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Multilevel models for evaluating the risk of pedestrian-motor vehicle collisions at intersections and mid-blocks

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Abstract

Walking is a popular form of physical activity associated with clear health benefits. Promoting safe walking for pedestrians requires evaluating the risk of pedestrian-motor vehicle collisions at specific roadway locations in order to identify where road improvements and other interventions may be needed. The objective of this analysis was to estimate the risk of pedestrian collisions at intersections and mid-blocks in Seattle, WA. The study used 2007-2013 pedestrian-motor vehicle collision data from police reports and detailed characteristics of the microenvironment and macroenvironment at intersection and mid-block locations. The primary outcome was the number of pedestrian-motor vehicle collisions over time at each location (incident rate ratio [IRR] and 95% confidence interval [95% CI]). Multilevel mixed effects Poisson models accounted for correlation within and between locations and census blocks over time. Analysis accounted for

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pedestrian and vehicle activity (e.g., residential density and road classification). In the final multivariable model, intersections with 4 segments or 5 or more segments had higher pedestrian collision rates compared to mid-blocks. Non-residential roads had significantly higher rates than residential roads, with principal arterials having the highest collision rate. The pedestrian collision rate was higher by 9% per 10 feet of street width. Locations with traffic signals had twice the collision rate of locations without a signal and those with marked crosswalks also had a higher rate. Locations with a marked crosswalk also had higher risk of collision. Locations with a one-way road or those with signs encouraging motorists to cede the right-of-way to pedestrians had fewer pedestrian collisions. Collision rates were higher in locations that encourage greater pedestrian activity (more bus use, more fast food restaurants, higher employment, residential, and population densities). Locations with higher intersection density had a lower rate of collisions as did those in areas with higher residential property values. The novel spatiotemporal approach used that integrates road/crossing characteristics with surrounding neighborhood characteristics should help city agencies better identify high-risk locations for further study and analysis. Improving roads and making them safer for pedestrians achieves the public health goals of reducing pedestrian collisions and promoting physical activity.

INTRODUCTION

"Walk to be healthy. Walk to be happy." – Charles Dickens

Walking is a popular form of physical activity associated with clear benefits for physical and mental health (Murtagh *et al.* 2014). To facilitate safe walking, public health experts, traffic engineers, urban planners, and health care providers seek to create walker-friendly environments, including ameliorating road crossing locations where walkers are at high risk of being struck by a motor vehicle (Ameratunga *et al.* 2006, Rydin *et al.* 2012). Determining which crossings and environmental characteristics are associated with risk for pedestrian collisions can help city transportation and planning officials to prioritize the locations of roadway improvements (Miaou and Song 2005). Studies estimating the risk of pedestrian collisions citywide are an important public health tool to perform site-specific assessment and amelioration of risk.

1.1 Identifying Locations at High Risk for Pedestrian Collisions

An extensive literature has identified locations at high risk for motor-vehicle collisions (Lord and Mannering 2010) but less attention has been given to crossing locations at high risk for pedestrian-vehicle collisions (Brüde and Larsson 1993, Lyon *et al.* 2002, Morency and Cloutier 2006, Pulugurtha *et al.* 2007, Schuurman *et al.* 2009, Lord and Mannering 2010, Miranda-Moreno *et al.* 2011, Moudon *et al.* 2011, Gladhill and Monsere 2012, Chen *et al.* 2013, Mannering and Bhat 2014, Strauss *et al.* 2014). Pedestrian collisions occur more frequently in areas with both higher pedestrian volumes and higher vehicle volumes due to the increased opportunities for pedestrian-vehicle conflicts (Lyon and Persaud 2002). There may be safety in numbers as higher pedestrian volume may eventually decrease the risk of collision (Leden 2002, Elvik 2009). Proxy characteristics for pedestrian activity, such as urban design and land use characteristics (e.g. population or employment density) are associated with a higher risk of pedestrian collisions (Harwood *et al.* 2008). Collision risk may be lower in walkable areas, such as those with higher intersection density and smaller street-blocks (Ewing *et al.* 2003). Furthermore, higher vehicular speeds greatly increase the risk of severe or fatal injury resulting from collisions (Rosen *et al.* 2011, Tefft 2013, Kröyer *et al.* 2014). Vehicle speeds over 20 MPH in areas with high pedestrian activity likely lead to a higher frequency of pedestrian collisions and fatalities.

The microenvironment around a crossing location is an important determinant of pedestrian collision risk. Certain microenvironment characteristics may attract pedestrians (e.g., bus stops) or deter them (e.g., vacant lots), thus affecting pedestrian volumes. Other factors may either increase or decrease pedestrian collision risk by modifying crossing safety, such as marked crosswalks, sidewalks, and traffic control devices. Evaluating the relationship of a specific road characteristic without accounting for other characteristics can lead to biased results, thus multivariate regression models are an important tool for assessing collision risk (Mannering and Bhat 2014). For example, marked crosswalks, meant to designate a safe crossing area for pedestrians, have been paradoxically associated with increased risk of pedestrian collisions (Koepsell *et al.* 2002). The effectiveness of a crosswalk varies greatly based on its location, vehicle speed, signal controls, number of lanes, and road user behaviors (Koepsell *et al.* 2002, Zegeer *et al.* 2005, Leden *et al.* 2006, Mitman *et al.* 2008, Chen *et al.* 2013), and without examining those other characteristics, it is difficult to understand why crosswalks might increase pedestrian collision risk. Traffic control is another important factor associated with pedestrian collisions that has been examined in detail, particularly for managing turning vehicles and conflicts with pedestrians. Additional potentially important factors associated with pedestrian collisions at intersections and midblock pedestrian crossings, are intersection geometry (number of intersecting segments), traffic direction (one-way or two-way), and the presence of medians, sidewalks, and vehicle parking (Miranda-Moreno *et al.* 2011, Moudon *et al.* 2011, Vasudevan *et al.* 2011, Ukkusuri *et al.* 2012, Chen *et al.* 2013, Elvik *et al.* 2013, Pratt *et al.* 2013, Dong *et al.* 2014, Schorr and Hamdar 2014, Quistberg *et al.* 2015).

1.2. Random Effects Models with Spatial and Temporal Correlation

There are at least two challenges when constructing pedestrian collision models to identify high-risk crossings. First, detailed data to describe the built environment around crossing location are often limited. The relative paucity of detailed data on the built environmental data may be addressed through field data collection or virtual approaches (Rundle *et al.* 2011), though this is resource and time intensive. Fortunately, more detailed and smaller spatial scale information of the microenvironment at specific locations, including modifications over time, is increasingly available (Miranda-Moreno and Fernandes 2011, Moudon *et al.* 2011).

Another important limitation to identifying high-risk locations is the relative rarity of pedestrian collisions. This often leads to simply aggregating collisions at specific locations across multiple years, even though spatiotemporal changes (e.g., in road characteristics, road user behaviors, or between-location differences in the distribution of collisions over time, etc.) may occur at the locations. Analysis of aggregate annual data that do not account for such changes can produce incorrect risk estimates (Li *et al.* 2008, Aguero-Valverde and

Jovanis 2010, Lord and Mannering 2010), and may have to be limited to cross-sectional analysis that reduces the ability to infer collision causes.

Statistical models with mixed fixed and random effects (or parameters) that are able to account for spatiotemporal correlation can help overcome this limitation. Such modeling is now facilitated by improved statistical software and computing ability (Lord and Mannering 2010, Mannering and Bhat 2014). While several studies have used such statistical approaches, most have focused on small geographic areas, such as road corridors, census units or postal codes rather than on specific road locations like intersections or mid-block crossings within a larger transportation area such as a large city (Shankar *et al.* 2003, MacNab 2004, Narayanamoorthy *et al.* 2013, DiMaggio 2015). This is likely due to the burden of collecting precise data at all road or crossing locations or the lack of available data at these locations. Small-area estimates can only provide useful information on pedestrian safety by area within cities, counties, or states, but not by specific collision location.

1.3 Study Objectives

The objective of this study was to assess the risk of pedestrian collisions at intersections and mid-blocks for an entire major U.S. city, using detailed spatiotemporal built environment data and statistical methods to account for spatiotemporal correlation. Our analyses incorporated detailed intersection and road segment descriptions as well as descriptions of the micro- (e.g., crosswalk) and the macro-environment (e.g., residential density) around each collision location over time. Our analysis focused on available built environment features, but did not examine any behavioral (e.g., jaywalking) or situational (e.g., time of day or weather) characteristics of pedestrian collisions. We hypothesized that pedestrian collisions were more likely to occur on arterial roads with complex road design and with surrounding built environments that encourage higher pedestrian activity. We also expected to observe a higher pedestrian collision rate at sites with different combinations of higher vehicle volumes, higher observed vehicle speeds, turning lanes, vehicle parking lanes, and wider streets. We hypothesized that pedestrian-friendly environmental features such as traffic circles, green spaces, higher residential property values, and sidewalk density would be associated with lower pedestrian collision rates.

2. METHODS

2.1. Study Design and Population

We conducted a retrospective, longitudinal analysis of collisions at all intersection and mid-block locations within the city limits of Seattle, Washington, USA. Seattle is located in the northwest USA and has a population of 662,400 (2015). Two major interstate highways bisect the city, one north-south, and another east-west (Figure 1). Using road network data from the city geographic information system (GIS), we identified road segments (road polylines drawn between intersections or endpoints), intersections (two or more intersecting road polylines), *cul-de-sacs* (road network end-point, road with no outlet, or “dead end” road), and mid-blocks (road polyline centerpoints). We excluded grade-separated road segments (e.g., interstate highways and ramps) from analysis because they lacked pedestrian access.

2.2. Measurements

2.2.1 Outcome—The primary outcome was the number of pedestrian-motor-vehicle collisions reported to the Seattle Police Department between January 1, 2007 and July 31, 2013. Each collision was counted as one incident, irrespective of the number of pedestrians involved or whether injury occurred. Police investigators identified the location of each collision, which the Seattle Department of Transportation (SDOT) geocoded to the intersection or mid-block centerpoint on the road network. Because collisions were geocoded to these centerpoints independently from the road segments, analysis at the road segment level was not possible (e.g., at a specific crossing location within an intersection) and the data were aggregated to intersection and mid-block locations.

2.2.2 Risk Factors—We considered a number of microenvironment and macroenvironment factors to estimate the risk of pedestrian collisions at each identified intersection and mid-block location.

2.2.2.1 Microenvironment Factors: We defined the microenvironment as characteristics that were in the immediate vicinity of intersections or mid-block locations as defined by a 25-meter radius circular buffer around each location. The majority of these factors originated from SDOT geodatabases, including the following: traffic lanes, traffic circles, traffic signals, road signs, vehicle volumes (annual average weighted daily traffic, AAWDT), posted and observed vehicle speed, marked pedestrian crosswalks, and sidewalks. A detailed description of how attributes were created and categorized for the analysis is in Appendix Table 1. While bicycle collisions were not considered in this analysis, we did include presence of bicycle lanes as a potential risk factor for pedestrian collisions.

Each road segment was classified by the SDOT as private, local/residential, collector, minor arterial, major arterial, or highway. Because an intersection may include several different intersecting road classes, we chose five mutually exclusive intersection classes to describe these potential combinations: local (residential or private roads); collector-local; minor arterial-other (collector and/or local); principal arterial-other (minor arterial, collector, and/or local); and highway-other (principal arterial, minor arterial, collector and/or local).

Intersection and mid-block collision points were spatially matched to road characteristics located within a surrounding 25-meter circular buffer. Collision locations typically contained multiple units of a given characteristic (e.g., multiple crosswalks). To evaluate the effect of multiple units of a characteristic at a given site, we created several types of analytical variables. These included: 1) a count variable indicating how many of each characteristic were joined to an intersection/mid-block point, 2) an indicator variable indicating the presence or absence of a characteristic, and 3) categorical variables for characteristics with mutually exclusive categories (e.g., type of traffic control signal) (Appendix Table 1). Indicator variables generally provided better fit and interpretation.

2.2.2.2 Macroenvironment Factors: Macroenvironment factors represented the built environment (BE), urban design, and land use characteristics of "neighborhoods" surrounding each intersection and mid-block location. These characteristics included residential and employment density, residential property values, office land use, parks, fast-food restaurants, intersection density, sidewalk density, daily bus ridership and terrain slope. The characteristics were captured using SmartMaps and a custom-built tool developed for previous studies in ArcGIS 10.2 ModelBuilder (ESRI Inc, Redlands, CA). SmartMaps are raster datasets whose values represent localized measures of built environment and land-use characteristics (Hurvitz *et al.* 2014). To produce SmartMaps, we created a grid of 30 by 30 m cells over the Seattle area. For each focal cell, values of individual BE characteristics were assigned as the sum or mean of all cell values within a 100 m radius circular buffer from the cell centerpoint. SmartMaps allow efficient measurement of BE characteristics for datasets with a large number of points. Intersection and mid-block geocoded points were spatially matched to a grid cell.

The property parcel GIS created by the King County, Washington, Department of Assessments provided data for residential density (number of units per acre in 2007 and 2010), office land uses (percent of land area occupied by office buildings in 2007 and 2010), parks (percent of land area occupied by parks in 2008), and residential property value (average assessed value of unit per acre in 2007 and 2010). Employment density (number of jobs per acre in 2007 and 2010) was derived by combining the tax assessor data with employment figures from the U.S. Bureau of Labor Statistics (Moudon *et al.* 2010). Intersection density (number of intersections per acre) was calculated using the 2006 King County Department of Transportation GIS road network. Sidewalk density (linear feet of sidewalk per acre) was calculated using data prepared by the Urban Form Lab (Kang *et al.* 2015). Fast food outlet density (number per acre in 2008) was created from geocoded Public Health –Seattle and King County food permits (Moudon et al. 2013). Daily bus ridership (average total daily boardings and alightings per acre in 2008) was acquired from King County Department of Transportation, Metro Transit Division. Slope (% of land area that is ≥ 5 degrees) was acquired from U.S. Geological Survey National Elevation Dataset (Gesch *et al.* 2002, Gesch 2007). Residential density, residential property values, intersection density, sidewalk density, fast food outlet density, bus ridership density, and employment density were all normalized by the land area (in acres) that fell within the 100m circular buffer. This normalization was done in order to account for locations that are close to water bodies.

We included sociodemographic data from the US Census 2010 at the block level including total population, sex, age, and race and ethnicity. To estimate these characteristics around intersection/mid-block, a 100m circular buffer was created around each location. We determined what proportion of each surrounding census block was within the buffer to calculate an area-weighted arithmetic mean for each characteristic of interest. We initially also examined household income and transportation modes for work (e.g., driving, walking, etc.) from the American Community Survey (ACS) 2008-2012 at the tract level. Neither variable, however, was associated with collisions and nesting intersections/mid-blocks within the tract level did not improve estimates significantly, thus household income and work transportation modes were not included in analyses.

2.2.3 Spatiotemporal Correlation—Most characteristics remained constant throughout the study time period, but we created two time periods for analysis based on when the majority of the few observed changes occurred: January 1, 2007 to December 31, 2009 and January 1, 2010 to July 31, 2013. Changes were assessed for the microenvironment characteristics by examining the dates of when a characteristic was installed and last modified. A road characteristic was considered present if it had been installed or modified by the beginning of each of the time periods. For changes in the macroenvironment around each intersection/mid-block, we used 2007 data for 2007-2009 and 2010 data for 2010-2013 for residential density, employment density, and residential property values.

2.3 Statistical Analysis

We first considered a binary outcome at each location: no collision vs. one or more pedestrian vehicle collisions anytime during the study time period (2007-2013). We examined the univariate association between environmental factors and this binary collision outcome, using Stata13MP software (StataCorp LP, College Park, TX). Next we used multilevel, mixed-effects Poisson regression to estimate the univariate incident rate ratio (IRR) and robust 95% confidence intervals (95% CI) for the association of factors of interest and the number of pedestrian vehicle collisions which occurred during the study period. In multilevel analyses, within-location correlation over time was accounted for by nesting variables within location considering time as the exposure in the models. While we explored several variables whose values changed over time as random parameters, we did not observe significant differences within locations and did not include them in the final model.

In order to identify risk and protective factors, we examined the joint associations of pedestrian, vehicle, and environmental factors with pedestrian collision rates in multivariable models. To produce the best-fit model, we initially included all variables in a main effects model. We used a manual stepwise procedure to remove variables with weak association with pedestrian collisions repeating this process until the most parsimonious, best-fitting model was found using Akaike's and Schwarz's Bayesian information criteria (AIC and BIC, respectively). We compared likelihood ratios in this parsimonious model to the full main effects model. Any additional variable associated with pedestrian collision outcomes in the univariate model (P value<0.25) was added back to the parsimonious analytical model. The variable was retained if the addition resulted in a significant (>10%) change in the estimated association of other retained variables and the likelihood ratio of the models (P<0.05). Based on findings from previous studies, we explored potential effect modification by stratifying analyses by intersection or mid-block status and road classification, but did not find significant effect modification (data not shown). We observed a high correlation between Census Block population and residential density and examined an interaction term in the final multivariable model, which was statistically significant (P value=0.045).

Controlling for pedestrian and vehicle volumes is important in assessing pedestrian risk. For vehicle volume, annual average weighted daily traffic (AAWDT) was available for most arterial roads, but was not available for most residential roads, and so we considered road classification, road geometry and road width as proxy measures of vehicle volume. To determine how well these characteristics functioned as a proxy for vehicle volume, we conducted a sensitivity analysis for sites where both AAWDT and proxy measures were available (not shown), and found road classification was preferable to AAWDT for predicting pedestrian collision risk. No reliable counts of pedestrian volumes were available citywide for most of the time period. We considered several proxy measures for pedestrian volumes, including total population (census blocks in 2010), residential density (2007 and 2010), employment density (2007 and 2010) and bus ridership (2007 and 2010) (Handy *et al.* 2002, Frank *et al.* 2005a, Hess *et al.* 2007, Hirsch *et al.* 2013).

2.4 Pedestrian Count Prediction and Kernel Density Map

Using the final model, we predicted the number of pedestrian collisions expected at each location in post-estimation tests in order to create a visualization of high density collision areas. To predict the expected counts, an empirical Bayes means (posterior means) process was used that calculates using an inverse link function applied to the linear prediction, and that includes both fixed and random effects. The expected counts were exported to ArcGIS 10.2, in which the Kernel Density tool was used to create a density map of sites displaying relatively low and high expected pedestrian collision counts. A range of 0.25 kilometers was used to define the kernel bandwidth using the Epanechnikov functional form (the ArcGIS 10.2 default).

2.5 Ethics and role of funding source

The Institutional Review Board at Seattle Children's Research Institute approved this study. DAQ was supported by the Eunice Kennedy Shriver National Institute of Child Health and Human Development of the National Institutes of Health. The funding source for this study had no role in the decision to interpret or publish study results.

3. RESULTS

3.1 General characteristics

There were 15,363 intersections and 21,997 midblock locations included in this study. From 2007 to 2013, there were 2,695 pedestrian collisions (65% at intersections and 35% at mid-blocks).

3.2 Univariate analysis

Collision locations with more complex road features (e.g., multiple road segments, truck routes, traffic signals, and multiple lane types) were significantly more likely to experience pedestrian collisions, based on univariate analysis (Table 1). Locations at roads designed for heavier vehicle traffic volumes, such as principal arterials, had a higher risk of pedestrian collisions compared to residential roads. Locations at more complex intersections (3 or more segments) had a higher rate of collisions. Locations with higher speed roads, whether determined by measured or posted speed, had a slightly higher risk of pedestrian collisions, as did wider segments. Locations in areas with more proxy factors for pedestrian exposure had slightly higher risk of pedestrian collisions, including areas with higher bus ridership, employment density, and office uses. Furthermore, areas with more bus ridership, fast food restaurants, and office uses were more likely to experience a pedestrian collision than locations in areas with more residences, park space, steeper slopes and higher property values.

3.3 Factors Increasing Risk for Pedestrian Collisions

In the multivariable mixed effects model, there was significant variation between locations (0.83, 95% CI 0.69-1.00). Many factors that were statistically significant in the univariate analysis were not included in the final model as their impact was likely captured by other model variables (Table 2). At the microenvironment level, road classification was the factor most strongly associated with pedestrian-vehicle collisions: principal arterial locations had a pedestrian collision incident rate five times higher when compared to local/residential roads. Intersections with 4 or 5 or more segments experienced nearly 2.5 times the collision rate than did mid-blocks. Wider streets were also associated with higher collision rates. Compared to locations with no traffic control features, locations with a traffic circle or yield sign did not have significantly different collision rates. Locations with traffic signals had a collision rate nearly twice that of places with no traffic control. Locations that had roads with two-way center turn lanes had slightly higher collision rates. Locations with crosswalks also had higher rates of collisions. The locations with bus stops, bus only traffic lanes, some types of parking signs, and photo enforcement had slightly higher collision rates. In terms of the macroenvironment, the rate of pedestrian collisions increased by 12% per 5 daily bus passenger boardings and alightings per acre. Each additional fast food restaurant per acre resulted in a 74% increase in the collision rate. More jobs and a higher percentage of land area in office use also had higher collisions rates. For every 5 residential units per acre, the collision rate increased 10% and for every 100 population, it increased 7%. Areas with higher proportions of Hispanic, non-Hispanic Black and non-Hispanic Asian populations had slightly higher collision rates.

3.4 Factors Reducing Risk for Pedestrian Collisions

Cul-de-sacs and road curves had significantly lower collision rates compared to mid-blocks. The presence of a one-way road resulted in collision rate 35% lower than two-way roads. Compared to locations with no traffic control, only those with stop signs had significantly lower collision rates. Locations with signs warning motorists to cede the right of way to pedestrians had a 40% lower collision rate. Stop sign locations had a collision rate 14% lower than those with no traffic control. Areas with higher street connectivity (i.e., more intersections per acre) were significantly less likely to have pedestrian collisions. Locations in areas with higher valued residential properties were less likely to experience pedestrian collisions. Speed bump signs, school zone signs, or turning prohibitions were not statistically associated with pedestrian collision rates.

3.5 Kernel Density Visualization

The kernel density map visually reflects the multilevel model results and the expected occurrence of collisions. The map indicates higher pedestrian collision risk along primary arterials, and higher risk in downtown locations and near larger commercial centers (Figure 1).

4. DISCUSSION

Our study provided a multivariable, multilevel, longitudinal perspective on risk factors for pedestrian collisions in a large city from 2007 to 2013. This study examined modifiable risk and protective factors of pedestrian collisions using detailed spatiotemporal environmental data, including both road characteristics as well as information about the surrounding neighborhoods. There were novel findings with some confirmations of previous research on pedestrian collision risk factors. As others have found, pedestrian collision risk was higher at locations with complex road configurations and features (Moudon *et al.* 2011). Locations with traffic signals had a higher rate of pedestrian collisions compared to no traffic control or other traffic control types (Elvik *et al.* 2013, Strauss *et al.* 2014). This finding may indicate potential limitations of engineering approaches to pedestrian safety and to the need to consider behavior changes (e.g., motorists respecting the right-of-way of pedestrians) and enforcement of traffic codes to reduce the risk of collisions (e.g., enforcement of speed limits). Consistent with previous studies, pedestrian collision rates were nearly doubled in locations with marked crosswalks (Koepsell *et al.* 2002, Zegeer *et al.* 2005, Mitman *et al.* 2008). Locations in areas that likely have higher pedestrian activity due to more businesses (i.e., higher employment and fast food density), higher residential density, and more bus use had higher pedestrian collision rates, similar to findings in previous studies (Lightstone *et al.* 2001, Kim *et al.* 2006, Miranda-Moreno *et al.* 2011, Moudon *et al.* 2011). Areas with higher proportions of non-Hispanic blacks or other races also experienced higher collision rates, which may be the result of greater pedestrian activity in these neighborhoods (Cottrill and Thakuriah 2010). Future approaches to improving safety should focus on areas with higher pedestrian activity and ensure equitable improvements in safety.

We also observed several protective factors whose presence was associated with a lower pedestrian collision rate. Locations with one-way roads had a lower collision rate relative to those with two-way roads. While one-way roads may lead to increased vehicles speeds, thus perhaps resulting in more risk to pedestrians (Heydari *et al.* 2014), they may help pedestrians scan for oncoming vehicles more easily because they come from only one direction (Persaud *et al.* 1997, Stemley 1998). Pedestrians may also avoid taking the risk of crossing one-way streets with higher traffic speeds. However, for special populations, such as child pedestrians, one-way roads may present higher risk because of the typically higher vehicular speeds and wider right-of-way (Wazana *et al.* 2000, Rothman *et al.* 2014). Locations with signs warning motorists to watch for pedestrians or encouraging motorists to stop for pedestrians had a lower risk of pedestrian collisions. This novel finding may indicate that visual cues to motorists may be effective in helping them to be more aware of and to stop for pedestrians. We also found that locations where right or left turns were not permitted had a lower collision rate, similar to previous studies, which suggested that road designs offering multiple choice for drivers had a negative effect on pedestrian safety (Shahla *et al.* 2009, Chen *et al.* 2015). There was an inverse relationship between macroenvironment area intersection density and pedestrian collisions. Areas with more intersections were found to be safer and are considered more walkable because they provide more direct, hence shorter, routes to destinations (Ewing *et al.* 2003). Similar to prior studies, we found that areas with higher residential property values were less likely to have pedestrian collisions (Morency *et al.* 2012, DiMaggio 2015). This could be another proxy for pedestrian activity since lower-income populations may have higher rates of walking (Santos *et al.* 2011).

This study highlighted some advantages of using public geospatial databases and models that control for spatiotemporal correlation. Similar to prior studies, we demonstrated that extensive fieldwork could potentially be avoided by taking advantage of various detailed geospatial local government data to assess built environment at both micro- and macro-environmental levels in relation to road safety (Lee and Abdel-Aty 2005, Miranda-Moreno *et al.* 2011, Moudon *et al.* 2011, Chen *et al.* 2013). Using detailed government data on road safety and the environment helps expand the number of sample locations to those of an entire city, county or state for evaluating specific changes (Chen *et al.* 2013, Richmond *et al.* 2014, Chen *et al.* 2015). This approach could be used to identify problematic locations in a city or region that could then be examined more thoroughly in terms of infrastructure, environment and road user behaviors. Second, we used multilevel models with fixed and random parameters to account for both changes within individual locations over time and for area clustering. Multilevel modeling is time and computationally intensive, but it provides reduced bias because it controls for correlated data while allowing the exploration of differences within and between clusters (Lord and Mannering 2010, Mannering and Bhat 2014). A potential weakness of multilevel analysis is its generalizability to other datasets, as well as the difficult in interpreting causality (Diez-Roux 2000, Gelman 2006). The generalizability of multilevel analysis depends on how representative or similar the study population is to the population to which the findings are being generalized.

We provided a visualization of the expected density of pedestrian collisions in Seattle based on the model results. This type of visualization may serve policy purposes by pointing to locations with higher frequency of collisions and to areas that are in greatest need of evaluation for safety improvements (Matthews *et al.* 2009). This visualization tool can also help facilitate the translation and dissemination of research results for wider audiences (Mabry *et al.* 2008).

This study has limitations. As indicated in the methods, we had no direct measure of pedestrian or motor-vehicle activity at all locations. Accounting for pedestrian and vehicle densities is important because the probability of a pedestrian collision increases as both of these densities increase (Elvik 2009). In this study, we used residential, bus ridership, and employment density as proxy variables for pedestrian activity. Other studies have demonstrated a strong association between these proxy measures and observed pedestrian activity (Moudon *et al.* 2004, Badland and Schofield 2005, Frank *et al.* 2005b, Forsyth *et al.* 2007, Adams *et al.* 2014, Knuiman *et al.* 2014). However, these proxy variables do not necessarily account for pedestrian activity at the time of the collision. Our study results may have residual confounding from challenges in controlling for time-dependent pedestrian exposure. For motor vehicle volumes, we relied on road classification and street width as proxy variables in the overall analysis. In a sensitivity analysis we did not observe major differences in the magnitudes of covariate estimates of the final multivariable model using AAWDT where available (N=7,029 locations) compared to the Table 2 model. This may be due to most collisions having occurred on non-residential roads where estimates of AAWDT were available.

Additionally, whereas our analyses included many characteristics of the microenvironment, we could not consider all attributes of the roadway that might have contributed to a collision. Examples include visual obstructions, road construction, or the specific spatial relationship to nearby features outside the 25m and 100m buffers (e.g., nearest crosswalk outside buffer). We also lacked measures of certain types of land uses known to attract pedestrian activity such as entertainment or tourist areas. Such factors, for which data were not available, are potentially important and may affect the relationship between the features studied and pedestrian collisions.

Finally, our analysis lacked situational and behavioral factors for both drivers and pedestrians. These types of factors would be difficult to examine over time and at all of a city's intersections and mid-blocks. Police investigations of the collisions could provide some of these data. However, situational and behavioral factors would also be needed of pedestrians who were not struck by vehicles in order to understand their contributions to pedestrian collisions. The lack of data for a control group would only allow a descriptive analysis of the study cases.

In conclusion, these results present the risk of pedestrian collisions at intersections and mid-blocks using rich, detailed spatiotemporal data on the microenvironment and the surrounding macroenvironment. The findings and methods point to high-risk areas for pedestrians and could guide transportation and urban planning agencies as they consider opportunities to encourage active and safe transportation. Identifying specific high-risk locations can also help cities prioritize resources to conduct studies at these locations and to examine potential risks for pedestrian collisions. The citywide approach may be useful in prioritizing system-wide changes of particular roadway features that consistently have a higher risk of pedestrian collisions. Making roads safer for pedestrians can potentially lead to increases in physical activity and active travel, and to more sustainable transportation options, resulting in long-term health benefits for the urban population. As detailed spatiotemporal data on the built environment become increasingly available, more powerful and frequent studies of pedestrian safety can be implemented to help identify risky areas and road features.

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Appendix

Appendix 1

Description of data sources and variable creation. We refer to geodatabase feature classes or data schema as GIS layer files.

	Description	Source Data	Source Agency	Values
Outcome				
Pedestrian Collisions	Pedestrian collisions were part of a GIS layer file of all motor vehicle collisions in Seattle. The Seattle Department of Transportation (SDOT) geocoded all collisions to either a road network junction (intersection) or road segment centerpoint (mid-block) depending on where the collision had occurred. Due to this coding, all built environment features were matched to intersections and mid-blocks, which were created as described in Location Type.	Motor Vehicle Collisions 2007-2013	SDOT	Continuous Count
Microenvironment	*Microenvironment characteristics were derived from GIS layer files from the Seattle Department of Transportation. We defined the microenvironment as a 25m buffer around each intersection/midblock location for spatially matching road characteristics that were not part of the road network GIS layer file or for when the road network GIS layer file was incomplete. A unique identifier for each intersection and mid-block was used to join spatially matched datasets in statistical software (Stata).*			
Location Type	Location type describes whether the unit of analysis is a mid-block or an intersection location, and if it is an intersection, what its road geometry is. These data originated from the linear and point features of the road network geodatabase. Intersection Creation: The GIS layer file of road network junctions was used to identify intersections. Intersection points were spatially matched to road segments from the road network that intersected road network junctions. The road network GIS layer file was used to input road segment characteristics. A summary count of the number of intersecting road segments was also generated to represent intersection geometry as a cul-de-sac (road segment endpoint), curve (two road segments), 3 road segments, 4 road segments and 5 or more road segments. Mid-block Creation: The GIS layer file of road network segments was used to generate mid-block points from the centerpoint of each road segment. All characteristics of the road segment were attributed to the new mid-block GIS layer file. The intersection and mid-block GIS layer files were merged into one layer file	1)Road network 2013 2)Road network junctions 2013	SDOT	Midblock Cul-de-sac Curve 3Segments 4Segments 5or more segments
Average Annual Weighted Daily Traffic (AAWDT)	Average annual daily traffic volume studies at selected locations. If an intersection had multiple AAWDTs available, we recorded the highest value.	AAWDT 2007-2013	SDOT	Continuous
Observed speed	Speed studies at selected locations, for each direction of traffic. For intersections, we recorded the lowest and highest observed average speeds if multiple speeds studies were available.	Speed studies 2007-2013	SDOT	Continuous
Speed Limit (legal)	A speed limit for each road segment was determined from three potential sources: 1)The road network GIS layer file recorded a legal speed limit for many of the major roads, but not for many residential roads; 2)A GIS layer file of all traffic signs in Seattle indicated where speed limits were posted. Speed limit signs that were posted within a 25m buffer around each point were used to assign a speed limit value to each intersection's road segments and to a mid-block point; 3)If no speed limits were available from source 1 or 2, then the speed limit was determined from the Seattle Municipal Code (Chapter 11.52, http://goo.gl/6sBjKP) by road classification (see below).	1)Road network 2013 2)Traffic Signs 2013 3)Seattle Municipal Code	SDOT	25 MPH or less 30 MPH 35 MPH 40 MPH or more

	Description	Source Data	Source Agency	Values
	At intersections, we examined both its segments' lowest recorded speed limit and Page 39 of 41 highest recorded speed limit. At intersections, we examined both its segments' lowest recorded speed limit and Page 39 of 41 highest recorded speed limit.			
Street Width	Street width was determined from three potential sources: 1)The road network GIS layer file recorded the segment's width for many major roads, but not for many residential roads. 2)The GIS layer of Traffic Lanes recorded characteristics for many major roads. Each lane in a segment was a separate spatial unit (polyline) with its own characteristic, including its width. Traffic lanes with in the 25m buffer of a intersection or mid-block point were spatially matched to the point. Within each point, the total segment width was calculated by adding together all lane widths. 3)If neither the road network or traffic lane layer files had segment widths, the Seattle Right-of-Way Improvements Manual (Chapter 4 http://www.seattle.gov/transportation/rowmanual/manual/4_6.asp) was used to assign width based on road classification and zoning codes. Zoning codes were available in a GIS layer file to identify the specific zone for a segment. For intersections, we used the maximum leg width for analysis.	1)Road Network 2013 2)Traffic Lanes 2013	SDOT	Continuous
Road Classification	To determine a road class for an intersection or mid-block point, we first determined the road class of each segment using 3 characteristics of the road network GIS layer file: 1)Network Class (Alias Street, Local Street, Major Street, State Highway, Interstate Highway) 2)Street Code (Open Public Street, Divided Public Street, Parks, Freeways & Freeway Ramps, Private Street) 3)Arterial Class (Not Designated, Principal Arterial, Minor Arterial, Collector Arterial, State Routes/Highways, Interstate Freeways, County Arterials) A matrix of the 3 attributes at the segment level was used to create the following road classes: Private Road, Local/Residential Road, Collector Arterial, Minor Arterial, Principal Arterial, Highway. For mid-blocks, the segment road class was simply the class of its origin road segment. For intersections, an initial categorization resulted in over 60 unique combinations of road classes depending on how many segments an intersection contained. After thorough examination of the frequencies and relationship to other characteristics, 7 categories of combinations of road classes were decided upon to capture general vehicle volume characteristics. Grade separated highways/freeways/ramp points were excluded.	Road Network 2013	SDOT	Local/Residential/Private Collector-Local Mix Minor Arterial Only Minor-Collector-Local Mix Principal Arterial Only Principal Arterial-Other Mix Highway-Other Mix
One-Way Street	A characteristic of the road network GIS layer file. For intersections, at least one intersecting road segment had to be present for this variable to be marked "yes."	Road Network 2013	SDOT	Y/N
Bike Lanes/Facilities	Attribute of traffic lanes GIS layer file. At intersections, at least one bike lane had to be present to be marked "yes."	Traffic Lanes 2013	SDOT	Y/N
Truck Route	Attribute of road network GIS layer file. At intersections, at least one truck route had to be present to be marked "yes."	Road Network 2013	SDOT	Y/N
Marked Crosswalk	Marked crosswalk presence was determined from 2 GIS layer files: painted crosswalks and signs. For intersections, at least one crosswalk had to be present to be marked "yes."	1)Marked Crosswalks 2013 2)Signs 2013	SDOT	Y/N
Traffic Control	Traffic control type was determined from 3 GIS layer files: traffic signals, traffic circles, and signs. Categories were mutually exclusive and where there	1)Traffic Signals 2013 2)Traffic Circles 2013 3)Signs 2013	SDOT	None Traffic Circle Yield Sign

	Description	Source Data	Source Agency	Values
	were multiple matches to more than one feature, category preference was given to were multiple matches to more than one feature, category preference was given to	traffic signal>stop sign>yield sign>traffic traffic signal>stop sign>yield sign>traffic	circle>none. circle>none.	Stop Sign Traffic Signal
Traffic Lanes	The traffic lanes GIS layer file was used to identify various types of traffic lanes present. Each lane on a segment was a unique spatial unit (polyline). After matching lanes within a 25m buffer of analysis points, a count of the specific type of lanes was completed. Lane types that were similar were merged together into new count variables (e.g., right turn lane 1 and right turn lane 2). The lane types of interest were: Medians (painted or raised) Two-way center turn lanes Left turn lanes Right turn lanes Bus lanes Parking lanes From the count variables, we created an indicator variable of the presence or absence of each type of lane at an intersection or mid-block. While counts were explored initially, there was little statistical difference between the number of each type of lane and whether they were present or not, thus indicator variables were used in the final analysis.	Traffic Lanes 2013	SDOT	Y/N
Signs	The signs GIS layer file identified the types of road signs at intersections and mid-blocks from a classification attribute of over nearly 800 types of signs. Signs that were recorded as present or absent included: Speed Bump Warning Bus Only Lane, Bus Stop No Parking within 30 Feet (intersection) No Parking (including No Stopping) No Peak Parking (hours depend on direction from from downtown) Parking Allowed (Various parking allowed sign types) Paid Parking (Various parking hours & rules) No Left Turns/No Right turns (combined both types of signs) No Pedestrian Crossing Allowed Pedestrian Signal Button Instruction Pedestrian Route or Guide or Informational Sign Pedestrian Warning Sign (for motorists) Photo Enforcement present (both red light and school zone speed) School Zone Warning Sign Reflection An indicator variable was created for each sign for its presence or absence within 25m of the intersection and mid-block points was.	Signs 2013	SDOT	Y/N
Macroenvironment	*These datasets were created by the Urban Form Lab (UFL) at the University of Washington for previous studies. Data are derived from raster datasets that were created using a 30 × 30 m grid of cells overlaid over King County, WA and clipped for this study by the Seattle, WA city limits. Final cell values were calculated as the sum or mean of surrounding cells within a 100 m search radius from the cell centerpoint. Values were normalized for land area within the 100 m radius on a per acre basis. The denominator was the total land area excluding bodies of water. Abbreviations: King County, Department of Transportation (KCDOT) and Department of Assessment (KCAOS), Public Health – Seattle King County (PHSKC), and Bureau of Labor Statistics (BLS).*			
Residential Density	Residential density was calculated from tax assessor data as the number of residential units per acre.	Property Parcel 2007 & 2010	KCAOS	Continuous
Employment Density	Employment density was calculated as the number of jobs per acre using data from the tax assessor and the US Bureau of Labor Statistics.	1)Property Parcel 2007 & 2010 2)Labor Statistics 2007 & 2010	1) KCAOS 2)BLS 3)UFL	Continuous

	Description	Source Data	Source Agency	Values
Mean Property Value	Mean property value per residential unit per acre was calculated from tax assessor data.	Property Parcel 2007 & 2010	KCAOS	Continuous
Office Land Use	Office building parcel area was determined from tax assessor data and was calculated as the proportion of land area occupied by office land uses.	Property Parcel 2007 & 2010	KCAOS	Continuous
Park Land Use	Park area was calculated from tax assessor data as the proportion of land occupied by parks.	Property Parcel 2008	KCAOS	Continuous
Fast Food Density	Using a food permit geodatabase and prior food establishment classifications, we calculated the number of restaurants classified as fast food per acre.	1)Food Permits 2008 2)Food Establishment Classification 2008	1)PHSKC 2)UFL	Continuous
Intersection Density	Intersection density was calculated from King County's road network as the number of intersections per acre. Interstate highways and ramps were excluded.	Road Network 2006	KCDOT	Continuous
Sidewalk Density	Sidewalk density was obtained from the UFL as georeferenced to King County, WA Department of Transportation road network, and density was calculated as linear feet of sidewalk per acre.	Sidewalk Network 2011	KCDOT UFL	Continuous
Bus Ridership Density	KCDOT Metro Transit Division records bus boardings and alightings (B&A) at each bus stop in King County. We calculated the average number of B&A per acre.	Bus Boardings and Alightings 2008	KCDOT	Continuous
Terrain Slope	Terrain slope data were obtained from the National Elevation Dataset of the US Geological Survey and calculated as the proportion of land area that is ≥ 5 degrees.	Elevation Data 2007	USGS NED	Continuous
US Census Block	All US Census Block data were from King County, WA Census 2010 data. Intersection and mid-block points were spatially matched to census block within a 100m buffer. The population values of each matched census block were apportioned according to what proportion of the census block polygon area the intersection/midblock buffer covered.			
Total Population	The census block total population.	Block 2010	US Census	Continuous
Gender	Proportion of people of each gender in the total block population.	Block 2010	US Census	Continuous
Race/Ethnicity	Proportion of people of each non-Hispanic race and those indicating Hispanic or Latino heritage in the total block population.	Block 2010	US Census	Continuous
Under 18	Proportion of the population under the age of 18 years in the total block population.	Block 2010	US Census	Continuous

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HIGHLIGHTS

- Novel spatiotemporal estimate of pedestrian collision rates citywide
- Spatiotemporal model estimated risk at intersections and mid-blocks
- Crosswalks and traffic signals had higher rates accounting for pedestrian activity
- One-way streets and pedestrian warning signs had lower pedestrian collision rates
- Rates were lower in more walkable areas (higher intersection density)

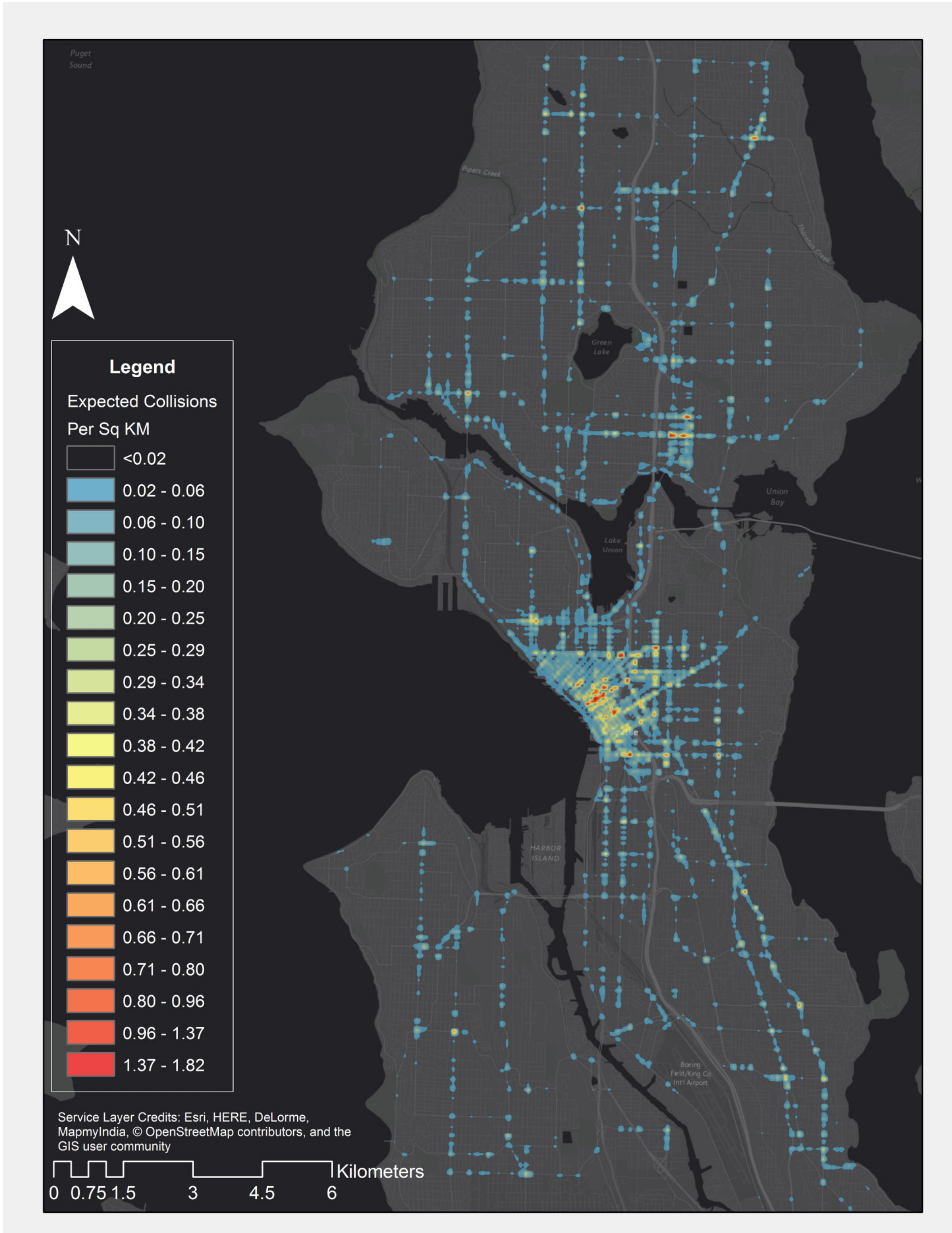

Figure 1.

Kernel density map of predicted counts of pedestrian collisions with a 250 meter kernel buffer.

Table 1

Descriptive statistics by locations with any collisions compared to locations with no collisions 2007-2013. Unadjusted multilevel (location and census block) incident rate ratio (IRR) of pedestrian collision counts and 95% confidence interval (95% CI) for each factor or characteristic.

	Any Collisions N=1,720 Mean (SD) or %	**No Collisions N=35,640 Mean (SD) or %**	**Unadjusted IRR (95% CI)**
Microenvironment Characteristics (25 m area around intersections and mid-block locations)			
Location Type (%)			
Midblock (1 segment)	38	59	Ref
Cul-de-sac (1 segment)	0	5	0.08 (0.03-0.20)
Curve (2 segments)	1	3	0.44 (0.26-0.72)
3 segments	13	16	1.34 (1.13-1.59)
4 segments	44	16	7.43 (6.51-8.49)
5 or more	3	1	19.3 (13.1-28.5)
Avg. Annual Weighted Daily Traffic (Mean, SD)[a]	20,671 (13,688)	19,314 (16,195)	1.05 (1.02-1.09)[b]
Min. Obs. Mean Speed (MPH) (Mean, SD)	31.2 (5.1)	29.9 (5.6)	1.06 (1.02-1.10)
Max. Obs. Mean Speed (MPH) (Mean, SD)	33.5 (5.2)	32.2 (5.8)	1.06 (1.02-1.10)
Maximum Posted Speed (%)			
25 MPH or Less	15	68	Ref
30 MPH	72	27	19.9 (17.1-23.2)
35 MPH	11	3	24.2 (19.1-30.6)
40 MPH or More	2	1	20.5 (13.9-30.4)
Widest Street (Feet) (Mean, SD)	48.1 (13.9)	31.9 (10.9)	2.02 (1.96-2.09)[c]
Road Classification (%)			
Local/Residential/Private	15	69	Ref
Collector-Local Mix	8	9	4.52 (3.64-5.63)
Minor Arterial Only	13	7	11.6 (9.54-14.1)
Minor-Collector-Local Mix	13	5	18.2 (14.9-22.3)
Principal Arterial Only	23	6	28.9 (24.2-34.6)
Principal Arterial-Other Mix	25	4	57.4 (47.9-68.9)
Highway-Other Mix	1	0.5	24.4 (15.2-39.2)
One Way Street (%)	22	7	6.04 (5.17-7.06)

	Any Collisions N=1,720 Mean (SD) or %	No Collisions N=35,640 Mean (SD) or %	Unadjusted IRR (95% CI)
Bike Lanes (%)	21	7	5.18 (4.41-6.09)
Truck Route (%)	19	5	6.63 (5.57-7.89)
Traffic Control (%)[d]			
None	32	69	Ref
Traffic Circle	1	3	0.69 (0.42-1.15)
Yield Sign	1	2	1.27 (0.79-2.05)
Stop Sign	34	24	3.15 (2.78-3.55)
Traffic Signal	31	2	62.9 (53.6-73.8)
Any Marked Crosswalk (%)[d]	50	11	14.4 (12.8-16.3)
Any Median (painted or raised) (%)[d]	6	1	6.63 (4.97-8.85)
Any Two-Way Center Turn Lanes (%)[d]	12	4	5.23 (4.24-6.44)
Any Left Turn Lanes (%)[d]	36	7	12.4 (10.8-14.3)
Any Right Turn Lanes (%)[d]	10	2	11.7 (9.11-15.0)
Any Bus Lanes (%)[d]	7	1	18.5 (13.4-25.5)
Any Parking Lanes (%)[d]	57	20	7.38 (6.49-8.40)
Any of these Signs Present (%)[d]			
Speed Bump	1	1	0.58 (0.30-1.14)
Bus Only Lane	42	12	9.13 (8.01-10.4)
Bus Stop	29	7	8.87 (7.67-10.2)
No Parking 30 ft	31	23	1.53 (1.33-1.75)
No Parking	83	44	9.91 (8.50-11.6)
No Peak Parking	11	3	6.34 (5.10-7.86)
No (L/R) Turn	11	3	11.8 (8.72-15.9)
Parking Allowed	67	27	8.71 (7.63-9.94)
Paid Parking	25	4	17.0 (14.4-20.1)
No Pedestrian Crossing	7	2	7.29 (5.58-9.50)
Pedestrian Signal Button	6	1	11.8 (8.72-15.9)

	Any Collisions N=1,720 Mean (SD) or %	No Collisions N=35,640 Mean (SD) or %	Unadjusted IRR (95% CI)
Pedestrian Route/Guide	10	4	3.93 (3.18-4.87)
Caution – Watch for Pedestrians	1	1	1.05 (0.62-1.79)
Photo Enforcement (Red Light Camera/Speed)	4	1	14.8 (10.1-21.7)
School Zone	11	10	1.02 (0.84-1.24)
Reflective Sign	94	60	17.0 (13.6-21.2)
Macroenvironment SmartMap (100 m area around intersections and mid-block locations)			
	Mean (SD)	**Mean (SD)**	**IRR (95% CI)**
Residential Density (units/acre)	3.79 (7.20)	4.33 (4.16)	0.98 (0.97-0.99)
Employment Density (jobs/acre)	3.94 (6.00)	1.16 (3.65)	1.11 (1.10-1.12)
Mean residential Property Value ($USD/unit/acre)	510,659 (803,203)	1,574,746 (1,265,007)	0.89 (0.88-0.90)[e]
Area in Office Land use (%)	7.61 (12.09)	1.68 (5.78)	1.95 (1.86-2.04)
Area in Park (%)	1.94 (6.91)	3.45 (11.11)	0.98 (0.97-0.99)
Fast Food Density (restaurants/acre)	0.33 (0.51)	0.046 (0.193)	11.2 (9.57-13.1)
Intersection Density (number/acre)	0.49 (0.29)	0.43 (0.26)	2.80 (2.27-3.45)
Sidewalk Density (linear feet/acre)	1.08 (0.39)	0.86 (0.47)	3.53 (3.08-4.05)
Bus ridership Density (daily avg. boardings & alightings/acre)	3.97 (8.72)	0.49 (2.54)	1.15 (1.14-1.17)
Slope (% land with slope ≥ 5 degrees)	0.45 (0.38)	0.59 (0.38)	0.29 (0.25-0.34)
Census Blocks (weighted mean of blocks within 100m buffer)			
Total Population (Mean, SD)	174.5 (170.8)	112.3 (99.7)	1.51 (1.45-1.57)[f]
Gender (Mean %) (Mean, SD)			
Male	51.6 (12.9)	49.0 (10.3)	1.17 (1.11-1.23)[g]
Female	45.8 (12.3)	48.6 (10.2)	0.75 (0.71-0.79)[g]
Race/Ethnicity (Mean %) (Mean, SD)			
Non-Hispanic White	58.0 (24.9)	66.0 (26.1)	0.88 (0.85-0.91)[g]
Non-Hispanic Black	10.5 (12.2)	7.2 (10.9)	1.09 (1.02-1.15)[g]
Non-Hispanic Asian	15.1 (14.9)	12.9 (14.9)	0.92 (0.87-0.97)[g]
Non-Hispanic Other[h]	6.2 (4.4)	5.5 (4.6)	1.19 (1.06-1.33)[g]

	Any Collisions N=1,720 Mean (SD) or %	No Collisions N=35,640 Mean (SD) or %	Unadjusted IRR (95% CI)
Hispanic	7.7 (7.1)	6.0 (6.6)	1.23 (1.14-1.33)[g]
Age			
<18	10.2 (9.5)	16.4 (8.6)	0.50 (0.46-0.54)[g]
18 to 34	37.9 (19.8)	26.4 (16.8)	1.20 (1.15-1.26)[g]
35 to 64	39.5 (15.3)	43.7 (12.9)	1.02 (0.97-1.07)[g]
≥65	9.8 (10.7)	11.1 (8.74)	1.03 (0.96-1.10)[g]

[a]Any Collisions N=1,111; No Collisions N=12,686

[b]IRR per 10,000 vehicles

[c]IRR per 10 feet

[d]Proportions are based on total number of units over time, N=2,695 locations with any collisions, N=72,691 locations with no collisions

[e]IRR per $500,000 per residential unit per acre

[f]IRR per 100 population

[g]IRR per 10%

[h]Includes Native American/Alaskan Native, Native Hawaiian/Pacific Islander, Two Races or More, Other Race

Table 2

Multivariable, multilevel models (site and census block level) estimating IRR and 95% CI of pedestrian collisions over time, comparison of full model and final model.

	Full Model IRR (95% CI)	Final Model IRR (95% CI)
Microenvironment (in 25m Area)		
Location Type		
Mid-block	Ref	Ref
Cul-de-sac (1 segment)	0.27 (0.10-0.74)	0.28 (0.10-0.77)
Curve (2 segments)	0.39 (0.24-0.63)	0.40 (0.25-0.65)
3 segments	0.98 (0.83-1.15)	0.96 (0.83-1.14)
4 segments	2.25 (1.97-2.57)	2.28 (2.00-2.61)
5 or more	2.60 (1.92-3.52)	2.41 (1.78-3.26)
Max. Legal Speed Limit		
25 MPH or Less	Ref	
30 MPH	1.08 (0.35-3.34)	
35 MPH	1.05 (0.34-3.32)	
40 MPH or More	1.10 (0.34-3.53)	
Widest Street Width (Feet)[a]	1.07 (1.03-1.12)	1.09 (1.04-1.14)
Road Classification		
Local/Residential/Private	Ref	Ref
Collector-Local Mix	2.16 (0.69-6.74)	2.47 (1.94-3.14)
Minor-Collector-Local Mix	2.82 (0.91-8.75)	3.19 (2.59-3.93)
Principal Arterial-Other Mix	4.44 (1.43-13.8)	4.98 (4.02-6.17)
Highway-Other Mix	3.66 (1.11-12.1)	3.83 (2.43-6.03)
One Way Street	0.64 (0.55-0.75)	0.65 (0.56-0.76)
Bike Lanes	1.17 (1.02-1.34)	
Truck Route	1.10 (0.93-1.31)	
Traffic Control		
None	Ref	Ref
Traffic Circle	0.88 (0.53-1.45)	0.84 (0.51-1.39)
Yield Sign	0.92 (0.56-1.58)	0.95 (0.57-1.56)
Stop Sign	0.87 (0.75-1.01)	0.86 (0.74-0.99)
Traffic Signal	2.16 (1.76-2.64)	2.19 (1.80-2.66)
Any Marked Crosswalk	1.63 (1.43-1.87)	1.59 (1.39-1.81)
Any Median (painted or raised)	1.16 (0.94-1.44)	
Any Two-Way Center Turn Lanes	1.23 (1.01-1.49)	1.34 (1.14-1.58)
Any Left Turn Lanes	1.13 (0.98-1.31)	
Any Right Turn Lanes	0.84 (0.71-1.01)	
Any Bus Lanes	1.02 (0.81-1.28)	
Any Parking Lanes	1.14 (1.00-1.31)	
Any of These Signs Present:		
Speed Bump Ahead	0.85 (0.53-1.35)	

	Full Model IRR (95% CI)	Final Model IRR (95% CI)
Bus Only Lane	1.28 (1.14-1.42)	1.27 (1.14-1.41)
Bus Stop	1.23 (1.08-1.39)	1.19 (1.04-1.35)
No Parking		1.19 (1.01-1.40)
Paid Parking		1.22 (1.04-1.42)
Parking Allowed		1.48 (1.31-1.68)
No Parking near Intersection (30 ft)	0.88 (0.74-1.04)	
No Peak Parking	0.95 (0.80-1.12)	
No Turns (Left or Right)	0.87 (0.74-1.03)	
No Pedestrian Crossings	0.93 (0.76-1.14)	
Pedestrian Crossing Button	1.06 (0.86-1.31)	
Pedestrian Route/Guide	0.95 (0.80-1.12)	
Cede Right-of-Way to Pedestrians	0.57 (0.36-0.89)	0.57 (0.36-0.89)
Photo Enforcement (Red Camera or Speed)	1.50 (1.19-1.89)	1.47 (1.18-1.84)
School Zone	0.93 (0.79-1.09)	
Sign Reflective		1.52 (1.16-2.00)
Macroenvironment (100m area)		
Residential Density[b]	1.02 (0.99-1.06)	1.10 (1.02-1.18)
Employment Density[c]	1.09 (1.04-1.14)	1.08 (1.03-1.13)
Mean Property Value ($USD)[d]	0.87 (0.83-0.91)	0.85 (0.82-0.89)
% Area in Office Land Use[e]	0.99 (0.96-1.02)	
% Area in Park Land Use[e]	0.99 (0.96-1.02)	
Fast Food Density	1.75 (1.52-2.02)	1.74 (1.52-1.99)
Intersection Density	0.65 (0.53-0.81)	0.64 (0.53-0.78)
Sidewalk Density[f]	1.03 (0.88-1.20)	
Bus Ridership Density[g]	1.13 (1.08-1.17)	1.12 (1.07-1.17)
% Slope ≥ 5 degrees	0.86 (0.75-0.99)	
Census Blocks (100m area)		
Total Population[h]	1.07 (1.03-1.11)	1.07 (1.03-1.12)
Male[e]	0.98 (0.93-1.02)	
Race/Ethnicity		
Non-Hispanic Black[e]	1.17 (1.11-1.23)	1.15 (1.10-1.20)
Non-Hispanic Asian[e]	1.06 (1.02-1.10)	1.06 (1.02-1.10)
Non-Hispanic Other[e]	1.00 (0.91-1.11)	
Hispanic[e]	1.14 (1.07-1.23)	1.12 (1.06-1.19)
Age Group		
<18	0.96 (0.88-1.04)	
18-34	1.06 (1.02-1.09)	1.05 (1.02-1.09)
≥65	1.07 (1.01-1.13)	1.06 (1.01-1.13)

[a]Per 10 feet

[b]Per 5 units per acre

[c]Per 5 jobs per acre

[d]Per $500,000 per residential unit per acre

[e]Per 5%

[f]Per linear foot per acre

[g]Per 5 boardings/alightings per acre

[h]Per 100 people