A Built Environment for an Ageing Society: A subpopulation analysis of pedestrian crashes at signalized intersections in Montreal, Canada

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ABSTRACT

Concern for pedestrian safety has grown recently because of ageing population not only in North-America but globally. Meanwhile the overrepresentation of older adults in fatal pedestrian crashes has been a longstanding problem. As sustainable transport policy becomes prevalent, planners and practitioners will have the opportunity to introduce countermeasures to better meet senior pedestrian needs. In this paper we focus on the built environment because this variable category translates into more accessible countermeasures. However, a gap in the literature makes it difficult for planners and practitioners to choose these. Past empirical studies suggest there is an *observed* risk increase for older adult pedestrians due to their slower walking speed, while crash history studies have yet to provide evidence for this. This gap in the literature begs the question: if there is a link between slower walking seniors and crash incidence. Two models were specified according to younger and older pedestrians involved in crashes that occurred at 191 signalized intersections in Montreal, Canada. We sought to determine if older adult pedestrian crash incidence was explained by different characteristics compared to the younger. Results not only showed that older pedestrians were more vulnerable and influenced by some different risk factors than the younger, but that they may be more responsive to some potential countermeasures.

Key words: senior pedestrians, older risk, built environment, negative binomial, center median refuge, pedestrian leading interval.

INTRODUCTION

In Canada, between 1992 and 2001, roughly 70% of pedestrian fatalities and on average 95% of injuries occurred in urban areas (*1*). Older pedestrians, or seniors, hereon implied as adults aged 65 and older, typically accounted for 50% of fatalities, but represented roughly 15% of the population (*2*). In addition, their pedestrian crash involvement happened mostly when crossing at intersections, as revealed by Quebec's road safety record: 85% (1300 of 1528) between 2003 and 2009 (*3*). For overall victims this is generally cited as 60% (*4*). In addition to the overrepresentation of older pedestrians (*5*) (*6*) (*7*), evidence suggests that with ageing there is a tendency for urban living (*2*), which eventually translates into more walking trips and therefore a greater number of exposed (*8*). This is partly why population ageing and its effect on road safety in urban areas is a growing preoccupation for researchers and planners.

Past studies specifically modeling the older pedestrian subpopulation are scarce. This is surprising considering they possess different individual characteristics (both physically and psychologically. Further, they have been involved in crashes under fairly different built environment conditions than the younger (*9*). Subpopulation models for predicting involvement in children pedestrian crash incidence have been commonplace for years (*10*) (*11*) (*12*). The scarcity of such studies for older adults is surprising considering their long standing overrepresentation in crashes as evidenced 25 years ago by Sklar, Demarest & McFeeley (*13*).

In this paper we explore characteristics associated with the count of older adult involvement in pedestrian crashes, in comparison to the younger, at signalized intersections in Montreal, Canada. We seek to determine if older adults are affected by different characteristics than the younger. We focus on the built environment because this variable category translates into more accessible countermeasures for local planners and practitioners. Two broad variable categories can be identified: (1) the environment, which includes exposure, transit, land-use, employment and population. On the other hand, (2) built environment variables include geometry, design, road types and Pedestrian Crossing Signal (PCS) phase time and types.

In addition, this study sought out to address a gap that exists between empirical and crash history studies. While past empirical studies suggest there is an *observed* risk increase for older adult pedestrians due to their slower walking speed, crash history studies measuring this are scarce. This gap in the literature begs the question: if there is an *actual* risk associated with characteristics that suggest a link between slower walking seniors and their crash incidence.

LITERATURE REVIEW

With the growing desire to promote active transport and healthy ageing, planners and practitioners will increasingly have the opportunity to introduce built environment countermeasures better suited for an ageing society. For example, this may include choosing the appropriate geometry or design of an intersection, such as adding a center median refuge or curb extensions, reducing the radius of a curb, or alternatively, modifying PCS phase times and types. The signalized intersection is suitable at these ends since all of these characteristics coincide at this spatial scale.

Intersections are indeed a significant determinant of older pedestrian crash location, particularly signalized intersections (*5*) (*6*) (*14*). Using a videotaping observational approach at five intersections in Florida, Unites States, Geurrier & Jolobois (*15*) showed that seniors have difficulty at intersections. They recommended that future countermeasures seek to improve the design of intersections to better suit older pedestrians.

Independent Variables: Crash History and Empirical Studies
Given that regression models focusing on senior pedestrian crashes are still scarce in the literature, to inform our variable selection we relied on studies modeling overall pedestrian crashes (all age-groups confounded), including empirical or descriptive studies. Variables of interest and their relation to pedestrian crash risk and our hypotheses when associated to older adult pedestrian crash incidence are presented in Table 1.

Table 1: Variables Influencing Pedestrian Risk and Hypotheses for Older Adults

Variable Category	Variable(s)	Found relationship in past research (effect on Pedestrian Crashes)	Hypothesis for older adult risk	
Environ-ment	Exposure: Automobile, Truck & Pedestrian	+ Exposure + Pedestrian Crashes (Positive)	+	
	Number of Transit Stops in 50 m Buffer	+ Transit stops + Pedestrian Crashes (Positive)	+	
	Commercial land use	+ Commercial activity in the area + Pedestrian Crashes (Positive)	+	
	Population (density)	+ Population density in the area + Pedestrian Crashes (Positive)	+	
	Employment	+ Employment in area + pedestrian crash (Positive)	-	
Built environ-ment	Center Median Refuge	+ Center Median Refuge - *Risk*	-	*
	Complex Intersection Geometry*	+ Complex Geometry + Pedestrian Crashes (Positive)	+	*
	Road type	If Artery + Pedestrian Crashes (positive)	+	
	Leading Pedestrian Interval (LPI)	+LPI - Pedestrian Crashes (negative)	-	*
	Pedestrian Cross Silhouette Time	+ Time - pedestrian *risk* (negative)	-	*

* *Scarce in the literature or mostly empirical evidence*

Environment Variables
Exposure Data & Transit
Exposure data is often captured as Average Annual Daily Traffic (AADT) for automobile, pedestrian and light or heavy truck traffic. While studies showing a positive effect on risk due to truck traffic are more sparse (*16*), those having a positive effect due either to automobile or pedestrian volume are common (*17*) (*18*) (*19*) (*20*) (*21*). The interest in this paper will be to evaluate if exposure has the same effect on older adults compared to the younger.

The presence of transit stops is thought to be of interest for older pedestrians since the combination of two transportation modes (walking and transit) is common in active ageing lifestyle, as well as when they can no longer drive (*2*) (*13*) (*22*). Transit stops, especially bus stops, also give them the opportunity to rest when there is a bus shelter or a bench. Past studies including it as a variable found a positive

relationship between number of transit stops and pedestrian risk (*18*) (*19*). However, some have cautioned that this effect is spuriously caused and that the underlying effect of pedestrian activity (*19*) (*23*).

Land-use and Demographic Proxies

Michael, Green & Farquhar (*24*) showed evidence that older adults are attracted to commercial built environments. On the other hand, Miranda-Moreno, Morency & El-Geneidy (*20*) (*19*) and Ukkusuri et al. (*23*) (*29*) found a positive relationship for commercial and industrial types of land-use to that of overall pedestrian crash incidence. Surprisingly, no study has modeled a variable specifically tailored for commercial arteries, which is a sub-sample of commercial areas after all.

Population factors have been added to models in past studies under the assumption that intersections in heavier populated areas would have more risk due to exposure. Pulugurtha & Sambhara (*18*) showed evidence of an exponential increase in pedestrian crash incidence according to population. Ukkusuri et al. (*23*) showed similar results for the 65 and older age group. On the other hand, Miranda-Moreno, Morency & El-Geneidy (*20*) provided evidence from their models that a doubling of population density would result in an average increase in pedestrian crash incidence of 15%. Similarly, Cloutier & al. (*4*) also found an odds ratio of 1.2 for population density.

Employment factors have also been added to models in past studies under the assumption that pedestrian crash rates are associated with the higher 'attractivity' of an area having more jobs, leading to more exposure. Several studies found a positive effect for employment (*4*) (*12*) (*23*). Again, in this study we are interested in determining if the effect remains the same for the older model.

Built Environment Variables

Geometry, Design and Road Attributes

Some studies have showed evidence that younger and older pedestrian crash incidence tends to happen under distinct built environment characteristics (*6*) (*14*). Ward et al. (*9*) showed evidence that senior pedestrian crashes tend to happen on more varied types of roads, while the younger are concentrated on main arteries. Ukkusuri et al. (*23*) showed that the likelihood of pedestrian crashes increased with a greater number of lanes and road width, two characteristics associated with arterial roads.

Geometrical characteristics have been commonplace as built environment attributes in past studies but have mostly been defined by physical characteristics such as road width or presence of medians. Few past studies have operationalized a variable based on complex intersection geometry. After all, the importance of intersection geometry is supported by intersection design standards. For example, the MUTCD recommends against an intersection skew of less than 70 degrees. In a study in Iowa based on 200 intersections, Burchett & Maze (*25*) showed that a horizontal curvature in approaches led to 50% greater fatal crashes than tangents. Other studies have tested horizontal road curvature on road segments (*26*) (*27*), however, results were inconclusive.

The benefit of the center median refuge has mostly been empirically founded thus far in the literature (*28*). For example, Li, Yang and Yin (*29*) showed that after the installation of a center median island that severe conflicts were observed to be reduced by 31%. Some have sought out to test this variable is a crash history regression model but given insignificant results researchers often end up removing them from final models (*19*) (*20*). Pratt, Bonneson & Songchitruksa (*21*) suggested that this variable could be difficult to interpret given that the median presence also occurs where there is a large crosswalk gap (greater number of lanes). Cloutier, Tremblay & Morency (*4*) also found this variable to be insignificant, but posited that given the negative sign this merited further investigation in future research.

Pedestrian Countdown Signal Characteristics and the Slow Walking Hypothesis
Due to ageing population researchers and planners are increasingly interested in the effect of PCS characteristics on older adult pedestrians. As such, some have posited that the slow walking speed of seniors, in association with limited PCS time, contributes to their risk –known as the slow walking speed hypothesis (*30*). The interest in this paper is to determine if there is a link between built environment characteristics that may suggest that the slower walking speed in seniors is associated with their crash incidence. However, the current body of literature makes the effectiveness of PCS characteristics difficult to interpret.

In a before-and-after study, after installing a PCS device at 106 intersections, Pulugurtha & Pulugurtha (*19*) provide evidence of a significant effect in the reduction of all accident types, yet an insignificant effect in reducing pedestrian crashes. Similarly, Persaud et al. (*31*) showed evidence of a reduction in pedestrian crashes after removing signalized lights by 4-way stops, showing that stop-signs are sometimes safer than lights. On the other hand, after implementing a PCS at 362 sites in Detroit, Michigan, Huitema, Houten & Manal (*32*) showed evidence of a one third reduction in pedestrian crash incidence.

Based on observation several empirical studies have showed evidence that older pedestrians rarely have sufficient time to cross with the allotted PCS time and contend that this leads to their greater risk (*15*) (*33*). For instance, Romero-Ortuno et al. (*34*) assert that the typical walking speed assumptions (1.1-1.2 m/s) at which most transportation agencies set the pedestrian clearing (hand) time (known by hand pictogram) were insufficient.

Dunbar (*30*) was one of few studies to provide a regression model with a focus on older pedestrians. However, the author interpreted results against an association of risk due to the slow walking speed of seniors. This was reasoned by the fact that his models showed greater coefficients for 3 lane roads compared to 4 lane roads, based on far-side crash types. Although interesting, the study did not account for PCS time or type, however, which could vary according to the practitioner's philosophy. This is important considering many North-American cities still favor the automobile rather than pedestrians (*35*).

The Leading Pedestrian Interval (LPI) is sparsely covered in the literature but gaining considerable popularity in different variants. Van Houten et al. (*36*) found that the LPI phase reduced observed pedestrian-vehicle conflict situations by 97% in non-seniors and 89% in seniors. Similarly, in a before-and-after study, King (*37*) found there to be a 12% reduction in crashes. Hubbard, Awwad and Bullock (*38*) suggested that the LPI phase could be beneficial if more than 15% of pedestrian crossings were compromised and suggested that less pedestrian wait time (better pedestrian LOS) led to better safety. On the other hand, in a before-and-after study after implementing a LPI at 10 signalized intersections in State College, Pennsylvania, Fayish & Gross (*39*) showed that crash occurrence can be reduced by 46.2%. Although these studies show the benefit of the LPI phase, most are empirical in nature and few have specified a crash history regression model. Further, none have tested the LPI with thru arrow as seen in the city of Montreal and even less so using a subpopulation model approach.

METHODOLOGY

Data sources
This study uses a crash history approach using police reported pedestrian data for the 2003-2009 period. The data originates in a disaggregate form from the provincial licensing and insurance authority (*3*) which was shared with us via the city of Montreal Safety and Planning Department. Disaggregate data was necessary to separate crash counts according to age-group: those aged 16-64 as the younger model and those aged 65 and older as the older model. These data were then aggregated to the random sample

of signalized intersections (N=191) in the Montreal urban core. A distance of 30m was used for aggregation buffers in order to account for the wider width of arterials at signalized intersections. Spatial joins from disaggregate to aggregate were done using Geographic Information Software (GIS) in a licensed version of ArcMap 10.1 (ESRI, 2013) (*40*). Several other explanatory were joined in a similar fashion. Commercial and industrial land-use information, raw traffic counts, PCS characteristics and other road characteristics were obtained from the city of Montreal central transportation agency.

A fair number of variables were obtained from a preexisting dataset based on a consorted university, provincial public health directorate and a non-for profit organization., namely: INRS-UCR: Institut National de Recherche Scientifique – Urbanisation, Culture et Société, DSP-Mtl: Direction de la santé publique de Montréal and CEUM: Centre d'écologie urbaine de Montréal (*4*).

Dependent variable

The dependent variables were based on a total of 586 disaggregate crashes, 479 involving younger pedestrians (16-64: model 1) and 107 involving older pedestrians (65 plus: model 2) occurring in the study area.

Independent Environment Variables

Exposure & Transit

Exposure data for automobiles, truck and pedestrian traffic were derived from sample counts and expanded to average annual daily traffic (AADT) using the AIPCR expansion factors (*41*). Pedestrian exposure (pedestrian AADT) however was expanded using expansion factors provided by Miranda-Moreno & Fernandes (*42*) (unpublished data) via the city of Montreal. The city of Montreal generally provides counts using 5-6 hour count samples. However, for intersections with less volume sample counts were expanded based on 3 hour samples.

Transit and Number of bus stops within a 50m buffer zone surrounding intersections

Derived from the local transit agency (STM: Société de transport de Montréal), the Number of bus-stops for each intersection was obtained by spatially aggregating bus-stops within a 50 m buffer zone surrounding the intersection centroid point. An aggregate of 50 meters as oppose to the 30 meters was chosen because STM bus-stop GIS points are represented by the location of the signage post and not the actual stop location. The signage post is generally located 15-30m away from the corner, while the corner is located 10-20m from the intersection centroid, dependent on the number of lanes. As such, 50 meters was in order to account for this offset. Different aggregates of number of metro stations in proximity too were tested but insignificant and omitted from final models.

Land-use and Demographic Proxies

Commercial land-use was a binary variable indicating whether or not the signalized intersection fell within a commercially zone area. Industrial land-use zone was tested but omitted from final models.

Variables describing population and employment were obtained from the intersection dataset. For more details see Cloutier, Tremblay & Morency (*4*). For final models total number of people and jobs were used.

Independent Built Environment variables

Geometry & Design and Road Type

Number of Commercial Arteries Connecting the intersection was a variable that counted the number of road segments defined as commercially zoned. Deriving from the city of Montreal's transport agency

geobase files, an artery segment does not necessarily follow the entire length of the artery but rather only the immediate street segment that is primarily concentrated with commercial activity buildings. A 30m buffer surrounding the intersection was used for the aggregation.

Complex geometry is defined by skewed, horizontal curvature in segment approaches or misaligned segments connecting the intersection (see Figure 1). The street pattern in the city of Montreal is generally that of a gridiron pattern. However, 23% (43 out of 191) of the time we observed a "non-standard or complex geometry". This data was identified in a binary fashion (1/0) 1 for non-standard or complex geometry and 0 for normal or standard geometry (see Figure 2). Our operationalization of this variable was in part inspired by Oxley et al.'s (*14*) conception of "complex intersections".

Standard Versus Non-standard (complex) Intersection Geometry

Standard Geometry	**Complex Geometry**	

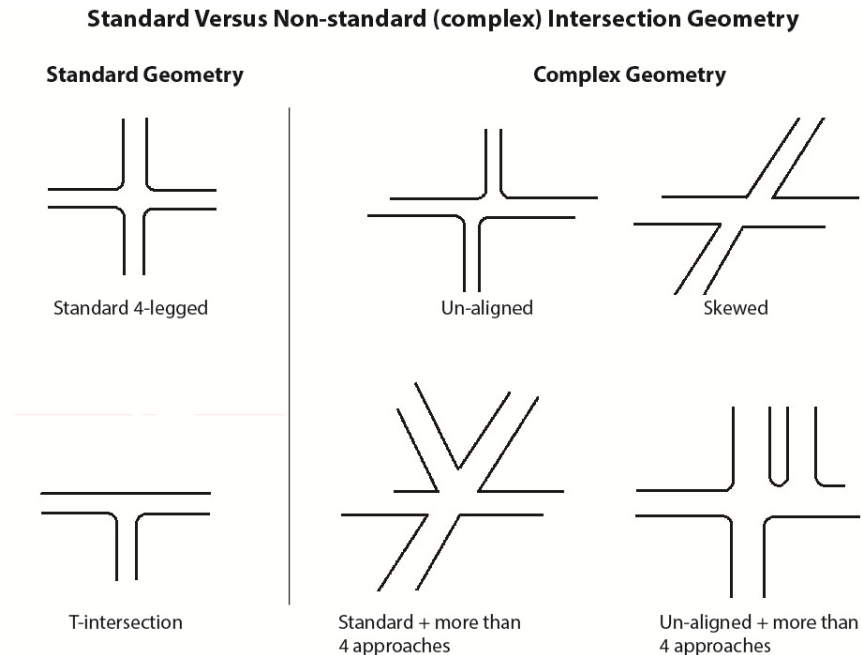| Standard 4-legged	Un-aligned	Skewed
T-intersection	Standard + more than 4 approaches	Un-aligned + more than 4 approaches

Figure 1: Non-standard Intersections Geometry Scheme

The Center Median Refuge was a subsequent geometry characteristic of intersections, defined in a binary fashion as either present or not (1/0), no matter how many road segments had this feature.

The Average Crosswalk Distance measured the average of each intersection crosswalk. When an intersection had to regulate crosswalk this number was doubled, otherwise it remained the same. Given that a regulated PCS is often installed on a single crossing, doubling this variable when in the presence of two PCSs accounts for the greater number of crossings. This distance was also necessary to measure the overall time or set-speeds to be discussed next.

Pedestrian Crossing Signal Characteristics
Intersections fitted with PCS device were present in 56% (n=107) of our study area. Five variables were tested in preliminary models: Leading Pedestrian Interval with thru arrow, More than 4 Phases (yes/no), Pedestrian Cross Silhouette Set-speed (meters/second), Pedestrian Clearing (hand) Set-speed (meters/second), Pedestrian Cross Silhouette Time (seconds) and Pedestrian Clearing (hand) Time (seconds). Below we discuss these.

Observed in 56% of our study area, the Leading Pedestrian Interval (LPI) has the objective to provide a *leading interval* for pedestrians to ensure vehicles do not "bully" their way thru the crosswalk. Figure 2 illustrates the combination of the pedestrian priority phase and the green thru arrow, later changing to a full green after 3-10 seconds. Although the thru arrow is distinct to the city of Montreal, it is similar in concept to the LPI found in the city of New-York and elsewhere. The New-York LPI phase starts the pedestrian cross priority phase (silhouette) in an exclusive all-red and then overlaps to either continue for a few seconds on the full-green or ends with the pedestrian clearing phase. The New-York city application does not require a 4 head traffic light, while the Montreal application does (see Figure 2). Other PCS characteristics were omitted from the final models, but are briefly discussed below.

Figure 2: Example of a Pedestrian Lead Interval Phase (with thru arrow)
Source: Google street view, 2012, Corner of St-Denis and Rachel, downtown Montreal, Canada

The Pedestrian Cross Silhouette Set-speed (m/s) was tested but produced inconsistent results. The Pedestrian Clearing (hand) Set-speed (meters/second), on the other hand, is regulated based on a theoretical walking speed by which practitioners dictate the time in total seconds to allow for pedestrians to cross once it goes on. This is usually assuming 1 to 1.2 meters per second walking speed (*Set-speed (m/s) = Crosswalk Distance (m) * Theoretical Walking Speed [1.0-1.2sec.]).* However, some practitioners may provide more or less time depending on his or her philosophy, the built environment, intersection geometry or other factors. It should be noted that while the times for PCS were available in disaggregate form for each crosswalk (typically no more than 2 per intersection), the distances were only available as average crosswalk distance. As such, for intersections having two PCS devices both the average crosswalk distance and the set-speed were multiplied by two.

Pedestrian Cross Silhouette Time (seconds) and Pedestrian Stop-crossing Hand Time (seconds) were also tested but did not prove to be significant.

Finally, in order to operationalize a characteristic of a complex intersection, a dummy variable for More than 4 Phases (yes/no) was tested. Finally, the exclusive (all-red) pedestrian phase was only found at four sites in our sample and was thus omitted from models.

Crash History Regression Models
The Poisson model is the foundation upon which count models are built and have been prevalent for many years in past crash studies. The Poisson probability function is given by:

$$= P(Yi) = \frac{e^{-\lambda i} \; \lambda i^{yi}}{yi!}$$

Equation 1

where P is the probability of intersection *i* having *yi* crashes and λi is the Poisson parameter for the intersection. However, because crash data is commonly has a different mean and variance, the Poisson model is no longer ideal but rather the Negative Binomial (NB). A dispersion test confirmed that the distribution was over-dispersed leading us to favor the NB model. The NB model can be re-written by adding a gamma-distributed error term to account for the unobserved heterogeneity in the data by allowing the mean and variance to vary. Formally, it can be written as follows:

$$\lambda_i = EXP \; (\beta X_i + \; \varepsilon_i)$$

Equation 2

where EXP is the multiplicative form common in the model and (ε_i) is the error term. Note that all statistical tests and modeling were done using the open software R-Studio.

DATA DESCRIPTION

Study Area
Two models were specified according to the younger aged 16-64 (82%, n=479) and those aged 65 and older (18%, n=107). Figure 3 shows a graduated symbol thematic map representing the count of crashes of the younger (left) and older (right) that occurred in our study area. Both maps show considerable crash concentration in the downtown portion along the southern metro line, which is particularly visible in the younger map. This southern downtown crash concentration follows the major artery Sainte Catherine Street which also has high a concentration of metro stations. Both maps show a more pronounced concentration where the primary downtown green metro line meets the orange metro line at the Berri-UQAM metro station hub. Two major arteries also intersect there, the Sainte Catherine and Saint Denis Streets. The second concentration is above the first one where again the north-south orange metro line meets the blue metro line at the Jean-Talon metro station hub. These areas are not only fairly populated but are also along the main arteries and metro lines of the city. In the older crash map it is possible to notice a more spread-out spatial distribution of crashes, especially with less concentration in the downtown core.
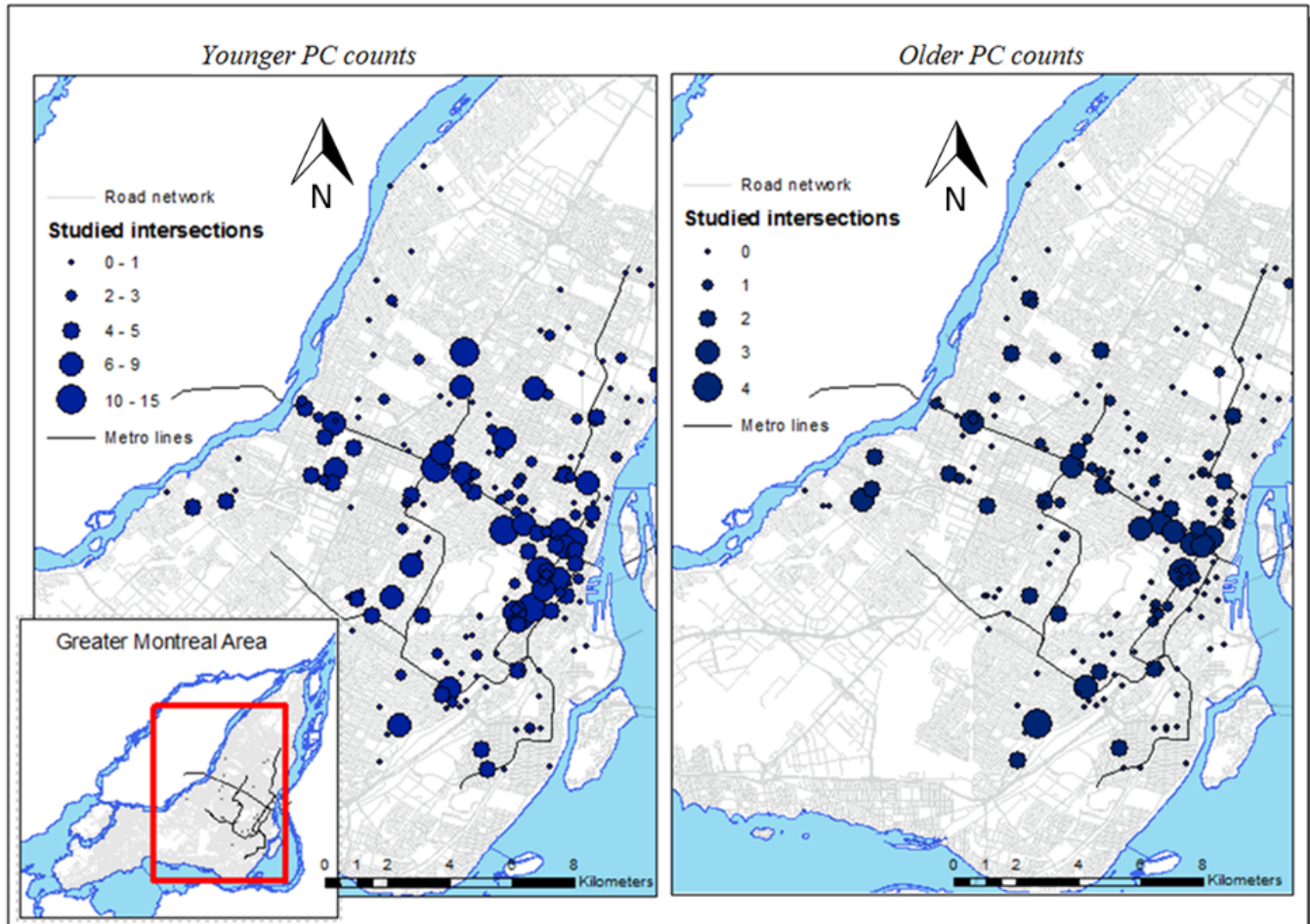
Figure 3: Geographic distribution of pedestrian crash sites at signalized intersection for younger (16-64) and older (65 +) pedestrians

Variables
The mean number of crashes per intersection was 2.5 in the younger distribution and 0.55 for the older one. A low mean in the senior model is largely attributed to a greater number of intersections recording zero crashes (68% of intersections) compared to the younger. This however is expected given the 65 and over represented roughly 15% of the population during this crash period. The greatest number of recorded crashes at one single signalized intersection was four (n=4) for the older age-group and 15 (n=15) for the younger. However, both models had a fairly similar distribution shape. For example, both populations recorded similar incidence proportions of intersections having recorded one crash count: 19% for the younger and 16% for the older. On the other hand, Table 2 lists the variables included in the final model including a few other select variables tested. Shown is the variable mean, Standard Deviation (sd), Minimum (Min.) and Maximum (Max.).

Table 2: Summary Statistics of Variables Across (N=191) Intersections

		Variable	Mean	sd	Min.	Max.	Yes	No
Dependent variables	*Younger*	**Pedestrian crashes aged 16 to 64 (479 victims)**	**2.5**	**2.8**	**0**	**15**		
	Older	**Pedestrian crashes aged 65+ (107 victims)**	**0.56**	**0.9**	**0**	**4**		
Environ-ment	*Exposure & transit*	Pedestrian AADT	4758	8187	0	65331		
		Automobile AADT	24837	15511	0	84141		
		Turning Truck AADT	204	240	0	1631		
		Bus stops (# in 50 m)	2.4	1.6	0	7		
		Metro Stations (# in 50 m)	0.7	1	0	4		
	Land-use and demogr-aphics	Commercial land-use (yes/no)					53 (28%)	138
		Overall Population in Dissemination Area	14126.6	6308	1159	27900		
		Population 65+ in Census Tract	522.6	379.1	0	1720		
		Jobs in Dissemination Area	16318.8	26979.7	788	141129		
Built environ-ment	*Geometry, Design & Road*	Non-standard or complex Intersection Geometry (yes/no)					43 (23%)	148
		Center Median Refuge (yes/no)					20 (10%)	171
		Number of Commercial Arteries Connecting Intersection	0.7	1.1	0	5		
		Average Crosswalk Distance	31.1	12.5	6.5	64.5		
	Pedestrian Crossing Signal	Pedestrian Crossing Signal					107 (56%)	84
		Pedestrian Clearing (hand) Set-speed (meters/second)	0.85	0.45	0	2		
		Pedestrian Cross Silhouette Time (seconds)	13.9	19.9	0	99		
		Pedestrian Clearing (hand) Time (seconds)	13.7	20.3	0	124		
		Leading Pedestrian Interval (with thru arrow) (yes/no)					87 (46%)	104
		More than 4 Phases (yes/no)					78 (40%)	113

RESULTS

Regression Models

Regression models were calibrated using a backward stepwise approach. Variables within a 10% significance level (or 90% confidence level) were deemed within our acceptance region. For final selected models the older model had six (n=6) significant variables while the younger had seven (n=7). At various stages multicolinearity tests were performed and controlled for. Final models were selected based on AIC score, parsimony and consistency with past studies. Given some sporadic and the suspicion of spurious effects, preliminary models are also shown.

1 Table 3: Younger Pedestrian Crash Models (ages 16-64)
2

	Model 1		Model 2			Model 3			Model 4		
Variables	Coef.	P-val	Coef.	Elas/IRR %	P-val	Coef.	Elas/IRR %	P-val	Coef.	Elas/IRR %	P-val
(Intercept)	-1.64	0.00	-1E+00		0.00	-1E+00		0.00	-1.22		0.00
Auto AADT	6.90E-06	0.09	9.03E-06	0.22	0.03	1.08E-05	0.27	0.03	1.24E-05	0.31	0.00
Pedestrian AADT	1.55E-05	0.01	1.77E-05	0.08	0.00	2.37E-05	0.11	0.00	2.77E-05	0.13	0.00
Turning Truck AADT	6.67E-04	0.01	7.42E-04	0.15	0.01	8.83E-04	0.18	0.00	1.06E-03	0.22	0.00
No. Bus Stops 50m	0.18	0.00	0.18	0.44	0.00	-	-	-	-	-	-
Commercial Land-use	0.36	0.01	0.33	39%	0.03	0.37	45%	0.03	0.41	51%	0.00
Population overall	6.12E-05	0.00	6.14E-05	0.87	0.00	6.28E-05	0.89	0.00	6.59E-05	0.93	0.00
Population 65+	-	-	-	-	-	-	-	-	-	-	-
Number of Jobs in Dissemination Area	7.17E-06	0.00	6.90E-06	0.11	0.01	4.86E-06	0.08	0.09	6.34E-06	0.10	0.02
Non-standard or complex Intersection Geometry (yes/no)	0.25	0.09	0.16	18%	0.26	0.27	30%	0.11	0.35	42%	0.02
Center Median Refuge (yes/no)	-	-	-	-	-	-0.12	-11%	0.69	-	-	-
LPI Phase	0.47	0.02	-0.20	-18%	0.59	0.50	65%	0.03	-	-	-
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	AIC: 430.1		AIC: 402.65			AIC: 446.61			AIC: 672.21		

Elas/IRR%: For models 2 to 4 decimal numbers represent elasticity and percentages represent Incidence Rate Ratio Effect

3
4
5

1 Table 4: Older Pedestrian Crash Models (ages 65+)
2

	Variables	Model 1 Coef	Model 1 P-val	Model 2 Coef	Model 2 P-val	Model 3 Coef	Model 3 Elas/IRR	Model 3 p-val	Model 4 coef	Model 4 Elas/IRR	Model 4 p-val
	(Intercept)	-2.24	0.00	-3.01	0.00	-3.09		0.00	-2.98		0.00
Exposure & Transit	Auto AADR	1.34E-05	0.09	2.10E-05	0.01	1.99E-05	0.49	0.02	2.55E-05	0.63	0.00
	Pedestrian AADT	-8.23E-07	0.96	-	-	-	-	-	-	-	-
	No. Bus Stops 50m	0.26	0.00	0.26	0.00	0.23	0.56	0.01	-	-	-
Land-use & Demographics	Commercial Land-use	0.76	0.00	0.90	0.00	0.91	150%	0.00	0.89	144%	0.00
	Overall Population	1.04E-05	0.67	-	-	-	-	-	-	-	-
	Population 65+	-	-	1.08E-03	0.02	9.88E-04	0.52	0.03	1.23E-03	0.64	0.01
Geometry, Road, Design & PCS	Number of Jobs in Dissemination Area	-4.86E-06	0.463	-	-	-	-	-	-	-	-
	Center median refuge	-1.55	0.02	-2.25	0.00	-2.34	-90%	0.00	-2.56	-92%	0.00
	No. Commercial Arteries	0.26	0.08	0.33	0.00	0.33	0.23	0.00	0.35	0.25	0.00
	Average Crosswalk Distance	0.02	0.17	-	-	0.01	0.34	0.34	0.02	0.67	0.09
	LPI Phase	-	-	0.17	0.644	-	-	-	-	-	-
		---		---		---			---		
		AIC: 230.9		AIC: 224.1		AIC: 223.4			AIC: 228.6		

Elas/IRR%: For models 3 and 4 decimal numbers represent elasticity and percentages represent Incidence Rate Ratio Effect

3
4

1 **Environment Variables**
2 *Exposure & Transit*
3 Pedestrian AADT was only significant for the younger model (p<0.05) with an elasticity of 0.13, which
4 indicates that a hypothetical doubling of this variable would result in a 13% increase in the expected
5 crash count for the younger. The insignificance in the older model was perhaps not surprising
6 considering that it suffered from a lack of direct exposure measures – because Pedestrian AADT was
7 measured for overall pedestrian volume. Nevertheless, this insignificance is interesting because it gives
8 credence to the fact that older adults do not follow the same walking patterns as the younger. As a
9 measure of indirect exposure, the population of those aged 65 and older in the Census Tract was
10 modeled.
11   Automobile AADT elasticity for the younger and older models were 0.31 and 0.63 (p<0.05),
12 respectively. A doubling of this variable would lead to an expected crash count increase of 31% in the
13 younger and 63% in the older. The significantly larger elasticity underlines the greater vulnerability of
14 senior pedestrians.
15   Turning Truck AADT in our study area was 204 vehicles. Turning Truck AADT was found to be
16 significant in the younger model, but not the older. Elasticity for this variable was 0.22 (p<0.01),
17 indicating that a hypothetical doubling of this variable would result in a 22% increase in the expected
18 count of pedestrian crashes in the younger. The insignificance of this variable in the older model may
19 reflect the fact that older adults tend to avoid arterial roads where trucks are permitted.
20   Readers will find that models 2 to 4 in the younger and models 3 to 4 in the older models reveal
21 what may be a spurious effect caused by the number of bus-stops. Although multicolinearity was not
22 problematic in our models, some have suggested that the number of bus-stops may cause spurious
23 effects given the correlation to pedestrian activity (*20*). When omitting this variable, exposure measures
24 rose on average by 47% in the younger and 29% in the older model. Assuming that the effect of bus-
25 stops is indirect, the lower rise could either attest to the lack of direct exposure measures for the older
26 model or it may suggest that the effect of bus-stops may be more important for their age-group.
27
28 *Land-use and Demographic Proxies*
29 Although past studies have found industrial land-use to be significant, this was not the case for either
30 younger or older models. For commercial land-use, however, there is clearly a greater association with
31 crash incidence compared to the younger. When the intersection was in commercially zoned area,
32 incidence increased by 51% for the younger (p<0.01) and by 144% for older pedestrians (p<0.01).
33 Again, the significantly higher incidence rate in the older underlines their greater vulnerability and the
34 need for planners and practitioners to be particularly attentive for senior safety in commercial built
35 environments.
36   Overall Population in the dissemination area was included in the younger model while Population
37 65+ was used in the older. The younger model had an elasticity of 0.93 (p<0.01) while the older an
38 elasticity of 0.64. These results indicate that a doubling of their respective populations would result in a
39 93% and 64% increase in their crash incidence. Although smaller than the younger model, the elasticity
40 for the older model is alarming considering their population has and will continue to grow compared to
41 the younger.
42   Total Jobs in the dissemination area was only significant for the younger pedestrian crash model
43 (p<0.01) showing an elasticity of 0.10. A hypothetical doubling of job density surrounding the
44 intersection would lead to a 10% increase in the count of younger PCs. Once again, the insignificance of
45 this variable for the older pedestrian crash model is perhaps not surprising under the assumption that
46 they do not walk in areas of high employment once they are retired, for example.

Built Environment Variables

Geometry & Design and Road Types

Non-standard or Complex Intersection Geometry was found to be significant for the younger pedestrian crash model (IRR%=42%, p<0.05), but not for the older model. For the younger, incidence increased by 42% when the intersection had a complex geometry.

The Center median refuge was only present in 10% of sampled intersections (19 out of 191). This variable had the strongest effect for reducing the count in older pedestrian crashes (IRR%= -92%, p<0.01). Incidence decreased by 92% for seniors when the intersection had a center median refuge. Although insignificant, preliminary models also showed a negative sign in the younger.

The Number of Commercial Arteries Connecting Intersection was only significant for the older model with an elasticity of 0.25, indicating a doubling of this variable would increase senior crash incidence by 25%. Although difficult to interpret in terms of elasticity, these results coincide with past studies (*24*) and may suggest that commercial activity surrounding an intersection will tend to attract more seniors and thus a potential for more representation of their crash incidence.

Pedestrian Crossing Signal Characteristics and the Slow Walking Speed Hypothesis

The LPI appeared to be promising to reduce crash incidence based on past studies, however, our models showed sporadic behavior when modeling this variable. This is perhaps not surprising considering that the LPI phase is also installed at intersections with a greater complexity and higher AADT. In order to test the slow walking speed hypothesis, we thus tested several PCS characteristics.

The only variable that appeared to suggest a link between crash incidence and slow walking speed was the Average Crosswalk Distance where a PCS was found. This is interesting considering it was only significant in the older model. The elasticity of this variable was 0.67, indicating that a doubling of this variable would lead to an increase of 67% crash incidence in seniors.

Discussions and Conclusions

This study set out to explore characteristics associated with pedestrian crash rates at signalized intersections in Montreal, Canada, with a particular focus on the built environment for an ageing society. Coefficients for like or same variables were generally significantly greater for seniors, showing evidence of their greater vulnerability despite being involved and fewer crashes.

The elasticity of the 65+ population in the surrounding Census Tract in the older model (0.65) raises further concern to the growing preoccupation of researchers and planners; namely because Statistics Canada reports that Canada's senior population is expected to double by 2036 (*2*). Although the 65+ population in the surrounding Census Tract was a crude and indirect measure of exposure in this study, based on our results the incidence of senior crashes would be expected to increase by 65% by 2036. This is assuming a doubling of the senior population is represented equally in Census Tracts surrounding signalized intersections. This can be considered a modest extrapolation given that population growth does not account for the tendency for urban migration with ageing (*2*).

It was one of our objectives to determine the extent at which planners and practitioners should be concerned about PCS compared to others, like geometry and design. At these ends there was interest to measure the effectiveness of the LPI with thru arrow as seen in the city of Montreal. Unfortunately, however, we contend that model results were sporadic due to other underlying factors of a more direct influence, such as exposure or geometry. Although this characteristic has been in practice in Montreal for many years, the exact date of LPI installation was unknown. Further, future work may benefit from a before-and-after study or a time-series regression model. Despite these limitations, the significance of the average crosswalk distance in the older model (0.67) and the absence thereof in the younger model

1   gives credence to the slow walking speed hypothesis – because seniors are more affected by crosswalk
2   distance according to our models.
3   This study used a random sample of 191 signalized intersections as oppose to an exhaustive sample.
4   It is unknown if a random sample suffers from bias compared to an exhaustive sample. Some differences
5   are thought to be effected by this different approach if we compare with a past exhaustive Montreal
6   crash history study (*20*). Namely, the effect of industrial land-use which did not come out in the younger
7   model as expected. Although the extent of this effect is still unknown, future studies should seek to
8   answer this.
9
10   *Concluding Remarks*
11   Although senior risk is largely a problem based on their overrepresentation in fatal crashes, this study
12   has showed that their greater vulnerability also is revealed in a crash incidence model. This paper has
13   shown that seniors are influenced by different factors and to different degrees than the younger.
14   Commercial land-use and commercial arteries were highly associated with high incidence rates,
15   suggesting that planners and practitioners should pay close attention, perhaps prioritize, intersections
16   close or within dense commercial built environments. While it appears clear to us that planners and
17   practitioners should optimize PCS characteristics, results show that they must not neglect geometry and
18   design characteristics. For example, the implementation of the center median refuge is an accessible
19   countermeasure that may reduce incidence by 92% in seniors at signalized intersections. Another is
20   intersection standardization which may reduce incidence in the younger by 30%. As the population
21   continues to age and as we stride toward safer sustainable transport policy, planners and practitioners
22   need to increasingly take into account the needs of their most vulnerable road users. Given their more
23   accessible nature, the built environment surrounding signalized intersections present an opportunity for
24   optimization in an ageing society.
25

1 **ACKNOWLEDGMENT**

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