Pratt, Bonneson, & Songchitruksa, 2013)
	Truck AADT	+ Trucks + Injuries (Positive)	(Sze & Wong, 2007)
	Number of bus stops	+ Transit stops + Injuries (Positive)	(Ukkusuri, Miranda-Moreno, Ramadurai, & Isa-Tavarez, 2012)
	Metro stations in area	+ Transit stops + Injuries (Positive)	(Ukkusuri, Miranda-Moreno, Ramadurai, & Isa-Tavarez, 2012)
Population, Jobs, Income & Land-use	Population 16 to 64	+ Population + Injuries (Positive)	(Pulugurtha & Sambhara, 2011); Ukkusuri et al. (2012); (LaScala, Gruenewald, & Johnson, 2004); (Miranda-Moreno, Morency, & El-Geneidy, 2011)
	Population aged 65+	+ Population + Injuries (Positive)	
	Jobs	+ Employment in area + injury (Positive)	
	Low income indicator	If low income + Injuries (Positive)	(Morency P. , Gauvin, Plante, Fournier, & Morency, 2012)
	Commercial land-use	If commercial land-use + Injuries (Positive)	(Miranda-Moreno, Morency, & El-Geneidy, 2011); Ukkusuri et al. (2012)
	Industrial Land-use	+ If industrial land-use + Injuries (Positive)	(Hadayeghi, Shalaby, & Bhagwant, 2010) (Ukkusuri et al. (2012)).
Road, Geometry & Crossing Characteristics	Center median refuge	If center median refuge - Injuries (Negative)	Cloutier et al. (2014); Li, Yang and Yin (2010); (Abdel-Aty & Radwan, 2000)
	Skewed intersection geometry	If intersection skew + Injuries (Positive)	(Oxley et al. (2006)); (DoT-FHWA)
	Pedestrian crossing signals (PCS)	If present - Observed crashes (Negative)	(Huitema, Houten, & Manal, 2014)
	Leading Pedestrian Interval (LPI)	+ If LPI - Observed conflicts (Negative)	Van Houten et al. (2001); Fayish & Gross (2010)

4.3.2 Traffic and transit

Average Annual Daily Traffic (AADT) and pedestrian volume (AADP) are generally used as exposure predictors in past studies. Both these variables have showed a positive effect on injuries

(Lee & Abdel-Aty, 2005); (Torbic, Douglas, Bokenkroger, Srinivasan, Carter, Zegeer, Lyon (2010)); (Pulugurtha & Sambhara, 2011); Miranda-Moreno et al. (2011); (Pratt, Bonneson, & Songchitruksa, 2013). However, the effect of senior pedestrian exposure on their own risk is still unknown (SWOV, 2002). In addition, metro stations (Ukkusuri, Miranda-Moreno, Ramadurai, & Isa-Tavarez, 2012) and number of bus stops nearby have also showed a positive relationship to pedestrian crashes (Torbic et al. (2010)); (Pulugurtha & Sambhara, 2011). The presence of bus stops is of concern for researchers given that a combination of walking and transit is common in active ageing lifestyle, especially when seniors can no longer drive (Statistics Canada, 2012); (Michael et al. (2006)).

4.3.3 Population, jobs, income and land-use

Population and employment have been identified as important injury predictors (Pulugurtha & Sambhara, 2011); Ukkusuri et al. (2012); (Cloutier et al. (2014); (LaScala, Gruenewald, & Johnson, 2004), although it can be considered to be mediated by exposure (Miranda-Moreno et al. (2011)). Some studies have used population and jobs as an indirect measure of exposure when pedestrian volumes were unavailable (Ukkusuri et al. (2012); (Cloutier et al. (2014)).

As part of the built environment, commercial areas increase the attractiveness and contribute to the exposure and traffic of an area. Miranda-Moreno et al. (2011) found a positive relationship for commercial indicators with an elasticity of 15%, while Ukkusuri et al. (2012) found an elasticity of 7% for commercial land-use. As such, industrial land-use has also been identified in some past studies to increase pedestrian crashes (Hadayeghi, Shalaby, & Bhagwant, 2010) (Ukkusuri et al. (2012)).

4.3.4 Road geometry and crossing characteristics

Road geometry and crossing characteristics vary in type and definition among past studies. Lane-width and number of lanes have been reported as having a positive influence of crash frequency. For example, Ukkusuri et al. (2012) showed that the effect size increased with each lane, while Miranda-Moreno et al. (2011) found that arterial roads (usually wider and with more lanes) have a double negative effect on overall pedestrian safety. On the other hand, descriptive studies comparing younger and older pedestrian crash frequency showed that senior pedestrian injuries tend to happen on more varied types of roads in contrast to the younger, occurring mostly on main arteries (Ward, Cave, Morrison, Allsop, Evans, Kuiper, Willumsen (1994)).

Complex or non-standard geometry intersections, such as skew, could create complexity and therefore a greater source of confusion for senior pedestrians (Oxley et al. (2006)). Although their effect has not been well documented for senior injuries, skewed intersections are a known source of injury for the overall pedestrian population (DoT-FHWA).

Crossing characteristics mostly include Pedestrian Crossing Signal (PCS) attributes but some geometric features that facilitate crossing, such as the center median refuge, can be considered a crossing aid. Li, Yang and Yin (2010) observed a 31% reduction in conflicts at 45 signalized intersections in Beijing after the implementation of a center median refuge. Abdel-Aty and Radwan (2000) found a negative relationship (β=-0.024) between all crash types and median width in meters leading to an elasticity of -0.12. However, Pratt, Bonneson & Songchitruksa (2013) found a positive association between median width and pedestrian-vehicle conflicts.

Although sparsely available, studies measuring the effect of PCS characteristics generally show positive benefits on road safety. For example, after implementing a pedestrian countdown timer at 362 sites in Detroit, Michigan a one-third reduction in injuries from the pre-intervention levels was found (Huitema, Houten, & Manal, 2014). Similarly, in a before-and-after study, Pulugurtha & Pulugurtha (2011) provide evidence of a significant effect in the reduction of all collision types, yet a non-significant effect in reducing pedestrian injuries, after installing a PCS device at 106 intersections. Finally, the Leading Pedestrian Interval (LPI) is a type of PCS that is sparsely covered in crash frequency regression based literature. The objective of a LPI is to provide a *lead* start for pedestrians allowing them cross all or part of the crosswalk before automobile turning or crossing is permitted. Photo 1 illustrates the combination of the pedestrian crossing phase (WALK) and the green thru arrow, later changing to a full green after 3-10 seconds. Although the LPI with thru arrow is distinct to the city of Montreal, it is similar in concept to the LPI found in New York City with the clearing phase that overlaps on the green ball (King, 2000). Van Houten et al. (2001) found that the LPI phase reduced observed pedestrian-vehicle conflicts by 97% in non-seniors and 89% in seniors. Similarly, Fayish & Gross (2010) showed that injury occurrence can be reduced by 23%.

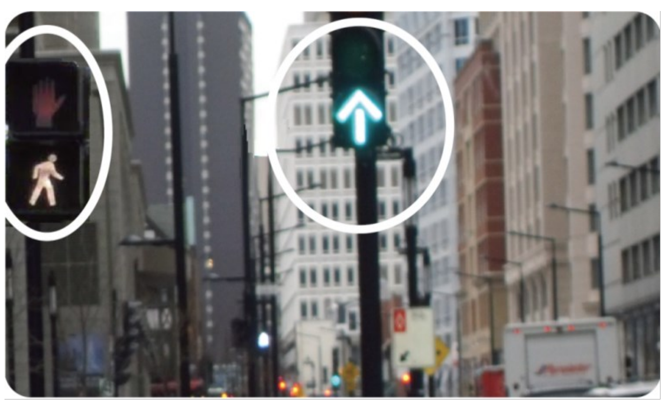

Photo 1: Example of a Leading Pedestrian Interval (LPI) with Thru Arrow (Montreal, Canada)

4.4 Methodology

4.4.1 Study area

The city of Montreal is the second largest in Canada with a metropolitan agglomeration population of 3.82 million and an urban agglomeration (Island) population of 1.64 million in 2011 (Statistics Canada, 2011). The study area includes 191 signalized intersections from central neighborhoods in the Island of Montreal (see Figure 9) that were selected from 512 intersections on a previous collaboration between the Montreal Department of Public Health (DSP, 2013) and the National Institute for Scientific Research (NRSR/INRS) (Cloutier et al. (2014)); (Tremblay, 2012), hereon to be referred to as the DSP (2013) collaboration. The original 512 intersections were derived by using a random sample of intersections in central Montreal boroughs stratified according to intersection types based on the six possible combinations of connecting road types: Arterial/Arterial, Collector/Collector, Arterial/Collector, Collector/Local, Arterial/Local and Local/Local. Signalized intersections were maintained in this study because we only had traffic and pedestrian sample counts for these intersections. After maintaining only signalized intersections, the original stratified composition is naturally skewed towards intersections that have major roads such as arterial and collector types. In fact, 97% of intersections in the study area had at least either one arterial or one collector road type connecting.

4.4.2 Pedestrian injury and crash data (dependent variables)

This paper specifies models based on pedestrian injury data, which includes all crash severities. This dataset includes all pedestrian crashes between 2003 and 2009 derived from police reports on the Island of Montreal, provided by the city of Montreal (DoT Montreal [a], 2011). Intersection characteristics were associated to each crash location within a 30-meter buffer zone, resulting in 479 younger and 107 older injuries used for the dependent variable in models. All mapping, spatial analysis and table joins for deriving predictor variables were done using a licensed version of ArcMap 10.1 (ESRI, 2014).

Figure 2 illustrates the study area and spatial distribution of crash locations according to the two specified subpopulation groups in this paper: younger (16-64 years-old) and older (65 year-old and older). This kernel density map illustrates differences in the spatial pattern for the two age-groups: the younger map (left) appears to have more pronounced hot-spots in the southern section of the downtown area, along a major metro line and downtown arterial roads, of which is major employment hub. The more spread-out spatial distribution for seniors (right) may suggest that they do not have the same mobility, as well as their injuries may be influenced by different factors.

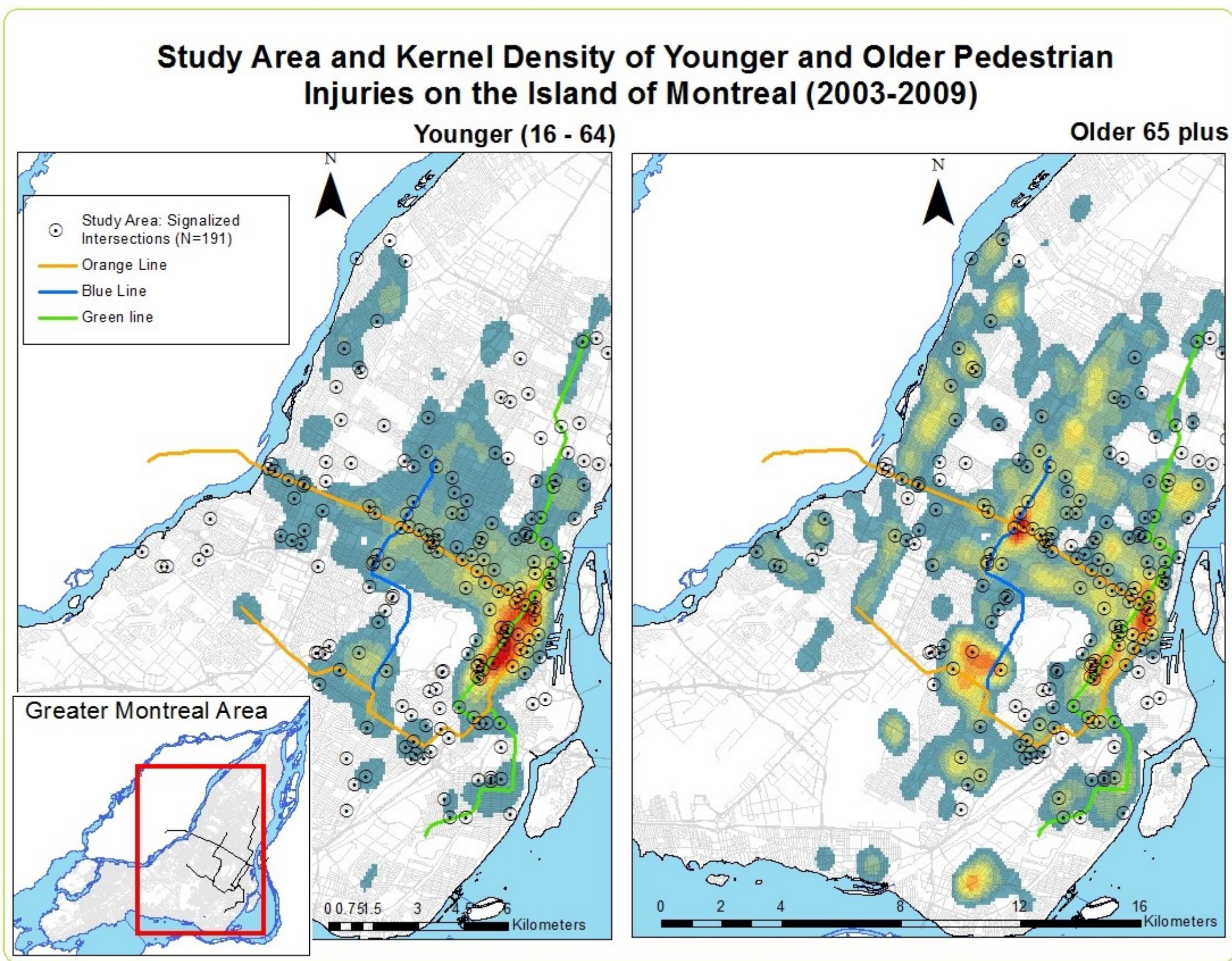

Figure 9: Intersections Surveyed and Younger and Older Crash Locations Kernel Density

4.5 Predictor variables

4.5.1 Traffic & transit

Automobile, pedestrian and Truck sample counts were provided by the city of Montreal and were expanded into AADT based on AIPCR expansion factors and methodology (AIPCR: Road Safety Manual, 2004). On the other hand, pedestrian sample counts were expanded to AADP (PedAADP) using factors provided by Miranda-Moreno & Fernandes (2011). Transit data were provided by the local transit agency in the form of geolocated point data for metro station and bus stops (STM, 2010). This variable was coded for each intersection as either having or not (1/0) a metro station within 500m and a bus stop within 50m of the signalized intersection. A distance of 50 m was used to account for an offset in the geolocation of points given that they represented the signage posts for the beginning of the bus zone rather than the actual bus-stop.

4.5.2 Population, jobs and income

Population for both younger (16-64) and older (65+) was derived by averaging the total census tracts 2006 population within a 500m buffer of the signalized intersection (Statistics Canada). The number of jobs was derived using a similar methodology, but in this case, a 1 km buffer distance was used (see Cloutier et al. (2014) for more methodological details).

4.5.3 Land-use and area-wide indicators

Industrial and commercial land-use data, provided by the city of Montreal (DoT Montreal [a], 2011), were coded into binary variables according to whether or not (1/0) the signalized intersection was within these land-use types. Similarly, each intersection was coded as 1 when they were located in a low-income census tract, according to the median low income cut-off (LICO) value of $21,359 (Statistics Canada, 2013).

Commercial arteries, provided by the city of Montreal, consisted of road segments primarily concentrated with commercial activity buildings and represent a proxy for higher vehicle and pedestrian activity. The derived variable introduced in our model is based on the number of commercial arteries within the 30-meter intersection buffer zone.

4.5.4 Road, Design, Geometry and Crossing Characteristics

Complex (or non-standard) intersection geometry is defined by skew, horizontal curvature, more than four approaches or misalignment in intersection segment approaches. Complex or non-standard intersection geometry was operationalized in a similar fashion as past empirical studies (Oxley et al. (2006). This variable was identified as whether or not (1/0) the intersection could be identified as complex according to the scheme shown in Figure 3.

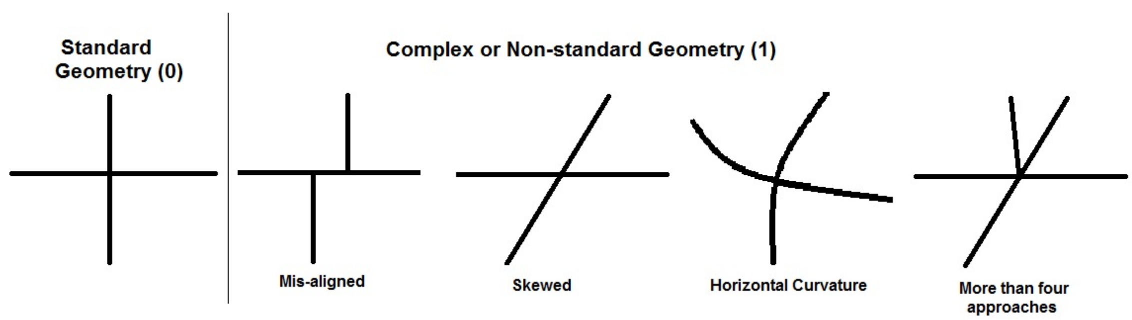

Figure 10: Non-standard (complex) Intersection Geometry Coding Scheme

The center median refuge could be considered both a geometric and a crossing characteristic and was defined as either present or not (1/0) for each intersection. This data derived from a field inventory done by past graduate students (DSP, 2013); (Tremblay, 2012).

4.6 Negative-Binomial Modelling Framework

The Negative Binomial (NB) is used when the injury data is overdispersed. Contrary to the Poisson model, it does not hold the mean and the variance constant (Posh & Mannering, 1996). The NB model is rewritten as follows:

$$\boldsymbol{\lambda}_i = EXP\ (\beta X_i + \ \varepsilon_i)$$

Equation 6

where $EXP\ (\varepsilon_i)$ is the gamma-distributed error term with mean 1 and variance α^2 (Washington, Karlaftis, & Mannering, 2011). The NB probability distribution is written as follows:

$$P(X = x\,) = \binom{x-1}{r-1}\, p^r(1-p)^{x-r}$$

Equation 7

where X is the random variable in the model, x is the number of injuries, r is the number of intersections. Statistical regression modelling was done with open source software R-Studio (RStudio, 2012).

A correlation matrix was specified in order to evaluate potential multicolinearity in models due to high correlation between predictors. Results showed fairly low correlation coefficients for every variable, with the exception of a large correlation between job density and AADP (r=0.66, p<0.01). A validation model for the younger (Table 3), which was specified for the purpose of validating results when including overall pedestrian exposure (AADP). Two *comparable* models were then computed (Table 4), one model for the younger (model Y1) and one for the older (model O1). In this model comparison overall pedestrian exposure was intentionally replaced by respective age-group population in order to compare and report relative incidence between both sub-populations.

Akaiki Information Criterion (AIC) was calculated to verify performance while model calibration was done using a stepwise backwards approach.

Although some past studies have specified a formal 'relative risk factor' when comparing populations, here we opted for a Relative Incidence percent-change (RI %Δ) instead, given that a direct exposure measure was unavailable. RI %Δ is calculated as follows:

$$(\beta^2 - \beta^1)/\beta^1 \; * 100$$

Equation 8

where the difference between β2 and β1 is the difference between the older and the younger coefficients. Readers will find that results are interpreted in percentages. Elasticity was used in combination with Incidence Rate Ration percent-change (IRR %Δ). IRR %Δ is more intuitive than to interpret and is derived using the following function.

$$(e^{\beta} - 1)/1 \; * 100$$

Equation 9

Elasticity was deemed appropriate for interpretative purposes given the very small units of certain continuous variables such as AADT, jobs and population.

4.7 Results

Table 2 provides the mean, Standard Deviation (SD), Minimum (Min.) and Maximum (Max.) of variables modeled including some that were tested yet omitted from final models because of non-significance. Both groups had a similar proportion of intersections with at least one injury: 19% for the younger and 16% for the older. However, the older had a greater proportion of intersections without any injury (68%) which reflects the smaller proportion of their age-group.

Table 4: Summary Statistics of Variables

Variable	Mean	SD	Min.	Max.	Yes	No
Younger injured pedestrians (n=479)	**2.5**	**2.8**	**0**	**15**		
Older injured pedestrians (n=107)	**0.56**	**0.9**	**0**	**4**		
Automobile AADT	24837	15511	0	84141		
Pedestrian AADT	4758	8187	0	65331		
Turning Truck AADT	204	240	0	1631		
No. of bus stops within a 50-m buffer	2.4	1.6	0	7		
No. of metro Stations within a 500-m buffer	0.7	1	0	4		
Avg. pop. aged 15-64 within a 500-m buffer	2110.6	6308	1159	27900		
Avg. pop. aged 65+ within a 500-m buffer	483.2	302.1	0	2102		
Number of jobs within a 1 km buffer	16318.8	26979.7	788	141129		
Commercial land-use (yes/no)					53 (28%)	138
Industrial Land-use (yes/no)					14 (7%)	177
School within 500-m buffer (yes/no)					18 (9%)	173
Low Income Indicator (LICO) (yes/non)					101 (53%)	90
Number of Commercial Arteries at the Intersection	0.7	1.1	0	5		
Center Median Refuge (yes/no)					20 (10%)	171
Non-standard or complex Intersection Geometry (yes/no)					43 (23%)	148
Pedestrian Crossing Signal (yes/no)					107 (56%)	84
Leading Pedestrian Interval With Thru Arrow) (yes/no)					19 (10%)	172

4.8 Comparison of the two models

Comparable model output results can be seen in Table 4. Eight variables were significant in the younger and seven in the older. The presence of commercial land-use, metro and bus stops nearby, as well as automobile AADT are positively associated to the number of injured pedestrians, regardless of the age group, but the older model having higher elasticity for all these variables. Not surprisingly, population sub-groups (proxy for pedestrian exposure) are significant in each model, the older having the highest elasticity. Some variables are significant in only one model. For the younger model, these are job density, the presence of low-income in the census tract and complex intersection geometry. For the older model, these are the presence of a center median refuge at the intersection and commercial arteries nearby.

Table 5: Validation Model Using the Younger Population With Exposure (PedAADP)

Younger Validation Model					
Variable	**Coef**	**IRR**	**Elas**	**s.e.**	***p***
AutoAADT x1000	0.013	1.013	0.33	0.00	0.00
PedAADP x1000	**0.03**	**1.029**	**0.14**	**0.01**	**0.00**
Turning truck AADT					
No. bus stops 50m buffer	0.23	1.26	0.55	0.04	0.00
No. of Metro stations within a 500m buffer	0.15	1.16	0.11	0.06	0.02
Avg. pop. aged 15-64 within a 500-m buffer	0.16	1.16	0.33	0.06	0.01
Avg. pop. aged 65+ within a 500-m buffer					
Jobs 1km buffer x1000	0.01	1.01	0.10	0.00	0.03
Low Income Indicator (LICO)	0.25	1.29		0.13	0.05
Commercial land-use	0.55	1.74		0.13	0.00
Center median refuge					
Complex intersection geometry	0.27	1.30		0.15	0.07
AIC			702.5		
McFadden R^2			0.15		

Coef. = Coefficient (estimate);
Elas = Elasticity;
s.e.; Standard error;
p: significance level;
IRR: The coefficient is raised to the base e^{β};
x1000: Coefficient is in one thousandths (must divide by 1000 for actual coefficient)

Table 6: Comparable Models: Younger (Y2) and Older Models (O1)

Comparable Models	Younger (model Y1)					Older (model O1)						
Variable	**Coef. (*β*)**	**IRR**	**Elas.**	**s.e.**	***p***	**Coef. (*β*)**	**EXP (*β*)**	**Elas.**	**s.e.**	***p***	**95% CI Lower**	**95% CI Upper**
AutoAADT x1000	0.01	1.01	0.36	0.00	0.00	0.02	1.02	0.39	0.00	0.02	-0.0020 (20844.8)	0.029 (25448.7)
PedAADP x1000												
No. bus stops 50m buffer	0.26	1.29	0.55	0.04	0.00	0.30	1.35	0.72	0.07	0.00	0.170 (2.14)	0.434 (2.59)
No. of Metro stations within a 500m buffer	0.16	1.17	0.11	0.07	0.03	0.30	1.35	0.20	0.11	0.00	0.087 (0.58)	0.507 (0.85)
Avg. pop. aged 15-64 within a 500-m buffer	0.14	1.14	0.29	0.06	0.03							
Avg. pop. aged 65+ within a 500-m buffer						0.001	1.001	0.48	0.00	0.03	0.000083 (440.4)	0.001878 (526.1)
Jobs 1km buffer x1000	0.010	1.00	0.21	0.00	0.00							
Low Income Indicator (LICO)	0.3	1.35		0.14	0.03							
Commercial land-use	0.66	1.93		0.14	0.00	0.73	2.08		0.23	0.00	0.286 (0.21)	1.176 (0.34)
Commercial arteries within 30m						0.17	1.19	0.12	0.10	0.09	-0.028 (0.59)	0.374 (0.89)
Center median refuge						-1.95	0.30		0.52	0.02	-2.317 (0.06)	-0.238 (0.15)
Complex intersection geometry	0.37	1.45		0.15	0.02							
AIC	712					350.2						
McFadden R^2	0.132					0.14						

CI: Lower and upper confidence intervals. The number in brackets represents the CI in the variables' actual units.

Comparison between the younger and older for the commercial land-use variable showed that seniors were two times more likely to be injured when the intersection was in a commercial land-use zone. Transit characteristics were significant injury predictors ($p<0.05$) showing that a doubling of the number of bus stops would increase the expected injury probability by 72% for the older and 55% for the younger. Similarly, a doubling in the metro stations within a 500-m buffer would increase the injury probability by 21% for older pedestrians and 11% in the younger. Automobile traffic predictors, although significant, had a lower than expected effect on injury risk, with an elasticity of 0.39 for the older model and 0.36 for the younger. Based on the indirect measure of exposure (population proxy), results show that a doubling of population density would increase injury probability by 29% in the younger and 48% in the older.

4.9 Discussions and conclusions

The primary objective of this paper was to evaluate senior pedestrian injury factors surrounding signalized intersections using Montreal, Canada, as a case study and to determine if they differed from the younger and to what extent. Three additional research questions were tangentially addressed:

i. To determine if it is possible to explore defining an optimally safe built environment of an older society,
ii. if a subpopulation modelling approach is more inclusive, and
iii. if model results give credence to the slow walking speed hypothesis.

4.10 Key findings and implications

Table 5 below shows a summary of findings in both the younger (left) and older (right). The subpopulation approach not only suggested that a built environment optimized for older pedestrian safety may indeed differ from one optimized for the younger, but that optimizing for the older appears to be a more inclusive approach. This is evidenced by the higher probability in injury factors in senior models compared to the younger, including those that were not significant in the younger at all (center median refuge and commercial arteries).

Most importantly, the center median refuge showed to be significant in reducing the probability of injury involvement by 60% in seniors. This variable was however not statistically significant in the younger. Given that pedestrians could ‘refuge’ themselves on the center median refuge, this variable could also be considered a crossing characteristic, giving credence to the slow walking speed hypothesis. This finding suggests that the center median refuge is a strong built environment countermeasure for an ageing society.

Table 7: Findings in the Younger and Older by Variable

Variables ($\chi 1,\ \chi 2 \ldots\ \chi^{i}$)	Findings in the Younger	Findings in the Older	RI %Δ
Auto AADT	• A doubling of *x* would increase the expected injury incidence by **36%**	• A doubling of *x* would increase the expected injury incidence by **48%**	8%
Pedestrian AADP	• A doubling of *x* would increases the expected injury incidence by **14%** *		
No. of bus stops in a 50 m buffer	• A doubling of *x* would increase the expected injury incidence by **55%**	• A doubling of *x* would increase the expected injury incidence by **72%**	31%
No. of Metro stations within a 500m buffer	• A doubling of *x* would increase the expected injury incidence by **11%**	• A doubling of *x* would increase the expected injury incidence by **21%**	91%
Avg. pop. aged 15-64 within a 500-m buffer	• A doubling of *x* would increase the expected injury incidence by **29%**		
Avg. pop. aged 65+ within a 500-m buffer	N/A	• A doubling of *x* would increase the expected injury incidence by **48%****	66%
Total Jobs	• A doubling of number of *x* would increase the expected injury incidence by **21%**		
Low income indicator	• In the presence of *x*, the expected injury incidence would increase **35%**		
Commercial land-use	• In the presence of a *x*, the expected injury incidence would increase by **93%**	• In the presence of *x*, the expected injury incidence would increase by **108%**	16%
Number of commercial arteries within 500m		• A doubling of *x* would increase the expected injury incidence by **10%**	
Center median refuge		• In the presence of *x*, the expected injury incidence would decrease by **70%** • Potential built environment countermeasure for an ageing society	
Non-standard intersection geometry	• In the presence of *x*, the expected injury incidence would increase by **45%**		
		Average RI %Δ	42%

*Reporting Model Y1

** Reporting the difference from older to younger

Likewise, some variables were significant in the younger but not in the older, namely, non-standard or complex intersection geometry, total jobs and the low-income indicator.

Commercial land-use was important for both seniors and the younger, showing that seniors and the younger were 108% and 93% more likely to be injured when in an area zoned commercial, respectively. This implies that seniors were 32% more likely to be injured compared to the younger when the signalized intersection was in a commercially zoned land-use. This finding, including the fact that commercial arteries was only significant in the older model, implies that planners and practitioners may wish to pay special attention to commercial areas when seeking to optimize the built environment for an ageing society.

4.10.1 Exposure as a Potential Key Factor: Seniors in Numbers?

In the introduction of this paper it was established that concern for senior pedestrian safety is largely premised in the assumption of a potential positive relationship with exposure given an expected increase in ageing population, among other factors mentioned. Given that "safety in numbers" is a phenomenon that nuances this, it therefore must be discussed. Indeed, some studies have showed evidence to support safety in numbers (Feng Wei & Lovegrove, 2012) (Miranda-Moreno et al. (2011)). However, some cautionary notes were also presented to nuance safety in numbers. For instance, Elvik et al. (2009) stated that: "…the precise behavioral mechanisms leading to this relationship are not very well known." (pp. 58-59). Further, safety in numbers does not necessarily imply less injury and fatality incidence, but only that risk is reduced relative to traffic and/or exposure. As such, from a health perspective practitioners have an opportunity to intervene and lower injuries. Most importantly, however, we must remember that the effect of exposure for seniors is still unknown (SWOV, 2002). As such, we cannot say with certainty that safety in numbers is true for seniors, a so to speak "seniors in numbers" phenomenon.

4.10.2 Vulnerable road user safety and prevention: A question of inclusivity

Findings in this paper both nuanced and supported the prevention paradox. Namely, both similarities and differences were found when comparing the older and younger models. For similarities, the older tended to be more vulnerable for *comparable* injury predictors, (Auto AADT, Number of bus stops and Commercial land-use) (see Table 4). Based on the average relative incidence percent-change (RI%Δ), seniors were 46% more likely to be injured relative to the younger.[8] Further, the confounded younger and older validation model (Table 3) that was specified, which included overall pedestrian exposure (Ped AADP) as a variable, showed similar results to past overall pedestrian injury studies. Results showed that younger injury predictors mirrored those of the confounded models and that overall pedestrian exposure was indeed significant. This finding suggests that younger (majority) injury factors over-dominant the older (minority), thereby presenting a potential nuance to the prevention paradox. On the other hand, findings support the prevention paradox insofar as the choice to include both subpopulations, rather than only seniors, showed nuances in the younger and older. Implicitly, had we focus solely on a senior model results would not have showed that the younger face a safety injustice based on low-income. This finding not only shows the importance of subpopulation modelling,

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[8] Comparable injury variables are those in Table 5 that show a percentage in the RI%Δ column. 46% is the average RI%Δ for variables appearing in this column: Auto AADT, Number of bus stops and Commercial land-use.

but that practitioners must not neglect low-income and the younger in their search for improving safety in an ageing society.

However, the overwhelming majority of variables showed that seniors were indeed more vulnerable. Given that there is a high probability that seniors will succumb to their injuries (Siram, et al., 2010), findings in this paper give credence to the need for a greater focus on this more vulnerable subpopulation. Implicitly, the benefit is not only for seniors but also for the younger because younger injury factors were also captured in the older model, making decision making based on the older model more inclusive and safer. On the other hand, implications of findings suggest that we would not have understood the extent of seniors safety needs without having specified subpopulation models. For example, the protective effect (negative sign) of the center median refuge, albeit more beneficial for seniors, is a more inclusive built environment countermeasure. Further, given that the center median refuge is a variable that doubles as a crossing and a geometric characteristic, its significance in the older model gives credence to the slow walking speed hypothesis.

An additional noteworthy finding is revealed by these results pertaining to the traditional assumption that seniors are mostly considered a vulnerable VRU subpopulation because of their frailty and high risk to succumb to their injuries (Siram, et al., 2010). Interestingly, results showed that seniors are also more vulnerable based on their relative involvement to the younger, which has not been widely shown in an inferential fashion in past studies. This shows that injury involvement is important and that it could be an important tool for safety performance and addressing public health problems of an ageing society.

4.10.3 Discussions and Future Work

The crudeness of the exposure proxy (average population) used to compare younger and older subpopulations raises a limitation in this study. This limitation however calls for transport agencies to increasingly associate age-group when sampling pedestrian traffic. For future research, this calls to question more closely: if the effect of exposure is different for seniors compared to the overall and compared to different subpopulations? Given the literature review and results here, there is reason to suspect that the effect of senior exposure on their injury risk may differ from the younger and overall pedestrian populations.

In this paper we also set out to determine if there is credence to the slow walking speed hypothesis. To validate this, some pedestrian crossing signals (PCS) variables were operationalized as crossing characteristics. At these ends, leading pedestrian interval (LPI) attributes were modeled. However, questions arising in the reliability of the data forced us to ultimately omit these characteristics. Future work should seek to test PCS characteristics such as phase time and type, including the LPI phase, using an injury regression based approach.

4.11 Concluding Remarks

Optimizing the built environment for VRU and pedestrian safety is important not only for transport planning and health reasons but also in the development of sustainable transport. Although many municipal and other governmental agencies have adopted transportation and health oriented objectives containing "statements of exhortation" towards sustainability and health (Wellar, 2006), planners and practitioners need to continue pushing for their the materialization of sustainable and safer policy. Safety and health planning would clearly benefit from the continued development of innovative VRU safety modelling methods. Findings show that planners and practitioners could benefit from subpopulations models to better understand not only senior pedestrian injury factors but also the younger. Given ageing society and the need to improve safety for a growing number of active and vulnerable road users, findings from this paper suggest that a population based approach is more inclusive and arguably therefore more sustainable.

4.12 Acknowledgments

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Chapter 5 Discussions and Conclusions

This thesis sought to evaluate senior pedestrian injury factors surrounding signalized intersections in Montreal, Canada, with the objective of reaching a better understanding of whether they differ from the younger and to what extent. In a secondary fashion, two additional objectives were stated: On one hand, it sought to explore defining a built environment that is optimal for pedestrian safety and to determine if a subpopulation modelling approach may be more inclusive for an ageing society.

5.1 Key Findings to Highlight

As it turns out, subpopulation models were effective in detecting senior injury factors while also pointing to the nuances between older and younger. Older adult pedestrian vulnerability was confirmed in the results of this thesis research, evidenced by their greater probability for involvement. However, variables that were present in the older model but absent in the younger (center median refuge and commercial arteries) is also revealing in pointing to the heterogeneity of both age-cohorts. Most importantly, the center median refuge showed to be significant in reducing the probability of injury involvement by 70% in seniors but was not statistically significant in the younger. Given that pedestrians could ‘refuge’ on the center median it could also be considered a crossing characteristic, giving credence to the slow walking speed hypothesis (see Chapter 4). Findings also revealed that a model focusing only on the younger would not have detected the significance of the center median refuge for seniors, showing the benefit and inclusivity of subpopulation models.

Likewise, had this thesis only specify a subpopulation model focusing solely on seniors it would not have detected some injury factors unique to the younger, like for example the safety injustice based on the selected low-income indicator, including complex intersection geometry and total jobs. This finding not only shows the importance of subpopulation modelling, but that planners must not neglect the younger despite an ageing society, especially considering equality principles that are intrinsic to sustainable transport.

Commercial land-use was important for both seniors and the younger, while the number of commercial arteries was an additional attribute that was significant in the older model. For commercial land-use, findings showed that seniors were 12% more likely to be injured compared to the younger when the signalized intersection was within a commercially zoned land-use. This finding, including the fact that commercial arteries was uniquely significant in the older model, implies that planners and practitioners may especially wish to pay particular attention to commercial areas when seeking to modify the built environment to optimize for pedestrian safety an ageing society.

5.2 Findings for Common Injury Factors

Overall, results showed that seniors were more sensitive (vulnerable) for the five *common* injury predictors (Auto AADT, number of bus stops, number of metro stations, respective population and commercial land-use) (see Chapter 4). Based on the relative incidence percent-difference (RI%Δ), seniors were on average 150% more likely to be injured compared to the younger[9], implying that seniors are indeed more vulnerable, all other variables included in models held constant.

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[9] RI%Δ was only calculated for common injury variables (see last column of Table 5 in Chapter 4).

Interestingly, the greater probability for seniors to be involved in a crash addresses a gap in the literature based on the contention that seniors are more vulnerable primarily due to their fatal overrepresentation (Siram, et al., 2010). Namely, findings here show that seniors are also more vulnerable in terms of injury (incidence) probability, all other variables in models held equal. This implies that injury models are also important in seeking to better understand senior pedestrian safety problem, especially in the context of an ageing society. If the ultimate objective of some planners is to eliminate fatalities, for example those subscribed to a Vision Zero initiative, findings here suggest that injury incidence models can be an important first step to better understand senior pedestrian vulnerability.

The validation model specified in the regression analysis (see Chapter 4) sought to determine if results in the younger were similar or different to a confounded (younger and older) model. The objective was to validate the hypothesis that the younger mirrored those of past overall studies. Results showed that younger injury predictors appeared to mirror those of confounded models, suggesting that both overall and majority population injury models such as the younger may over-dominate model results to the point of excluding injury factors of older adults. This finding reiterates the importance of secondary research objectives previously expressed. Namely, this findings suggests that a built environment optimized for an ageing society may indeed be different than one optimized for the younger, and that a subpopulation modelling approach appears to be more inclusive. As such, these findings both support and nuance to the notion of the prevention paradox in the context of pedestrian safety. On one hand, the incidence approach (as oppose to fatal models) is supported by Rose's preventive medicine strategy and although subpopulation models were specified, the majority of the population was included. However, given that the preventive medicine strategy does not outline a subpopulation approach, it could nevertheless lead planners to specify overall (population) models and thereby overlook injury factors in very vulnerable subpopulations. This implies that potential opportunities for prevention would be lost which, for all intents and purposes of the preventive medicine strategy, is in itself a paradox. More importantly perhaps, some key tenets of contemporary and sustainable transport is aimed precisely at encouraging inclusivity, health and access to safety. Without subpopulation models it appears that these intrinsic elements of sustainable transport may be challenged.

5.3 Seniors in Numbers: Prevention Opportunity?

In the introduction of this thesis it was established that two key problems surrounding senior pedestrian safety are concerning for researchers and planners: the longstanding overrepresentation of senior pedestrian injuries and fatalities (injury risk) and future concern given ageing population (exposure). As implied, this thesis assumed that exposure is a menace to older adult pedestrian injury risk, largely due to ageing population. Safety in numbers could not be tested accurately in this thesis because of the absence of subpopulation exposure data. However, results nevertheless showed that seniors were 620% more sensitive to the exposure proxy (respective population), suggesting that their individual risk may not follow the same patterns as the younger. More importantly, this may indicate that safety in numbers may not apply to seniors. Rather, a so to speak ‘seniors in numbers’ phenomenon appears to be more of an opportunity for prevention, as should be any rise in incidence. In other words, despite a fall in individual risk, a rise in incidence, whether for older or younger, should always be seen as an opportunity for prevention.

5.4 Future Work

The crudeness of the exposure proxy (average census tract population within 500-m) used in the study in Chapter 4 raises a limitation in this study due to the lack of subpopulation exposure data. This limitation attests to the absence of this data collected by transport agencies, however. Most past studies have used the overall pedestrian crash population, and accordingly the overall traffic and pedestrian exposure data. The benefit of specifying subpopulation models, however, calls for future studies, including transport agencies, to increasingly associate age-group when sampling pedestrian traffic. In addition, future research would benefit from methods developed to accurately estimate pedestrian exposure based on surrounding population.

In addition, this thesis did not include fatal probability models to detect fatal injury factors in seniors. Although it was contended that understanding senior injury involvement is a first step to then address the factors affecting fatal injuries, this was not included in this thesis. Future work should seek to address senior fatal injury factors in comparison to the younger using a similar approach to the one applied here.

5.5 Concluding Remarks

This thesis contained two levels of discussion – one being a more scientific approach applied in the regression analysis of pedestrian injuries (Chapter 4) and the other being the more theoretical considerations and the conceptual framework addressed in Chapter 1 and 2. This conceptual framework was largely based on the first objective of understanding, namely seeking a better understanding of senior pedestrian injury factors and the optimal built environment for pedestrian safety in an ageing society. The methodologically approach used to reach findings was relatively simple as it was based on intuitive classification of age-groups to specify subpopulation regression models. As such, the first objective in this thesis was therefore not intended to produce complex statistical models, but rather to seek a better understanding of pedestrian safety in an ageing society. Although scientific and results driven studies are highly commendable, researchers and planners must also not forget the fundamental value of understanding, as captured in the historical text of Hannah Arendt:

> *…Yet while our standards for scientific accuracy have constantly grown and are higher today than at any previous time, our standards and criteria for true understanding seem to have no less constantly declined.* (Arendt, 1994, p. 339)

A clearer understanding of the nuances between younger and older was indeed achieved, which allowed for translating these into policy recommendations that can be used by health and transport planners, such as the center median refuge not only as a countermeasure, but as a demonstrated opportunity for prevention.

5.5.1 Senior Pedestrians: An Opportunity for Prevention

As stated throughout this thesis, North-American policy and the built environment countermeasures are lacking for pedestrians, particularly compared to Europe (Pucher & Dijkstra, 2000). Unfortunately, it appears that these issues may continue to be challenged and perhaps are linked to a boarder issue addressed by Wellar (2006). For example, although many transportation agencies and government bodies have currently adopted Master Transportation Plans containing favorable statements toward sustainability and VRU policy, if they are not applied on the ground, planners must question their existence (Wellar, 2006). Or for example if one considers the recent federal cutbacks in scientific research which significantly affected transportation research, such as the elimination of the long-form census questionnaire. Implicitly, planners and researchers must persist in encouraging sustainable and VRU safety policy, especially so in the present context of an ageing society – because addressing senior pedestrian safety in indeed an ageing society appears to present itself as an opportunity for prevention.

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