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Managing Pedestrian Safety II: A case-control study of collision locations on State Routes in King County and Seattle, Washington

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ABSTRACT

The safety of non-motorized transportation systems is essential to the public acceptance and overall success of Washington State and local jurisdictions efforts to reduce congestion. The State and the jurisdictions goals to increase non-SOV travel options and the use of transit, need to be combined with those to insure the safety of these alternatives.

This project is the continuation of current work developing and using a database of 13,914 individual pedestrian and bike collisions. This database is the first in the nation to have geocoded individual collisions in Geographic Information Systems (GIS) for the entire State (1999-2004). Having the precise location of a large number of collisions over a period of several years promises that significant progress can be made in explaining factors associated with collisions and in identifying underlying causes. The new Washington State collision database is particularly momentous that the State also has some of the most advanced data on road characteristics and land uses associated with trip origins and destinations. These latter data are accessible in GIS for all populated areas of the State and available at the finest resolution.

In the proposed project, current research on road design and land use correlates of collision frequency and severity will be augmented by :

1. Analyses of pedestrian motor vehicle collisions on city streets;
2. Analyses of bicycle motor vehicle collisions on SR and on city streets;
3. Longitudinal analyses of the collision data to identify potential causes of collisions;
4. Scenario planning examinations of safety-dependent locations, such as (a) freight routes, (b) transit hubs, (c) areas that are experiencing major development and growth, (d) areas subject to substantial infrastructure investments, and (e) areas with different levels of transportation efficiency (measured as travel options available beyond SOV travel, and derived from the Transportation Efficient Land Use Mapping Index TELUMI.

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EXECUTIVE SUMMARY

The study examined the associations between the road and neighborhood environment characteristics with the risk of collisions occurring between pedestrians and motor vehicles. This individual-level case-control study analyzed the risk of a location with pedestrian collisions compared with a location without a pedestrian collision from 1999-2004 on state routes in King County, Washington. Binomial logit models estimated the odds of a collision occurring, accounting for road design and the presence of pedestrian activity generators, and adjusting for exposure. Separate models were run for SR 99, the principal transregional four-plus-lane arterial, and for all the other state routes.

The strongest significant correlates of the risk of collisions occurring at a location were: the presence of crosswalks with or without signals, the facility's number of lanes, and the presence of retail uses near the collision or control location. Also positively significant were the number of traffic signals and the street-block size near the collision location; and the collision being located outside of the City of Seattle. Exposure variables including road-level measures such as ADT and posted speed, and neighborhood-level measures such as residential units and bus ridership were significant in at least one of the models. Employment density appeared to be an unreliable measure of exposure. Pedestrian activity generators such as neighborhood centers and schools and colleges were not significantly associated with the risk of collision.

Research assessing the risk of collision based on the characteristics of location provides tangible information as to WHERE safety measures should be targeted and WHAT specific aspects of the collision environment need attention to prevent future collisions. This research indicated that effective safety measures should be different for different classes of roads, based on number of lanes and ADT. Furthermore, pedestrian safety programs should focus on crosswalk locations, especially for roads with three and more lanes and near retail uses, where signals and other engineering and design features may not be sufficient to decrease the risk of a collision occurring.

INTRODUCTION

Pedestrians are an important part of traffic and transportation safety programs. In 2005, 4,900 pedestrians were killed and 64,000 injured in the U.S. (NHTSA 2006). Set into the larger context of assessing risk of death or injury, collisions involving pedestrians are a significant public health matter. Considering all possible agents of death, pedestrian crashes account for one in 628 deaths, versus one in 84 deaths for motor-vehicle crashes (2006). Considering traffic-related deaths only, collisions involving pedestrians make up for between 11 and 13% of all fatalities. In terms of distance traveled, pedestrians were estimated to be 23 times more likely to get killed than car occupants (140 vs. 6 fatalities per billion kilometers in 2001) (Pucher and Dijkstra 2003). Further inequities come to light as many pedestrians are from the vulnerable portion of the population: 33% of those reported to be involved in pedestrian collisions are children under the age of 15, who represent only 22% of the population (2004). These statistics are particularly relevant to transportation safety as transportation policy now supports alternatives to SOV driving; specifically, kids are increasingly encouraged to walk to school, transit use is rising in metropolitan areas, and transportation engineers are anxious to resolve vehicular traffic congestion while securing the mobility of the population.

Much of the pedestrian safety research to date has focused on the 4 Es (Engineering, Education, Enforcement, and Encouragement) (U.S. Department of Transportation 1993).[1] Results of such research have informed approaches to pedestrian safety with the primary aim being changing pedestrian and drivers behaviors through (a) direct interventions, such as driver and pedestrian education ("Education and Encouragement"), and law enforcement ("Enforcement"), or (b) indirect strategies, such as new approaches to road design (in the form of "Engineering" countermeasures, or approaches to change standard design procedures). Importantly, many of these approaches seek to prevent collisions (Retting et al. 2003; Zegeer et al. 2006).

Less well addressed is the environmental context that contributes to pedestrian safety. Safety research has considered collisions involving pedestrians as "rare events" that, as a result, are difficult to predict or anticipate (Zegeer et al. 2006; Zegeer et al. 2002a). However, these rare events are spatially determined and not randomly distributed. Their

[1] The "5 E's" are also referred to – Engineering, Education, Enforcement, Encouragement and Evaluation.

definition is dependent on the spatial or environmental extent (meaning the size of the context) within which these events take place. Generally, the larger the spatial extent considered for the events, the lower the chance of one event taking place. For example, considering that there are 140 pedestrian fatalities incurred per billion kilometers traveled in the U.S., the chance of getting killed as a pedestrian is “only” one in more than 7 million kilometers traveled (NHTSA 2006). Similarly, considering the entire network of state routes in Washington State (7,080 miles), only 4.7% of this network has had one of more pedestrian collisions between 1999 and 2004. However, changing the spatial extent under consideration, the same network of state routes in King County, Washington, has more than 28% of its 506 miles with one or more pedestrian collisions per mile. In King County, the median number of pedestrian collisions per mile of state route is almost one (0.95; SD 2.29; range of 0.08 to 9.65). Only 6 miles of these routes in King County have not had a collision during the time period (versus 1334 miles in the State). Median distance between collisions on King County State Routes is 0.88 miles (SD 3.32), against 2.96 on Washington State (SD 15.09) (Figure 1).

Simply put, pedestrian collisions cluster not with the network of roads, but together with the population. This suggests that pedestrian safety research should focus on transportation systems in towns, cities, and metropolitan areas (LaScala et al. 2000; Lassarre et al. 2007) . Even within such specific spatial definitions, there will be an uneven distribution of collision events. Based on police report data from 1999-2004, for example, King County, Washington, had approximately 290 collisions per 100,000 persons, while the City of Seattle collision rate was more than 350 per 100,000. This variation is explained by the fact that today, motorized mobility is accommodated and available just about everywhere in populated areas; as a result, the vast majority of pedestrians will be found only in the few areas where car travel is limited by traffic congestion and high parking costs.

To make progress in insuring the safety of pedestrians, research must focus on spatial extents or areas where pedestrians concentrate, and examine the characteristics of these environments that are associated with the risk of collision occurrence. A body of literature is emerging that takes such locations into account (Clifton and Kreamer Fults 2006; Graham and Glaister 2003). New approaches are being tested to measure the “exposure” conditions that lead to a collision outcome (Hedlund 2000; Raford and Ragland 2006). As well, research based on land use as proxy for demand for transportation has shown that higher densities of development along road facilities, “attractor” land uses, traffic volumes, and transit are associated higher numbers of collisions (Kim et al. 2006; LaScala et al. 2000).

These studies are bringing important new information regarding pedestrian safety: some show that while pedestrian volumes affect the risk of collision occurrence, the relationship between the two is not linear: beyond certain thresholds, the risk of collision occurrence decreases with increases in pedestrian volumes (Graham and Glaister 2003; Raford et al. 2006).

This study adds to this literature. It focuses on King County, the State of Washington’s most populous area. It examines the risk of pedestrian collision taking place at a given location in the road system, adjusting for “exposure” and road design. Exposure is defined by traffic conditions and various pedestrian travel “attractors” or pedestrian activity generators. The study considers two “Es”: one, the established “Engineering” or road design “E”, and a second, newly defined “Environment” “E,” or the environment along the road that attracts pedestrians. The principal question posed is: given pedestrians and drivers actions and behaviors (“Education”), and given current law enforcement practices (“Enforcement”), do road design and the environment around and along the road (“Environment”) contribute to making a location safe or unsafe? Therefore, the study targets the design and environmental determinants of collision locations, which, if modified, could improve safety.

OBJECTIVES

The objectives of this study were to estimate the odds of a pedestrian-motor-vehicle collision taking place at a location along a state route. The study sought (a) to inform pedestrian safety policies regarding the characteristics of environments at locations associated with higher risk of collision occurrence, and (b) to guide road design safety standards for environments where pedestrian travel is common.

The study uniquely took advantage of new data on individual collisions, which could be geocoded to their specific location on roads and streets. These data were available at the regional and state level and compatible with detailed data on transportation networks and land uses. The study built on previous research using Pedestrian Accident Locations (PALs) data on locations with multiple collision records (Hess et al. 2004). It also used the results of an increasing amount of research findings in King County and elsewhere on the characteristics of environments associated with the likelihood of walking (McCormack et al. 2007; Moudon et al. 2007a).

Finally, the study benefited from the availability of increasingly sophisticated methods in geographic information systems (GIS) that allowed the capture of a wide range of spatial data for multiple individual point locations (Lee and Moudon 2006a; Lee et al. 2006; Leslie E et al. 2007).

METHODS

Study design and concepts

This study focused on state routes in King County, Washington, which included the City of Seattle. This disaggregate, individual-level study used the case-control method to calculate the odds of a location on state routes to have a pedestrian collision compared with a location without a pedestrian collision (Davis et al. 2006). The unit of analysis was a point location along a state route. Case points were locations where a collision or collisions had occurred, and control points were randomly selected locations where no collision had occurred between 1999 and 2004 (Figure 2).

State routes are primary vehicular and transit circulation corridors. While initially built as transregional facilities, these routes have become the contemporary versions of “main street”: in many urbanizing areas, land along them has been and continues to be redeveloped with high-density commercial and residential uses that are often politically difficult to accommodate elsewhere because of opposition by established communities. State routes also provide the direct, high capacity facilities favored by transit operators. As a result, these routes typically have relatively high traffic AND pedestrian volumes at specific crossing locations. Finally, being under the jurisdiction of the State, these routes have been designed and signalized according to established standards and regulations.

The study was limited to the likelihood of a collision taking place or not. Parallel studies are being carried out to predict the number or type of collisions in a location, and to address the risk of severity of injury or fatality once a collision occurs (Moudon et al. 2007b).

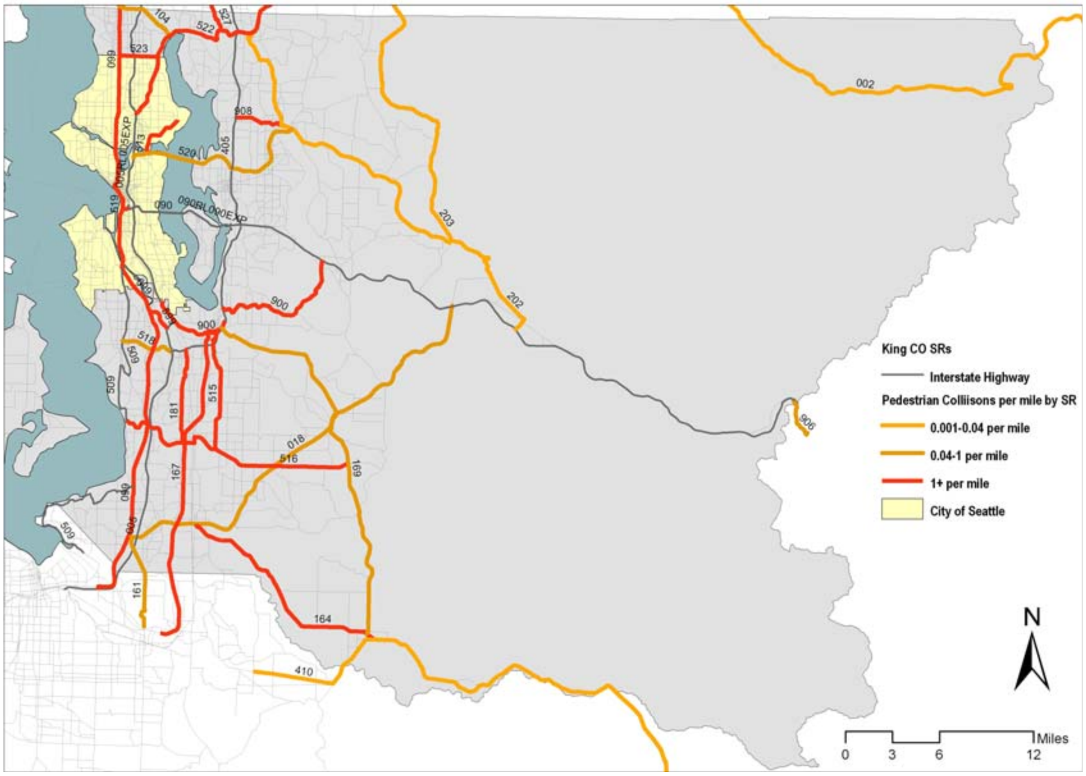

Figure 1: State routes in King County, Washington, showing pedestrian collision frequency per mile of state route (1999-2004).

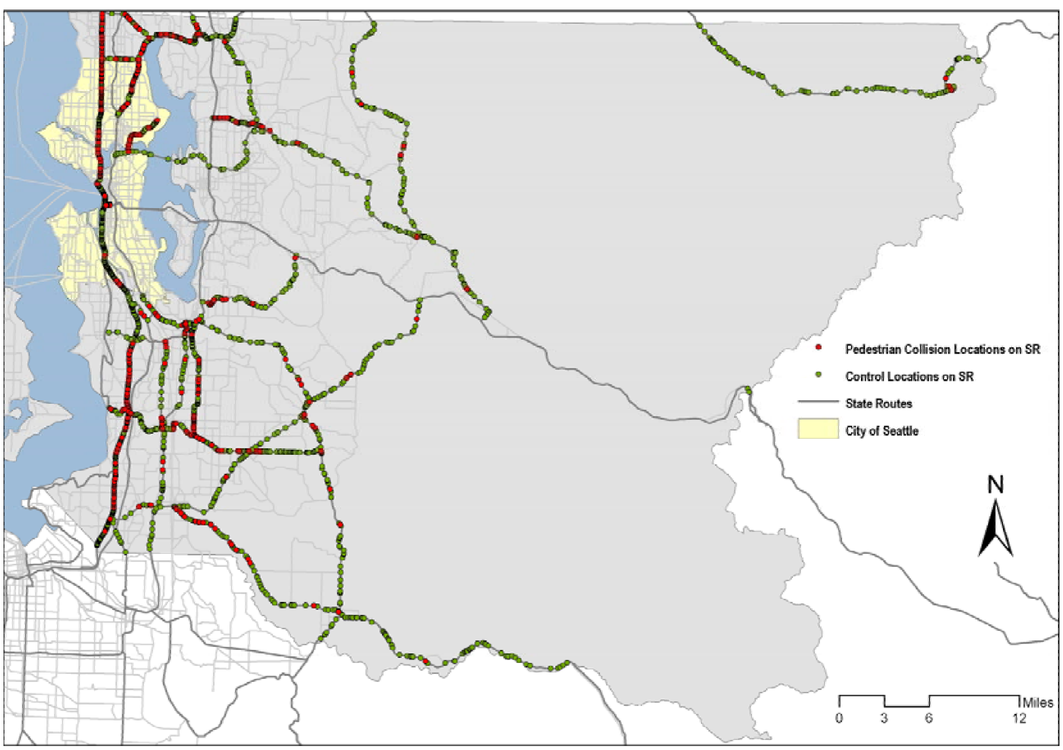

Figure 2: Case and control collision points on state routes in King County, Washington (1999-2004)

Risk of collision occurrence was defined as the quantifiable likelihood of a collision between motor-vehicles and pedestrians occurring at a location. Estimating the risk of a collision occurring is semantically different from estimating the risk of a pedestrian to be involved in a collision (Raford et al. 2006). The latter focuses on an individual person's likelihood of being hit by a motor vehicle, with the denominator being the total number of pedestrians or the total number of miles traveled by pedestrians. The former seeks to estimate the likelihood of a location to be the scene of a collision, with the denominator being the total number of collisions.

The odds of a collision occurring was conceptualized as depending on the characteristics of *conflicts* between vehicles, their drivers and pedestrians. A traffic conflict was "….an observable situation in which two or more road-users approach each other in space and time to such an extent that a collision [would be] imminent if their movements remained unchanged" (Amundsen F.H. and Hyden C. 1977). Clearly, increases in either the number of pedestrians, the number of vehicles, or both could increase the risk of collision. Yet these conflicts took place within spatially defined confines of streets and roads, and the design and the use of these facilities would also influence the outcome, and influence whether a collision did or did not take place.

Measures of exposure were taken to address the magnitude, frequency, and duration of a potential conflict between pedestrians and motor vehicles (Ott et al. 2007). They included both actual and proxy measures of pedestrian and traffic volumes (addressing the *magnitude* of a potential conflict); presence of an intersection, a crosswalk, a traffic signal, and a sidewalk (addressing *frequency*); width of the road and vehicular speed (addressing *duration*). Measures of magnitude, frequency, and duration of exposure were taken at two levels of space: the location of the case or control point, which defined the "road environment," and the "neighborhood environment" around the case or control point.

Data

The collision data comprised all collisions involving pedestrians on state routes in King County, Washington, recorded over a period of six years (1999 to 2004). These data came from the Transportation Data Office (TDO) of the Washington State Department of Transportation's (WSDOT) Strategic Planning and Programming Division. The TDO is responsible for collecting, processing, analyzing, and disseminating traffic, roadway, and collision data pertaining to all roadways in Washington State. These collision data originated from collision reports submitted by police officers and citizens. Individual collision records were compiled in a geocodable flat file containing milepost information.

Objective data on the road environment came from the Puget Sound Regional Council (PSRC), which provided data on state routes and major arterials, including sidewalks, estimated average daily traffic (ADT) counts and estimated speed (from EMME2 modeled data); from WSDOT, which provided data on state routes only, including number of traffic lanes, traffic signals, intersections, sidewalks, and crosswalks (assumed to be marked) ; from King County GIS, which had network data on all streets, including road classes, traffic signals, and sidewalks (major streets only); and from King County Metro Automatic Passenger Counts (APC), which collected daily boardings and alightings at bus stops.

Objective data on the neighborhood environment came from the King County Assessor's office, which provided land uses, property assessment values, and residential density data at the parcel or tax lot level. Employment data were generated at the Urban Form Lab (UFL) based on the assessor's land-use data and by combining several sources of data on employment (Moudon and Sohn 2005). The UFL also provided data on certain land uses and agglomerations of land uses developed from the assessor's files and GIS analyses.

Measurements

Dependent variable

Ninety percent of the collisions involving pedestrians on King County's SRs could be geocoded by using milepost data with a spatial resolution of 1/10th of a mile. The statistical distribution of geocoded and total collisions was similar. There were 716 collision locations on 29 different state routes. Collisions on Interstate routes were excluded from this study since these routes prohibited pedestrian travel and pedestrian collisions reported on them likely represented special circumstances. Also excluded were collisions for which traffic data were missing.

For sampling the control locations, points were created every 50 m along the different state routes, generating a total of 14,988 points. The 50 m value was derived from data-driven analyses of distance between collisions. Ten percent of the points were sampled randomly to identify control point locations. A higher sampling percentage was used for about a third of the routes in order to obtain a minimum of a 1 to 2 case to control ratio for all facilities. Sample points within 50 m or less of a case location were excluded, as were points for which traffic data were missing. A total of 642 case and 1786 control locations on 26 state routes were used in this study (n = 2428).

Independent variables

Following the conceptualization of conflicts between pedestrians and motor-vehicle-drivers potentially leading to a collision outcome, the independent variables captured the road and neighborhood environments at and near the case and control points. Figure 3 explains the spatial extents within which variables capturing the road and neighborhood environments were measured. Table 1, columns A through E, summarizes the range of variables considered and their potential to serve as proxies for measuring the magnitude, frequency, and duration of exposure.

In the road environment category, both road design and traffic conditions were considered. Road design variables *at the collision location* included the number of lanes, the presence of sidewalks, crosswalks (assumed to be marked),[2] and traffic signals. Road design variables *in the vicinity of the collision* included elements of the pedestrian infrastructure in the form of sidewalks (on state routes and major streets), crosswalks (on state routes only), intersections, street-block size, and traffic signals on all roads or streets, all within a 0.5 km collision buffer area. Studies on the effect of road design on collision frequency had identified the presence of sidewalks and the width of a street as significant predictors of collisions (Abdel-Aty and Wang 2006; McMahon et al. 1999). Also, the frequency and severity of injury in collisions occurring at the intersections of two-lane roads was found to not differ significantly whether crosswalks were marked or unmarked (Zegeer et al. 2002b).

Traffic conditions variables included bus stops and ridership, estimated average daily traffic (ADT), estimated speed, and posted speed limit.

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[2] Not clearly specified in WSDOT data. Also, the crosswalk inventory does not address the quality of the markings, which field observation shows can vary greatly from freshly painted to faintly visible.

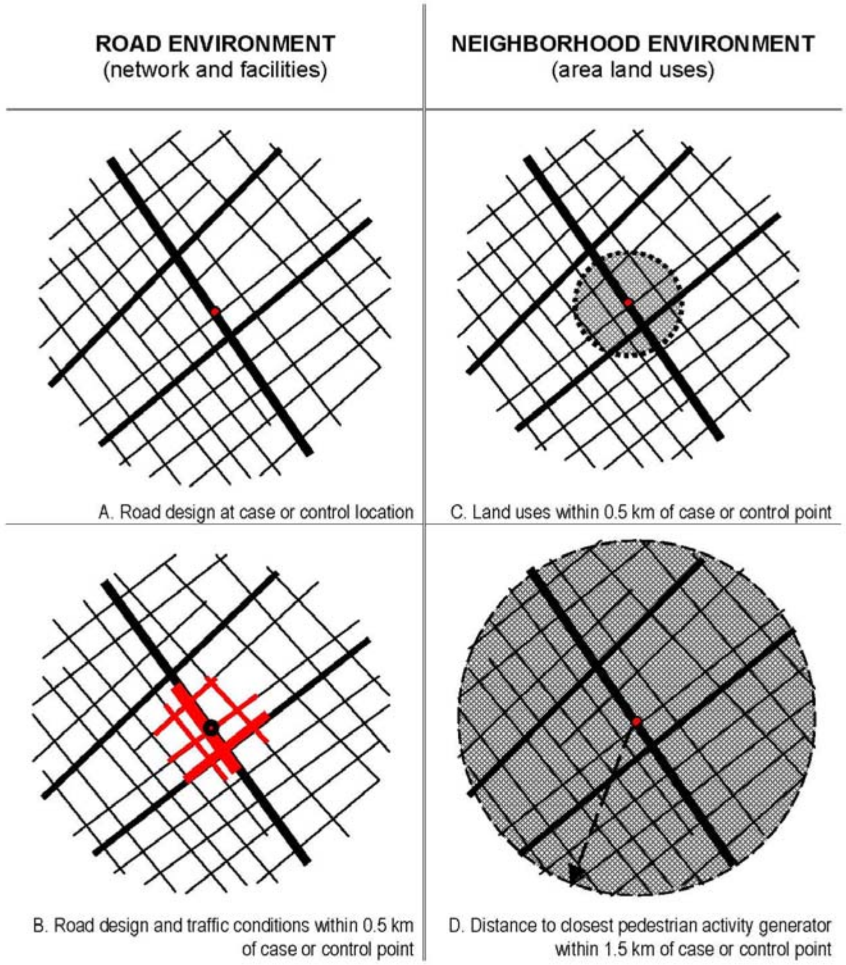

Figure 3: Conceptual framework for selecting independent variables. Both the road and the neighborhood environments are considered to capture environmental attributes that are known or assumed to influence the risk of a collision occurring at a location. The road environment consists of (A) attributes of road design at the case or control location; and (B) road design and traffic conditions within a 0.5 km radius of the case or control point. The neighborhood environment consists of land uses that are pedestrian activity generators. Those land uses are captured (C) within a 0.5 km radius of a case or control point; and as (D) distances to the closest pedestrian activity generators are also captured up to 1.5 km.

In the neighborhood environment category, variables included density of residential and employment development, neighborhood wealth, and the presence of a range of land uses, considered "attractors," or pedestrian activity generators. The latter variables had been associated with higher probabilities of walking in a previous study, the Walkable and Bikable Communities project (WBC), documented elsewhere (Moudon et al. 2007a;

Moudon et al. 2006). The WBC study results were validated for King County, and based on a survey of 608 subjects randomly selected from the County population living in areas that offered a supportive environment for walking. Individual variables strongly associated with walking sufficiently to enhance health (>150 minutes per week) included lower household income and using transit ($p < .01$). Fourteen objectively measured variables capturing land use and transportation infrastructure were shown to be significantly associated with more walking. They included shorter distances to grocery stores/markets, restaurants, and retail stores, but longer distances to offices or mixed-use buildings ($p < .01$ or $.05$); and the presence of a neighborhood commercial center (called NC2), which was defined as a cluster of at least one grocery store, one restaurant, and one retail outlet within 50 m of each other The density of the respondent's parcel was also strongly associated with walking sufficiently for health ($p < .01$).

The WBC study findings had been supported by other research. Transit use had been associated with more pedestrian travel as well as with locations of multiple pedestrian collisions (Hess et al. 2004; McCormack et al. 2007). Neighborhood wealth and neighborhood destinations had been shown to attract significantly more walking in different locales (Giles-Corti et al. 2005; McCormack et al. 2007).

A dummy variable was used for regional location, with the case or control point being inside or outside of the City of Seattle. This regional location indicator was a general measure of urbanization, which had long been strongly associated with mode split. Its inclusion in this research seemed particularly relevant to address local-level policies and standards affecting traffic safety.

Data capture in GIS

Variables capturing the road and neighborhood environments were measured by using a 0.5 km airline buffer radius from each case and control point. The size of this buffer, which contained 194 acres, corresponded to pedestrian travel catchment areas used in previous research (Moudon et al. 2007b). Both count measures and measures of shortest distance from the collision and control locations to the road design features and the attractor destinations were obtained to test in the models. Distance measures captured features of destinations closest to a case or control point and up to 1.5 airline km away from it. Measures were taken by using routines in geographic information systems (GIS) that had been developed in previous projects (Lee and Moudon 2006b).

Analyses

Independent variable selection

Four criteria were used to select the independent variables to be used in the models:

- theoretical importance based on previous studies that had found the variables to be significantly associated with pedestrian collisions and injury severity
- significance in bivariate analyses with the dependent variables (p-value < 0.05)
- availability, quality, and completeness of the data
- minimizing correlations between independent variables

Bivariate analyses with the dependent variables used one-way ANOVA for continuous independent variables, Kendall's tau-c for ordinal variables, and contingency coefficients for categorical and dummy variables.

Final model construction

The final models were developed based on three steps(Gelman and Hill 2007). First, a base model included the theoretically important variables in the road and neighborhood environment. As mentioned in the study design section, these variables also captured the different aspects of pedestrian exposure: number of lanes at the collision location, relation to crosswalk and traffic signal at crosswalk, mean ADT, average posted speed limit, median bus ridership, total residential units, and employment density. Second, variables that were significant ($p < 0.05$) in bivariate analyses with the dependent variable were added one-by-one to the base model. Third, different combinations of the variables that were significant in the one-by-one testing were investigated to estimate the final models.

Two separate binomial logit models were estimated, for SR 99 only, and for all other state routes (AllOtherSR). Previous studies had found SR 99 be a special case in the County (Hess et al. 2004). This first north-south transregional highway had more lanes than most other state routes, 16 % of pedestrian collisions in the State, and almost 43 % of those in King County. There were 264 case points and 560 control points on SR99, and 376 and 1226 respectively on all the other state routes.

RESULTS

Descriptive statistics

More than 23% of the cases and controls were on roads with two lanes, 62% on roads with 3 to 4 lanes, and 15% on roads with 4 or more lanes. More than 70% of the points were not at crosswalks; 21% at crosswalks with no traffic signals and 6% at crosswalks with a traffic signal. The distribution of independent variables was similar for cases and controls, except for SR 99 locations with crosswalks with traffic signals for which there were few control points.

The mean posted speed was 45 mph (SD = 8.34). The maximum ADT was 90,000, with a mean of almost 4,000 (SD 11,000). Only 28% of the points had more than 11 median daily bus boardings and alightings per bus stop within the 0.5 km buffer (mean =13.10, SD=34.22). The mean average block size within 0.5 km was 250.48 acres (SD=1,452.37). The mean sidewalk length within 0.5 km was 2.52 miles (SD=2.67).

Almost 24% of the cases and controls were inside of City of Seattle. Within the 0.5km buffer of case or control points, there was an average of 553 residential units (SD = 581) and an average of 30 employee per acre (SD=68). More than 70% of the points had at least one office parcel, and only 27% had no retail nearby. Thirty percent had a grocery store within 0.5 km; 54% had an eating/drinking establishment; 33% had a Neighborhood Commercial Center; 30% had an elementary school; 2.5% had a middle school; and only two had a college within that same distance.

Bivariate analyses and one-by-one testing

Table 1, columns F through I, summarizes the independent variables considered at the various stages of model construction and provides descriptive statistics.

The number of intersections and bus stops, and the presence of high schools and vocational schools were not significant in bivariate analyses. Most of the distance measures to specific land uses were shorter than 0.5 km, which meant that they were highly correlated with count measures within 0.5 km, and dropped from the models.

Five neighborhood environment variables that showed significance in the one-by-one testing were excluded from the final models because they failed to contribute to increasing goodness of fit of the models. They were the total length of sidewalks, the median home value, the number of grocery store parcels, number of eating and drinking establishment parcels, and the number of NC2 (Neighborhood Center with at least one grocery store, one restaurant, and one retail parcels within 50 m of each other). In the one-by-one testing, all these variables were positively associated with the risk of collision occurrence, except for home value, which was negatively correlated with the probability of a collision.

In addition to the variables included in the base model, the final models contained four variables that showed significance in the one-by-one testing: the number of traffic signals, median block size, and the number of office and of retail parcels pedestrian activity generators.

Model results

The SR 99 model had a –2 log likelihood value of 585.900, capturing approximately 60% of the variation (Nagelkerke Pseudo R-square value of 0.589). The –2 log likelihood values of the AllOtherSR model (excluding SR 99) were 1133.456 (Pseudo R-square = 0.479) (Table 2).

A total of 12 variables were significant: 9 in the All SRs model and 7 in the SR 99 model.

Four variables were significant in both models:

- A collision occurring in a crosswalk with or without a signal, versus a collision occurring farther than 100 ft of a crosswalk, was associated with a higher risk of a collision taking place ($p < 0.0001$). The odds ratios were very high: 156.33 and 26.47 in the SR 99 and AllOtherSR model, respectively, for collisions in a crosswalk with a signal; and 6.80 and 5.35, respectively, for collisions occurring in a crosswalk without a signal.

- The number of lanes at the collision location was positively associated with higher risk of a collision. SR 99 having more than 4 lanes, versus 3 or 4 lanes was negatively associated with the likelihood of a collision (OR 0.26). In the AllOtherSR model, the likelihood of a collision taking place was higher if the road had 3-4 lanes (versus 2 lanes) (OR 2.23), and if the road had 4 plus lanes (OR 3.43).

- The number of traffic signals within 0.5 km of a location on state routes was associated with a collision taking place. For SR 99, having 1 to 3 signals decreased the likelihood of a collision (OR 0.37) ($p < 0.05$), but having more than 4 signals

Table 1: Summary of independent variables: selection process and descriptive statistics

A	B	C	D	E	F	G	H	I
	Domains	Variables	Proxy for conflict and exposure	Data Source	Measures	Selection criteria	Treated in the models (2)	One by one testing (1)
Road environment	Road design at a location on SR	Number of lanes	Length of time a pedestrian is potentially in conflict with vehicles.	WSDOT	11=2 lanes: 565 12=3-4 lanes: 1495 13= >4 lanes: 368	Theory	Cat.	
		Relation to crosswalk and traffic signal at crosswalk	Pedestrian restricted area	WSDOT	11= not at crosswalk (>100 ft of a crosswalk on state route): 1760 12= at crosswalk no traffic signals (<=100 ft of a crosswalk on state route): 513 13= at crosswalk with traffic signals (<=100ft of a crosswalk on state route): 155	Theory	Cat.	
		Presence of sidewalk at a location along SR	Pedestrian restricted area	WSDOT	Not significant in bivariate analysis			
	Road design characteristics within 0.5 km of a location on SR	number of traffic signals (on all streets)	Time limit for pedestrian exposure to vehicle	KING CO	11=0 signals: 806 12=1-3 signals: 975 13=4+ signals: 647	Bivariate	Cat.	+
		Total length of sidewalk along SR and major streets (1 unit increment=1 mile)	Pedestrian restricted area	KING CO	Recoded value: (Min: 11, Max: 27, Mean: 13.91, SD: 2.80) Original value in mile: (Min: 0, Max: 16, Mean: 2.52, SD: 2.67)	Bivariate	Cont.	+
		Intersections	Area of high potential pedestrian-vehicle conflict	KING CO	correlated with crosswalk measures			
		Bus stop	Pedestrian volumes	KING CO METRO	Not significant in bivariate analysis			
	Traffic Conditions	Median bus ridership	Pedestrian volumes	KING CO METRO	11=0 rider: 900 12=1-10 riders: 853 13=11+ riders: 675	Theory	Cat.	
		Mean ADT (log (number of vehicles))	Motor vehicle volumes	PSRC	Log value: (Min: 3.37 , Max: 11.39, Mean: 8.28, SD: 1.68) Original value: (Min: 28, Max: 88173, Mean: 10161, SD: 11606)	Theory	Cont.	
		Average posted speed limit (1 unit increment=1mph)	Motor vehicle volumes and length of time a vehicle is potentially in conflict with pedestrians in a given location	KING CO	Min: 25, Max: 60, Mean: 45.03, SD: 8.34	Theory	Cont.	
		Estimated speed	Motor vehicle volumes and length of time a vehicle is potentially in conflict with pedestrians in a given location	PSRC	correlated with average posted speed limit and mean ADT			

(1) "-" and "+" for significant test results ($p<0.05$)
(2) "Cat." presents category variable. "Cont." presents continuous variable.

Table 1: Summary of independent variables: selection process and descriptive statistics (cont.)

A	B	C	D	E	F	G	H	I
	Domains	Variables	Proxy for conflict and exposure	Data Source	Measures	Selection criteria	Treated in the models (2)	One by one testing (1)
Neighborhood environment	Transportation network	Median block size (log (acres))	???	KING CO	Log value: (Min: 0, Max: 20.27, Mean: 13.26, SD: 2.00) Original value in acre: (Min: 0, Max: 14594.78, Mean: 250.48, SD:1452.37)	Bivariate	Cont.	+
	Regional location	Inside or outside of city of Seattle	Pedestrian volumes		0=1855 1=573	Bivariate	Cat.	+
	Development	Total residential units (1 unit increment=100 residential units) (min=11, 0-100 units (0.5 km)	Pedestrian volumes	KING CO ASSESSOR	Recoded value: (Min:11 , Max: 42, Mean: 17.00, SD: 5.66) Original value: (Min: 0 , Max: 4504, Mean: 552.23, SD: 581.15)	Theory	Cont.	
		Total employment density (log (jobs/acre))	Pedestrian volumes	UFL	Log value: (Min: 0, Max: 6.80, Mean: 2.65, SD:1.39) Original value: (Min: 0, Max: 893.19, Mean: 30.30, SD:68.47)	Theory	Cont.	
	Neighborhood wealth	Home median home value ($)	Neighborhood wealth and income effects	KING CO ASSESSOR	11=0-10000: 512 12=10001-40000: 546 13=40001-80000: 698 14=80001-120000: 312 15=120001-160000: 194 16=160001-200000: 83 17=200001+: 83	Bivariate	Cont.	-
	Land uses	Number of office parcels	Pedestrian volumes	KING CO ASSESSOR	11= 0: 656 12=1-10: 1208 13=10+: 564	Bivariate	Cat.	+
		Number of grocery store parcels	Pedestrian volumes	UFL	1=1+: 750 0=0: 1678	Bivariate	Cat.	+
		Number of drinking and eating establishment parcels	Pedestrian volumes	UFL	1=1+: 1319 0=0: 1109	Bivariate	Cat.	+
		Number of retail parcels	Pedestrian volumes	KING CO ASSESSOR	11= 0: 798 12=1-10: 935 13=11+: 695	Bivariate	Cat.	+
		Number of NC2 (3)	Pedestrian volumes	UFL	1=1+: 799 0=0: 1629	Bivariate	Cat.	+
		Number of elementary school parcels	Pedestrian volumes	KING CO ASSESSOR	1=1+:736 0=0: 1692	Bivariate	Cat.	
		Number of middle school parcels	Pedestrian volumes	KING CO ASSESSOR	1=1+: 61 0=0: 2367	Bivariate	Cat.	
		Number of high school parcels	Pedestrian volumes	KING CO ASSESSOR	Not significant in bivariate analysis			
		Number of vocational school parcels	Pedestrian volumes	KING CO ASSESSOR	Not significant in bivariate analysis			
		Number of college parcels	Pedestrian volumes	KING CO ASSESSOR	1=1+: 2 0=0: 2426	Bivariate	Cat.	

(1) "-" and "+" for significant test results ($p<0.05$).
(2) "Cat." presents category variable. "Cont." presents continuous variable.
(3) NC_2 is a measure of neighborhood commercial center, which is defined as a cluster of at least one grocery store, one restaurant, and one retail outlet within 50 m of each other.

Table 2: Model results

	Domains	Variables	Measures	Df	SR 99 Model B	Sig.	EXP(B)	95.0% C.I. for EXP(B) Lower	Upper		AllOtherSR Model B	Sig.	EXP(B)	95.0% C.I. for EXP(B) Lower	Upper	
Road environment			11 =2 lanes ### (1)									0.002				
			12 =3-4 lanes ### (2)								0.802	0.002	2.23	1.34	3.71	
		Number of lanes	13 = <4 lanes SIX???	2	-1.343	0.001	0.26	0.12	0.57	√	1.233	0.002	3.43	1.59	7.38	√
			not at crosswalk (>100 ft of a crosswalk on state route) ###			0.000						0.000				
			at crosswalk without traffic signals (<=100 ft of a crosswalk on state route)		1.677	0.000	5.35	3.17	9.03	√	1.917	0.000	6.80	4.90	9.44	√
	Road Design at a location on SR	Crosswalks and traffic signals	at crosswalk with traffic signals (<=100ft of a crosswalk on state route)	2	3.276	0.000	26.47	13.71	51.06	x	5.052	0.000	156.33	20.20	1209.17	x
	Road design characteristics around a location on SR	Number of traffic signals	11=0 ###			0.075						0.001				
			12=1-3		-0.992	0.031	0.37	0.15	0.91		0.503	0.046	1.65	1.01	2.71	
			13=4+	2	-0.752	0.132	0.47	0.18	1.25		1.166	0.000	3.21	1.73	5.94	
			11=0 ride r####			0.666						0.034				
			12=1-10 riders;		0.443	0.391	1.56	0.57	4.28		0.134	0.543	1.14	0.74	1.76	
		Bus ridership	13=11+ riders	2	0.317	0.528	1.37	0.51	3.67	√	0.637	0.018	1.89	1.12	3.20	√
		Estimated ADT		1	0.343	0.000	1.41	1.18	1.69	√	0.053	0.426	1.05	0.92	1.20	√
	Traffic conditions	Average posted speed limits		1	-0.009	0.785	0.99	0.93	1.06		-0.027	0.032	0.97	0.95	1.00	x
Neighborhood environment	Transportation network	Block size		1	-0.394	0.099	0.67	0.42	1.08		0.237	0.000	1.27	1.11	1.44	x
	Regional location	In Seattle		1	-0.105	0.795	0.90	0.41	1.98	√	-0.501	0.031	0.61	0.38	0.95	√
		Total residential units		1	0.041	0.055	1.04	1.00	1.09	√	0.069	0.000	1.07	1.04	1.11	√
	Development	Employment density		1	-0.698	0.008	0.50	0.30	0.83	x	-0.145	0.176	0.87	0.70	1.07	x
			11= 0 ###			0.125						0.187				
			12=1-10		1.707	0.045	5.51	1.04	29.33		-0.327	0.181	0.72	0.45	1.16	
		Number of office parcels	13=10+	2	1.595	0.072	4.93	0.87	27.91	√	-0.626	0.067	0.53	0.27	1.05	√
	Lane uses (potential destinations and attractors of pedestrian travel)		11= 0 ###			0.000						0.000				
			12=1-10		1.309	0.039	3.70	1.07	12.83		1.074	0.000	2.93	1.79	4.79	
		Number of retail parcels	13=10+	2	2.571	0.000	13.08	3.45	49.59	√	1.610	0.000	5.00	2.62	9.54	√
		Constant		1	-0.132	0.977	0.88				-7.046	0.000	0.00			
			-2 Log likelihood		585.900						1133.456					
			Cox & Snell R Square		0.422						0.318					
			Nagelkerke R Square		0.589						0.479					
			number of observations		826						1602					

Reference category; (1) AllOtherSR model; (2) SR99 model
Exp(B) represents odds ratio.
√ as hypothesized
X counterintuitive

(versus none) was insignificant. For the AllOtherSR model, having more than 4 traffic signals increased the odds of a collision by 3.21 ($p < 0.0001$).

- The number of retail parcels within 0.5 km of a location on state routes was significantly associated with increased risk of collision occurrence ($p < 0.05$ for SR 99 and $p < 0.000$ for AllOtherSR model). Having one to ten, and more than ten, retail parcels (versus none) increased the odds of a collision taking place on SR 99 by 3.70 and 13.08, respectively. For the AllOtherSR model, the corresponding odds of a collision were 2.93 and 5.00.

  Assessor-based land uses classified under "retail" included retail store, discount store, line/strip retail, but excluded grocery stores, restaurants, fast food restaurants, bar/pubs, convenience stores, banks, mixed-use office and retail, neighborhood/community shopping centers, big box retail, regional shopping centers.

Three additional variables were significant in the SR 99 model:

- Average ADT (log value) in the 0.5 km buffer was associated with a higher risk of a collision occurring (OR 1.41; $p < 0.0001$).
- Higher employment density within the 0.5 km buffer decreased the likelihood of a collision occurring (OR 0.498; $p < 0.001$)
- The number of office parcels within the 0.5 km buffer was significantly associated with higher risk of collision occurrence if the number of such parcels ranged from one to 10 (versus none) (OR 5.51; $p < 0.05$); it was insignificant if the number of parcels was higher than 11.

The AllOtherSR model had five additional significant variables:

- The average posted speed in the 0.5 km buffer was negatively associated with the risk of collision occurrence (OR 0.97; $p < 0.05$). For 5 mph increments of posted speed, the odds of a collision occurring increased by 13%.
- Larger street-block size increased the odds of a collision occurring by 1.27 ($p < 0.0001$).
- Higher levels of bus ridership increased the odds of a collision occurring if the median number of daily riders per bus stop within the 0.5 km buffer was higher than 11 (OR 1.89; $p < 0.05$).

- Higher number of residential units within the 0.5 km buffer was significantly associated with increased risk of a collision occurrence (OR 1.07; $p < 0.0001$). For each additional 100 residential units in the 194 acre buffer (0.5 unit per acre), the chance of a collision increased by 7%.
- Being within the City of Seattle decreased the risk of a collision occurrence on state routes (OR 0.61; $p < 0.05$).

DISCUSSION

SR 99 versus all other state routes (AllOtherSR)

SR 99 and AllOtherSR models yielded results that showed common issues with road design, crosswalk, signalization, and the presence of retail uses as collision risk factors on all state routes. However, variables capturing traffic conditions and other road and neighborhood environment affected the model results differently for the two models, suggesting that safety measures should distinguish between classes of roads and address their specific requirements.

Regional location

The regional location variable was insignificant in the SR 99 model indicating that the route was similarly unsafe along its entire length, whether it was running through the City of Seattle or not. Regional location was strongly significant in the AllOtherSR model. Interestingly, the introduction of the dummy in this latter model brought both the average speed limit and bus ridership up to a $p < 0.05$ of significance (from $p = 0.10$ to $p = 0.03$; and from p = 0. 0.54 to $p = 0.02$, respectively) (data not shown). This effect is difficult to explain. However, development densities were considerably higher within the City of Seattle, as were traffic volumes and bus ridership.

Road design

For both models, the number of lanes and the presence of a crosswalk (versus no crosswalk) at the location were positively associated with the likelihood of a collision occurring. A road with more lanes would be expected to have more collisions since it would contain more vehicles. However, the significantly higher likelihood of a collision occurring at a crosswalk suggested that standard safety precautions and measures were not sufficient. Crosswalks are locations where pedestrians are expected to cross roads and streets and where, as a result, both highway design and drivers' behavior must aim to protect the pedestrian. The finding was made worse by the strong association found to exist between crossing at a signalized crosswalk and the risk of collision occurrence. This indicated that current signalization might not protect the pedestrian from the risk of a collision occurring. Nor did it seem that signals effectively encouraged safe driver's or pedestrian's behavior.

These finding were not consistent with other studies showing that the risk of a collision occurring was reduced at signalized crosswalks (Koepsell et al. 2002; Zegeer et al. 2002b). However, Zegeer et al.'s study (Zegeer et al. 2002b) was not limited to state routes, which are typically wider than city streets, and where vehicular travel speeds and traffic volumes are usually higher than those of city streets. On the other hand, Koepsell et al's (Koepsell et al. 2002) was limited to a population of older adults. Also, our other research (using the same collision data) found that signalized crosswalks on state routes were significantly associated with collisions ending in lower injury severity (Moudon et al. 2007b). Together, these findings suggested that signalized crossings on state routes be further studied, and approaches to their design, traffic management and enforcement be reviewed in order to secure the safety of pedestrians. Also, signalized intersections should be of special concern on multi-laned roads.

The SR 99 model showed significantly higher risk of collision occurrence at signalized crosswalks as well. The very high odds ratio (156.33) for collisions in a crosswalk with a signal in this model might be due to the fact that there were few control locations with these characteristics. Because most of the collisions on that facility occurred at crosswalks with a traffic signal, there were not enough control locations with these same characteristics to sample from.

Interestingly, however, the risk of a collision occurring on SR 99 was *lower* when the road had more than 4 lanes. This might be explained by the fact that whenever this particular road had 6 lanes, it was designed as a limited access road, prohibiting pedestrian access. As well, the 6-plus-lane configuration for SR 99 typically went through industrial areas with few people traveled on foot.

Posted speed and street-block size were only significant in the AllOtherSR model. In this model, lower speeds and larger streets blocks were related to higher probability of a collision. Because mean posted speed in the dataset was 45 mph (SD 8.34), it was likely that lower speed was associated with higher pedestrian volumes. The positive relationship between larger street-block size and the likelihood of a collision could be explained by the fact that larger block sizes were associated with fewer or no traffic signals or crosswalks near the collision location.

Presence and volume of vehicles and pedestrians

Variables selected as proxy variables for the presence of vehicles and pedestrians and related volumes (total residential units in 0.5 km of cases or controls, and employment density, ADT, and bus ridership) had the expected inconsistent results across the two models, supporting the position that SR 99 is a special type of state route. Association between ADT and the likelihood of a collision was positive, but only significant in the SR 99 model. Higher traffic volumes on this route expectedly led to higher risk of a collision occurring. Interestingly, our other research showed that higher ADT on all state routes (SR99 and all others) was associated with lower injury severity, which we interpreted as an association between ADT and speed: lower ADT on SR 99 meant lower speeds that, in turn, might suggest that lower injury severity if a collision occurred.

Residential densities in the 0.5 km of a case or control were low at 2.85 units per acre (SD = 3.00, ranging from 0 to 23.2). Associations with the total number of residential units were positive as expected, but only in the AllOtherSR model. However, this association was significant in the SR 99 model where density was calculated in the 1 km radius of the collision (data not shown). This indicated that residential density was a proxy for pedestrian volumes, but this proxy measure was sensitive to distance from the road where collisions might take place. In contrast with other state routes, SR 99 is a primarily commercial arterial. Residential development has occurred (and actually continues to occur at rapid rates within a block or more of the commercially zoned band of parcels facing the road itself).

The association was negative in the case of employment density, but only significantly so in the SR 99 model. The mean employment density within 0.5 km of case and control locations on SR 99 was 52.69 employees per acre (SD = 109.94), almost twice as high as the mean for the whole King County dataset. This finding could be interpreted in two ways: areas with dense employment along SR 99 generated few pedestrians (and therefore employment density is not a proxy measure for pedestrian volumes); or, the characteristics of the road passing through these areas were safer for pedestrians than those of the same road passing through areas of low employment density (in which case employment density would remain a proxy measure for pedestrian volumes). More research is needed to understand safety conditions around employment centers.

Bus ridership was expectedly positively related to the odds of a collision taking place in the AllOtherSR model. It was insignificant in the SR 99 model. Bus ridership is a known predictor of pedestrian volumes (Cervero 2001). Prior research on the same set of state routes found that the likelihood of a large number of collisions taking place at one location (using Pedestrian Accident Location or PALs as the dependent variable) was significantly and consistently related to bus ridership for all state routes (Hess et al. 2004). The lack of a significant relationship between the likelihood of a collision (as opposed to a PAL) could be explained by the fact that SR 99 was a heavily traveled transit corridor: more than half of case and control points on SR 99 had 11 or more bus boardings and alightings (mean = 26.57; SD = 42.78), compared with all the other state routes where more than half of locations had a median of zero bus riders (mean = 6.16; SD = 26.27)

Pedestrian activity generators

Strong and significant associations were found in both models with the number of retail parcels in the 0.5 km buffer and the likelihood of a collision. This finding confirmed previous results showing significant associations between the presence of retail and PALs in models excluding SR 99 (Hess et al. 2004). It suggested that retail could be a proxy measure for pedestrian volumes. Roads along and near retail facilities would thus require special safety treatment.

The SR 99 model showed a *positive* significant association between the risk of a collision occurrence and having 1 to 10 office parcels within 0.5 km of a collision or control point. This finding, in combination with the negative association with employment density in the same model, raised questions since offices typically generate the highest employment densities. It appeared that along SR 99, areas with medium density employment were associated with a higher risk of collision occurrence than areas with either low or high employment densities. Bivariate analyses produced expected results, showing that employment density was significantly related with a higher number of office parcels, more sidewalks, smaller street-blocks, and lower posted speeds. These and other research findings related to employment and office uses suggested that the relationship between employment and pedestrian volumes on state routes was not linear, and that research was needed to better understand travel, and specifically safe travel, on routes lining different densities of employment uses (Moudon et al. 2007a).

Several known generators of pedestrian activity were significant in the one-by one-testing, but insignificant in the models: grocery stores, restaurants and drinking establishments, clusters of neighborhood food and retail services, elementary and middle schools, and colleges. This could be interpreted as a positive finding indicating that land uses associated with more walking might not be a contributing factor to the risk of a collision taking place. However, the strong association between retail parcels and risk of collision suggest that retail activity in general increases the likelihood of collision. Retail parcels were significantly correlated with grocery store, restaurants and drinking establishment parcels and with the Neighborhood Commercial areas.

Sidewalks as pedestrian infrastructure

The presence of sidewalks on the state route was not significant in the bivariate analysis. The length of sidewalks on major roads in the neighborhood of a case or control point was positive and significant in the one-by-one testing, but did not contribute to increase the goodness of fit of the models. As expected, sidewalk length was negatively correlated with street-block size. The majority of the case and control locations had few sidewalks near them and a quarter of them had none. The mean of 2.52 miles (SD = 2.67) of sidewalks within the 0.5 km of the case or control points was relatively high given that the data only included major streets (in comparison, a medium sized urban grid of streets with sidewalks on both sides of major streets would generate 4 to 10 miles of sidewalks). This finding did not suggest that sidewalks did not contribute to safety. The models only showed that road or street crossings were highest risk locations—as locations with highest number of possible conflicts between people and motor vehicles. The positive significance of sidewalks in the one-by-one testing could be an indication that sidewalks are proxies for pedestrian volumes. The length of sidewalks near the case and control points was positively associated with the total number of residential units, employment density, and the number of retail parcels

Data and methodology

The previously developed models based on collisions aggregated in PALs suggested inconsistent and weak relationships between land use and collisions (Hess et al. 2004). Being based on disaggregate data on individual collisions, this study presented clearer significant correlations between land use and pedestrian safety. It also pointed to strong associations between key aspects of road design and pedestrian safety.

From a methodological perspective, calculating risk related to location characteristics rather than risk to individual pedestrians allowed for linking research results with safety programs, and specifically, for translating research results into intervention strategies and countermeasures. While individual pedestrians would like to know what their probability of colliding with a motor vehicle is, and while an epidemiologic perspective is useful for assessing trends in prevalence rates of collisions between pedestrians and motor vehicles, transportation safety policy and programs also need to know WHERE conditions are unsafe in order to implement countermeasures or in order to proactively prevent collisions. Being able to identify with confidence the high-risk locations will therefore help direct safety programs where they are most needed. The methods used in this study also suggested that high-risk locations could be revealed for large geographic areas. Overall, the ecological basis of the methods offered an alternative to the quasi-epidemiologic approaches often proposed in pedestrian safety. Such an alternative seems practical since the latter approach relies on monitoring pedestrian traffic and on collecting primary data on individual pedestrians, which are unlikely to be available in the foreseeable future for the many communities where people walk, and especially for the large areas where the population lives.

Finally, the case-control study design offered simple binary results and did not require the specification of segment length as units of analysis.

CONCLUSION

The study examined the independent effects of two “Es”: one, the established “Engineering” or road design “E”, and the second, a newly defined “Environment” “E,” or the environment along the road that attracts pedestrians. The goal was to identify the design and environmental determinants of collision locations, which, if modified, could lead to improve safety.

The study showed that some characteristics of both the road and neighborhood environments were associated with a higher risk that a pedestrian-motor-vehicle collision would occur. The presence of crosswalks and retail uses near state routes, and wider roads, were strong correlates of the risk of a collision occurring. Measures of exposure

(ADT, posted speed, bus ridership, residential units, and employment densities) affected the risk of a collision taking place differently for SR 99, the primary transregional arterial, than for all the other state routes. This indicated that future studies and analyses should differentiate between road type or class.

In terms of study design, the availability of individual geocoded collision data, combined with detailed spatial data on roads networks, traffic characteristics, and land uses, offered unique opportunities to identify where collisions would likely occur. These data pointed to the characteristics of high-risk locations at the level of the road design and traffic conditions, and at the level of the neighborhood immediately surrounding possible collision locations.

Research assessing the risk of collision based on the characteristics of location provide tangible information as to where safety measures should be targeted, and what specific aspects of the collision environment need attention to prevent future collisions. Case-control study design rely on relatively sophisticated analytical methods, yet yield results that are reasonably easy to interpret. They provide useful information on the relative magnitude of association of the independent variables to the dependent variables, which could guide the implementation of safety programs and the assignment of areas where further research would be needed.

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