Studying the Impact of Roadway Cross-Section, On-Street Parking and Traffic Volume on the Crash Frequency of Urban Road Segments

Muhammad Wisal Khattak, Corresponding author
UGent, Department of Civil Engineering
Technologiepark 60, 9052 Zwijnaarde, Belgium
Email: Muhammad.Khattak@UGent.be
&
UHasselt, Transportation Research Institute (IMOB)
Agoralaan, 3590 Diepenbeek, Belgium
Email: muhammadwisal.khattak@uhasselt.be
ORCID iD: https://orcid.org/0000-0002-0187-2519

Ali Pirdavani
UHasselt, Faculty of Engineering Technology
Agoralaan, 3590 Diepenbeek, Belgium
&
UHasselt, Transportation Research Institute (IMOB)
Agoralaan, 3590 Diepenbeek, Belgium
Email: ali.pirdavani@uhasselt.be
ORCID iD: https://orcid.org/0000-0001-8374-9305

Pieter De Winne
UGent, Department of Civil Engineering
Technologiepark 60, 9052 Zwijnaarde, Belgium
Email: P.DeWinne@UGent.be
ORCID iD: https://orcid.org/0000-0002-0772-3709

Tom Brijs
UHasselt, Transportation Research Institute (IMOB)
Agoralaan, 3590 Diepenbeek, Belgium
Email: tom.brijs@uhasselt.be
ORCID iD: https://orcid.org/0000-0003-2622-4398

Hans De Backer
UGent, Department of Civil Engineering
Technologiepark 60, 9052 Zwijnaarde, Belgium
Email: Hans.DeBacker@UGent.be
ORCID iD: https://orcid.org/0000-0002-3605-150X

Word Count: 6615 words + 3 tables (250 words per table) = 7365 words

Submitted 31/03/2022

ABSTRACT

One of the critical decisions highway designers make involves the selection of roadway cross-section since it influences the safety, capacity, and function of the facility. While assessing its impact on other factors is relatively easy, it is not always straightforward for safety. Previous literature reported contradictory observations concerning the complex relationship between crash frequency and roadway cross-section design, particularly in urban areas. Another related issue is the lack of fresh insights in the literature about the safety implications of on-street parking in urban areas. In this study, we developed safety performance functions to examine the impact of roadway cross-section elements, on-street parking, and traffic volume on the crash frequency of urban roadways using negative binomial framework. We also discussed whether the results could be used to improve safety. For modeling, a dataset consisting of six-year crash counts, traffic volume, and road cross-section design data including parking information was created. Our findings revealed statistically significant relationships between crashes and the number of lanes, segment length, and traffic volume but results for lane width were insignificant. The on-street parking was significant only for injury and injury & fatal crashes. Roads with the higher number of lanes would experience more crashes. Besides, injury and injury & fatal crash frequency would be highest on roads with two-sided parking than one-sided/no parking. To conclude, road cross-section elements and on-street parking play a vital role in crash occurrence in urban areas and, therefore, should be designed adequately for safety.

Key Words: Roadway Cross-Section, Urban Roads, Safety Performance Functions, Negative Binomial Distribution, On-Street Parking

INTRODUCTION

The selection of a proper cross-section is an important point in the geometric design process of roadways. Choices made about the cross-sectional elements, such as, the number of lanes, lane width, roadway width, median width, shoulder width, curbs, et cetera, considerably affect the capacity, safety, and function of the desired facility. Highway engineers are expected to propose designs that not only satisfy the capacity and functional requirements but also provide safe mobility. From a designer perspective, evaluation of the capacity and function considerations with regard to cross-section is relatively easy compared to its safety implications. A review of previous literature revealed that although the roadway cross-sectional characteristics influence road safety, there is a lack of clear understanding of the association between cross-sectional elements and crash frequency. Studies on this subject have shown inconsistent and contradictory conclusions (*1*). It is also important to note that most of these studies are conducted for rural highways and urban freeways. On the other hand, only a few studies have considered the relationship between cross-sectional elements and road crashes in urban areas (*2*), probably because of the associated complexities of the factors involved (*3*). The presence of on-street parking and their safety implications in urban areas is another highly debated subject in transportation and urban design studies (*4*). Thus, fresh investigations that consider the relationship between roadway cross-section and on-street parking with crash frequency would provide new insight into understanding crash occurrence on local roads in urban areas. This paper investigated the association between roadway cross-section elements (e.g., lane width and the number of lanes) and crash frequency by developing safety performance functions (SPFs). The impact of on-street parking was also studied since this influences the selection of cross-section width, traffic flow, and consequently safety.

LITERATURE REVIEW

Transportation agencies confer prime importance to the design of roadway cross-sectional elements because of their impact on key operational characteristics (i.e., safety, capacity, and function). The provisions in the Highway Capacity Manual (HCM) (*5*), and the role assigned by the local road agencies that these facilities are supposed to play in the road network, both make the assessment of the capacity and the function relatively easy. On the other hand, evaluating the safety implications of cross-sectional elements requires extra efforts. Many studies have attempted to determine this association in the past. A summary of the related literature is provided below:

Relationship between Roadway Cross-Section and Crash Frequency

A decent volume of literature has informed about the significance of cross-sectional characteristics in crash prediction (*6*, *7*). Their findings revealed that lane width, shoulder width, median width, and roadway width significantly affect the safety of highway facilities. In certain instances, researchers have used other related variables, like shoulder type, pavement type, etc., when roadway cross-sectional elements were either not available or were found insignificant. For example, Nowakowska (*8*) attempted to capture the influence of cross-sectional elements along with shoulder type on crash occurrence. The author found that shoulder type was a significant predictor of crashes but its presence in the model resulted in lane width and shoulder width to be insignificant variables. Nowakowska (*8*) reported that paved shoulders decreased the crash counts by 30% to 70% compared to unpaved shoulders. Another study on rural two-lane highways found that roads with narrow or no shoulders were safer than the roads with wider shoulders (*9*). Studies in the urban areas, on the other hand, have shown inconsistent results. For instance, wider facilities have been reported to have higher crash frequencies than the narrower facilities (*10, 11*). Dumbaugh (*12*) found the opposite results and concluded that an increase in lane width and a subsequent decrease in the shoulder width in urban arterials were associated with fewer segment crashes. Gross et al. (*13*) used several combinations of lane width and shoulder width to study their safety trade-off while keeping the total width constant. They did not find any clear relationship between the lane width and crashes due to variation in the shoulder width but reported a small improvement in the safety benefits of increasing lane width over the shoulder width. Consequently, they proposed to develop crash modification factors (CMFs) considering the interaction between lane and shoulder width.

Lane Width

Lane width is one of the most widely used roadway characteristics in studying crashes on urban roads but its safety effects are often inconsistent (*3*). In highway engineering, wider lanes are usually linked with higher operating speeds and increased safety than the narrower lanes. The HCM acknowledges this by documenting higher free-flow speeds for multi-lane highways with wider lanes (*5*). Safety literature, however, lacks tangible evidence on the safety implications of wider lanes. Mohammed (*14*) attempted to show how lane width could affect roadway safety. He argued that it makes sense to assume that wider lanes provide an additional space and time threshold that helps the drivers take corrective actions and avoid collisions compared with narrower lanes. However, an opposing argument suggests that drivers are capable of adapting to the available space and positive safety effects of wider lanes may be counterbalanced by an increase in operating speed (*15*). Though some studies have found positive safety effects of wider lanes (*16*, *17*), classical studies have mentioned an optimal lane width (usually around 3.5m) for safe traffic operations (*18*, *19*). Beyond that lane width, the safety benefits of widening lanes decrease and even can increase crash risk in some cases (*20*). Mehta and Lou (*21*) found similar results for rural two-lane and rural four-lane divided roads.

Number of Lanes

The number of lanes is another important roadway cross-sectional variable that affects the crash counts either positively or negatively. To say, an increase in the number of lanes could result in a reduced traffic density, which could have a positive effect on safety. On the other hand, an increase in the number of lanes could also reduce safety since overtaking and lane changing maneuvers increase significantly. In many studies, it has been established that a higher number of lanes is associated with an increased crash rate (for detailed discussion, please see (*22*)). While studying the relationship between roadway cross-section and crash occurrence, Noland and Oh (*23*), and Milton and Mannering (*24*) reported an increase in crash counts as the number of lanes increased. Similar results were found by Abdel-Aty and Radwan (*25*) for urban road segments. Garber and Ehrhart (*26*) used a different perspective by considering flow per lane of the roadway and found an increase in crash rates when flow per lane increased.

On-Street Parking

The safety implications of on-street parking was the subject of many studies carried out between the 1940s and 1970s (*4*). Since then, a small number of studies have considered the issue of on-street parking and its safety implications, which implies that, possibly, the effect of on-street parking on traffic safety has already been well-researched and solid conclusions have been established. The general findings of these studies indicated that on-street parking is crash-prone and decrease the safety of road users (*27*, *28*). Other studies have found an increase in traffic safety as a result of the removal of on-street parking. For example, in a very old study, a reduction of about 37% of non-intersection crashes was reported for six segments when on-street parking was removed from the arterials in the city of Hamilton, Ontario (*29*). Dumbaugh and Gattis (*30*) and El-din (*31*) have mentioned that on-street parking allows for the row of stationary vehicles to act as a buffer between moving vehicles and pedestrian and, thereby, increase safety by segregating them from fast-moving vehicles. In terms of parking type, parallel parking is usually described as safer than perpendicular and angled parking (*27*, *32*). Perpendicular parking and angled parking, however, are previously reported to result in less severe crashes because of more separation (i.e., increased buffer zone) between vehicles and pedestrians (*33*). Interested readers are referred to Sisiopiku (*32*) for a detailed review of the effects of on-street parking on safety.

Safety Performance Functions

Safety performance functions (SPFs) are regression models, developed to find a statistical relationship between road crashes, traffic variables, and roadway characteristics. They are also known as crash prediction models, accident prediction models, or collision prediction models. These are widely used to measure the safety of roadway entities (i.e., segments and intersections). In particular, SPFs have found applications in determining factors contributing to various crash types and severities, in the identification of crash-prone areas (i.e., network screening), planning of hazardous sites through ranking, and in safety considerations while designing roadway geometry. Road safety studies also use other techniques, such as computational intelligence or artificial intelligence to find the relationship between crashes, traffic variables, and roadway characteristics. However, SPFs are preferred because of the solid mathematical base associated with these methods and because SPFs make the interpretation of results and causalities of the dependent variables easy to determine (*34*). Further, SPFs take care of the regression-to-the-mean bias and are capable of addressing the problem of unobserved heterogeneity in the crash data by using random-effects or by appropriate modification of model specification. Finally, SPFs are good tools to account for the nonlinear relationship between crash frequency and predictors (*35*).

In the beginning, researchers used simple linear regression to create crash prediction models, assuming a normal distribution for road crash data while ignoring the problem of unequal variance (*36*). Many studies, however, had proved the inadequacy of simple linear regression to model crash data (*37*). Due to the limitations of linear regression to model discrete, non-negative, and asymmetrically distributed random events (*36*, *38*), researchers proposed generalized linear models (GLMs) for crash data analysis (*39*). Several types of GLMs including Poisson regression (*36*, *40–42*), Poisson-gamma or Negative Binomial (NB) (*41*, *42*), Quasi-Poisson (*43*), Gamma regression model (*41*), and other variations of the NB regression model (*44*, *45*) were used by researchers in road safety studies. The GLMs used for modeling crash data have certain pros and cons depending on the characteristics of the available data. For example, Poisson models are only suitable when the variance of the response variable is equal to its mean, which is rarely the case with crash data. Further, using Poisson regression for crash data modeling directly tends to underestimate the parameters standard error (SE), which can cause a biased selection of parameters in the final model. To solve the problem of over-dispersion, researchers suggest the NB regression approach. It is important to note that the relationship between the dependent and independent variables is not always linear and hence typical NB models cannot be used. To deal with the non-linearity issues, most recent studies have used generalized non-linear models (*43*, *46*).

DATA PREPARATION AND DESCRIPTION

A dataset consisting of the information of urban roads of the city of Antwerp (Belgium) was prepared. It comprised of crash, traffic, and road geometry data for 6 years period (2010-2015). The total length of the road network used in this study was 268.80 km and it was divided into 2467 homogeneous road segments (**Table 1**). Crash data was acquired from the City Police of Antwerp. It contained information about crash severity, time and date of the crash, geographical coordinates of the crash location, and information about road conditions, drivers and vehicles involved. Crash data was divided into various severity levels (i.e., All crashes, Injury crashes, Injury & Fatal crashes, Property Damage Only (PDO) crashes). The road geometry data consists of road width, number of lanes, and type of pavement. It was derived from an online official database of the Flemish government called Flanders Road Register (*47*). Road segments were separated from intersections, as per the Highway Safety Manual (HSM) guidelines (*35*), and homogeneous segments were defined using an open-source geographical information system

(GIS) application package QGIS, Version 3.6.2 (*48*) (QGIS Development Team, 2019). Since the original data obtained from the Flanders Road Register did not contain a variable "lane width", a roadway cross-section variable "lane width" used in this study was defined as the width from curb to curb or an edge-line to edge-line of a roadway segment divided by the number of lanes in that segment as per the definition in Hauer (*49*). Data about parking (i.e., presence, arrangement, and type) was manually obtained using Google Maps (*50*). The presence of on-street parking takes a certain amount of roadway width that cannot be used for traveling purposes. Segments with such parking settings were identified in the database and after detailed scrutiny, it was decided to use the following study-specific definition of modified lane width using Google Maps (*50*) and Google Earth Satellite Imagery (*51*);

- If there is parking on both sides, and the parking width equals to PW and roadway width equals to RW, then lane width, LW, is defined as follows:

$$LW = RW - 2PW$$

- If there is parking on one side, and the parking width equals to PW and roadway width equals to RW, then lane width is defined as follows:

$$LW = RW - PW$$

- Otherwise: $LW = RW$

It was decided to divide the parking settings into two discrete variables: (i) Parking Type and (ii) Parking Arrangement. The parking type referred to the orientation in which the vehicle was parked relative to the traveling lanes. Parking types used in this study included (a) Parallel (b) Mixed (c) Perpendicular (d) Angled as shown in **Figure 1**. Parking arrangement was defined as the capability of the roadway to allow for parking either on one or both sides. In the case of divided roads, it was possible to provide parking on three or four sides (i.e., one or two-sided parking in each direction). Parking arrangements illustrated as (a) One-sided (b) Two-sided (c) Three-sided (d) Four-sided are shown in **Figure 2**.

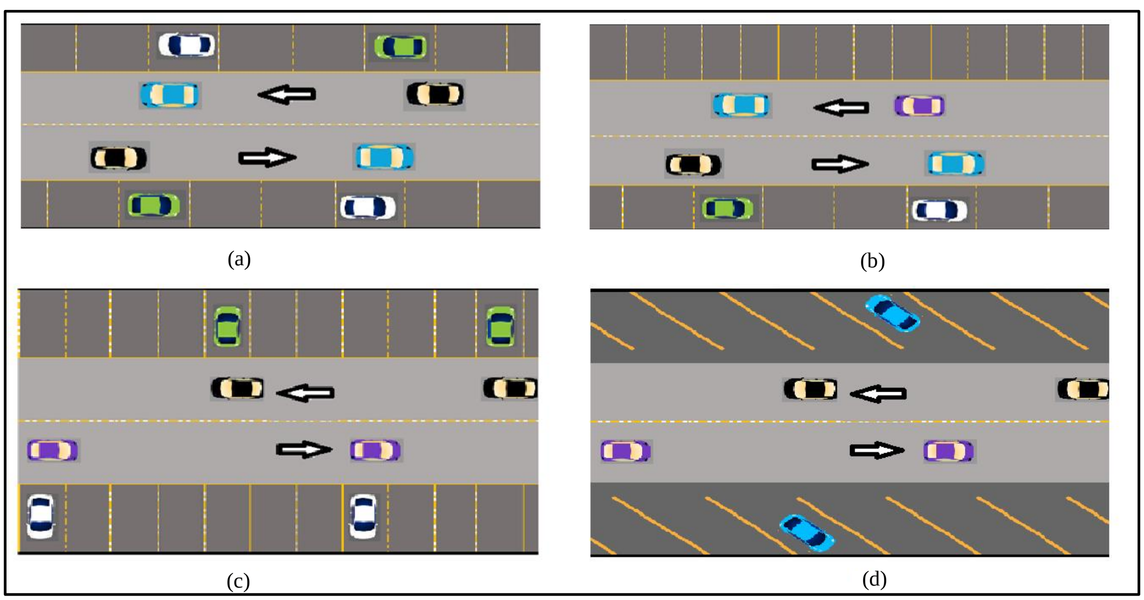

Figure 1 Parking type: (a) Parallel (b) Mixed (c) Perpendicular (d) Angled

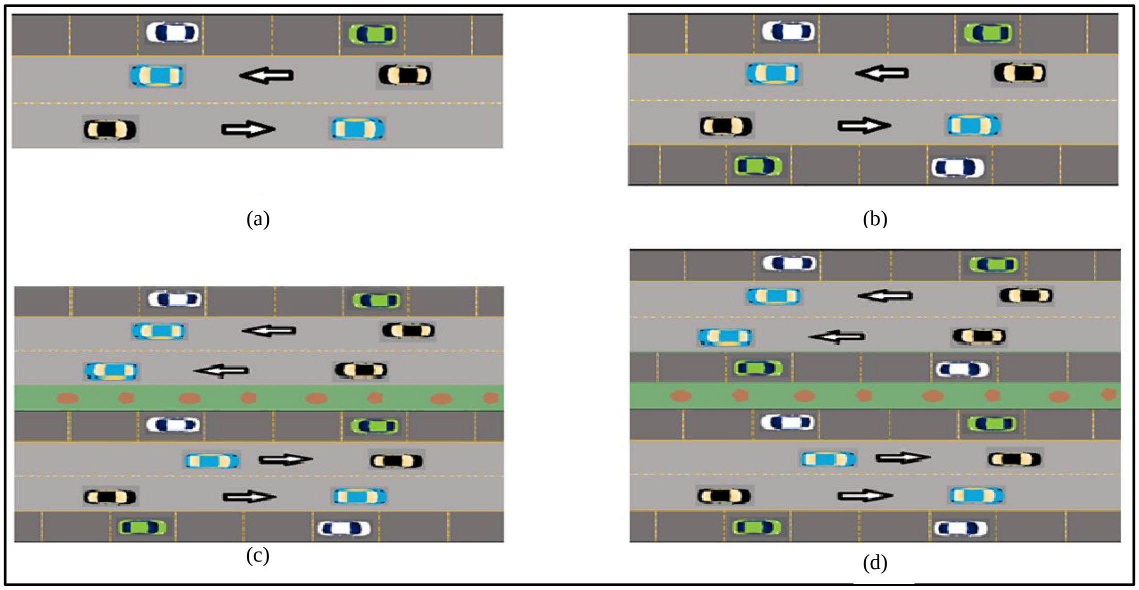

Figure 2 Parking arrangement: (a) One-sided (b) Two-sided (c) Three-sided (d) Four-sided

Traffic flow data were obtained from Lantis, a mobility management company in Antwerp. In the current study, the actual traffic count data was used in combination with the results from the Lantis's microsimulation traffic model called Dynamisch Model Kernstad Antwerpen (DMKA). Mobiliteit en Parkeren Antwerpen Ag, an office looking after parking and mobility services of Antwerp city also uses the same model for optimizing its operations. The average traffic counts from the simulation results were checked for residuals against the actual counts. The overall difference of the simulation counts from that of the actual data was less than 5% for the study network. Finally, it was decided to use both actual counts and simulation counts to obtain as much as possible traffic counts for the local streets and with the accuracy as near as possible to the actual counts. **Table 1** shows a summary of the data used in this study.

TABLE 1 Descriptive Statistics of a Dataset for the Urban Roads of Antwerp

(a) Traffic and roadway cross-section variables				
Variables	Minimum	Maximum	Mean	Std. Deviation
Length(km)	0.05	1.557	0.109	0.104
Lane width(m)	2.50	5.00	3.51	0.50
No of Lanes	1	14	2.33	1.52
AADT (veh/day)	13	42783	4842	6543
Parking variables				
Parking Type [a]	0=738 sites, 1=1565 sites, 2=164 sites			
Parking Arrangement [b]	0= 740 sites, 1= 719 sites, 2= 949 sites, 3=59 sites			
(b) Crash Frequency				
	Minimum	Maximum	Mean	Std. Deviation
All crashes	0	243	7.52	10.28
Injury & Fatal crashes	0	142	2.01	4.421
Injury crashes	0	142	1.99	4.402
PDO crashes	0	101	5.51	6.937

[a] 0= No parking, 1= Parallel parking, 2= Others (Perpendicular, angular and mixed parking)
[b] 0= No parking, 1= One-sided parking, 2= Two-sided parking, 3= Others (Three-sided and Four-sided parking)

METHOD

Functional Form

Generalized Linear Model (GLM) with the NB framework was used to estimate the crash frequency as a function of various explanatory variables (i.e., road traffic, road geometry, and roadside environment characteristics). A literature review showed that several studies in the past have used the following GLM functional form (**equation 1**) that allows for the NB distribution framework;

$$N_{predicted_i} = exp\ (\beta_0 + \beta_{1.}\ L_i + \beta_2.\ ln(AADT_i) + \cdots + \beta_k.\ (X_{ki})) \qquad (1)$$

Where, $N_{predicted,i}$ = Predicted crash frequency on segment "i", β_0 = intercept, L_i = length of roadway segment "i" (km), $AADT_i$ = Average annual daily traffic of segment "i" (veh/day), β_k coefficient of variable "k", X_{ki} = other predictors (e.g., geometric characteristic) of segment "i". Taking the natural logarithm of AADT ensured the logical outcomes of the models, that is, to yield zero crashes when there is no traffic on a specific road segment (*52*).

Multi-Collinearity

Multi-collinearity was checked for all potential predictors before developing the SPFs using the variance inflation factor (VIF) test. The VIF is a value by which multi-collinearity among predictor variables inflate the variance of the regression coefficients and is, therefore, used to quantify the severity of multi-collinearity in regression analysis *(54)*. In the literature, there is inconsistency in the thresholds of the VIF test. Values less than 5 are considered acceptable (*53*), although some previous studies have also used a VIF equal 10 as a cut off value (*54*, *55*). The current work has used a VIF value of 5 as a more conservative threshold. The variables with VIF measures above 5 were excluded from the analysis in a step-wise order.

Validation of SPFs

The study data was divided into model training and validation sets. Randomly selected 20% of the data was used for validation purposes while the remaining 80% was used for developing and training the SPF models. The goodness of fit (GOF) measures including mean prediction bias (MPB), mean absolute deviation (MAD) and mean squared prediction error (MSPE) were calculated using the validation dataset (*56*). The smaller the absolute values of GOF measures were, the better the prediction performance was. The model performance was further investigated by using the percentage CURE deviation analysis (*57*). A factor similar to the calibration factor which we called a model validation factor (MVF) was also calculated using the validation dataset (*57*). The MVF is equal to the ratio of the total predicted crashes to the total observed crashes, thus, a value close to 1 indicates better prediction performance.

RESULTS

We developed models for "All crashes", "PDO crashes", "Injury crashes", and "Injury & Fatal crashes". The GLM using the NB framework was used for model construction. Roadway cross-section variables (i.e., lane width and number of lanes) and on-street parking variables (i.e., parking type and parking arrangement) were considered for modeling. The parameter estimates for the variables were statistically significant at 95% confidence level.

Model Results

The results (**Table 2**) showed that crash frequency was positively associated with the traffic variable and segment length for all crash severity levels. This means that with an increase in AADT on road segments, the expected crash frequency will also increase. Similarly, longer segments will results in higher expected crash frequency than the shorter segments. It is important to note that the increase in expected crash frequency was, however, not uniform across the severity levels. An increase in the traffic volume will

TABLE 2 Safety Performance Functions for Urban Roads of Antwerp by Crash Severity Level

Parking type and parking arrangement in combination with ln (AADT), number of lanes and lane width													
		All crashes			**PDO crashes**			**Injury crashes**			**Injury & Fatal crashes**		
Parameters		**Coef.**	**SE**	**p-value**	**Coef.**	**SE**	**p-value**	**Coef.**	**SE**	**p-value**	**Coef.**	**SE**	**p-value**
Intercept		-0.847	0.231	0.000	-0.666	0.234	0.004	-3.954	0.354	0.000	-3.900	0.353	0.000
Length		2.314	0.261	0.000	2.434	0.275	0.000	2.080	0.347	0.000	2.506	0.304	0.000
ln(AADT)		0.270	0.018	0.000	0.203	0.019	0.000	0.551	0.029	0.000	0.547	0.030	0.000
No of Lanes		0.051	0.017	0.002	0.061	0.018	0.001	0.037	0.023	0.108	0.052	0.023	0.025
Lane width		-0.043	0.047	0.358	-0.054	0.048	0.261	-0.107	0.070	0.125	-0.157	0.069	0.023
Parking Type													
Base: No Parking	Others [a]	0.169	0.688	0.806	1.123	0.614	0.067	-1.293	1.069	0.227	-1.454	0.830	0.080
	Parallel	0.314	0.681	0.645	1.110	0.607	0.068	-1.185	1.059	0.263	-1.236	0.817	0.131
Parking Arrangement													
Base: No Parking	Others [b]	0.812	0.697	0.244	-0.034	0.624	0.956	1.673	1.074	0.012	1.884	0.839	0.025
	2-sided parking	0.390	0.682	0.567	-0.318	0.608	0.600	1.372	1.060	0.020	1.460	0.818	0.074
	1-sided parking	0.115	0.684	0.866	-0.660	0.609	0.278	1.297	1.061	0.022	1.406	0.820	0.087
Dispersion		0.646	0.029		0.670	0.032		0.769	0.055		0.755	0.055	
Log-likelihood		-4946.370			-4528.728			-2821.160			-2766.602		
AIC		9914.740			9079.457			5664.320			5555.203		

[a]= Perpendicular, angled and mixed parking
[b] = 3-sided and 4-sided parking

cause a greater increase in expected "Injury crashes" and "Injury & Fatal crashes" compared to "All crashes" and "PDO crashes".

The variable "lane width" was not significant in the developed models except for "Injury & Fatal crashes" where a negative association was found, i.e., an increase in lane width will reduce the frequency of "Injury & Fatal crashes". The variable "number of lanes" was positively associated with crash frequency in all models, which confirmed the findings of Noland and Oh (*23*), and Abdel-Aty and Radwan (*25*). The increase in frequency for "PDO crashes" was higher than other crash severities. Further, the parameter for the number of lanes, estimated for "All crashes", can be seen nearly similar to that of "Injury & Fatal crashes" in the developed models.

Parking type and parking arrangement, both, were not significant for "All crashes" and "PDO crashes". Parking arrangement was, however, significant for "Injury crashes", and "Injury & Fatal crash". The presence of on-street parking revealed an increase in "Injury crashes", and "Injury & Fatal crashes". Two-sided parking showed slightly more "Injury crashes" than one-sided that, in turn, showed more "Injury crashes" than no parking settings. Crash frequency was highest when there was parking on either one or both sides of traveling lanes on divided roadways (i.e., three- or four-sided parking arrangement, as shown in **Figure 2c** and **Figure 2d**) relative to undivided roadways (i.e., one- or two-sided parking arrangement, as shown in **Figure 2a** and **Figure 2b**). The increased number of crashes with injuries and fatalities as a result of increased complexity in parking arrangement could be due to more potential conflicts and difficult traffic movements in case of two-, three- or four-sided parking. From a policy recommendation point of view, no parking on the streets or one-sided parking could improve traffic flow and also results in less severe crashes, where possible.

Performance Evaluation of the Developed SPFs

Table 3 shows the performance evaluation and validation of the developed SPFs. The MPB, MAD, and MSPE values for "Injury" and "Injury & Fatal" crashes' SPFs were close to zero, showing better goodness of fit than "All crashes" and "PDO crashes" models. When % CURE deviation was calculated, the percentage of the CURE points outside the two standard deviation limits was higher for "PDO crashes". Upon the inspection of the data, it was revealed that reported values of PDO crashes for a few segments were relatively huge and the corresponding predictive values were smaller, which caused an increase in the cumulative residuals, and consequently, some of the points were seen out of the threshold limits. Removing the outliers could have potentially resolved this issue. The validation factor showed around plus-minus 5% over- or under-estimation in the crash prediction. The SPF for "All crashes" showed under-estimation while the remaining SPFs showed slight overestimation.

TABLE 3 Performance Evaluation and Validation of the Developed SPFs

GOF measures	All	PDO	Injury	Injury & Fatal
MPB	-0.076	0.052	0.014	0.024
MAD	0.795	0.633	0.290	0.290
MSPE	1.584	1.140	0.512	0.379
% CURE Deviation	1.3%	10.1%	3.2%	0.5%
Model Validation Factor	0.942	1.060	1.044	1.075

DISCUSSION

The results of our study indicated an increase in crash frequency with an increase in the traffic volume and length of a road segment. As the number of vehicles grows on a particular facility, it increases the risk of conflicts, which in few instances are resulted in actual collisions. Similarly, drivers tend to speed on longer homogeneous segments because of a uniform design and similar traffic conditions, which could potentially increase the risk of involvement in a collision, given the acknowledged association between high speed and crashes.

The “lane width” was not found to be a significant predictor of crash frequency in our models except for “Injury & Fatal” crashes. Similar findings have been reported by a few studies (*8*, *58*, *59*). The significant part of the above result, however, deserves some explanation. An increase in the lane width is found to be negatively associated with the frequency of “Injury & Fatal” crashes. This might be because wider lanes provide drivers an additional space and time thresholds to take corrective measures and avoid crashes. Even if the outcome of the events on a roadway with wider lanes is a crash, an extra width might still help in converting a potential injury crash to a non-injury crash. The relationship of “lane width” with crash frequency was also negative for other severity levels, although insignificant (**Table 2**).

The number of lanes was associated positively with crash frequency for all severity levels, which confirmed the findings of Noland and Oh (*23*), and Abdel-Aty and Radwan (*25*). More lanes provide more space for the drivers, resulting in more lane changing, weaving and overtaking maneuvers, potential higher speed, and increased perception of safety. Hence, one would indeed expect more crashes on roads with more lanes. Moreover, with an increase in the number of lanes, pedestrian and cyclist crossing distances also increase. This increases the risk of involvement in a crash, particularly on roads with higher traffic volume and no control.

The insignificance of parking type and parking arrangement variables for “All crashes” and “PDO crashes” in the models was rather unexpected, especially since it was previously established in the literature indicating that parking often affects the safety of road network. Although insignificant, very interesting differences were noticed regarding the impact of parking type on different crash severities. For instance, the models for “All crashes” and “PDO crashes” showed a positive association between crash frequencies and parking type, meaning that these crashes increased when some type of parking was present compared to no parking. There was, however, no substantial difference in the increase among various parking types (i.e., approximately similar coefficient estimates for parallel parking and others) for “PDO crashes”. For “Injury crashes” and “Injury & Fatal crashes”, a negative association between crash frequency and parking type was observed. The negative sign and the magnitude of “parking type” parameters reveals important insights regarding severe injury crashes. The negative parameters obtained shows that perpendicular and angled parking result in a more reduction of “Injury crashes” and “Injury & Fatal crashes” than parallel parking. This could be explained by the fact that when drivers encounter complex parking designs, e.g., perpendicular, angle, or mixed, they drive slower and more cautiously, which in return decreases the crash severity. Also, perpendicular and angle parking provide more separation (buffer zone) between vehicles and vulnerable road users compared to parallel parking or no parking (*33*), which could be another reason for less severe crashes in case of perpendicular, angle, or mixed parking settings. These results can interest policymakers given that higher injury severity crashes often lead to greater social costs (3) and minimizing those crashes will not only have economic advantages to the society but also help us improve the sustainability of the transportation system. To sum up, the following recommendations can be made based on the findings of this study:

- Increasing lane width could potentially reduce the frequency of high severity crashes including fatal crashes in the urban areas.
- Minimizing the number of lanes could results in a reduction of all crashes, irrespective of the severity.
- On-street parking should be carefully provided on urban roads. Perpendicular and angled parking types could relatively reduce injury and fatal crashes compared to parallel parking.

Parking on one side of a roadway segment is safer compared to two sides. Parking on both sides of each direction of divided roadways is the most dangerous one and should be avoided, if possible.

CONCLUSIONS

Cross-section design is a crucial decision a highway engineer makes since it can impact capacity, function, and safety of a roadway facility. While there are tools available to evaluate the impact of cross-section elements on roadway capacity and function, assessment of their safety implications is not always straightforward. Researchers have developed several models to evaluate the safety effects of roadway width, shoulder width, median width, etc., but the results are often inconsistent and in some cases, contradictory. Also, it is important to note that there is a lack of research on urban roads compared to rural roads. Thus, the relationship between roadway cross-section and crash frequency was investigated to provide new insights into the understanding of the identified problem.

In this study, we developed several SPFs to understand the impact of roadway cross-section elements and on-street parking on crash occurrences in urban areas. Models were created for four crash severity levels (i.e., All crashes, Injury crashes, Injury & Fatal crashes, and Property Damage Only crashes). Results indicated that segment length, traffic flow, and the number of lanes were positively associated with the crash occurrence. The variable "lane width" was, however, not significant except for the "Injury and Fatal crashes" where it has a negative association with the crash occurrence. Both of the parking-related variables were not significant when they were included in the models for "All crashes" and "PDO crashes". For "Injury crashes" and "Injury & Fatal crashes", parking arrangement was, however, significant. All parking arrangements were associated with higher "Injury crashes" and "Injury & Fatal crashes" frequencies compared to no parking. This was particularly an important finding with significant policy implications concerning severe injury crashes.

This study has also some limitations. First of all, a linear relationship between the crash frequency and lane width was assumed in this work. Consideration of generalized non-linear models used in relatively recent studies (*43*, *46*) might provide more realistic insights about the influence of lane width on crash occurrence. This study has only used lane width, the number of lanes and parking-related variables to analyze crash data. Allowing for other variables, like median width and type, presence/absence of tramlines, etc. in the analysis could provide a relatively more complete set of predictors, although their association is yet to be verified. Also, since most of Antwerp urban roads have adjacent bicycle lanes, including this variable could provide a detailed understanding of crash causation. Future work is scheduled to include those variables and use generalized non-linear models for the prediction of crash frequency.

ACKNOWLEDGMENTS

The authors thank the Police of Antwerp for providing crash data for this work. Acknowledgment on the authors' behalf is also made to Lantis (a mobility company of Antwerp city) for providing the necessary traffic data and the Flemish Government for the road infrastructure data used in this research.

AUTHOR CONTRIBUTIONS

The authors confirm the following contribution. Conception and design of the work: Khattak, Pirdavani, Brijs, De Backer; data collection: Khattak, De Backer, De Winne; analysis and interpretation of the results: Khattak, Pirdavani; draft manuscript preparation: Khattak; critical feedback: Pirdavani and De Backer. All authors reviewed the results, discuss, agreed on the reported findings, and approved the current version of the text.

REFERENCES

1. Barua, S., K. El-Basyouny, and M. T. Islam. Safety Performance Functions to Assess the Safety Risk of Urban Residential Collector Roads. Presented at Conference of the Transportation Association in Canada, Montréal, QC, 2014.
2. Manuel, A., K. El-Basyouny, and Md. T. Islam. Investigating the Safety Effects of Road Width on Urban Collector Roadways. *Safety Science*, 2014. 62: 305–311. https://doi.org/10.1016/j.ssci.2013.09.005.
3. Brijs, T., and A. Pirdavani. Urban and Suburban Arterials. In *Safe Mobility: Challenges, Methodology and Solutions* (Lord, D. and Washington, S.), Emerald Publishing Limited, Bingley, United Kingdom, 2018, pp. 85–106.
4. Marshall, W. E., N. W. Garrick, and G. Hansen. Reassessing On-Street Parking. *Transportation Research Record*: *Journal of the Transportation Research Board,* 2008. Vol. 2046, No. 1, pp. 45–52. https://doi.org/10.3141/2046-06.
5. *Highway Capacity Manual*. Transportation Research Board, Washington, D.C., 2010.
6. Ahmed, M., H. Huang, M. Abdel-Aty, and B. Guevara. Exploring a Bayesian Hierarchical Approach for Developing Safety Performance Functions for a Mountainous Freeway. *Accident Analysis & Prevention*, 2011. 43(4): 1581–1589. https://doi.org/10.1016/j.aap.2011.03.021.
7. Pande, A., and M. Abdel-Aty. A Novel Approach for Analyzing Severe Crash Patterns on Multilane Highways. *Accident; Analysis and Prevention*, 2009. 41(5): 985–994.
8. Nowakowska, M. Logistic Models in Crash Severity Classification Based on Road Characteristics. *Transportation Research Record: Journal of the Transportation Research Board*, 2020. Vol. 2148, No. 1, pp. 16–26. https://doi.org/10.3141/2148-03.
9. Gårder, P. Segment Characteristics and Severity of Head-on Crashes on Two-Lane Rural Highways in Maine. *Accident; Analysis and Prevention*, 2006. 38(4): 652–661.
10. Hauer, E., F. M. Council, and Y. Mohammedshah. Safety Models for Urban Four-Lane Undivided Road Segments. *Transportation Research Record*: *Journal of the Transportation Research Board*, 2004. Vol. 1897, No. 1, pp. 96–105. https://doi.org/10.3141/1897-13.
11. Potts, I. B., D. W. Harwood, and K. R. Richard. Relationship of Lane Width to Safety on Urban and Suburban Arterials. *Transportation Research Record*: *Journal of the Transportation Research Board*, 2007. Vol. 2023, No. 1, pp. 63–82. https://doi.org/10.3141/2023-08.
12. Dumbaugh, E. Design of Safe Urban Roadsides: An Empirical Analysis. *Transportation Research Record*: *Journal of the Transportation Research Board*, 2006. Vol. 1961, No. 1, pp. 74–82.
13. Gross, F., P. P. Jovanis, E. Kimberley, and C. Ko-Yu. *Safety Evaluation of Lane and Shoulder Width Combinations on Rural, Two-Lane, Undivided Roads*. Publication FHWA-HRT 09-031. FHWA, U.S. Department of Transportation, Washington, DC, 2009.
14. Mohammed, H. The Influence of Road Geometric Design Elements on Highway Safety. *International Journal of Civil Engineering & Technology (IJCIET)*, 2013. 4(4): 146-162
15. Stamatiadis, N., J. G. Pigman, D. Lord, J. Sacksteder, W. Ruff. National Cooperative Highway Research Program, NCHRP REPORT 633: *Impact of Shoulder Width and Median Width on Safety*. Transportation Research Board, Washington, D.C., 2009.
16. Lord, D., and J. A. Bonneson. Development of Accident Modification Factors for Rural Frontage Road Segments in Texas. *Transportation Research Record: Journal of the Transportation Research Board*, 2007. Vol. 2023, No. 1, pp. 20–27. https://doi.org/10.3141/2023-03.
17. Harwood, D. W., F. M. Council, E. Hauer, W. E. Hughes, and A. Vogt. *Prediction of the Expected Safety Performance of Rural Two-Lane Highways*. Report FHWA-RD-99-207. FHWA, U.S. Department of Transportation, 2000.
18. Zegeer, C., and F. M. Council. Highway Design, Highway Safety, and Human Factors. *Transportation Research Circular*, No. 414, 1993.
19. Zegeer, C. V., R. C. Deen, and J. G. Mayes. Effect of Lane and Shoulder Widths on Accident Reduction on Rural, Two-Lane Roads. *Transportation Research Record*: *Journal of the Transportation Research Board*, 1981. No. 806.

20. Strathman, J. G., K. J. Dueker, J. Zhang, and T. Williams. Analysis of Design Attributes and Crashes on the Oregon Highway System. *Applied Health Economics and Health Policy*, 2003. 2(4): 201–212.
21. Mehta, G., and Y. Lou. Calibration and Development of Safety Performance Functions for Alabama: Two-Lane, Two-Way Rural Roads and Four-Lane Divided Highways. *Transportation Research Record*: *Journal of the Transportation Research Board, 2013.* Vol. 2398, No. 1, pp. 75–82. https://doi.org/10.3141/2398-09.
22. Chimba, D. *Evaluation of Geometric and Traffic Characteristics Affecting the Safety of Six-Lane Divided Roadways*. Masters of Science. The Florida State University, 2004.
23. Noland, R. B., and L. Oh. The Effect of Infrastructure and Demographic Change on Traffic-Related Fatalities and Crashes: A Case Study of Illinois County-Level Data. *Accident Analysis & Prevention*, 2004. 36(4): 525–532. https://doi.org/10.1016/S0001-4575(03)00058-7.
24. Milton, J., and F. Mannering. The Relationship among Highway Geometrics, Traffic-Related Elements and Motor-Vehicle Accident Frequencies. *Transportation*, 1998. 25(4): 395–413.
25. Abdel-Aty, M. A., and A. E. Radwan. Modeling Traffic Accident Occurrence and Involvement. *Accident Analysis & Prevention*, 2000. 32 (5): 633–642. https://doi.org/10.1016/S0001-4575(99)00094-9.
26. Garber, N. J., and A. A. Ehrhart. *The Effect of Speed, Flow, and Geometric Characteristics on Crash Rates for Different Types of Virginia Highways*. Publication FHWA/VTRC 00-R15. Virginia Transportation Research Council, Virginia, USA, 2000.
27. Box, P. C. Curb-Parking Problems: Overview. *Journal of Transportation Engineering*, 2004. 130(1).
28. Cao, Y., Z. Z. Yang, and Z. Y. Zuo. The Effect of Curb Parking on Road Capacity and Traffic Safety. *European Transport Research Review*, 2016. 9(1): 4. https://doi.org/10.1007/s12544-016-0219-3.
29. Desjardins, R. J. Effective Low Cost Traffic Engineering. Presented at the Compendium of Technical Papers of the 47th Annual Meeting of the Institute of Transportation Engineers at the Fourth World Transportation Engineers Conference, Mexico City, October 2-6, 1977.
30. Dumbaugh, E., and J. L. Gattis. Safe Streets, Livable Streets. *Journal of the American Planning Association*, 2005. 71(3): 283–300. https://doi.org/10.1080/01944360508976699.
31. El-din, R. The Streets in a Livable City. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies*, 2015. 6: p. 10.
32. Sisiopiku, V. P. On-Street Parking on State Roads. Presented at ITE Annual Meeting Compendium, Institute of Transportation Engineers, Washington DC, USA, 2001.
33. Kraus, J. F., E. G. Hooten, K. A. Brown, C. Peek-Asa, C. Heye, and D. L. McArthur. Child Pedestrian and Bicyclist Injuries: Results of Community Surveillance and a Case-Control Study. *Injury Prevention*, 1996. 2(3): 212–218. https://doi.org/10.1136/ip.2.3.212.
34. Karlaftis, M. G., and E. I. Vlahogianni. Statistical Methods versus Neural Networks in Transportation Research: Differences, Similarities and Some Insights. *Transportation Research Part C: Emerging Technologies*, 2011. 19(3): 387–399. https://doi.org/10.1016/j.trc.2010.10.004.
35. *Highway Safety Manual*. AASHTO, Washington, DC, 2010.
36. Miaou, S. P. and H. Lum. *A Statistical Evaluation of the Effects of Highway Geometric Design on Truck Accident Involvements*. Publication CONF-930120-2. Oak Ridge National Lab., TN (United States), 1993.
37. Miaou, S.-P. Measuring The Goodness-Of-Fit Of Accident Prediction Models. 1996.
38. Huang, H., and M. Abdel-Aty. Multilevel Data and Bayesian Analysis in Traffic Safety. *Accident Analysis & Prevention*, 2010. 42(6):1556–1565. https://doi.org/10.1016/j.aap.2010.03.013.
39. Wang, C., M. A. Quddus, and S. G. Ison. Predicting Accident Frequency at Their Severity Levels and Its Application in Site Ranking Using a Two-Stage Mixed Multivariate Model. *Accident Analysis & Prevention*, 2011. 43(6): 1979–1990. https://doi.org/10.1016/j.aap.2011.05.016.

40. Maher, M. J., and I. Summersgill. A Comprehensive Methodology for the Fitting of Predictive Accident Models. *Accident Analysis & Prevention*, 1996. 28(3): 281–296. https://doi.org/10.1016/0001-4575(95)00059-3.
41. Oh, J., S. P. Washington, and D. Nam. Accident Prediction Model for Railway-Highway Interfaces. *Accident Analysis & Prevention*, 2006. 38(2): 346–356. https://doi.org/10.1016/j.aap.2005.10.004.
42. Lord, D., S. P. Washington, and J. N. Ivan. Poisson, Poisson-Gamma and Zero-Inflated Regression Models of Motor Vehicle Crashes: Balancing Statistical Fit and Theory. *Accident Analysis & Prevention*, 2005. 37(1): 35–46. https://doi.org/10.1016/j.aap.2004.02.004.
43. Lao, Y., G. Zhang, Y. Wang, and J. Milton. Generalized Nonlinear Models for Rear-End Crash Risk Analysis. *Accident Analysis & Prevention*, 2014. 62: 9–16. https://doi.org/10.1016/j.aap.2013.09.004.
44. El-Basyouny, K., and T. Sayed. Comparison of Two Negative Binomial Regression Techniques in Developing Accident Prediction Models. *Transportation Research Record*: *Journal of the Transportation Research Board*, *2006*. Vol. 1950, No. 1, pp. 9–16. https://doi.org/10.1177/0361198106195000102.
45. Chin, H. C., and M. A. Quddus. Applying the Random Effect Negative Binomial Model to Examine Traffic Accident Occurrence at Signalized Intersections. *Accident Analysis & Prevention*, 2003. 35 (2): 253–259. https://doi.org/10.1016/S0001-4575(02)00003-9.
46. Park, J., M. Abdel-Aty, J.-H. Wang, and C. Lee. Assessment of Safety Effects for Widening Urban Roadways in Developing Crash Modification Functions Using Nonlinearizing Link Functions. *Accident Analysis & Prevention*, 2015. 79: 80–87. https://doi.org/10.1016/j.aap.2015.03.025.
47. The Road Register: The Reference Tool for Roads in Flanders, 2019. *GIM*. Received from: https://www.gim.be/en/our-customers/the-road-register-the-reference-tool-for-roads-in-flanders. Accessed Jul. 26, 2020.
48. QGIS Development Team, 2019. QGIS Geographic Information System. Project URL: https://www.qgis.org/en/site/.
49. Hauer, E. Lane Width and Safety. Review of Literature for the Interactive Highway Safety Design Model , 2000.
50. Google Maps, 2020. Antwerp, Belgium. Available from: https://goo.gl/maps/SMgba2wYXCF9eSw4A. Accessed Jul. 26, 2020.
51. Google Earth, 2020. Antwerp, Belgium. Available from: https://earth.google.com/web/search/Antwerp,+Belgium/. Accessed Jul. 26, 2020.
52. Sawalha, Z., and T. Sayed. Traffic Accident Modeling: Some Statistical Issues. *Canadian Journal of Civil Engineering*, 2006. 33(9):1115–1124. https://doi.org/10.1139/l06-056.
53. Field, A. *Discovering Statistics Using IBM SPSS Statistics*. Sage Publications Ltd., 2013.
54. Pirdavani, A., T. Bellemans, T. Brijs, and G. Wets. Application of Geographically Weighted Regression Technique in Spatial Analysis of Fatal and Injury Crashes. *Journal of Transportation Engineering*, 2014. 140(8). https://doi.org/10.1061/(ASCE)TE.1943-5436.0000680.
55. Gomes, M. M., A. Pirdavani, T. Brijs, and C. Souza Pitombo. Assessing the Impacts of Enriched Information on Crash Prediction Performance. *Accident Analysis & Prevention*, 2019. 122: 162–171. https://doi.org/10.1016/j.aap.2018.10.004.
56. Oh, J., C. Lyon, S. Washington, B. Persaud, and J. Bared. Validation of FHWA Crash Models for Rural Intersections: Lessons Learned: *Transportation Research Record*: *Journal of the Transportation Research Board*, 2003. https://doi.org/10.3141/1840-05.
57. Wang, K., S. Zhao, and E. Jackson. Functional Forms of the Negative Binomial Models in Safety Performance Functions for Rural Two-Lane Intersections. *Accident Analysis & Prevention*, 2019. 124: 193–201. https://doi.org/10.1016/j.aap.2019.01.015.
58. Ackaah, W., and M. Salifu. Crash Prediction Model for Two-Lane Rural Highways in the Ashanti Region of Ghana. *International Association of Traffic and Safety Sciences* (*IATSS) Research*, 2011. 35(1): 34–40. https://doi.org/10.1016/j.iatssr.2011.02.001.

59. Yanmaz-Tuzel, O., and K. Ozbay. A Comparative Full Bayesian Before-and-after Analysis and Application to Urban Road Safety Countermeasures in New Jersey. *Accident Analysis and Prevention*, 2010. 42(6) :2099–2107. https://doi.org/10.1016/j.aap.2010.06.023.