Examining the relationship between road safety outcomes and the built environment in Bogotá, Colombia

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Key Findings

- The presence of pedestrian bridges is associated with higher severity of crashes.
- Recent BRT corridors leads to a decrease in traffic fatalities and injuries.
- Population density has a negative association with severity of crashes.
- Crashes are more severe at night probably due to higher speeds.

Abstract

The study of the relationship between the built environment and road safety suggests that density and urban design features may be associated with traffic incidents. In this study, quantitative data analysis using generalized ordinal logit models, and linear and log-linear regressions was conducted to estimate the influence of the built environment on road safety in Bogotá, focusing on road crash outcomes by estimating the influence of built environment attributes on fatalities and injured victims. The analysis was performed using georeferenced road crash data from 2012 to 2016 provided by Bogotá's Department of Mobility. The quantitative data analysis focused on arterial roads, considering crash severity and types of road users involved, as well as Bus Rapid Transit System corridors. This analysis was complemented with on-site interviews. The results suggest that the presence of pedestrian bridges is positively associated with the number of road crashes for all road users. Other urban variables such as density and distance to intersections showed significant correlations with safety.

Keywords

Built environment, road safety, BRT, road crashes, infrastructure, pedestrian bridges

Introduction

The study of the relationship between the built environment and road safety implies several challenges from an urban planning perspective, particularly in areas with compact urban form and high densities where multiple road users interact. Cities promoting and investing in sustainable mobility, such as public transport, walking and bicycling, and encouraging compact and mixed-use urban forms, face the task of attracting more road users around busy areas. This in turn increases the probability of crashes taking place unless road safety countermeasures are implemented. Certain urban design features such as the provision of infrastructure, traffic-calming measures, traffic lights and enhanced transit stations can help to attract road users. In this order of ideas, in this paper such information is used to examine the influence of built environment attributes on road crash data in Bogotá (Colombia) relating to the 2012 – 2016 period.

Bogotá is well known globally for the progress it has made in the promotion of sustainable transport, including the implementation of a Bus Rapid Transit (BRT) system and the provision of walking and bicycling infrastructure. Despite this, however, Bogotá still recorded a considerable number of road crash fatalities and injuries after a period of significant progress between 1996 and 2006 (Vergel-Tovar, Hidalgo, & Sharpin, 2018). In addition to policy, regulation, and enforcement measures, pedestrian bridges, traffic lights, and enhanced crosswalks have been implemented in order to improve road safety for pedestrians. Despite these efforts, 49% of the traffic fatalities in 2007 were pedestrians (Alcaldía Mayor de Bogotá, 2017). This is partially due to the fact that Bogotá –as many other cities- was planned as a car-centric model before the implementation of the BRT and walking and bicycling infrastructure at the end of the twentieth century (Quiñones, Pardo, Moscoso, Sánchez, López, & López, 2017).

We use three types of quantitative data analyses. First, we examine the influence of the built environment on road safety with data from segments between two intersections of arterial roads as each observation. Second, we examine how the built environment influences road crashes by road users.

Lastly, we examine arterial corridors by comparing the corridors with BRT trunk lines and the ones without them.

This paper is structured in six parts, which include: The Literature Review with a description of previous road safety studies by road user types for different regions globally; the Methodology which describes the study area, the data used, the data processing, and the methods used for the three analyses; the Results section which describes each type of analysis; and, finally, the study's Discussion and Conclusions.

Literature Review

Road safety and the built environment

Road safety is a public health issue across different countries with significant interest in the influence of city design on road crashes. The built environment, as a result of urban space design, plays an important role on road user behavior and on the probability of road traffic injuries and fatalities (Elvik, Høye, Vaa, & Sørensen, 2009).

From an urban planning perspective, context matters in terms of how the built environment influences road safety. According to the analysis of built environment attributes and their influence on road safety, the results suggest that dense urban areas tend to be safer as speeds are relatively low, and compounded with design features such as narrow lanes and traffic calming measures. These measures significantly improve road safety performance in relation to more conventional road designs (Ewing, & Dumbaugh, 2009). In addition to the role of density and urban design features, a number of studies have analyzed the influence of built environment attributes on road safety. In Montreal (Canada), studies on this influence have found that measures that promote dense and compact urban forms associated with sustainable transport modes, such as the mixture of land uses and transit supply, increase pedestrian activity and attract road users who might be at risk if road safety strategies were not included in the design of the built environment (Miranda-Moreno, Morency, & El-Geneidy, 2011).

Studies analyzing the influence of the built environment on road safety reveal mixed results. One study conducted with crash data from San Antonio-Bexar County (Texas, USA) found that four-lane intersections and commercial land uses associated with the presence of big-box developments are positively associated with the number of road crashes (Dumbaugh, & Li, 2010). Mixed results were found in another study examining the influence of land use and road design on crash frequency in New York City, pointing to a lower probability of crashes in areas characterized by industrial, commercial, and open land uses, but a higher probability of pedestrian-vehicle collisions in locations with more lanes, greater road width, and a higher concentration of schools and transit stops (Ukkusuri, Miranda-Moreno, Ramadurai, & Isa-Tavarez, 2012). A study of 24 cities in California on the effect of street design and network characteristics on crashes, found that denser street networks with higher intersection counts are negatively associated with the number of crashes and their severity. In contrast, additional traffic lanes and increased connectivity are positively associated with crashes (Marshall, & Garrick, 2011).

Several studies have also examined the use of pedestrian bridges in urban environments. It has been found that pedestrians are more likely to use these more often if time loss (Räsänen, Lajunen, Alticafarbay & Aydin, 2007) and the increased walking distance are not considerable. Thus, increased distance and time raise the likelihood of direct –at risk- crossing by pedestrians (Cantillo, Arellana, & Rolong, 2015) despite the fact that this infrastructure might appear to be safer (Rizati, Ishak, & Endut, 2013).

Thus, there are mixed results in terms of the role played by the built environment in road safety, and this complex set of outcomes must be carefully considered. This is especially true for busy areas with high attraction of road users, especially in those areas where mass transit and walking and bicycling infrastructure implies greater use volume and flow.

Road safety and Bus Rapid Transit (BRT)

Although the implementation BRT systems has rapidly evolved globally, the relationship between road safety and BRT is still unclear (Vecino-Ortiz, & Hyder, 2015; BRTData, 2019). BRT systems incorporate rail-based system features such as enhanced boarding stations and exclusive lanes segregated from the mixed traffic. These characteristics imply better infrastructure with the flexibility of a BRT system, and they improve system operations in terms of safety (Vecino-Ortiz, & Hyder, 2015). However, the influence of BRT on road safety is still being examined and the relationship between road-user fatalities and injury severity is, as yet, unknown.

Studies examining the influence of BRT on road safety in Melbourne (Australia) found a 15% road crash reduction (Goh, Currie, Sarvi & Logan, 2013), a second analysis for bus priority measures applied in Melbourne found a reduction of the proportion of road crashes as a result of improvements in the maneuverability of buses (Goh, Currie, Sarvi & Logan, 2014). Another analysis of road safety data in nine cities implementing BRT systems found road safety improvements in cities like Guadalajara (Mexico), and the positive influence of infrastructure and operational features such as center-lane systems on reducing road crashes (Duduta, Adriazola, Hidalgo, Lindau, & Jaffe, 2012).

An analysis of road safety and BRT in Bogotá suggests that there is an overall reduction of road crashes. However, an increase was found within the influence area of the busiest BRT stations and along the corridors where speed increments occurred as a result of fewer intersections and traffic lights, as well as infrastructure improvements for mixed traffic along BRT corridors (Bocarejo, Velasquez, Díaz, & Tafur, 2012). An ex-post evaluation found a significant reduction in road crash injuries and fatalities as a result of the implementation of Phases 1 and 2 of the BRT system between 1998 and 2006 (Hidalgo, Pereira, Estupiñán, & Jiménez, 2013).

Despite the emerging evidence of the relationship between BRT and road safety, there is still a gap in terms of the influence of BRT on the type of road users involved in road crashes as well as on the severity level of these collisions in terms of injuries and fatalities. Little is also known about the influence of built environment features such as pedestrian bridges on road safety.

Methodology

Study Area

Bogotá is the capital of Colombia and its largest city with a population of 7,980,001 inhabitants. Its urban area measures 37,945.23 hectares and, according to the Urban Master Plan, there are 2,973.93 hectares reserved for urban expansion (Alcaldía Mayor de Bogotá, 2017a). The city has 15,400 km of road lanes, 472 km of bike paths, and there are 9 BRT trunk corridors measuring a total length of 114 km (Alcaldía Mayor de Bogotá, 2017b). The mode share of daily trips in Bogotá includes 21% pedestrian trips, 27% in conventional and integrated buses, 18% of trips on BRT, 13% in private vehicles, 5.5% on motorcycles, 4.5% on bicycles, and 5.5% in taxis. On a daily basis, approximately 15 million trips are made within the city, while more than 188,000 vehicles commute to Bogotá from neighboring municipalities (Alcaldía Mayor de Bogotá, 2017b; Secretaría Distrital de Movilidad, 2015).

Data

The data set used includes georeferenced road crashes from 2012 to 2016 (Secretaría Distrital de Movilidad, 2017). The traffic crashes analyzed are divided into three different levels of severity according to the most severe injury experienced in the crash: fatality, injury (non-fatality), and damage-only (no injury). The dataset also provided information about crash type (multi-vehicle crashes, run over (pedestrian involved), risk of the passenger falling, and overturn) and time of day. The built environment data for BRT and arterial roads was provided by Bogotá's City Planning Department (Alcaldía Mayor de Bogotá, 2018).

The built environment features selected as independent variables were determined based on previous studies in terms of urban design characteristics such as number of lanes and connectivity, land uses within the influence area at parcel level, presence of pedestrian bridges, estimation of population density at block level, identifying and counting the number of intersections and number of blocks within the study area, and average speed for motorized vehicles. The frequency of crashes was considered in geographical terms as the number of crashes within the study area (arterial roads buffer and BRT corridors data). All the data was processed using geographic information systems.

Data processing

Arterial roads data

The road crash data was processed using the ArcGIS software for GIS. First, road crashes along main arterial roads were identified by taking a buffer of 70 meters along major arterials in the city (Figure 1 in the Annex), using the routes classified as V1 and V0 in accordance with the Urban Master Plan for Bogotá. Road classification in the city depends entirely on road width; V1 and V0 are 60 meters and 100 meters wide respectively, which results in 79 official arterial roads generated by 531 polylines. Built environment features such as blocks, land uses, traffic lights, and presence of pedestrian bridges were also identified within the polygons determined by a 70-meter buffer area from arterial roads in order to include blocks and their urban attributes in the analysis, excluding intersections between major arterial roads to avoid double counting (Figure 2 in the Annex).

BRT corridors data

The traffic crash data was processed by identifying road collisions along treatment corridors (BRT) and control corridors (main arterial roads) as shown in Figure 1c in the Annex. The data was then processed identifying road collisions within a 70-meter buffer area. The built environment attributes were identified intersecting the parcels, blocks, intersections, pedestrian bridges, and traffic lights within the buffer area.

Methods

Data analysis 1

The first phase of data analysis ran a generalized ordinal logistic regression model taking the severity level of the crash as the dependent variable. The ordinal dependent variable was road crash outcome: i) damage-only (no injury) =3; ii) injured victim (non-fatality) =2; and, iii) fatal victim=1. This structure assumes that the highest severity outcome is a fatal victim. The independent variables included in the model are described in Table 1. The probabilities estimated for the dependent variable in the generalized ordinal logistic regression models for data analyses 1 and 3 are based on the following equations (Williams, 2006):

$$P(Y_i = 1) = 1 - g(X_i\beta_1)$$

$$P(Y_i = j) = g\left(X_i\beta_j - 1\right) - g\left(X_i\beta_1\right)\ j = 3, \ldots., M - 1$$

$$P(Y_i = M) = g(X_i\beta_m - 1) \tag{1}$$

Data analysis 2

The second phase of data analysis hypothesizes the number of road crashes with casualties per mode in each polygon as the dependent variables, with built environment attributes as the independent variables. Table 2 describes the built environment attributes included in the linear regression models. The units of observations are each of the polygons shown in Figure 2 in the Annex.

Data analysis 3

The third data analysis runs a generalized ordinal logistic regression model also using severity level as the dependent variable. The ordinal dependent variable is structured in the same way as in Data analysis 1. This model includes binary explanatory variables for the BRT corridors studied in order to determine the probabilities of reaching each potential outcome for each phase of the system. The generalized ordinal logistic regression model allowed a comparison of the three different outcomes by running the GOLOGIT2 command on STATA (Williams, 2005, 2006). The independent variables included in the model are described in Table 3. The estimated probabilities for the dependent variable are estimated with the same equations described for the data analysis.

Table 1. Descriptive statistics, severity level (damage-only=3, injured victims=2 and fatal victims=1) and independent variables (N=12,312). Model 1.

Variables	Definition	Mean	St. Dev.	Min	Max
Dependent variable					
Severity level (ordinal variable)					
Fatal victim (level 1)	Road crash outcome is a fatal victim	0.018	0.132	0.00	1.00
Injured victim (level 2)	Road crash outcome is an injured victim	0.283	0.450	0.00	1.00
Damage-only (level 3)	Road crash outcome is damage-only	0.699	0.459	0.00	1.00
Independent variables					
Crash type					
Multi-vehicle crashes	If multi-vehicle crash=1; otherwise=0	0.860	0.347	0.00	1.00
Run over (pedestrian involved)	If run over=1; otherwise=0	0.093	0.290	0.00	1.00
Passenger falling	If passenger falling=1; otherwise=0	0.025	0.156	0.00	1.00
Overturn	If overturn=1; otherwise=0	0.010	0.099	0.00	1.00
Other (fire, self-damage, other)	If other type=1; otherwise=0	0.012	0.109	0.00	1.00
Time of day					
Range 1 (between 00:00 and 02:59 hours)	If crash occurred in range 1=1; otherwise=0	0.031	0.173	0.00	1.00
Range 2 (between 03:00 and 05:59 hours)	If crash occurred in range 2=1; otherwise=0	0.058	0.234	0.00	1.00
Range 3 (between 06:00 and 08:59 hours)	If crash occurred in range 3=1; otherwise=0	0.177	0.382	0.00	1.00
Range 4 (between 09:00 and 11:59 hours)	If crash occurred in range 4=1; otherwise=0	0.162	0.368	0.00	1.00
Range 5 (between 12:00 and 14:59 hours)	If crash occurred in range 5=1; otherwise=0	0.183	0.386	0.00	1.00
Range 6 (between 15:00 and 17:59 hours)	If crash occurred in range 6=1; otherwise=0	0.166	0.372	0.00	1.00
Range 7 (between 18:00 and 20:59 hours)	If crash occurred in range 7=1; otherwise=0	0.145	0.352	0.00	1.00
Range 8 (between 21:00 and 23:59 hours)	If crash occurred in range 8=1; otherwise=0	0.078	0.269	0.00	1.00
Land uses					
Proportion of parcels with residential uses	Proportion of parcels with residential uses within buffer area	0.357	0.216	0.00	0.87
Proportion of parcels with industrial uses	Proportion of parcels with industrial uses within buffer area	0.024	0.051	0.00	0.20
Proportion of parcels with commercial uses	Proportion of parcels with commercial uses within buffer area	0.286	0.220	0.00	0.73
Proportion of parcels with institutional uses	Proportion of parcels with institutional uses within buffer area	0.056	0.102	0.00	0.40
Proportion of parcels with other uses	Proportion of parcels with other uses within buffer area	0.074	0.095	0.00	0.29
Proportion of parcels with public space uses	Proportion of parcels with public space uses within buffer area	0.133	0.131	0.00	0.44
Pedestrian bridges					

Variables	**Definition**	**Mean**	**St. Dev.**	**Min**	**Max**
Distance to the closest pedestrian bridge	Linear distance in meters from crash to the closest pedestrian bridge	419.681	324.466	3.79	1835.56
Number of pedestrian bridges (within polygon)	# pedestrian bridges within the buffer area	1.823	1.625	1.00	6.00
Pedestrian bridge length in meters	Average length of pedestrian bridges within buffer area	216.512	153.002	29.36	783.71
Density, intersections and average speed					
Population density at the polygon level	Density of people per hectare within buffer area	100.308	66.593	12.03	400.44
Number of blocks (within polygon)	# blocks within buffer area	43.957	30.863	14.00	124.00
Distance to the closest intersection	Linear distance from collision to the closest intersection in meters	548.192	367.204	0.23	1683.63
Number of intersections (within polygon)	# intersections within buffer area	1.212	1.898	0.00	6.00
Average speed	Average speed of motorized vehicles within buffer area	30.816	9.244	5.42	45.11
Road attributes					
Lane width		3.335	0.228	2.86	3.92
Road section (between sidewalk borders)		36.778	10.537	17.21	83.83
Total number of carriageways		2.733	0.926	2.00	4.00
Road length		2072.380	1124.701	549.00	4500.00
Total number of lanes		5.715	1.623	1.00	8.00

Table 2. Descriptive statistics dependent and independent variables per vulnerable road user involved (N=216) Model 2

Variables	Definition	Mean	St. Dev.	Min	Max
Dependent variable					
Number of road crashes involving a motorcyclist casualty	# crashes involving motorcyclists casualties normalized by buffer length	29.33	31.01.	0	211
Number of road crashes involving a cyclist casualty	# crashes involving cyclists casualties normalized by buffer length	8.71	11.98	0	106
Number of road crashes involving a pedestrians casualty	# crashes involving pedestrians casualties normalized by buffer length	26.63	29.32	0	175
Independent variables					
Population density	Average population by buffer area	134.6	100.8	0	587.2
Urban Design					
Number of blocks	Average number of blocks within the buffer length	31.29	83.45	2.149	1,508
Lane width	Width of lanes in meters	2.23	0.31	2.54	4.42
Section width	Width of section between sidewalks	603.8	451.0	38.31	2,836
Number of lanes	Total number of lanes in the section of each polygon	5.68	2.03	2	12
Pedestrian bridges	Number of pedestrian bridges	0.60	1.08	0	9
Traffic lights	Number of traffic lights in the polygon	498.8	441.1	18.22	4,496
Land Uses					
Mixticity	Ratio between the combination of the proportions of residential land use and non-residential land use within the polygon, and 0.25 (scenario where residential and non-residential proportions are the same)	0.704	0.304	0	1

Table 3. Descriptive statistics. (N=49,408) Model 3.

Variables	Definition	Mean	Std. Dev.	Min	Max
Dependent variable					
Severity level (ordinal variable)					
Fatal victim (level 1)	Road crash outcome is a fatal victim	0.014	0.117	0.00	1.00
Injured victim (level 2)	Road crash outcome is an injured victim	0.285	0.451	0.00	1.00
Damage-only (level 3)	Road crash outcome is damage-only	0.702	0.458	0.00	1.00
Independent variables					
Crash type					

Variables	**Definition**	**Mean**	**Std. Dev.**	**Min**	**Max**
Crashes	If crash=1; otherwise=0	0.853	0.354	0.00	1.00
Run over (pedestrian involved)	If runover=1; otherwise=0	0.101	0.301	0.00	1.00
Passenger falling	If passenger falling=1; otherwise=0	0.024	0.153	0.00	1.00
Overturn	If overturn=1; otherwise=0	0.009	0.097	0.00	1.00
Other (fire, self-damage, other)	If other type=1; otherwise=0	0.013	0.113	0.00	1.00
Time of day					
Range 1 (between 00:00 and 02:59 hours)	If crash occurred in range 1=1; otherwise=0	0.029	0.168	0.00	1.00
Range 2 (between 03:00 and 05:59 hours)	If crash occurred in range 2=1; otherwise=0	0.051	0.220	0.00	1.00
Range 3 (between 06:00 and 08:59 hours)	If crash occurred in range 3=1; otherwise=0	0.168	0.374	0.00	1.00
Range 4 (between 09:00 and 11:59 hours)	If crash occurred in range 4=1; otherwise=0	0.167	0.373	0.00	1.00
Range 5 (between 12:00 and 14:59 hours)	If crash occurred in range 5=1; otherwise=0	0.187	0.390	0.00	1.00
Range 6 (between 15:00 and 17:59 hours)	If crash occurred in range 6=1; otherwise=0	0.166	0.372	0.00	1.00
Range 7 (between 18:00 and 20:59 hours)	If crash occurred in range 7=1; otherwise=0	0.150	0.357	0.00	1.00
Range 8 (between 21:00 and 23:59 hours)	If crash occurred in range 8=1; otherwise=0	0.081	0.273	0.00	1.00
Pedestrian bridges					
Distance to the closest pedestrian bridge	Linear distance in meters from collision to the closest pedestrian bridge	753.312	623.344	1.42	3168.90
Number of pedestrian bridges (within polygon)	# pedestrian bridges within buffer area	3.207	3.507	0.00	15.00
Density, intersections and average speed					
Population density at the polygon level	Density of people per hectare within buffer area	128.980	79.843	1.475	476.53
Number of blocks (within polygon)	# blocks within buffer area	132.730	81.466	19.00	389.00
Number of intersections (within polygon)	# intersections within buffer area	2.516	4.221	0.00	18.00
Average speed	Average speed of motorized vehicles within buffer area	11.936	7.820	1.68	36.68
BRT					
Distance to BRT station	Linear distance in meters from collision to the closest BRT station	841.661	772.962	109.62	2912.96
BRT corridors phase one	Crash occurred within a BRT corridor (phase one)	0.178	0.382	0.00	1.00
BRT corridors phase two	Crash occurred within a BRT corridor (phase two)	0.196	0.397	0.00	1.00
BRT corridors phase three	Crash occurred within a BRT corridor (phase three)	0.084	0.278	0.00	1.00

Results

Data analysis 1: Arterial roads

Results are shown in Table 4. The probabilities of involvement in a fatal crash are higher when the type of crash is a multi-vehicle crash or when a passenger falls out, than they are when the accident involves running someone over. The probabilities of causing injury are higher when the type of collisions are multi-vehicle crashes, overturn, or other. In terms of the time of day, road crashes taking place between noon and 6.00 pm show the highest probabilities of resulting in fatalities, with similar results for injured victims. Commercial and institutional land uses within the buffer area show negative associations with fatal and injured victims while residential use shows positive association with injuries. This suggests that particular attention should be paid to road safety measures in residential areas. The distance to pedestrian bridges is negatively associated with fatal victims compared to crashes with injuries or property damage-only, suggesting that the severity of road crashes increases around pedestrian bridges. Similarly, the number of pedestrian bridges in the buffer area increases the probability of causing fatalities and injury to victims. A higher number of intersections within the buffer area decreases the likelihood of there being fatal victims and increases the probability of injury or damages only outcomes for road crashes in the study area. The width of lanes and the number of carriageways are positively associated with the probability of causing injury to victims.

Data analysis 2: Crashes per type of vulnerable road user

Results are shown in Table 5. Crashes involving all types of vulnerable road users have a positive correlation with population density in the polygon, the presence of pedestrian bridges and traffic lights. The marginal effect of pedestrian bridges is higher for motorcyclist casualties. Similarly, Model 1 shows a negative association between mixed land use and the number of pedestrian casualties. Model 2 shows a negative association between the number of blocks per kilometer and the number of cyclist casualties. Model 3 shows that the number of lanes is positively correlated with the number of motorcyclist casualties.

Data analysis 3: BRT corridors

Regarding the type of road crash, the results suggest that multi-vehicle crashes increase the probability of there being fatal victims as well as that of the passenger falling and other crash types (Table 6). The overturn crash type increases the probability of injuries and fatalities. Regarding the time of day, off-peak hours increase the probability of road crash fatalities, and the results for panel 2 suggest that the probability of injuries is higher during peak hours as is the probability of fatal victims.

Results for pedestrian bridges suggest that the likelihood of injured victims and damage-only crashes is higher in close proximity to pedestrian bridges in the study area. Results for the number of pedestrian bridges suggest that the greater the number of such bridges, the greater the likelihood of road crash injuries and fatalities. However, similarly to the results obtained in Data analysis 1, this positive association should be taken with caution. In the Conclusion section, we describe a number of factors explaining these results. A higher population density suggests a lower likelihood of injured victims and thus a higher probability of the occurrence of damage-only crashes in the study area.

The number of blocks increases the likelihood of injuries and fatalities, but a higher number of intersections implies a lower probability of there being injured victims and thus increases the probability of there being damage-only crashes. A higher average speed increases both the likelihood of injury being caused to a victim, and the probability of a road crash fatality. Larger block sizes within the study area suggest a higher probability of road crash fatalities.

In terms of the BRT, the results suggest that the likelihood of a fatality diminishes when the crash takes place near BRT stations. Crashes taking place along BRT corridors in Phase 2 are less likely to result in fatalities and injuries, and road crashes taking place along BRT corridors in Phase 3 are less likely to result in injuries, meaning that there is a higher probability of there being damage-only crashes in these corridors.

Table 4. Generalized ordered logit model results, severity level (damage-only=3, injured victims=2 and fatal victims=1)

	Panel 1 **Severity level=1 (Fatal victim)** *In relation to levels 2 and 3*		**Panel 2** **Severity level=2 (Injured victim)** *In relation to levels 1 and 3*	
	Estimated coefficients	**Standard errors**	**Estimated coefficients**	**Standard errors**
Crash type				
(reference: Run over: pedestrian involved)				
Multi-vehicle Crashes	2.1232 ***	(0.1527)	8.4488 ***	(1.0011)
Passenger falling	2.4135 ***	(0.7213)	-13.5872	(1490.3467)
Overturn	0.1164	(0.3594)	5.3918 ***	(1.0324)
Other (fire, self-damage, other)	18.3236	(2746.5435)	3.9997 ***	(1.0655)
Time of day				
(reference: between 00:00 and 02:59 hours)				
Range 2 (between 03:00 and 05:59 hours)	-0.0504	(0.2992)	0.2043	(0.1535)
Range 3 (between 06:00 and 08:59 hours)	0.8885 **	(0.3015)	0.3768 **	(0.1351)
Range 4 (between 09:00 and 11:59 hours)	0.7253 *	(0.3106)	0.9131 ***	(0.1397)
Range 5 (between 12:00 and 14:59 hours)	1.2878 ***	(0.3294)	1.1012 ***	(0.1397)
Range 6 (between 15:00 and 17:59 hours)	1.2484 ***	(0.3337)	0.8075 ***	(0.1384)
Range 7 (between 18:00 and 20:59 hours)	0.6044 *	(0.2973)	0.6316 ***	(0.1392)
Range 8 (between 21:00 and 23:59 hours)	0.9071 **	(0.3312)	0.3284 *	(0.1486)
Land uses				
Proportion of parcels with residential uses	-0.3804	(1.5065)	1.4099 **	(0.4408)
Proportion of parcels with industrial uses	2.4190	(2.7694)	2.2290 *	(0.8916)
Proportion of parcels with commercial uses	-1.1182	(1.3855)	-0.0973 ***	(0.3929)
Proportion of parcels with institutional uses	-4.6358 **	(1.7355)	-1.8935 ***	(0.5388)
Proportion of parcels with other uses	-3.9955	(2.7688)	1.4861 *	(0.7239)
Proportion of parcels with public space uses	-1.5276	(1.1860)	-0.6216	(0.4180)
Pedestrian bridges				
Distance to the closest pedestrian bridge	-0.0006 *	(0.0002)	-0.0001	(0.0001)
Number of pedestrian bridges within buffer area	0.4279 **	(0.1633)	0.2573***	(0.0514)
Pedestrian bridge length in meters	-0.0007	(0.0005)	0.0001	(0.0002)
Density, intersections and average speed				
Population density within buffer area	-0.0021 *	(0.0020)	0.0008	(0.0007)
Number of blocks within buffer area	-0.0144	(0.0101)	-0.0178 ***	(0.0031)
Distance to the closest intersection	-0.0001	(0.0003)	0.0001	(0.0001)
Number of intersections within buffer area	-0.5335 ***	(0.1364)	-0.3603 ***	(0.0391)
Average speed	-0.0033	(0.0115)	-0.0065	(0.0036)
Lane width	-0.3521	(0.3894)	0.4128 **	(0.1313)
Section width	-0.0041	(0.0188)	-0.0085	(0.0054)

	Panel 1 **Severity level=1 (Fatal victim)** *In relation to levels 2 and 3*		**Panel 2** **Severity level=2 (Injured victim)** *In relation to levels 1 and 3*	
	Estimated coefficients	**Standard errors**	**Estimated coefficients**	**Standard errors**
Total number of carriageways	0.3347	(0.2259)	0.3212 ***	(0.0633)
Polygon length	0.0004	(0.0004)	0.0005 ***	(0.0001)
Number of lanes	0.0519	(0.0653)	-0.0322	(0.0196)
Constant term	3.5411 ***	(2.1094)	-10.0177 ***	(1.2311)
N			12312	
Log likelihood			-5802.4918	
LR chi2(50)			5099.69	
Prob > chi2			0.0000	
Pseudo R squared			0.3053	

Standard errors in parentheses*** p<0.01, ** p<0.05, * p<0.1

Table 5. Linear regression, number of vulnerable road users' casualties and built environment attributes

Variables	**Model 1** **Pedestrian casualties**		**Model 2** **Cyclist casualties**		**Model 3** **Motorcyclist casualties**	
	Estimated coefficients	**Standard errors**	**Estimated coefficients**	**Standard errors**	**Estimated coefficients**	**Standard errors**
Lane width	-1.805	(5.110)	3.023	(1.887)	4.306	(5.073)
Section Width	0.0335	(0.129)	-0.0307	(0.0476)	0.0734	(0.128)
Number of lanes	0.982	(1.018)	0.580	(0.376)	2.171 **	(1.011)
Mixticity	-41.38 **	(20.84)	-8.942	(7.693)	-21.22	(20.69)
Blocks per km	0.0288	(0.163)	-0.182 ***	(0.0601)	-0.198	(0.162)
Population density	0.0414 ***	(0.00892)	0.0226 ***	(0.00329)	0.0428 ***	(0.00886)
Pedestrian bridges	4.903 ***	(1.807)	3.326 ***	(0.667)	8.986 ***	(1.794)
Traffic lights	7.432 ***	(0.914)	3.344 ***	(0.338)	8.281 ***	(0.908)
Constant	5.029	(18.11)	-11.94 *	(6.688)	-23.55	(17.98)
N	216		216		216	
R-squared	0.420		0.526		0.489	

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6. Generalized ordered logit model results, severity level (damage-only=3, injured victims=2 and fatal victims=1) and BRT corridors

	Panel 1 Severity level=1 (Death victim) In relation to levels 2 and 3		**Panel 2 Severity level=2 (Injured victim) In relation to levels 1 and 3**	
	Estimated coefficients	**Standard errors**	**Estimated coefficients**	**Standard errors**
Crash type				
(reference: Run over: pedestrian involved)				
Multi-vehicle crashes	2.3793 ***	(0.0848)	9.9923 ***	(1.0002)
Passenger falling	1.8621 ***	(0.2964)	1.3262	(1.4146)
Overturn	0.1870	(0.1975)	6.5641 ***	(1.0103)
Other (fire, self-damage, other)	2.7528 ***	(0.5820)	5.9168 ***	(1.0117)
Time of day				
(reference: between 00:00 and 02:59 hours)				
Range 2 (between 03:00 and 05:59 hours)	0.0593	(0.1878)	0.0516	(0.0806)
Range 3 (between 06:00 and 08:59 hours)	0.8398 ***	(0.1798)	0.3176 ***	(0.0705)
Range 4 (between 09:00 and 11:59 hours)	1.0098 ***	(0.1887)	0.8784 ***	(0.0728)
Range 5 (between 12:00 and 14:59 hours)	1.0455 ***	(0.1859)	0.9263 ***	(0.0721)
Range 6 (between 15:00 and 17:59 hours)	1.0418 ***	(0.1867)	0.7159 ***	(0.0721)
Range 7 (between 18:00 and 20:59 hours)	0.7359 ***	(0.1750)	0.6760 ***	(0.0730)
Range 8 (between 21:00 and 23:59 hours)	0.2356	(0.1744)	0.0943	(0.0760)
Pedestrian bridges				
Distance to the closest pedestrian bridge	0.0000	(0.0001)	-0.0001 *	(0.0000)
Number of pedestrian bridges within buffer area	-0.0044	(0.0169)	0.0257 ***	(0.0052)
Density, intersections and average speed				
Population density within buffer area	-0.0005	(0.0008)	-0.0028 ***	(0.0003)
Number of blocks within buffer area	0.0017 *	(0.0007)	0.0008 ***	(0.0002)
Number of intersections within buffer area	0.0116	(0.0147)	-0.0196 ***	(0.0041)
Average speed	-0.0047	(0.0061)	0.0078 ***	(0.0020)
Average block size in sq. mt within buffer area	0.0001 **	(0.0000)	-0.0000	(0.0000)
BRT				
Distance to BRT station	-0.0004 ***	(0.0001)	0.0000	(0.0000)
BRT corridors phase one	0.0136	(0.1689)	0.0438	(0.0527)
BRT corridors phase two	-0.4322 **	(0.1458)	-0.2439 ***	(0.0483)
BRT corridors phase three	-0.1220	(0.1757)	-0.1935 **	(0.0592)
Constant term	1.8122 ***	(0.3136)	-8.8235 ***	(1.0065)
N			49408	
Log likelihood			-22229.689	
LR chi2(44)			21328.47	
Prob > chi2			0.0000	
Pseudo R squared			0.3242	

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Discussion

The data analysis clearly shows that the multi-vehicle crash type increases the probabilities of road crash fatalities, as well as the fact that such crashes are more likely to occur during peak hours, presumably due to road users' higher risk of exposure during peak hours (Santos, Behrendt, Maconi, Shirvani & Teytelboym, 2010). The coefficients by hour demonstrate that crash severity increases at night given a reduced marginal effect of the time variable on injuries compared with peak hours, which is lower for fatal road crashes. This could be associated with higher speeds recorded at night in the entire arterial network (Hidalgo, López, Lleras, & Adriazola-Steil, 2018). The positive association of lane widths with crash severity can in turn be associated with a higher probability of filtering by motorcyclists (Peña Cabra, 2014), longer crossing distances for pedestrians, and higher speeds for all road users (Welle, Liu, Li, Adriazola-Steil, King, Sarmiento & Obelheiro, 2015).

The results of the models also show that the presence of pedestrian bridges is associated with an increase in the number and severity of road crashes for all road users. This association could be due to the fact that pedestrian bridges prioritize motor vehicles eliminating possible intersections, which increases vehicle speeds along the corridors, thus reducing safety for all road users (Welle at al., 2015).

To better understand these results, we conducted 7 visits to intersections with high and low crash levels and the presence of pedestrian bridges. After interviewing pedestrians and street vendors, who are frequent users and had spent several hours at the locations respectively, we found a number of explanations for the results obtained. First, participants pointed out the spatial mismatch between transit stops and pedestrian bridges. They preferred to cross the arterial roads at level because using the pedestrian bridge implied an increase in their travel time. Second, some of the pedestrian bridges situated in locations with a high number of road crashes are of a large scale and length, which tends to be a disincentive for potential users. Participants suggested that the length of the pedestrian bridge implied longer commutes when transferring between transit routes or when trying to reach a transit stop. Finally, participants mentioned personal safety as a main concern, as they often avoid pedestrian bridges due to the possibility of theft. These three factors could help to explain the results of the quantitative data analysis.

The results for the models for road users show a positive association between density and road safety which goes against the results found in the literature (Ewing & Dumbaugh, 2009), in this case, probably due to a higher exposure of vulnerable users. Results for all road users show a positive association between the presence of pedestrian bridges and the number of casualties. This could be associated with the fact that pedestrian bridges allow motorized traffic to get up to higher speeds (Dumbaugh & Li, 2010), which, in turn, is associated with a higher probability for crashes occurring and their severity (Hidalgo et al., 2018). Mixed land uses decrease the number of pedestrian casualties, as also mentioned in the literature (Welle et al., 2015). The number of lanes is only significant for motorcyclists, which can be explained by the filtering options and higher traffic speeds (Peña Cabra, 2014).

The use of pedestrian bridges to access BRT stations is a measure that increases speeds for all motorized users. Pedestrian bridges increase the risk for all road users even in BRT corridors. This is aligned with the literature as being the result of giving priority to motorized traffic in urban areas, which affects all road users, not only pedestrians (Welle et al., 2015).

The data analysis for BRT corridors also reflects that the most recent BRT corridors (Phases 2 and 3) are having an important effect on reducing the probabilities of road crash injuries and fatalities; however, the corridors in Phase 1 are no longer producing this positive effect. As the results for Phase 1 are not similar to the current literature (Bocarejo et al., 2012; Duduta, Adriazola-Steil, Wass, Hidalgo, Lindau, & John, 2015), further research is needed to understand the causes.

Conclusions

The results explored in the discussion section about the association of speed and the probability and severity of crashes highlight the importance of promoting speed management measures during peak hours, especially in areas where there are pedestrian bridges and where the number of crashes is high. Speed management measures should also be implemented in off peak hours in the locations with the highest concentration of crashes and the highest speeds recorded (Hidalgo et al., 2018).

Land use seems to have a significant impact on road safety outcomes. The mixture of the land uses variable, measured in the Data analysis 2, is an interesting association that could be further explored based on the data analysis relating to the buffer area of major arterial roads.

The presence of pedestrian bridges plays an important role in road safety and the future planning of major arterial roads. Intersections have a positive impact on road safety while pedestrian bridges increase the probability of crashes for all road users. If the presence of pedestrian bridges along major arterial roads is positively associated with higher levels of crash severity (fatalities and injuries), it is important to further analyze this type of infrastructure including the role of pedestrian fencing, determine the level of use, reevaluate its need, and study its replacement if necessary.

Results for vulnerable-user models suggest that built environment features affect vulnerable users differently. For pedestrians, including more midblock safe crossings might be key to improving their safety. Also, urban infrastructure that incentives high speeds, such as pedestrian bridges, have a significant negative impact all road users. As for cyclists, the results show similar associations but their safety should be further explored using other variables involved in infrastructure design such as the five main principles of design requirements for cycling infrastructure (Ministerio de Transporte de Colombia, 2016).

The effect of pedestrian bridges and BRT users, who cross the road instead of using the bridge in order to avoid paying, also needs to be studied as a life risk. Infrastructure improvements where pedestrians and BRT users could access the stations without being penalized, in terms of the length and time, could improve road safety for all users, as could access at ground level instead of pedestrian bridges which would could decrease speeds around BRT stations. In the short term, speed management measures for BRT buses should be implemented in areas with higher concentrations of road crash victims involving BRT vehicles.

Regarding the results discussed of the effects of the different BRT phases on road safety outcomes, policy measures to improve the infrastructure for Phase 1 should be implemented. This is especially true for Av. Caracas, Bogotá's main arterial road for public transit, where it is important to conduct maintenance around BRT stations, implement speed management measures, and improve infrastructure conditions. It is also important to consider urban design measures that reduce pedestrian exposure at the intersections along these corridors.

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Annex

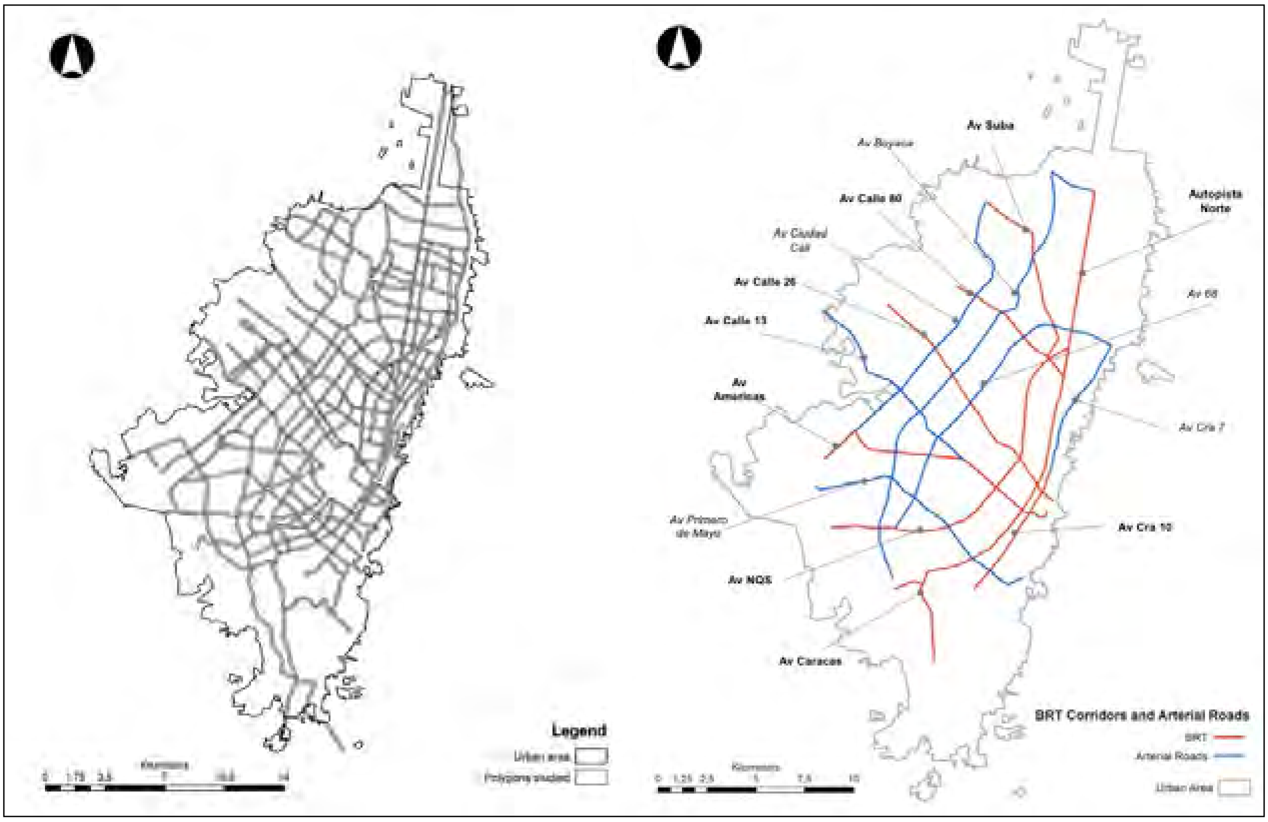
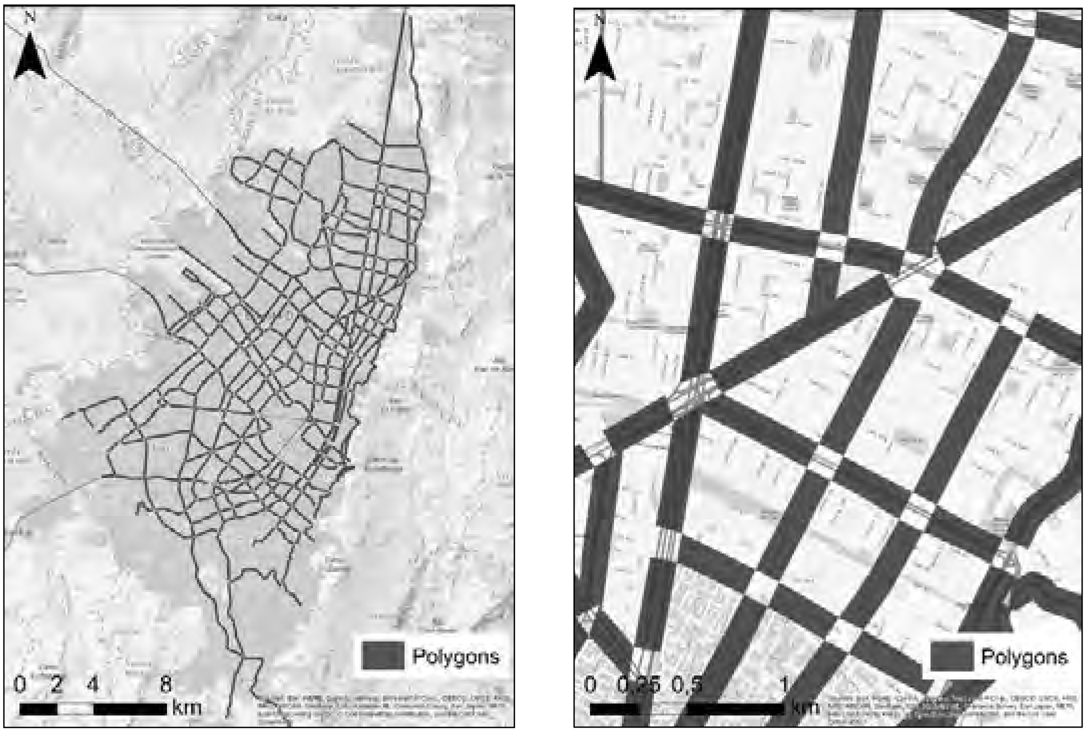


Figure 1. Study areas.

Source: Authors based on Alcaldía Mayor de Bogotá (2017, 2018)



Poligons studied in Bogota

Polygons in detail (arterial roads)

Figure 2. Polygons studied.
Source: Authors based on Alcaldía Mayor de Bogotá (2017, 2018)

Example of pedestrian bridge in front of a hospital in Av. Boyaca and Carrera 18b from an orthophoto

Example of the same pedestrian bridge from Google Street View

Figure 3. Pedestrian bridge in Bogota.
Source: IDECA mapas.bogota.gov.co (2020) and Google Street View (2020)