Evaluation of Pedestrian Safety at Midblock Crossings, Porto Alegre, Brazil

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This paper proposes a method to evaluate the potential risk of pedestrian crashes at midblock crossings, which can be applied in developing countries. The method is quantitative because it uses modeling techniques to represent the relationship of risk factors with the occurrence of pedestrian crashes. Application of the method described here comprised the analysis of reported pedestrian crashes in the city of Porto Alegre, in southern Brazil, between 1998 and 2006, and the identification of midblock crossings with the highest number of pedestrian crashes. Twenty-one midblock crosswalks were selected for evaluation. A Poisson regression model was developed to relate pedestrian crashes to the prevailing operational and physical characteristics of midblock crossings. The results indicate that pedestrian crash risk is influenced by a combination of interactive risk factors, such as the presence of busways and bus stops, the road width, the number of traffic lanes, and the volume of pedestrians and vehicles.

Pedestrians are the most vulnerable road users and are at a greater risk of being injured in a traffic crash than vehicle occupants. In developing countries, they represent the group of road users with the largest number of fatalities (*1*). In Brazil, pedestrians accounted for 24% of all traffic fatalities reported in 2005. In urban areas, where 35% of all trips are made on foot, (*2*) pedestrians accounted for 40% of the reported traffic fatalities (*3*).

Risk analysis is necessary to develop cost-effective countermeasures capable of reducing the risk of pedestrian crash (*4*). Researchers apply different methods to evaluate the risk of pedestrian crash by using either crash- or noncrash-based measures, including historical crash data, change in user behavior, conflict and avoidance maneuvers, and ratings on the basis of expert and user opinion (*5, 6*). Few studies have focused on quantification of the relationship between site-specific characteristics and pedestrian crashes (*6–8*). Because resources are scarce and reliable crash data are not always available, most pedestrian safety studies conducted in Brazil are performed on the basis of expert and user opinion (*8*).

The Public Company for Transportation and Circulation, which regulates and enforces transit and traffic in the city of Porto Alegre, the southernmost capital of Brazil, has maintained a detailed georeferenced traffic crash database since 1998. This database is highly useful to identify high-frequency crash locations that involved pedestrians and to analyze pedestrian safety at crossings.

The main objective of this paper is to present the development of a method to evaluate the potential risk of pedestrian crashes at midblock crossings, consistent with the realities of developing countries. The method comprises the identification of high-frequency crash locations that involve pedestrians, the selection of factors associated with pedestrian crashes, the determination of data collection procedures, and the development and analysis of a Poisson model that associates pedestrian crashes with selected risk factors. It also provides results that are valuable for use in the improvement of pedestrian safety management in Porto Alegre. The methodological framework presented in this paper is transferable and can thus be used to assess pedestrian safety in other urban areas.

LITERATURE REVIEW

One of the methods used most often in pedestrian risk analysis is to identify pedestrian crash patterns from historical data. Studies generally point to male pedestrians as those most frequently involved in pedestrian crashes, and they point to the elderly and children as the most vulnerable pedestrians (*7–12*).

Human behavior has also been observed as part of the evaluation of pedestrian safety. Gårder concluded that, the higher the driving speed, the lower the percentage of drivers that yields to pedestrians at nonsignalized crosswalks (*9*). Sisiopiku and Akin verified that most drivers of right- or left-turning vehicles fail to yield to pedestrians when all share the same traffic signal green phase (*13*). Tiwari et al. collected pedestrian behavior data at intersections in Delhi, India, and noticed that a long wait time plays an important role in the unsafe behavior of pedestrians (*14*).

Knoblauch et al. conducted a before-and-after study to determine the effect of crosswalk markings on driver and pedestrian behavior at nonsignalized intersections (*15*). They concluded that drivers seem more cautious at marked crosswalks and drive slightly slower there than elsewhere. Marked crosswalks also channel the pedestrian flow to intersections.

Qualitative research methods are also widely applied to identify the road factors related to pedestrian-involved crashes. Ariotti et al. applied focus group techniques to identify the main factors that influence the behavior of pedestrians when they cross signalized intersections in Porto Alegre, Brazil (*16*).

Baltes and Chu used risk perception techniques to model the level of service at midblock crossings (*17*). Results reveal 15 factors as significantly correlated with pedestrians' perceived quality of service. The study suggests that difficulty in crossing increases with vehicle volume, vehicle speed, crossing width, and the length of traffic signal cycles; it decreases with the presence of marked crosswalks, traffic signals, and wide, restricted medians.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2193, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 37–43.
DOI: 10.3141/2193-05

Petritsch et al. built a service level model for pedestrians at signalized intersections (*18*). His study showed that pedestrian risk perception is influenced by right-turn-on-red volumes for the street being crossed, permissive left turns from the street parallel to the crosswalk, vehicle volumes, speed of the vehicles, number of traffic lanes, pedestrian delay, and presence of right-turn channelization islands.

Crash prediction models have also been developed to assess pedestrian risk. Most of these models were developed, however, for wide areas or roadway segments, and very few focused on intersections or midblock crossings. Pedestrian crashes are dispersed on the road network and, consequently, they are rare at any specific crossing (*5, 8, 19, 20*). Some models focus only on the volume of pedestrians and vehicles (*20–23*), and few have taken into account other risk factors that can influence the occurrence of a pedestrian crash (*6, 8*).

Zegeer et al. developed generalized linear models of pedestrian crashes at marked and unmarked crosswalks in the United States (*24*). Their models indicated that the probability of a pedestrian crash becomes greater as vehicle or pedestrian volumes increase. Other variables, such as speed limit, were not statistically significant.

Harwood et al. proposed a methodology to construct pedestrian crash models at intersections, which they have recommended be included in the Highway Safety Manual (*6*). The statistically significant factors in their base models included motorized traffic volumes, number of travel lanes, pedestrian volumes, presence of bus stops, presence of schools, presence of establishments that sell alcohol, and neighborhood incomes.

The literature review indicates a lack of specific models to evaluate pedestrian safety at midblock crossings. Also, the existing models and indexes cannot be used to assess pedestrian safety in most developing countries where weather, traffic flow, and the walking culture vary widely (*25*).

METHOD

The proposed method was designed to be simple and easily adaptable to different realities (*8*). It is composed of seven steps:

1. Crash database analyses. Researchers must understand how the data were collected. It is important to verify the data consistency and try to identify the crossings where most crashes occur. If the data are geo-referenced, it is possible to develop models on the basis of pedestrian crash data. Otherwise, researchers should use the database to identify pedestrian crash patterns and use perception risk techniques to evaluate pedestrian safety at midblock crossings.
2. Determination of criteria to select midblock crossings. If crossings are selected randomly, it is possible to obtain a sample that includes many crossings where no pedestrian crashes were observed for 10 or more years. Such a procedure would require large samples to generate crash models, and consequently more resources (*5*). Researchers with limited resources can opt to select for analysis only pedestrian high-crash crossings. Under this option, a crash-based model can be developed by using a smaller sample. A random sample can be used to estimate models on the basis of risk perception data.
3. Visits to selected crossings. Researchers should observe the characteristics of the crossings and determine the limitations each spot poses to data collection. The visits should also help in the selection of risk factors and the choice of data collection procedures.
4. Selection of risk factors and data collection procedures. The literature review highlights many factors that can influence pedestrian safety, and thus it is hard to develop a model that takes all of them into account. The researcher should select factors that are relevant. Data on the selected factors must be readily available or feasible to collect. Data collection procedures must be chosen concomitantly with risk factors and budget constraints.
5. Data collection. It is important to note the possible pitfalls during the data collection process and take them into account when the data are analyzed.
6. Model development. Regression models are generally estimated by using appropriate statistical software. It is advisable to remove the nonsignificant variables one by one to get an adequate model. To develop a crash model, researchers should use a generalized linear model, because crashes are count data. If the model is based on ratings, linear regression can be used (*17, 18*).
7. Conclusions and discussion. Researchers should conduct a critical analysis of the model and emphasize its limitations. They should also describe the advantages and disadvantages of the method.

CASE STUDY

The case study consisted of an application of the proposed method to evaluate pedestrian safety in the city of Porto Alegre, Brazil. This city has a population of 1,420,667 inhabitants and an area of 149 km^2 (57.53 mi^2) (*26*). Car ownership is high: about one motor vehicle per 2.5 inhabitants (*27*). Porto Alegre is one of the pioneer cities in Brazil for high-capacity bus transit, and today some 50 km (31 mi) of busways run through the city (*28*).

According to the city's official traffic crash database made available to this study, 12,799 pedestrian crashes occurred in Porto Alegre during a 9-year period (1998–2006), which represents an average of four pedestrian crashes per day.

Crash Database Analyses

The database contains all traffic crashes reported in Porto Alegre from 1998 to 2006. Details include the date of the occurrence, time of day, weather conditions, pedestrian age and gender, vehicle characteristics, and severity level in most pedestrian crashes.

The database also provides information on location. Each crash is classified by occurrence at an intersection or road section, as shown in Figure 1. If the person responsible for collecting data classifies the crash location as an "intersection," the names of both intersecting roads are registered. If the location is classified as a "road section," the address of the building in front of where the crash occurred is written down. If, for example, a crash takes place in Area 2a, the number to be registered is either 221 or 222. This information is used to geo-reference the crash data.

According to this classification, 88% of the pedestrian crashes in Porto Alegre occur at road sections. In this study, crashes at road sections are associated with midblock crossings. To determine the volume of pedestrian crashes that occur in midblock crossings (Areas 2a, 2b, or 2c in Figure 1), the crashes linked to opposite addresses were grouped (e.g., Street number 225 and 226). In this way, it was possible to relate the number of crashes with the crossing characteristics.

Determination of Criteria to Select Midblock Crossing

The preliminary midblock crossings were selected through the identification of addresses in the database that presented the highest

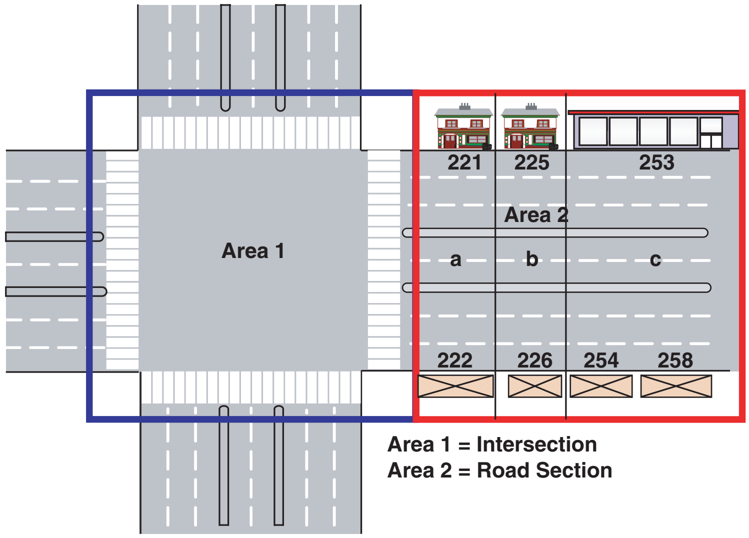

FIGURE 1 Classification of crash location.

number of pedestrian crashes. These addresses were used to determine the midblock crossing areas. The 25 selected locations corresponded to 3% of all pedestrian crashes reported in Porto Alegre. The pedestrian crash rates in the selected sites ranged from .89 to two crashes per year.

Visits to Selected Crossings

During the visits to the 25 selected addresses, it was evident that eight buildings (including malls, grocery stores, and hospitals) had a length of more than 50 m (164 ft), which delimited a road section and not a crossing. In these cases, site observations made it possible to define a representative crossing area for the crash location (Figure 2): (*a*) when there was a midblock marked crosswalk, it was adopted as the crossing area; and (*b*) when there was no crosswalk, the adopted crossing area was delimited by the entrance of the building. Six addresses were within the intersection influence area, located at street corners, and 11 corresponded to a midblock crossing but not necessarily to a regular crosswalk.

Four sites were excluded from the analysis: (*a*) three addresses identified buildings that were more than 350 m (1,148 ft) in length, and their corresponding road sections had more than one marked crosswalk; (*b*) one site was located in a remote area where the researchers did not feel secure to collect data.

Once crashes registered for the opposite buildings were aggregated to the selected crossings, pedestrian crash rates at the 21 selected midblock crossings ranged from 0.89 to 2.39 pedestrian crashes per year. On average, 1.39 pedestrian crashes occurred per crossing per year. At all selected crossings, at least one pedestrian crash occurred over the last 3 years.

Selection of Risk Factors and Data Collection Procedures

The selection of risk factors comprised an initial phase, with the selection of factors based on the literature review and the characteristics of selected crossings (*8*). The final classification of risk factors in four categories (Table 1) took into the account the possibility of collecting the data, given that no data were readily available.

To simplify the data collection on the site, video images, filmed and visually analyzed by the researchers, provided the characteristics

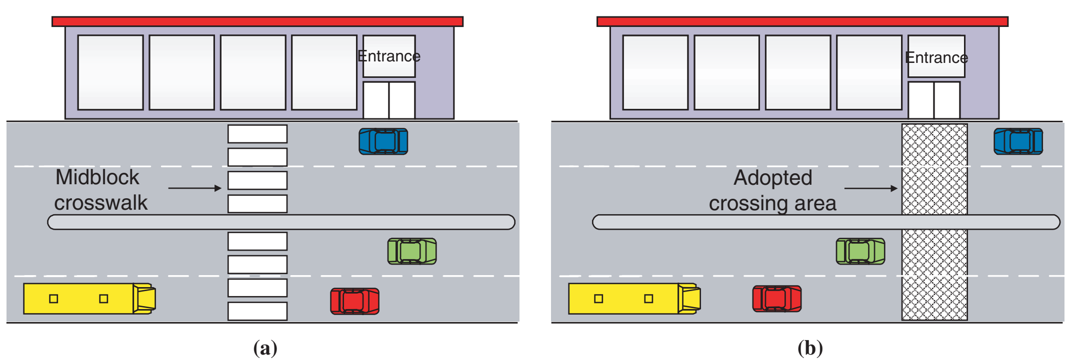

FIGURE 2 Adopted crossing area in front of trip generator buildings: (*a*) with a midblock crosswalk, which is the adopted crossing area, and (*b*) without a midblock crosswalk (the area in front of the building entrance is the adopted crossing area).

TABLE 1 Selected Risk Factors

Category	Risk Factors
Public transportation characteristics	Presence of busway transit system Presence of a bus stop (close to the crossing area but not at the busway) Distance from the crossing center to the closest bus stop (including bus stops in the busway system)
Road features	Road width Number of traffic lanes Maximum number of crossing stages (e.g., if there is a median island, the maximum number of stages is two; if there is a median busway with two refuge islands, the crossing will take three stages) Number of traffic directions (one or two ways) Presence of refuge island Parking permission
Road pedestrian facilities	Presence of a marked crosswalk Presence of a traffic signal Distance to the closest marked crosswalk or intersection Average sidewalk width
Pedestrian and vehicle flow characteristics	Percentage of male pedestrians Percentage of elderly pedestrians Percentage of public transportation vehicles on traffic flow Pedestrian waiting time Pedestrian volume Vehicle volume

of the pedestrian and the vehicle flows. Data related to other characteristics were collected in loco.

The crossings were videotaped with a digital camera for a minimum period of 1 h. To avoid any over- or underestimation of pedestrian and vehicle volumes, the videos were shot on weekdays and during off-peak hours. Ideally, manual counts should be extrapolated to estimate annual pedestrian and vehicle volumes. Yearly volume patterns were not available, however.

At crossings located in front of buildings with long lengths, it was useful to have two people in the field. One videotaped the selected crossing area, and the other counted pedestrians who crossed outside the video coverage area.

Data Collection

A busway road environment existed in 10 of the selected midblock crossings, and 12 of the other crossings were located close to a bus stop that was not part of the busway system. Only one crossing was neither close to a bus stop nor to a busway. The distance between the middle of the crossing and the closest bus stop ranged from 0 to 68.9 m (226.05 ft). Other data collected in the field are summarized below:

- Road width. Road width ranged from 9.6 to 28.8 m (31.5 to 94.5 ft). Only four crossings were wider than 25 m (82 ft).
- Number of traffic lanes. The number of lanes ranged from three to eight.
- Maximum number of crossing stages. Five crossings had no refuge island and had to be traversed in one stage, 14 entailed two stages, one involved three stages, and another entailed four stages. Figure 3 shows an example of a crossing with four stages.
- Number of traffic directions. Sixteen crossings were on two-way roads.
- Presence of refuge islands. Refuge islands occurred in 15 crossings.
- Parking permission. Parking was allowed at three sites.
- Presence of a marked crosswalk. Marked crosswalks existed at nine crossings.

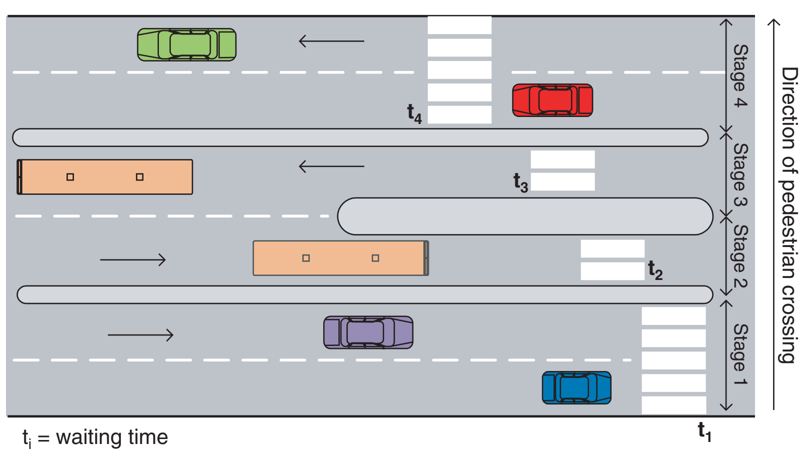

FIGURE 3 Schematic drawing of crossing.

- Presence of a traffic signal. A signal was in place at nine crossings with marked crosswalks.
- Distance to the closest marked crosswalk or intersection. The distance ranged from 0 to 78.9 m (258.9 ft). Eight crossings were located more than 40 m away (131 ft) from a marked crosswalk or intersection.
- Average sidewalk width. The width ranged from 2.4 to 6.5 m (7.9 to 21.3 ft).

To ensure reliability, the videos were analyzed by the same person who shot them. On average, 1 h of videotape required 1.5 h of video analysis to characterize each direction of vehicle traffic. The percentage of public transit vehicles within the overall flow of motorized vehicles varied between 2.6% and 80.2%, and the total vehicle flow ranged from 242 to 4,721 vehicles per hour.

Of the videos analyzed, characterization of the pedestrian flow required, on average, 5 h per crossing stage. Pedestrian movements are erratic and demand much attention. Not every pedestrian completed the crossing; some people used the median as a sidewalk after they had crossed one stage.

The total waiting time for each pedestrian was calculated as the sum of the waiting time in each crossing stage. In the crossing shown in Figure 3, which is typical of a site that has a median busway, the pedestrian wait time was the sum of waiting times in each stage ($\sum t_i$). Waiting time per crossing presented high variances (in some cases the time varied from 14 s to 176 s). Averages with high variances can generate significant distortions in the formulation of models. Thus waiting time was excluded from model estimation.

A classificatory count of pedestrians was carried out during analyses of the videos. Included in the counts were pedestrians who crossed only certain stages, people who carried children, and babies in strollers, since they, too, were exposed to motor vehicles and the risk of collision. Pedestrian volumes represented the sum of pedestrians that crossed the road outside and inside the video coverage area and ranged from 37 to 706 pedestrians per hour. The percentage of male pedestrians varied from 29.6% to 67.7%, and the percentage of elderly pedestrians from 15.2% to 24.8%.

Model Development

Categorical variables were converted in dummy variables: "yes" = 1; "no" = 0. The dummy variables related to the presence of traffic signals and marked crosswalks were merged, to avoid the perfect multicollinearity.

A correlation matrix was calculated for all possible pairs of quantitative variables. Strong correlations ($|\rho| > 0.70$) were observed between road width, vehicle volume, and number of traffic lanes. The percentage of male pedestrians was positively correlated with the distance to the closest marked crosswalk or intersection ($\rho = 0.63$), whereas the percentage of elderly pedestrians was negatively correlated to this distance ($\rho = -0.55$).

The pedestrian crash rate was selected as the model outcome. This rate is calculated by dividing the number of reported crashes by the pedestrian volume. The use of this rate mitigates possible errors derived from the adoption of a crossing area to represent the location of reported crashes (Figure 2).

In this study, Poisson models were considered the most appropriate, since the statistical distribution of the number of pedestrian crashes per midblock crossing meet the requirement that the mean be roughly equal to the variance ($\mu = 12.48$; $\rho^2 = 12.76$). Pedestrian volumes were used as exposure variables. Equation 1 presents the basic formulation of the model:

$$\text{NPC}_i = \text{Pv}_i e^{\Sigma \beta j\, Xij} \quad (1)$$

where

NPC_i = number of reported pedestrian crashes at crossing *i* from 1998 to 2006,
Pv_i = hourly pedestrian volume at crossing *i*,
e = Euler's number,
βj = model coefficients, and
Xij = determinant variables.

Many different models were tested with Poisson robust regression in STATA software. The robust option in STATA uses a degree of freedom correction of $n/(n - k)$ times the error variance to improve the small sample estimates (*29*). It was not possible, however, to develop a statistically significant model without including strongly correlated variables, which raised the issue of multicollinearity.

Multicollinearity leads to inaccurate estimates of the coefficients of highly correlated variables. It is a serious problem if it is necessary to understand how individual determinant variables affect the outcome variable. If the objective of the model is to estimate an outcome, however, multicollinearity should not be a serious concern as long as two conditions are reasonably satisfied: (*a*) correlated variables as a group are precisely estimated and (*b*) a correlation pattern prevails in the situation being estimated (*17*).

This study did not aim to evaluate the effect of individual risk factors on pedestrian safety, so correlated variables could be used. Other studies also have used correlated variables in the formulation of pedestrian safety evaluation models (*17, 30*).

The model, including all determinant variables, was developed on the prediction apart from the pedestrian volume that was used as an exposure variable. The least statistically significant variables at a confidence level of 95% (p-value ≤ .05) were dropped one by one from the analysis. The final model revealed 12 significant variables to explain the pedestrian crash rates at midblock locations (Table 2).

This model was tested with a likelihood ratio chi-squared statistic test of the overdispersion parameter alpha (goodness-of-fit). If the test is not significant (p-value > .05), alpha is equal to 0, and Poisson distribution is appropriate. In the developed model, the p-value was equal to .0944, so Poisson could be used to represent the data. Furthermore, it was significantly better than a model based only on constant values (Prob > chi^2 = 0.00). The McFadden pseudo-R^2 calculated by using STATA was equal to 0.66.

The estimated model shows that several interactive factors can influence pedestrian safety. Although some multicollinearity is present in the data, it is possible to make inferences about weakly correlated variables. The pedestrian crash rate at midblock crossings seems to increase in the presence of busway transit systems or bus stops and in two-way roads. The pedestrian crash rate decreases, however, if a marked crosswalk with a traffic signal exists and if the number of crossing stages or sidewalk widths increases.

An increase in the percentage of public transportation tends to reduce the estimated pedestrian crash rates significantly. One possible explanation is that more transit vehicles imply a higher vehicle equivalent flow and lower speeds. Slow traffic implies a smaller chance of pedestrians being hit by a motor vehicle.

Figure 4 shows the relationship between the number of crossing stages (NCS) and the pedestrian crash rate (NPC/Pv) on one-way

TABLE 2 Final Model

Risk Factor[a]	Coefficient	Robust Standard Error	(*z*)	*p*-Value
BS	1.5208550	0.3876066	3.92	.000
BTS	0.6563034	0.2403136	2.73	.006
NTL[b]	0.2913042	0.0962700	3.03	.002
NCS	−0.2867297	0.1200696	−2.39	.017
NTD	0.8560028	0.3621792	2.36	.018
PMCTS[c]	−0.6257014	0.3277582	−1.91	.056
DMC[c]	0.0193243	0.0068193	2.83	.005
SW	−0.4229680	0.0833831	−5.07	.000
PPTV	−3.4243790	0.3271213	−10.47	.000
PMP[c]	−2.0971560	0.6455293	−3.25	.001
Vv[b]	−0.0004593	0.0002193	−2.09	.036
RW[b]	−0.0570603	0.0241332	−2.36	.018
Constant	−1.1526730	0.5214371	−2.21	.027
Pv	(exposure variable)			

NOTE: Sample size = 21; Wald $chi^2(12)$ = 2,915.66; prob > chi^2 (*p*-value) = .0000; pseudo $R^2 = 0.66$; goodness-of-fit chi^2 = 13.54708; prob > $chi^2(8)$ (*p*-value) = .0944

[a]Significant risk factors list:
BS: presence of a bus stop (dummy variable: "yes"= 1; "no"= 0)
BTS: presence of busway transit system (dummy variable: "yes"= 1; "no"= 0)
NTL: number of traffic lanes
NCS: maximum number of crossing stages
NTD: number of traffic directions
PMCTS: presence of marked crosswalk and traffic signal
DMC: distance to the closest marked crosswalk or intersection (meters)
SW: average sidewalk width (meters)
PPTV: percentage of public transportation vehicles on traffic flow
PMP: percentage of male pedestrians
Vv: hourly vehicle volume
RW: road width (meters)
Pv: hourly pedestrian volume
[b]Variables strongly correlated ($|\rho| > 0.70$)
[c]Variables moderately correlated ($|\rho| > 0.50$)

and two-way roads. The graph shows that, although crash rates decrease with NCS, the model is more sensitive to NCS on two-way roads (higher slope of curve) than on one-way roads. The graph indicates that, to improve pedestrian safety, implementation of a refuge island on a one-way road is not as effective as an increase in the NCS on a two-way road.

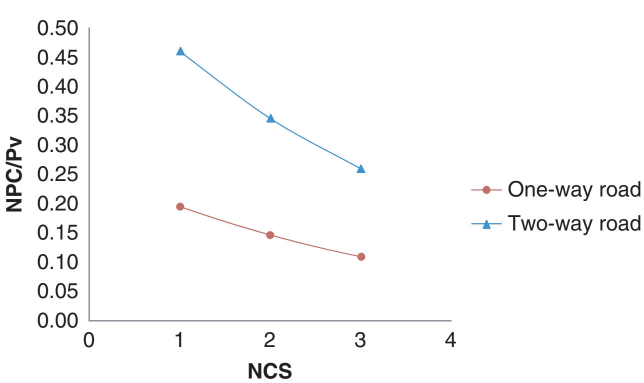

FIGURE 4 Relationship between NCS and NPC/Pv.

CONCLUSIONS AND DISCUSSION

This paper presents an exploratory study of pedestrian safety at midblock crossings in Porto Alegre. It points out that public transportation influences pedestrian safety. Crossings located close to bus stops, or busway systems, experience higher pedestrian crash rates. Several arterial avenues in Porto Alegre contemplate busway corridors, and public transportation accounts for about 50% of all motorized trips in the city. It is also likely at these crossings that pedestrians behave unsafely (e.g., run to catch a bus). In some cases, it is possible that the location of a bus stop is not the most appropriate to meet the needs of pedestrians.

The results of this study are useful to improve pedestrian safety in Porto Alegre. The case study demonstrates that the proposed method is appropriate to evaluate the potential risk of pedestrian crashes at midblock crossings. The main advantage of the method is that it can be adapted to prevailing realities in developing countries, where resources and data are scarce.

The method has some limitations, however, which should be considered when pedestrian safety is analyzed. The model is appropriate to evaluate crossings where a correlation of variables prevails, but the correlation pattern between vehicle volumes, number of traffic lanes, and road widths seems to be applicable to other crossings in Porto Alegre.

Selection of midblock crossings because they are located at the site of frequent crashes can lead to a sample that excludes some important risk factors. In this study, for example, it was not possible to model the effect of a marked crosswalk or traffic signal individually, since all selected crossings with marked crosswalks had traffic signals. Thus, if this model were used to evaluate a marked crosswalk without a traffic signal, pedestrian safety either would be under- or overestimated.

Another limitation results from the way that pedestrian and vehicle data were obtained. Collecting data for short periods can generate errors in the estimation of the volumes, and, consequently, in the formulation of the model. Nonetheless, as a similar data collection procedure was adopted at every crossing, this problem was mitigated. Moreover, the objective of the model is to provide information about pedestrian risk levels rather than to predict pedestrian crashes.

These limitations do not invalidate the use of the proposed model to assess pedestrian safety in Porto Alegre. The researcher or practitioner should be aware of its limitations, however, before any general conclusions are drawn about pedestrian safety.

ACKNOWLEDGMENTS

The authors appreciate the enthusiastic and cooperative participation of Henrique Simonetti, João Rodrigo Mattos, Marcelo Hansen, Gustavo Meneses, and Paula Ariotti in the data collection process. They thank the Empresa Pública de Transporte e Circulação for providing crash data, and are grateful to CNPq, Brazil, for financial support of this research.

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The Transportation in the Developing Countries Committee peer-reviewed this paper.