Analyzing the effects of place on injury: Does the choice of geographic scale and zone matter?

Syed Morad Hameed, Nathaniel Bell, Nadine Schuurman

ABSTRACT

Background: Recent studies have shown that the morbidity and mortality associated with injury of pedestrians are inversely related to socio-economic status (SES). However, in drawing inferences from this association, investigators have paid little attention to the modifiable artifacts related to scale and how the data are partitioned. The purpose of this population-based study was to identify the relation between SES and incidence patterns of pedestrian injury at 4 different geographic scales.

Methods: We used a Poisson generalized linear model, stratified by age and sex, to analyze the relation between each of 4 area measures of SES and incidence patterns of pedestrian injuries occurring in metropolitan Vancouver between 1 January 2001 and 31 March 2006. The 4 area measures of SES were based on boundaries of dissemination areas, census tracts, custom-defined census tracts (generated by reassignment of dissemination area boundaries by means of a geographic information system) and census subdivisions of the Canadian census. We measured the SES of the location where the injury occurred with the Vancouver Area Neighbourhood Deprivation Index.

Results: A total of 262 injuries in adults (18 years of age or older) were analyzed. Among adult men, the odds ratio (OR) for injury of pedestrians at the scale of dissemination area was 4.93 (95% confidence interval [CI] 2.89–8.42) for areas having the lowest SES relative to those with the highest SES. For the same population, the OR for injury was lower with increasing aggregation of data: 2.33 (95% CI 1.45–3.74) when census tracts were used, 3.26 (95% CI 2.06–5.16) when modified census tracts were used and 1.27 (95% CI 0.47–3.45) when census subdivisions were used. Among adult women, the OR for pedestrian injury by SES was highest at the scale of census subdivision within medium–low SES areas (4.33, 95% CI 1.23–15.22). At the census subdivision scale, the relation between SES and incidence pattern of injury was not consistent with findings at smaller geographic scales, and the OR for injury decreased with each increase in SES.

Interpretation: In this analysis, there was significant variability when different administrative boundaries were applied as proxy measures of the effects of place on incidence patterns of injury. The hypothesized influence of SES on prevalence of pedestrian injury followed a statistically significant socio-economic gradient when analyzed using small-area boundaries of the census. However, researchers should be aware of the inherent variability that remains even among the more homogenous population units.

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To fully understand the burden of injury, researchers have used national censuses to explore the relation between patterns of injury-related hospital admission and death and relative disparities in social and economic factors.[1–13] The strength of the association between socio-economic indicators and injury is differentially related to age,[14] sex,[15] ethnicity,[16] occupation,[17] population density[18] and behaviour,[19] and these characteristics interact differently according to the specific cause of trauma.[20] Despite these nuances, the relative risk of injury corresponds to disparities in factors such as income, education, employment and demographic characteristics, as well as neighbourhood socio-economic conditions.[21,22]

The literature on geographic variation in injuries is growing, a trend that has been aided by advances in the spatial analysis of hospital registry data by means of geographic information systems.[23–25] This technology has tremendous potential to increase our understanding of the socio-economic risk factors that influence injury, as evidenced by the growing application of such tools in analyzing how environmental factors can shelter individuals from or expose them to potentially harmful events.[26–30] To date, however, the intersection between research on geographic information systems and research on injury prevention has focused on identifying ecological processes associated with increased risk. Little attention has been directed toward the sensitivity of ecological models to the variation that arises from reliance on particular administrative data.

Although health effects are fundamentally associated with the individual, research on the socio-economic determinants of injury primarily involves the use of population-level administrative data obtained from the census. Consequently, the strength of ecological analyses emphasizing the effects of place on injury depends on the extent of data aggregation and the ways in which the areal units are subdivided. This problem, referred to as the modifiable areal unit problem, can be condensed into 2 distinct but closely related issues, illustrated in Figure 1. The first is the scale effect, which refers to the variation in statistical results obtained from analysis of the same set of geographic units when they are organized into increasingly larger (or smaller) groups.[31] The second problem is the zoning effect, which refers to the problem of basing a hypothesis on areal geographic units, which, if subdivided differently at the same spatial extent, would lead the investigator to different conclusions.[31]

The modifiable areal unit problem is receiving increased attention in other health outcomes studies, partly because of the reliance on census data to generate meaningful inferences about the effects of place on health.[32–35] Despite the importance of this factor, little attention has been given to the effect of the modifiable areal unit problem on the relation between socio-economic status (SES) and injury. A review of its consequences is of particular import, given the increasing application of geographic information system technology in defining linkages between the urban environment and injury.

To illustrate the effects of the modifiable areal unit problem, we investigated the variation in SES within a metropolitan area in Canada according to 4 different geographic scales, which were based on the census and a custom-designed repartitioning of administrative data. For this analysis, we used data for pedestrian injuries, for which issues related to the modifiable areal unit problem are of particular importance because of the increasing use of geographic information systems to characterize how both poverty and aspects of the built environment correspond to incidence patterns.[36–39]

Methods

Participants. In this retrospective study of the variation in the association between population socio-economic factors and incidence patterns of severe nonfatal pedestrian injuries, we examined data for adults (age 18 years or older) in metropolitan Vancouver, British Columbia. We obtained aggregated patient records from the British Columbia Trauma Registry for the period 1 January 2001 to 31 March 2006. We selected for analysis the records of patients who had sustained a severe single or a multisystem injury. Injuries were classified according to the Injury Severity Score, one of the most widely used measures of physical injury,40,41 with potential values ranging from 0 to 75. The provincial trauma registry contains data for patients with multisystem trauma requiring a hospital stay of 2 days or more and an Injury Severity Score greater than 12. We subclassified the records according to mechanism of injury, using the classification codes of the International Statistical Classification of Diseases and Related Health Problems, 10th revision (Table 1).

Measurement of SES. We modelled SES with the Vancouver Area Neighbourhood Deprivation Index (VANDIX). The VANDIX, developed previously by 2 of the authors (NS, NB) and described in full elsewhere,[42] is based on a survey of provincial medical health officers, who were asked which census indicators they believed best characterized negative health outcomes throughout the province. The final index incorporates the 7 variables

Table 1: Codes from the International Statistical Classification of Diseases and Related Health Problems, 10th revision, used to identify types of pedestrian injury as recorded in the British Columbia Trauma Registry

Code	Type of injury
V01	Pedestrian injured in collision with pedal cycle
V02	Pedestrian injured in collision with 2- or 3-wheeled motor vehicle
V03	Pedestrian injured in collision with car, pick-up truck or van
V04	Pedestrian injured in collision with heavy transport vehicle or bus
V05	Pedestrian injured in collision with railway train or railway vehicle
V06	Pedestrian injured in collision with other nonmotor vehicle
V09	Pedestrian injured in other or unspecified transport incidents

Figure 1: Illustration of the scale and zoning effect of the modifiable areal unit problem. A change in either scale or zoning changes the geographic distribution of the variable in question. In this figure, subsets A and B illustrate how different permutations of the 9 cells representing area unemployment can alter the final statistic for perceived unemployment areas.

most frequently selected by the medical health officers, weighted according to frequency of responses (Table 2): not having a high school education, unemployment rate, having a university degree, being a lone parent, average income, home ownership and the employment ratio. The weighted values for the 7 variables are summed to create a single marker of relative SES. We standardized the variables by subtracting the regional average from the observed value within each administrative unit and then dividing this sum by its standard deviation. At the time of writing, the VANDIX was being used by several health authorities throughout British Columbia, and it has previously been used as a population-level indicator of SES and risk of injury in the province.[13,30,43,44]

Geographic data. Representations of the socio-economic conditions in the location where each injury occurred were based on 4 different census administrative boundaries (2001 census records). The smallest geographic unit used in this analysis was the dissemination area, which is also the smallest administrative unit used in the Canadian census. A dissemination area is roughly the size of a small number of neighbourhood blocks within an urban area. A single dissemination area in metropolitan Vancouver contains an average of 605 (standard deviation [SD] 235) people. Three additional measures of SES were derived from the administrative boundaries of census tracts, modified census tracts (created by means of a geographic information system) and census subdivisions. In metropolitan Vancouver there were, on average, 12 dissemination areas within each census tract and 21 census tracts within each census subdivision. Census tracts are relatively small and stable administrative areas containing, on average (for metropolitan Vancouver), 5185 (SD 1927) people. To construct the modified census tracts, we used the Districting add-on tool for ArcGIS software (Environmental Systems Research Institute, Redlands, Calif.) to reassign every dissemination area within metropolitan Vancouver to a modified set of census tracts. The Districting tool also allowed us to maintain a desired range of population counts in the new units. For this analysis, we designed the modified census tract boundaries to be continuous spatial areas containing an average of 12 dissemination areas, with an

Table 2: Variables and their relative weights for the Vancouver Area Neighbourhood Deprivation Index

Variable	Weight, %
No high school completion	0.250
Unemployment rate	0.214
University degree	0.179
Single-parent family	0.143
Average income	0.089
Home ownership	0.089
Employment ratio	0.036

Table 3: Pedestrian injuries in metropolitan Vancouver between 1 January 2001 and 31 March 2006, by sex and age group

	Sex; no. of injuries	
Age	Men	Women
18–39	54	35
40–59	49	31
≥ 60	47	46
Total	150	112

average population within 1 SD of the average population of the official census tract units. The largest census areas used in this analysis were census subdivisions, which are equivalent in size to urban municipalities. In metropolitan Vancouver, census subdivisions are designated for city boundaries, regional district areas, reserves and villages, and their average population was 50 304 (SD 104 882). The British Columbia Trauma Registry contains geographic information about the location of each injury, recorded by street address, street intersection or postal code. Using geographic information systems, we employed address-matching to link the information about locations of incidents with Statistics Canada's Postal Code Conversion File (September 2006 version). Once a spatial identifier had been assigned, each patient record was linked with each of the 4 census boundaries that encapsulated its location. This study was approved by the ethics committees of Simon Fraser University and the University of British Columbia.

Statistical analysis. We used a Poisson generalized linear model to assess the relation between SES, as measured by dissemination area, census tract, modified census tract and census subdivision boundaries, and the likelihood of pedestrian injury. We stratified injury rates by sex and partitioned them into 4 age groups: 18–39 years, 40–59 years, 60 years and older, and 18 years and older. We constructed dummy variables from the SES scores and recoded them into categories of high, medium–high, medium–low and low SES. The reference category in each analysis was the high SES quartile (i.e., the least economically deprived area). To reduce the effects of sampling error and data suppression in the Canadian census, we excluded from the analysis injuries that occurred in dissemination areas with a population of less than 250.

Results

Participants and descriptive data. Of the 434 cases of pedestrian injury identified from the British Columbia Trauma Registry for the study period, 9 were excluded from analysis because they occurred in dissemination areas with fewer than 250 people. Of the 425 injuries remaining, 262 (62%) occurred within metropolitan

Table 4: Census areas and corresponding number of pedestrian injuries in each socio-economic status (SES) quartile for different geographic units

Geographic unit and SES quartile	No. of census areas per quartile	VANDIX score*	Injuries: Total no. per quartile	Injuries: No. (%) among men
Dissemination areas				
Low	819	3.52 to 0.35	99	57 (58)
Medium–low	845	0.36 to -0.01	77	46 (60)
Medium–high	799	0.00 to –0.39	52	29 (56)
High	812	–0.40 to –2.37	34	17 (50)
Census tracts				
Low	96	1.92 to 0.51	110	57 (52)
Medium–low	96	0.52 to 0.19	76	49 (64)
Medium–high	97	0.20 to –0.02	32	20 (62)
High	96	–0.03 to –1.06	44	24 (54)
Modified census tracts				
Low	100	1.64 to 0.49	102	53 (52)
Medium–low	100	0.50 to 0.19	76	47 (62)
Medium–high	101	0.20 to –0.07	38	19 (50)
High	99	–0.08 to –1.15	46	27 (59)
Census subdivisions				
Low	7	0.45 to 0.10	43	27 (63)
Medium–low	7	0.11 to 0.00	184	99 (54)
Medium–high	7	0.01 to 0.00	29	19 (65)
High	7	0.01 to –0.91	6	4 (67)

VANDIX = Vancouver Area Neighbourhood Deprivation Index.
* The VANDIX is calculated as the sum of values for 7 census indicators characterizing negative health outcomes (standardized by means of z scores) and is a proxy measure of the SES of a particular area.[42]

Vancouver and were included in our analysis (Table 3). Table 4 shows the number of census areas within each SES quartile and the numbers of injuries within each census area.

Main results. In this study, the relation between SES of an area and incidence pattern of pedestrian injury varied with the geographic scale and the shape of the areal unit used to generate the SES score. As such, the significance of the relation between SES and prevalence of injury varied according to the geographic units used for the analysis. These 2 components of the modifiable areal unit problem further contributed to variations in the direction of the association (e.g., positive or negative socio-economic gradient) between SES and injury, the numeric range of the odds ratios (ORs) and the statistical significance of the association (expressed as 95% confidence interval [CI]).

At the smallest spatial scale (census dissemination area), the incidence of pedestrian injury for the entire sample increased stepwise along a socio-economic gradient, with the OR for injury (relative to the high SES quartile) ranging from 1.72 for areas in the medium–high SES quartile to 4.11 for areas in the low SES quartile (Table 5). The OR for injury nearly doubled between areas classified as having medium–low SES and those classified as having low SES. When stratified by age, the relation between area SES and prevalence of injury persisted within areas of low SES but not areas with medium–low or medium–high SES.

For data at the same spatial scale (dissemination area) stratified by sex and age, the OR for injury, relative to areas with high SES, was greatest for men (Table 6) and women (Table 7) injured in areas with low SES, regardless of age. The OR for injury was 2.79–4.76 for men and 2.33–4.00 for women (for the oldest to youngest age groups) in areas with low SES. The relation between SES of the area and incidence pattern of injury followed a socio-economic gradient when the data were stratified by age and sex, but this pattern was not statistically significant across all socio-economic categories.

At the scale of census tracts, the OR for injury among all participants ranged from 2.48 to 3.27, for older to younger age groups, in areas with low SES (Table 5). Among women the OR ranged from 2.50 to 4.92 for older to younger age groups (Table 7), whereas among men,

Table 5: Odds ratios (ORs) for injury of pedestrians (sexes combined), according to socio-economic status (SES) of the area where the injury occurred, for various geographic units

Geographic unit and SES quartile	Age group; OR (95% CI)			
	18–39 yr	40–59 yr	≥ 60 yr	≥ 18 yr
Dissemination areas				
Low	4.48 (2.43–8.26)‡	4.47 (2.24–8.9)‡	2.66 (1.30–5.45)†	4.11 (2.79–6.05)‡
Medium–low	1.96 (1.03–3.75)*	1.86 (0.89–3.87)	2.41 (1.17–4.96)†	2.26 (1.51–3.37)‡
Medium–high	2.36 (1.24–4.51)†	1.15 (0.51–2.58)	1.40 (0.64–3.09)	1.72 (1.12–2.65)†
High (reference)	1.00	1.00	1.00	1.00
Census tracts				
Low	3.27 (1.83–5.83)‡	3.25 (1.67–6.33)‡	2.48 (1.41–4.38)†	2.73 (1.93–3.86)‡
Medium–low	1.30 (0.72–2.36)	1.60 (0.79–3.23)	1.55 (0.83–2.89)	1.39 (0.96–2.01)
Medium–high	0.96 (0.46–2.02)	0.86 (0.37–1.98)	0.59 (0.28–1.26)	0.71 (0.45–1.12)
High (reference)	1.00	1.00	1.00	1.00
Modified census tracts				
Low	3.51 (1.96–6.30)‡	4.37 (2.37–8.04)‡	2.94 (1.61–5.36)‡	3.66 (2.59–5.17)‡
Medium–low	2.70 (1.52–4.79)‡	1.57 (0.79–3.13)	1.94 (1.03–3.66)*	2.25 (1.57–3.25)‡
Medium–high	1.78 (0.87–3.64)	1.36 (0.65–2.86)	1.03 (0.49–2.17)	1.48 (0.97–2.27)
High (reference)	1.00	1.00	1.00	1.00
Census subdivisions				
Low	0.40 (0.13–1.19)	3.10 (0.19–51.57)	2.19 (0.58–8.33)	1.53 (0.67–3.50)
Medium–low	1.09 (0.42–2.83)	5.44 (0.34–88.06)	3.93 (1.11–13.92)*	3.12 (1.43–6.82)*
Medium–high	0.39 (0.11–1.37)	4.27 (0.25–72.93)	4.31 (1.13–16.51)*	2.31 (0.99–5.41)
High (reference)	1.00	1.00	1.00	1.00

CI = confidence interval.
*$p < 0.05$
† $p < 0.01$
‡ $p < 0.001$

the OR was similar across age groups (2.24–2.41; Table 6). Similar to observations at the scale of dissemination areas, the OR for prevalence of injury among those less than 60 years of age doubled when moving from census areas classified as having medium–low SES to areas classified as having low SES.

Also at the scale of census tracts, the OR of injury within the same SES category (sexes combined, ages ≥ 18) decreased by 33%–59% versus ORs measured at the scale of dissemination areas. The relation between area SES and incidence pattern of injury among all adult men (Table 6) and women (Table 7) (i.e., ≥ 18 years of age) was statistically significant for the low SES quartile, but not for the remaining SES groups. Areas with medium–high SES consistently exhibited lower OR for injury than the areas in the reference category (i.e., OR < 1).

We observed a greater number of statistically significant relations between area SES and incidence pattern of pedestrian injury when analyzing the data for the modified census tracts. Similar to the analysis for both dissemination areas and census tracts, modified census tracts categorized as having low SES exhibited the greatest OR for injury across all age groups and for both men and women (Tables 6 and 7, respectively) and for both sexes combined (Table 5). With the modified census tracts, the OR for injury increased stepwise along an SES gradient for men and women combined (Table 5). Among men, the OR for injury (all ages) increased from 1.51 in areas classified as having medium–high SES to 3.26 in areas classified as having low SES (Table 6). Among women, the OR increased from 1.40 to 4.13, respectively (Table 7). Using census tracts, which had populations within 1 SD of the modified census tracts, ORs for injury within the same SES category (sexes combined, ages ≥ 18) increased by 34%–108% versus ORs measured using the modified census tracts.

Observations from the census subdivisions were inconsistent with findings from the smaller administrative units. At the scale of census subdivision, the OR for injury among men 18–39 years of age was higher for the reference population than for the other SES groups (Table 6). Among men in all other age groups, a downward trend was observed across SES groups, with OR decreasing from the medium–high to low SES quartiles. For the other population strata, the ORs for pedestrian injury were inconsistent with the findings at all

Table 6: Odds ratios (ORs) for injury of male pedestrians, according to socio-economic status (SES) of the area where the injury occurred, for various geographic units

Geographic unit and SES quartile	Age group; OR (95% CI)			
	18–39 yr	40–59 yr	≥ 60 yr	≥ 18 yr
Dissemination areas				
Low	4.76 (2.18–10.4)*	3.85 (1.52–9.79)†	2.79 (0.89–8.76)	4.93 (2.89–8.42)‡
Medium–low	2.10 (0.93–4.75)	1.39 (0.52–3.75)	2.56 (0.82–8.00)	2.60 (1.50–4.50)‡
Medium–high	2.45 (1.07–5.63)*	0.95 (0.33–2.72)	0.89 (0.25–3.15)	1.74 (0.96–3.15)
High (reference)	1.00	1.00	1.00	1.00
Census tracts				
Low	2.24 (1.06–4.74)*	2.41 (1.04–5.60)*	2.30 (0.99–5.34)	2.33 (1.45–3.74)‡
Medium–low	0.86 (0.40–1.85)	1.13 (0.48–2.68)	1.87 (0.79–4.44)	1.26 (0.77–2.04)
Medium–high	0.89 (0.36–2.20)	0.74 (0.27–2.04)	0.76 (0.25–2.28)	0.75 (0.42–1.35)
High (reference)	1.00	1.00	1.00	1.00
Modified census tracts				
Low	2.67 (1.24–5.72)*	3.65 (1.73–7.67)‡	2.61 (1.07–6.39)*	3.26 (2.06–5.16)‡
Medium–low	2.11 (1.02–4.34)*	1.16 (0.50–2.67)	2.07 (0.83–5.13)	2.08 (1.30–3.32)†
Medium–high	1.61 (0.66–3.90)	1.40 (0.56–3.45)	1.19 (0.42–3.41)	1.51 (0.87–2.61)
High (reference)	1.00	1.00	1.00	1.00
Census subdivisions				
Low	0.28 (0.08–0.99)*	2.59 (0.15–43.52)	1.35 (0.23–7.96)	1.27 (0.47–3.45)
Medium–low	0.59 (0.20–1.75)	2.64 (0.16–43.26)	4.03 (0.78–20.71)	2.22 (0.86–5.71)
Medium–high	0.34 (0.09–1.39)	3.70 (0.21–64.75)	4.78 (0.84–27.14)	2.24 (0.80–6.25)
High (reference)	1.00	1.00	1.00	1.00

CI = confidence interval.
* $p < 0.05$
† $p < 0.01$
‡ $p < 0.001$

other geographic scales, across both SES quartiles and age groups.

Interpretation

Through this analysis, we have shown that the association between disparities in area socio-economic conditions and ORs for pedestrian injury varies according to both the scale of the analysis and how the areal units are partitioned.

Although the ORs for the relation between SES and incidence pattern of pedestrian injuries were highest when measured with the dissemination area boundaries, we obtained the most consistent evidence of a stepwise socio-economic gradient in incidence patterns of pedestrian injury with the modified census tracts. We observed the same pattern in the data at the scale of dissemination areas, but with fewer statistically significant results. At the scale of census tracts, the data provided evidence of a dichotomous rather than graded relation between area SES and pedestrian injury. However, at the municipal scale (i.e., boundaries of census subdivisions) there was a positive relation between area SES and injury. These results suggest that the relation between area SES and pedestrian injury is highly susceptible to both the scale and the zoning effect of the modifiable areal unit problem.

Although we have shown that a population-wide relation between area SES and incidence pattern of injury is susceptible to the modifiable areal unit problem, we were unable to assess this relation at the scale of the individual because socio-economic data corresponding to individual patient records are not available through the British Columbia Trauma Registry. In this situation, a multilevel model could have been used to identify the amount of variation between SES and incidence patterns of pedestrian injuries at the various spatial scales.[45–47] However, as with many registry databases, the British Columbia Trauma Registry contains no information for patient-level socio-economic factors, such as income, employment status, level of education or family structure. This limitation is common to most studies that use data from trauma registries and leads to a reliance on data from the census to determine the effects of place on injury. Appropriately, many such studies cite the limitations inherent to inferring individual-level relationships from ecological data, but they do not discuss the susceptibility

Table 7: Odds ratios (ORs) for injury of female pedestrians, according to socio-economic status (SES) of the area where the injury occurred, for various geographic units

Geographic unit and SES quartile	Age group; OR (95% CI) 18–39 yr	40–59 yr	≥ 60 yr	≥ 18 yr
Dissemination areas				
Low	4.00 (1.55–10.32)†	3.95 (1.46–10.64)†	2.33 (0.94–5.78)	3.36 (1.92–5.87)‡
Medium–low	1.76 (0.63–4.88)	1.71 (0.60–4.88)	1.81 (0.72–4.55)	1.80 (1.00–3.23)*
Medium–high	2.40 (0.88–6.50)	1.13 (0.33–3.93)	1.78 (0.67–4.74)	1.88 (1.01–3.50)*
High (reference)	1.00	1.00	1.00	1.00
Census tracts				
Low	4.92 (2.04–11.88)‡	4.50 (1.59–12.77)†	2.50 (1.18–5.31)†	3.15 (1.89–5.25)‡
Medium–low	1.98 (0.79–4.96)	2.29 (0.73–7.17)	1.16 (0.46–2.92)	1.41 (0.80–2.50)
Medium–high	0.87 (0.24–3.08)	1.08 (0.27–4.36)	0.52 (0.19–1.42)	0.59 (0.29–1.19)
High (reference)	1.00	1.00	1.00	1.00
Modified census tracts				
Low	4.99 (2.05–12.18)‡	3.89 (1.36–11.10)*	3.10 (1.40–6.85)†	4.13 (2.44–6.97)‡
Medium–low	3.66 (1.46–9.19)†	1.47 (0.46–4.72)	1.79 (0.74–4.34)	2.27 (1.28–4.02)†
Medium–high	1.97 (0.61–6.35)	1.00 (0.29–3.47)	0.92 (0.33–2.54)	1.40 (0.72–2.73)
High (reference)	1.00	1.00	1.00	1.00
Census subdivisions				
Low	0.64 (0.09–4.35)	0.61 (0.03–11.34)	2.45 (0.44–13.72)	1.75 (0.46–6.63)
Medium–low	2.48 (0.48–12.77)	2.89 (0.18–47.58)	2.76 (0.54–14.24)	4.33 (1.23–15.22)†
Medium–high	0.42 (0.04–4.02)	1.00 (0.05–19.29)	2.91 (0.49–17.21)	2.09 (0.53–8.32)
High (reference)	1.00	1.00	1.00	1.00

CI = confidence interval.
* $p < 0.05$
† $p < 0.01$
‡ $p < 0.001$

of more robust models, such as multilevel or hierarchical models, to the geographic bounding parameters used to contextualize the effects of place on injury. As the current study has demonstrated, reorganizing areal data introduces another level of variation.

In addition, attention must be given to the locations of injuries whenever geographic boundaries have been imposed on dependent variables. Areas that are close together tend to have similar characteristics (i.e., they are autocorrelated), which increases the likelihood of type I error, because the assumption of independence among the dependent variables cannot be sustained.[48] One approach is to measure the level of spatial autocorrelation between the injury locations.[27,28] This approach has been used to both justify the selected regression model and to identify the effects of place on injury.[43,49]

Although measurement of spatial autocorrelation can be used to specify the regression model, the residuals in the regression of spatial data are typically an artifact of the model (e.g., linear, logistic or Poisson regression), which assumes that observations are independent of their location.[50] One technique to minimize this limitation, which is receiving increasing attention in epidemiologic studies, is geographically weighted regression.[51] This type of regression allows researchers to identify if there is any inherent local variation in SES and to determine the frequency of injury on an area-by-area basis, similar to multilevel models. This in turn allows researchers to quantify how different hypothesized effects of incidence patterns of injury vary from one area to another in response to the same stimuli. Using this technique, researchers might be able to generate meaningful information about how population-level factors, such as neighbourhood cohesion or residential zoning, may influence pedestrian injury patterns on an area-by-area basis, thus effectively reducing problems associated with the modifiable areal unit problem. One caveat, however, is that extensive data are required to obtain reliable parameter estimates from geographically weighted regressions. This often means that data from databases with low counts cannot be subclassified by injury mechanism (e.g., assault, falls, motor vehicle), which removes critical information from the analysis.

The difficulties associated with the modifiable areal unit problem should be interpreted as being applicable to all analyses of injury data derived from administrative boundaries. Researchers should carefully consider the geographic variability inherent in the analysis when they rely on the census to measure the effects of place on injury. Increasing attention has been paid to the socio-economic risk factors of the urban environment that increase the likelihood that pedestrians will be injured.[37] For example, unemployment has a direct link to community wealth and the ability to determine, in part, local access to health care services, as well as the means to pay for goods such as pedestrian traffic lights and safe playgrounds.[52] As this analysis has demonstrated, hypothesized effects of the influence of the built environment on the effects of place on injury are best observed using small-area boundaries of the census, but researchers should be aware of the inherent variability that remains even among the more homogeneous population scales.

In many analyses, reliance on the smallest areal units provided by the census has a tendency to introduce rate instability, because the base population used to derive the rate is relatively small and more variable. Larger census units, such as census tracts or wards, provide a more stable base population but may also mask meaningful geographic variation, which becomes evident when health outcomes are mapped with smaller dissemination or enumeration areas.[33] However, it is difficult—if not impossible—to generalize the effects of the modifiable areal unit problem from one dataset to another. A priori frameworks for analyzing the effects of place on risk of injury are required. However, such frameworks, which must be rigorously tested, are rarely made explicit in analyses of socio-economic risk factors associated with occurrence of injury. The results of this analysis illustrate the variability when different administrative boundaries are applied as proxy measures of area or individual socio-economic position.

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