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Influence of the urban environment on unsafe speeds: analysis of arterial roads using naturalistic data and an H3 grid

Influência do ambiente urbano sobre velocidades inseguras: análise em vias arteriais com dados naturalísticos e grade H3

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ABSTRACT

Speed is a central factor in urban road safety, especially on arterial roads embedded in heterogeneous land-use contexts. This study analyzes the relationship between the built environment and speed behavior on arterial roads in Curitiba, Brazil, considering both mean speed and the occurrence of unsafe speeds. Naturalistic driving data and built environment variables were used and aggregated into H3 hexagonal spatial units. The methodology included the selection of records under conditions in which drivers had the opportunity to choose their speed, the definition of minimum representativeness criteria for observations in each spatial unit, and the integration of the databases through spatial association procedures. Mean speed was analyzed using robust linear regression, while the occurrence of unsafe speed was estimated using penalized logistic regression. The results indicate consistent associations between traffic regulation elements and the two variables analyzed, as well as differences in speed behavior according to land use and occupation patterns. The comparative analysis shows that reductions in mean speed do not necessarily imply that speed is appropriate to the urban context, highlighting the importance of approaches that consider multiple metrics in speed management on urban arterial roads.

RESUMO

A velocidade é um fator central para a segurança viária urbana, especialmente em vias arteriais inseridas em contextos heterogêneos de uso do solo. Este estudo analisa a relação entre o ambiente construído e o comportamento de velocidade em vias arteriais de Curitiba, considerando a velocidade média e a ocorrência de velocidades inseguras. Foram utilizados dados naturalísticos de direção e variáveis do ambiente construído, agregados em unidades espaciais hexagonais H3. A metodologia compreendeu a seleção de registros em condições nas quais os condutores tinham oportunidade de escolher sua velocidade, a definição de critérios mínimos de representatividade das observações em cada unidade espacial e a integração das bases por procedimentos de associação espacial. A velocidade média foi analisada por regressão linear robusta, enquanto a ocorrência de velocidade insegura foi estimada por regressão logística penalizada. Os resultados indicam associações consistentes entre elementos de regulação do tráfego e as duas variáveis analisadas, além de diferenças no comportamento de velocidade conforme os padrões de uso e ocupação do solo. A análise comparativa mostra que reduções na velocidade média não implicam necessariamente adequação da velocidade ao contexto urbano, ressaltando a importância de abordagens com múltiplas métricas na gestão da velocidade em vias arteriais urbanas.

1. Introduction

Speed is a central factor in road safety because it simultaneously influences the probability of crashes and the severity of the injuries resulting from these events (Aarts & van Schagen, 2006; Nilsson, 2004). An increase in speed reduces the time available for perception and reaction, increases the distance required for braking, and raises the energy involved in a potential impact, intensifying the consequences for road users. Within the Safe System approach, this understanding shifts the analysis from the individual responsibility of the driver to the organization of the mobility system itself, so that road design, operation, and enforcement are compatible with the limits of human tolerance to impact (WHO, 2021). From this perspective, driving speed results from the interaction between the driver, the road, and

the urban surroundings, and is influenced by both statutory speed limits and the physical, operational, and environmental characteristics of the road space (Ewing & Dumbaugh, 2009).

As small variations in mean speed can substantially alter the frequency and severity of crashes (Nilsson, 2004), the discussion of safe speed also involves the criteria used to set statutory speed limits. In many contexts, these limits are still based on road type, statutory speed, as in the Brazilian Traffic Code (CTB) (Brasil, 1997), and observed speed, including the 85th percentile (NACTO, 2020), which may reduce sensitivity to urban risk and exposure conditions (ITF, 2016; WHO, 2018). By contrast, approaches aligned with the Safe System define speeds on the basis of risk, type of conflict, urban activity, and the presence of vulnerable road users (ITF, 2016; WHO, 2018). Figure 1 summarizes this distinction based on the City Limits (NACTO, 2020) and Roads for Life (Turner *et al.*, 2024) frameworks.

On arterial roads, this discussion is particularly relevant because these corridors carry high traffic volumes and cross areas with different levels of urban activity, subject to conflict points, control devices, and temporary operational disruptions such as roadworks, closures, and traffic circulation changes. In these contexts, observed speed responds not only to the statutory speed limit but also to road characteristics, operating conditions, and attributes of the surrounding area. In Curitiba, recent studies have identified spatial heterogeneity in speeding, a reduction in this behavior in the presence of automated speed enforcement, and a non-random concentration of crashes along travel corridors (Santos *et al.*, 2026; Monteiro & Bastos, 2024; Szeliga *et al.*, 2026). Findings from Porto Alegre reinforce that the relationship between arterial roads and risk also occurs in another Brazilian urban context, where a greater proportion of these roads was associated with a higher occurrence of injury crashes (Obelheiro, 2024). These studies demonstrate the spatial relevance of the problem, but the microspatial comparison between the mean level of driving speed and its suitability for the immediate urban context remains underexplored. Consistently, the international literature has associated speed and risk with segment characteristics, proximity to intersections, the built environment, and predictive models at multiple scales, while also identifying operational limitations in the integration of naturalistic datasets applied to infrastructure (Gitelman *et al.*, 2018; Yan *et al.*, 2024a,b; Nicolosi *et al.*, 2025; Howell *et al.*, 2025).

Against this background, this article investigates how characteristics of the urban context are associated with speed behavior on arterial roads in Curitiba. Naturalistic driving data were first filtered to represent situations in which drivers had the opportunity to choose their speed and were then aggregated into a hexagonal spatial grid. Based on this analytical structure, two response variables were considered:

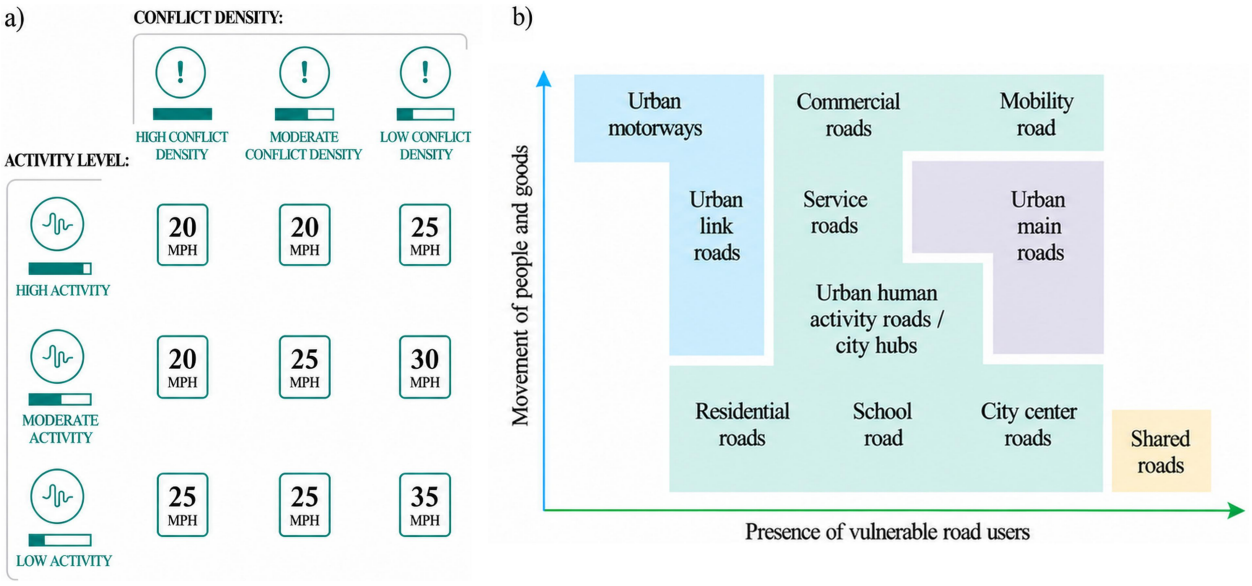

Figure 1 • Frameworks for safe speeds: (a) City Limits, relating recommended speeds to conflict density and activity level; (b) Roads for Life (R4L), relating road types to the movement of people and goods and the presence of vulnerable road users [adapted from NACTO (2020) and Turner *et al.* (2024), using ChatGPT Plus (GPT-5.6 Sol)]

mean driving speed and the occurrence of unsafe speed, defined by the incompatibility between observed speed and the road context. The analysis relates these variables to indicators of land use and occupation, road infrastructure, and control devices, seeking to understand how different attributes of urban space are associated with speed behavior along these corridors.

2. Method

The method was organized into stages that integrate data acquisition, processing, integration, and analysis. Figure 2 presents the methodological workflow adopted, comprising: (*i*) acquisition and organization of road infrastructure and operation, land-use, and naturalistic speed data; (*ii*) processing and standardization; (*iii*) integration into a geographic database; (*iv*) spatial analyses; and (*v*) application of statistical models.

2.1. Study area

The study area corresponds to the municipality of Curitiba, Paraná, selected because of the availability of naturalistic driving data from the Brazilian Naturalistic Driving Study (NDS-BR), which enable driving behavior to be observed under real-world traffic conditions (Bastos *et al.*, 2020). The road network scope focuses on arterial roads, which collect and distribute traffic between different areas of the city (Brasil, 1997). Locally, these roads correspond to the so-called express roads, with speed limits ranging from 50 to 70 km/h (Curitiba, 2022). Figure 3 presents the study area and the spatial distribution of these roads within the municipality.

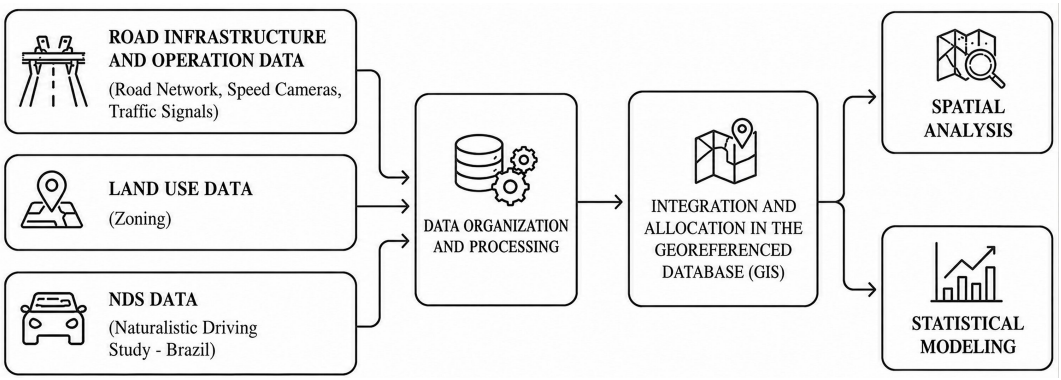

Figure 2 • Methodological workflow of the study



Figure 3 • Study area and arterial-road scope in Curitiba, Paraná.

2.2. Data

The data used were organized into two groups: (*i*) naturalistic driving data (NDS-BR) and (*ii*) municipal datasets.

2.2.1. Naturalistic driving data

Data from the Brazilian Naturalistic Driving Study (NDS-BR) were obtained using onboard instrumentation that records vehicle-motion variables, such as geographic coordinates, timestamps, instantaneous speed, and acceleration, as well as images of the road environment under real-world driving conditions (Bastos *et al.*, 2020). The dataset covers Curitiba and comprises records collected between March 2019 and June 2023, totaling 57 drivers, 1,689 trips, approximately 381 hours of telemetric data, and 11,800 kilometers traveled within the municipality's urban perimeter.

The participant sample was relatively balanced by gender and included drivers aged 19 to 62 years. The largest age group comprised drivers between 25 and 34 years of age. Table 1 summarizes the demographic profile of the participating drivers.

2.2.2. Built urban environment variables

The built urban environment variables were organized into two groups to analyze their association with the speed measures: (*i*) road infrastructure and operation and (*ii*) land use and occupation.

Three road infrastructure and operation variables associated with speed behavior on arterial roads were considered: (*i*) automated speed enforcement, whose locations were obtained from official lists published by the Municipality of Curitiba (Curitiba, 2025) and integrated into a GIS environment, with a 100 m buffer around each point to represent its local influence on speed (Amancio *et al.*, 2024), as illustrated in Figure 4; (*ii*) Traffic signal control, whose locations were also obtained from the Municipality of Curitiba (Curitiba, 2025) and assigned a 100 m buffer; and (*iii*) proximity to intersections, derived from road-network connectivity using IPPUC cartographic datasets (IPPUC, 2026), by converting crossings into points and applying a 25 m buffer to represent their immediate influence.

The land-use and occupation variables were defined to indirectly represent the intensity of urban activities surrounding arterial roads, an aspect associated with variations in speed behavior in urban environments (Ewing & Dumbaugh, 2009; Dumbaugh & Rae, 2009). Two variables were considered: (*i*) commercial density, estimated from the business-license database available on the Municipality of Curitiba Open Data Portal (Curitiba, 2026), with records geocoded and aggregated to the spatial unit of analysis; and (*ii*) housing-unit density, constructed from the total number of households in the 2022 Demographic Census and the corresponding digital census-tract grid (IBGE, 2024), with values transferred to the study's spatial units by overlay and weighting according to the intersected area, resulting in an indicator expressed as housing units per hectare. Based on the Curitiba Master Plan, the housing indicator was classified as low density, up to 80 housing units per hectare; medium density, from 81 to 200 housing units per hectare; and high density, from 201 to 400 housing units per hectare (Curitiba, 2015).

2.3. Spatial unit of analysis and aggregation procedures

To relate the naturalistic driving records to the urban environment variables, a common spatial unit capable of integrating information from different geometries and sources was adopted. This choice sought to reduce dependence on administrative boundaries and mitigate biases associated with the

Table 1 • Demographic profile of the participating drivers

Gender	18–24 years	25–34 years	35–44 years	45–54 years	≥55 years	Total
Female	7	9	5	5	1	27
Male	7	14	5	2	2	30
Total	14	23	10	7	3	57

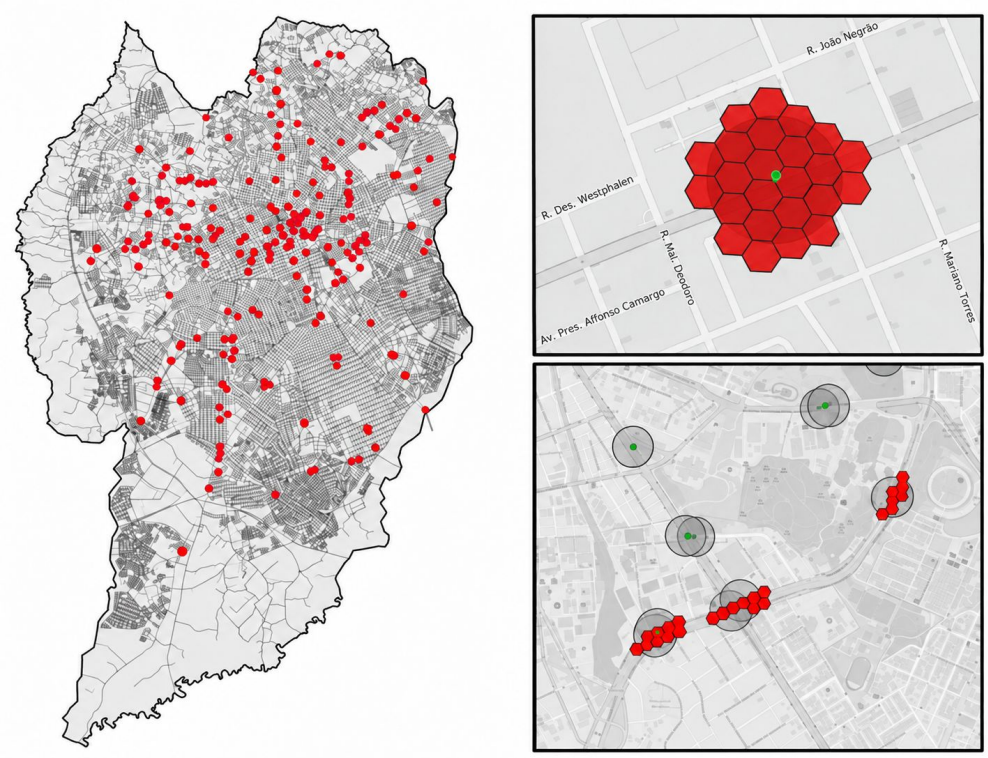

Figure 4 • Spatial distribution of speed cameras and speed reduction devices in Curitiba and representation of the adopted radius of influence [ChatGPT Plus (GPT-5.6 Sol) was used in the preparation of this figure]

Modifiable Areal Unit Problem, whose results may vary according to the scale and delineation of the aggregation units (Openshaw, 1983; Javanmard *et al.*, 2023; ESRI, 2024). A regular grid based on the H3 geospatial indexing system was therefore used, with hexagonal cells whose geometric properties support more consistent neighborhood analyses (Uber, 2017).

The grid was generated in QGIS for the urban perimeter of Curitiba using H3 cells at resolution 11, with an average area of approximately 2,150 m^2 and an average edge length of 28.7 m. This resolution was selected to analyze speed behavior at a fine scale, capturing local variations in the urban environment that could be diluted in larger spatial units. Spatial aggregation comprised three stages: (*i*) assigning the H3 identifier to georeferenced driving records, (*ii*) consolidating speed measures by spatial unit, and (*iii*) associating the explanatory variables of the urban environment with the same spatial unit. This strategy reduces dependence on administrative boundaries and helps mitigate the effects of the Modifiable Areal Unit Problem (MAUP), although it does not eliminate them because the analysis remains conditional on the spatial scale adopted.

2.4. Data filtering and processing

The Brazilian Naturalistic Driving Study (NDS-BR) records were processed in five stages: (*i*) spatially linking points to the road network, (*ii*) restricting the records to arterial roads, (*iii*) applying a speed opportunity filter, (*iv*) aggregating the records using the concept of passage, and (*v*) controlling the minimum number of observations and the precision of the estimates in each spatial unit.

The NDS-BR records correspond to speed observations obtained at one-second intervals, with a geolocation associated with each point along the trajectory (Bastos *et al.*, 2023). To link these records to the road network, each point was initially associated with the nearest segment in a GIS environment, considering a maximum distance of 10 meters. Directional validation was then performed by comparing the azimuth estimated from the sequence of vehicle points with the azimuth of the corresponding road segment. Associations with an angular difference of up to 30 degrees were retained. When this criterion was not met, the adjacent segment with the smallest angular difference relative to the observed direction

of travel was assessed, reducing incorrect associations in areas with complex geometries, closely spaced carriageways, or parallel roads. After this procedure, the dataset was restricted to records associated with arterial roads.

The speed opportunity filter was then applied to select observations in which drivers had a minimum opportunity to develop speed. This procedure seeks to remove from the analysis records associated with stops, queues, congestion, or low-speed approaches. Following the opportunity for speeding rationale proposed by Richard *et al.* (2013) and adopted by Santos *et al.* (2026), only records with speeds greater than the statutory speed limit minus 10 km/h were retained. This interval corresponds to the metric-system adaptation of the 5 mph criterion used in the literature to characterize speed opportunity conditions. Because the lowest statutory speed limit observed on the arterial roads analyzed was 50 km/h, a minimum threshold of 40 km/h was adopted to compose the sample. Figure 5 illustrates this procedure.

After filtering, the records were aggregated into H3 cells using the concept of passage, defined as the occurrence of the same trip within a given cell. Only passages with at least three GPS points within the spatial unit were considered valid, a criterion adopted so that passage speed was estimated from a minimum sequence of observations rather than from a single record. Subsequently, only cells with three or more valid passages were retained, the minimum number required to estimate variation between trips and calculate the sampling error of the mean. The speed representative of each cell was obtained as the mean of the mean speeds of the passages, preserving each passage as a unit of contribution to the aggregated measure. This choice reflects the structure of naturalistic data, in which second-by-second records form passages and passages form the cell's spatial estimate.

Finally, the consistency of the speed estimate in each cell was assessed using the sampling error of the mean passage speeds, considering a 95% confidence level and a maximum admissible error of 7 km/h. The value of 7 km/h was adopted as the acceptability threshold for the estimate because of the uncertainty associated with GPS speed measurement in urban environments and because it corresponds to the order of magnitude of the margin considered in speed enforcement in Brazil, according to CONTRAN Resolution No. 798/2020 (CONTRAN, 2020). This procedure was applied to all cells in the hierarchy analyzed. Although three passages were defined as the initial minimum requirement, whether a cell remained in the final dataset depended on the relationship between the variability of the observed speeds and the number of available passages. Thus, cells with greater dispersion between passages required a larger number of trips for the sampling error to remain within the established limit. Cells that did not meet the minimum composition and precision criteria were excluded from the final dataset

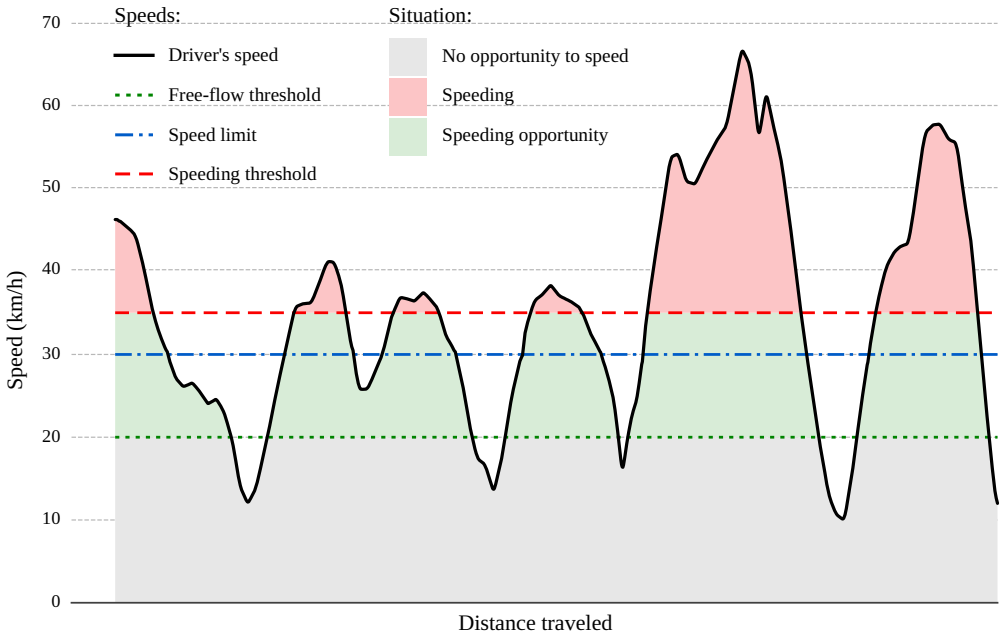

Figure 5 • Illustration of the speed opportunity filter [originally from Santos *et al.* (2026), modified using ChatGPT Plus (GPT-5.6 Sol)]

used in the analysis.

2.5. Response variables

Two complementary response variables were adopted: mean driving speed and the occurrence of unsafe speed. The first corresponds to the mean speed observed in each spatial unit, while the second identifies speeds incompatible with the local road context, that is, a speed greater than the value recommended by City Limits (NACTO, 2020) and Roads for Life (Turner *et al.*, 2024). Table 2 summarizes the operational definitions and units of measurement.

2.6. Analyses and models

The data analysis sought to assess the association between the response variables and the characteristics of the built urban environment on the arterial roads analyzed. The procedure involved three stages: (*i*) initial description of the data, (*ii*) verification of statistical assumptions, and (*iii*) model estimation.

Initially, a descriptive analysis of the response and explanatory variables was performed, including an examination of the distribution of values and the identification of extreme observations. To guide the choice of modeling strategy for mean speed, an auxiliary linear model was fitted using the same explanatory variables as in the final analysis. Based on this model, the residuals were assessed for normality using the Shapiro–Wilk test and graphical inspection (Shapiro & Wilk, 1965), and for heteroscedasticity using the Breusch–Pagan test (Breusch & Pagan, 1979). Multicollinearity among the explanatory variables was examined using the variance inflation factor (VIF) (Kutner *et al.*, 2005). Given the spatial structure of the data, spatial autocorrelation of the residuals was explored using global Moran's I.

For the continuous response variable, mean speed, robust linear regression with M-estimation, a Huber loss function, and HC1 robust standard errors was adopted (Huber, 1964). For the binary response variable, unsafe speed, penalized logistic regression with L1 regularization was adopted. The analyses were conducted in a computational environment using the Python language and statistical and geospatial libraries. A significance level of 5% was adopted. Table 3 summarizes the models used in the study.

3. Results

The results are presented in subsections covering the characterization of the final sample, the descriptive patterns of the response variables, the statistical diagnostics, and the results of the estimated models.

Table 2 • Definition of the response variables used in the analysis

Response variable	Mean speed	Unsafe speed
Type	Continuous	Binary
Unit	km/h	0 = does not exceed; 1 = exceeds
Definition	Mean of the mean speeds of valid passages aggregated within each spatial unit	Indicates whether the aggregated mean speed is appropriate or inappropriate for the road context of the spatial unit
Interpretation	Represents the mean speed at the location, reflecting recurrent travel behavior	Identifies spatial units in which speed is incompatible with the road context analyzed

Table 3 • Summary of the models adopted in the study

Dependent variable	Model adopted	Methodological rationale
Mean speed (continuous)	Robust linear regression using M-estimation, with a Huber function and HC1 covariance matrix	Lower sensitivity to influential observations and to violations of residual normality and homoscedasticity
Unsafe speed (binary)	Penalized logistic regression with L1 regularization	Coefficient regularization, sparsity induction, and a parsimonious model for a binary outcome

3.1. Characterization of the final sample

The final analytical dataset comprised 2,018 spatial units associated with arterial roads in Curitiba, all compatible with the methodological criteria adopted. Low housing-density areas predominated, with 1,685 units (83.5%), followed by medium-density areas, with 285 (14.1%), and high-density areas, with 48 (2.4%). The distribution of mean speed showed a predominance of intermediate values and right skewness, as shown in Figure 6, indicating a departure from normality.

3.2. Descriptive patterns of mean speed and unsafe speed

The descriptive analysis of speed patterns was performed by stratifying the spatial units into housing-density classes. The results indicate a reduction in mean driving speed as housing density increases. At the same time, the proportion of units classified as having unsafe speed increases as the contextual thresholds for safe speed become more restrictive. Table 4 presents the speed and safety indicators for each class.

3.3. Statistical diagnostics and implications for modeling

Before estimating the models, an auxiliary linear model for mean speed was fitted using the same explanatory variables as in the final analysis. The residuals were assessed for normality using the Shapiro–Wilk test and for homoscedasticity using the Breusch–Pagan test. Multicollinearity among the explanatory variables was examined using VIF. The diagnostics indicated low multicollinearity, rejection of normality, and heteroscedastic residuals, supporting the adoption of robust linear regression for the continuous variable.

The spatial structure of mean speed and unsafe speed was assessed using global Moran's I, applied to the values observed on the H3 grid. The indicator showed positive spatial clustering, highlighting the relevance of the spatial dimension to the interpretation of the data. This result is consistent with the continuous nature of speed behavior on arterial roads, as nearby cells belonging to the same road hierarchy and often to the same corridor tend to share similar road, urban, and operational characteristics. Spatial models were assessed but were not sufficiently stable for the selected scope because of the fine, linear, and discontinuous structure of the valid cells on arterial roads. As a sensitivity test, an

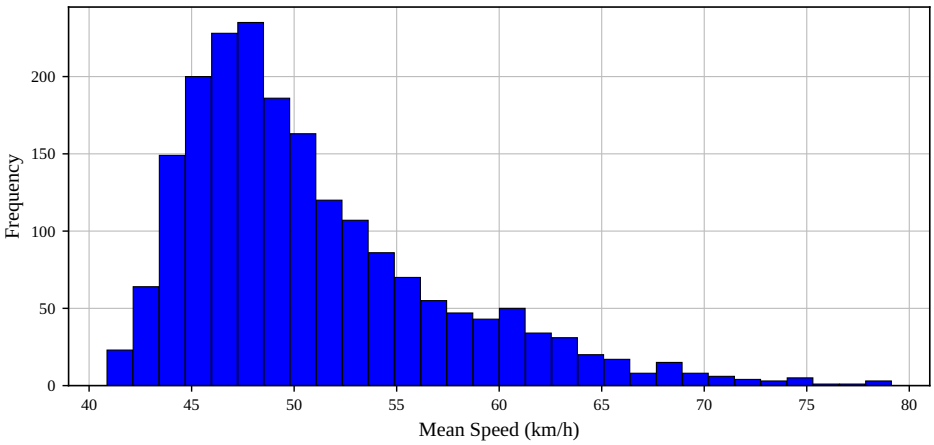

Figure 6 • Frequency distribution of mean speed on arterial roads

Table 4 • Speed and safety indicators by density class

Housing density class	Number of hexagons	Safe speed (km/h)	Mean driving speed (km/h)	Percent of hexagons with unsafe speed
Low	1685	60	51.8	13.60%
Medium	285	50	47.8	20.00%
High	48	40	47.7	100.00%

OLS model with standard errors clustered by connected components of the H3 grid was estimated to determine whether accounting for spatial dependence would alter the interpretation of the coefficients. The comparison indicated that the estimated effects remained in the same direction. Based on these diagnostics, the more stable and interpretable global models were retained, using robust linear regression for mean speed and penalized logistic regression with L1 regularization for unsafe speed. Table 5 summarizes the diagnostics performed.

3.4. Mean-speed model

The association between the built urban environment variables and mean driving speed was estimated using robust linear regression, in accordance with the diagnostics presented above. The estimated coefficients represent the mean change in speed, in km/h, associated with each explanatory variable, holding the others constant.

The results indicate a negative association between mean speed and the traffic regulation and control variables. The largest effects were observed for traffic signal control and for the combined presence of automated speed enforcement and traffic signal control, while automated speed enforcement alone produced a smaller reduction. Among the land-use and occupation variables, medium and high housing-density classes were associated with lower speeds than low-density areas, and commercial density also showed a negative association. Proximity to intersections was not significantly associated with mean speed. Table 6 presents the model results.

3.5. Unsafe-speed model

The association between characteristics of the urban environment and the occurrence of unsafe speed was estimated using penalized logistic regression with L1 regularization, owing to the binary nature of the response variable and the need to regularize the coefficients. The results indicate a negative association between the occurrence of unsafe speed and the traffic regulation and control variables. Traffic signal control, automated speed enforcement, and their combined presence had effects in the same direction, as did proximity to road intersections.

By contrast, the variables related to housing density showed a positive association with the probability

Table 5 • Statistical diagnostics and assumptions assessed before modeling

Assessment	Test	Statistic	*p*-value	Interpretation
Residual normality	Shapiro–Wilk	$W = 0.922$	< 0.001	Normality rejected
Homoscedasticity	Breusch–Pagan	$LM = 26.84$ $F = 5.42$	< 0.001	Homoscedasticity rejected
Multicollinearity	VIF (min–max)	1.01–1.09	—	Negligible collinearity
Spatial autocorrelation: mean speed	Global Moran's I	$I = 0.789$	0.001	Spatial clustering present
Spatial autocorrelation: unsafe speed	Global Moran's I	$I = 0.619$	< 0.001	Spatial clustering present
Spatial sensitivity	OLS with std errors clustered by H3 components	—	—	Did not change the direction of the effects

Table 6 • Robust linear regression for mean speed

Variable	Coefficient (km/h)	Std error	*p*-value	95% CI
Intercept	54.29	0.27	< 0.001	53.77 to 54.81
Automated speed enforcement	−1.43	0.49	0.003	−2.39 to −0.47
Traffic signal control	−5.01	0.28	< 0.001	−5.55 to −4.46
Combined speed enforcement and signal control	−5.16	0.39	< 0.001	−5.92 to −4.39
Road intersection	−0.15	0.25	0.553	−0.63 to 0.34
Medium housing density	−2.11	0.34	< 0.001	−2.77 to −1.45
High housing density	−1.95	0.77	0.011	−3.45 to −0.45
Commercial density	−0.46	0.12	< 0.001	−0.69 to −0.22

of unsafe speed. Medium-density areas showed an increase in the odds of this behavior relative to low-density areas, while the effect was substantially greater in high-density areas. For the latter class, the magnitude of the odds ratio should be interpreted with caution because of the wide confidence interval and the high concentration of the outcome in this category. Commercial density, in turn, showed a negative association. Table 7 presents the model results.

Table 7 • Logistic regression for unsafe speed

Variable	Coefficient (log-odds)	*p*-value	Odds ratio	95% CI
Intercept	−1.01	< 0.001	0.36	0.28 to 0.47
Automated speed enforcement	−0.53	0.030	0.59	0.36 to 0.95
Traffic signal control	−1.20	< 0.001	0.30	0.22 to 0.40
Combined speed enforcement and signal control	−1.12	< 0.001	0.32	0.21 to 0.51
Road intersection	−0.33	0.015	0.72	0.55 to 0.94
Medium housing density	0.79	< 0.001	2.21	1.56 to 3.12
High housing density	7.39	< 0.001	1623.30	98.99 to 26608.80
Commercial density	−0.35	0.001	0.71	0.57 to 0.87

3.6. Comparative synthesis of results

The comparison between the results of the models estimated for mean speed and unsafe speed showed partial convergence between the observed effects. Figure 7 jointly presents the coefficients estimated in the robust linear regression model and the odds ratios estimated in the logistic model.

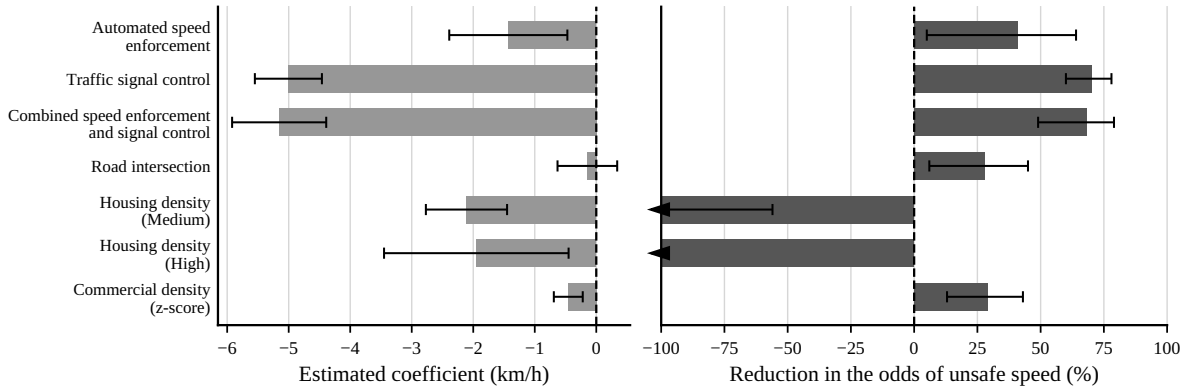

Figure 7 • Estimated effects in the linear regression (mean speed) and logistic regression (unsafe speed) models

The variables associated with traffic regulation and control behaved similarly in both models. The presence of traffic signal control, automated speed enforcement, and the combined presence of these devices was associated with both a reduction in mean speed and a reduction in the probability of unsafe speed. Housing density behaved differently across the outcomes. The medium- and high-density classes were associated with a reduction in mean speed and, simultaneously, an increase in the probability of unsafe speed, indicating that the lower mean speed observed in these areas was not sufficient to meet the safe thresholds defined for denser contexts. For high density, this result should be interpreted primarily in terms of the direction of the association because of the concentration of the outcome and the width of the confidence interval in the logistic model. Proximity to intersections was statistically significant only in the unsafe-speed model and had no significant effect on mean speed. This finding suggests that the influence of intersections may be more clearly expressed in the occurrence of speeds incompatible with the road context than in the mean travel pattern observed in the cell. Commercial density showed an association in the same direction in both models and was related to a reduction in mean speed and a reduction in the probability of unsafe speed.

4. Conclusion

This article analyzed the relationship between the built urban environment and speed behavior on arterial roads in Curitiba, based on the understanding that speed should be assessed not only in terms of mean values but also in terms of its suitability for the urban context. To this end, naturalistic driving data were integrated with urban environment variables and aggregated into regular spatial units.

The methodology adopted made it possible to observe driving speed under real-world traffic conditions and relate it to characteristics of the urban surroundings within the same analytical database. The joint analysis of mean speed and unsafe speed proved suitable for capturing distinct dimensions of speed behavior, in line with the Safe System approach.

The results indicated that traffic regulation and control elements, such as traffic signal control and automated speed enforcement, were associated with both a reduction in mean speed and a reduction in the probability of unsafe speed. These findings suggest that such devices help constrain speed behavior, even on arterial roads. Planning for speed management in urban environments should therefore consider the influence of the traffic signal network, both independently and in conjunction with automated speed enforcement. Thus, traffic signals may also be considered a speed-management measure, although their implementation requires justification linked to reducing overall delays.

Regarding the land-use and occupation variables, areas with more intense commercial activity tended to have lower mean speeds and a lower probability of unsafe speed. Conversely, increased housing density was associated with a reduction in mean speed but an increase in the probability of unsafe speed. This result points to the presence of a density paradox, in which the reduction in the mean speed level does not occur in the same proportion required by the limits considered appropriate in denser urban environments.

The comparison between the two measures analyzed showed that reductions in mean speed do not necessarily ensure compatibility between driving speed and the actual urban context of road use. In denser areas, speed may remain above the limits considered safe even when mean values are lower than those observed in less dense areas. In addition, proximity to intersections was not significantly associated with mean speed but was associated with a lower probability of unsafe speed. This result should be interpreted with caution because it indicates that intersections may more directly influence the compatibility of speed with the road context than the mean level observed in the cell. In this sense, the two outcomes analyzed proved complementary. The influence of the statutory speed limit on speed must also be considered. When this limit is above a level considered safe, speeds will also tend to be unsafe. On the arterial roads analyzed, statutory speed limits are predominantly 50 km/h and may range from 50 to 70 km/h.

Some limitations should be considered, including the driver sample size, the representativeness of the observed speed patterns in relation to the population of drivers and Curitiba's vehicle fleet, the temporal gap between the datasets used, the adoption of a single spatial scale, and the presence of residual spatial autocorrelation. Nevertheless, the sensitivity analysis preserved the direction of the estimated effects, and the methodological approach proved suitable for identifying consistent patterns and integrating speed behavior with characteristics of the urban environment.

Overall, the results suggest that setting speed limits primarily based on road hierarchy is insufficient to ensure speeds compatible with risk in denser urban areas. Coordinating a speed-management policy that considers safe limits, road design, and land use and occupation is relevant to promoting speeds more compatible with the urban context on arterial roads.

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CRediT authorship contribution statement

Jefferson Artigas Guerra: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft; *Jorge Tiago Bastos*: Supervision, Writing – review & editing.

Use of artificial intelligence-assisted technology

The authors declare that ChatGPT Plus (GPT-5.6 Sol) was used in the preparation of this article for the purposes of rewriting and textual revision of the manuscript, as well as improving the clarity and resolution of Figures 1, 4, and 5. The authors take full responsibility for the use of this tool.

Competing interests statement

No competing interests have been declared with regard to this paper or its contents.

Data availability statement

The data supporting the findings of this study may be made available upon reasonable request to the corresponding author, Jefferson Artigas Guerra. Tabular and telemetric data may be shared subject to applicable ethical and institutional requirements. Video and image recordings are confidential and cannot be made publicly available due to participant privacy considerations. The NDS-BR research project received ethics approval under CAAE No. 52443421.8.0000.0102.

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