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Bus Stop Environment and Pedestrian Crash Risk in Kumasi, Ghana: Implications for Safe and Sustainable Urban Mobility

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Abstract

Pedestrians are amongst the most vulnerable road user groups. Efforts to enhance pedestrian safety have mainly focused on intersections and midblock crossings. This study investigated the effect of bus stop environments on pedestrian safety in Kumasi, an area with a high incidence of pedestrian fatalities in Ghana. Crashes within a 50 m radius of bus stops were extracted using a spatial join. The Negative Binomial regression model was applied to model pedestrian crashes around bus stops as a function of three distinct non-collinear independent variable groups: road design features, bus stop characteristics, and pedestrian exposure measures. Formal bus stops were associated with higher crash rates than informal ones. The presence of medians and crosswalks was associated with lower crash rates, whereas wider carriageways were associated with higher crash rates. Higher crashes were linked to passing pedestrians and waiting pedestrians, while crossing pedestrians were associated with reduced crashes. These findings suggest that the combined effects of infrastructure and behavioural factors influence pedestrian safety at bus stops. Prioritising low-cost safety treatments, such as guard-railed waiting areas, marked crosswalks, medians, and raised crossings, around bus stops will yield substantial safety benefits for resource-constrained contexts and advance sustainable urban mobility.

Keywords: pedestrian safety; bus stop environment; pedestrian exposure; roadway infrastructure design; sustainable urban mobility; Kumasi; Ghana

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1. Introduction

Walking is recognised as a sustainable mode of transport, as it is healthful and has virtually no carbon footprint [1]. In many developed countries, walking is considered a recreational activity; however, in many developing countries, particularly in Africa, it is a significant transport mode, accounting for 50% to 90% of all daily trips [2,3]. However, pedestrians are vulnerable, particularly in developing countries, representing a fifth of the 1.19 million annual deaths globally [4]. Pedestrians are overrepresented in Ghana's crash data, accounting for 40% of the 2000 annual fatalities [5]. The pedestrian injury burden calls for urgent action to prevent social exclusion among vulnerable road users.

Several studies have examined the relationship between pedestrian safety and the built environment, with a primary focus on intersections and midblock crossings (Table 1).

Table 1. Comparative Summary of Pedestrian Safety Studies by Location of Analysis.

Study Reference	Location	Study Focus	Method	Exposure Measure	Bus Stop Environment Considered
[6]	United States	Pedestrian crashes at intersections	Log-linear model	Pedestrian and traffic volumes	No
[7]	Ethiopia	Pedestrian crashes at roundabouts	Poisson/Negative Binomial model	Pedestrian and traffic volumes	No
[8]	Hong Kong	Pedestrian crashes/injury severity at intersections	Spatiotemporal logistic regression	General pedestrian activity	No
[9]	Canada	Pedestrian crashes at intersections	Generalised Negative Binomial	Pedestrian and traffic volumes	No
[10]	Canada	Pedestrian crashes at intersections	Full Bayes Spatial Poisson Log-Normal model	Pedestrian and traffic volumes	No
[11]	United States	Pedestrian crashes at intersections	Negative binomial model	Pedestrian and traffic volumes	No
[12]	United States	Pedestrian crashes at midblocks	Poisson model	Pedestrian and traffic volumes	No
[13]	Poland	Pedestrian injury severity at midblocks	Binary logistic regression	None	No
[14]	Brazil	Pedestrian crashes at micblocks	Poisson regression model	Pedestrian and traffic volumes	No
[15]	Philipiness	Pedestrian injury severity at midblocks	Binomial logistic regression	None	No
[16]	United States	Pedestrian crashes near bus stops	Negative Binomial-Lindley	Traffic volume Boarding/alighting activity	Yes
[17]	United States	Pedestrian crashes near bus stops	Negative binomial model	None	Yes
[18]	Canada	Pedestrian crashes near bus stops	Negative binomial model	Traffic volume	Yes
[19]	India	Pedestrian injury severity near bus stops	Logistic regression model	None	Yes
This study	**Ghana**	**Bus stop environments and Pedestrian crash risk**	**Negative Binomial Model**	**Behavioural-specific exposure**	**Yes (formal vs informal bus stops)**

Road design elements, such as wider carriageways and multilane roads, are generally associated with an increased risk of pedestrian crashes [20,21]. In contrast, medians and pedestrian refuge islands are associated with lower crash frequencies, as they facilitate two-stage crossings and reduce exposure [7,22]. Sidewalk provision is widely recognised as a key safety measure. Sidewalks on both sides of the road reduce pedestrian crashes [23,24], with greater benefits associated with greater width, separation from traffic, continuity, and connectivity [20,25–29]. Conversely, narrow or obstructed sidewalks compromise safety, particularly in dense urban environments [24,30], indicating that sidewalk provision alone is insufficient without adequate capacity. Evidence on crosswalk effectiveness is mixed. Some studies report no significant association with crash occurrence [31,32], while others find reduced injury severity rather than crash frequency [33,34], suggesting a moderating effect on injury outcomes.

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Traffic characteristics also play a crucial role, with higher traffic and pedestrian volumes often associated with increased crash frequency [7,9,10,12,35]. However, several studies report lower crash rates in high-activity areas, reflecting the "safety-in-numbers" effect [36,37]. Vehicle speed remains one of the risk factors influencing pedestrian crashes and more severe injuries [32,38,39]. Some studies report lower crash frequencies on high-speed roads, likely reflecting reduced pedestrian presence rather than safer conditions [27,40,41]. Similarly, in Ghana, exposure, median, and road shoulder width have been identified as significant risk factors [42,43].

Beyond the broader infrastructure, other studies have examined the effects of spatially targeted specialised contexts, such as Senior Safety Zones (Senior Silver Zones), aimed at enhancing pedestrian safety for elderly people (65 years and older). The effect of these specialised areas has been mixed. Earlier studies found no statistically significant reduction in crash frequency or injury severity among elderly pedestrians, largely due to a spatial mismatch between crash hotspots and the designated silver zones [44,45]. Recently, efforts have been made to address this limitation. For example, ref. [46] developed a safety index for selecting suitable areas for Senior Safety Zones, emphasising the importance of proximity to transit facilities and pedestrian infrastructure, as well as road geometric characteristics, as critical factors for elderly pedestrian safety in such spatially targeted environments.

Improving the selection of Senior Safety Zones yields significant safety benefits for the elderly. A more recent study reported a significant safety benefit of Senior Safety Zones, with a reduction of 30.3% in total pedestrian crashes and 25.3% in elderly pedestrian crashes [47], with greater protection observed in areas with a larger elderly population and high commercial activity. These findings are consistent with recent systematic literature reviews on pedestrian safety in urban transportation systems [48,49], which emphasises that safety interventions should be targeted at areas of high pedestrian concentration, at the heart of the safe system approach, through an inclusive, pedestrian-oriented design. This view is particularly important in bus stop environments, a critical node in the transportation system, with frequent pedestrian–vehicle interactions but relatively under-researched. Understanding how environmental and operational factors are linked to pedestrian crash risk in such locations is therefore critical for informing targeted interventions.

A wide range of approaches has been used for safety analysis, including spatial analysis, statistical methods, and artificial intelligence (AI) techniques, to inform evidence-based interventions. Geographic Information Systems (GIS) have been widely used to identify pedestrian crash hotspots and examine crash clustering patterns, providing valuable insights into high-risk areas and informing targeted interventions. For instance, GIS techniques, such as Getis–Ord GI* and Moran I*, have been utilised to identify pedestrian crash hotspots, prioritise unsafe bus stops, and delineate pedestrian zones [50–52]. The effectiveness of these spatial techniques underscores the importance of applying spatial approaches to examine pedestrian safety in areas of high pedestrian concentration. This is particularly important in bus stop environments, a critical node in the urban transportation system, where pedestrian–vehicle interactions are frequent and require localised safety interventions. Geographically Weighted Regression (GWR) has been utilised to account for spatial non-stationarity [53,54].

Statistical methods have been extensively used to examine the relationship between pedestrian crash risk and the built environment, particularly the Poisson and Negative binomial models to address over-dispersion concerns in crash data [10,12,18]. Statistical models remain pivotal to safety research, providing interpretable estimates of the effects of infrastructure, pedestrian exposure, and environmental factors on pedestrian crash risk.

Recently, machine learning/artificial intelligence techniques have been increasingly applied in pedestrian safety studies, including decision Trees, Random Forests, XGBoost,

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Deep Learning, and Neural Networks, to analyse large and complex datasets and uncover hidden patterns [55–58]. However, traditional approaches remain critical to safety analysis because of their ease of interpretation and direct relevance to policy implementation.

Despite improvements in pedestrian safety research methods, existing studies have largely focused on intersections and midblock crossings, with limited research in other areas, such as bus stops, where pedestrian–vehicle interactions are common. Pedestrian activities, such as boarding/alighting and crossing roads, are frequent in bus stop environments, which elevates crash risk, but are rather understudied [52,59,60]. This gap has consistently been highlighted by systematic reviews of pedestrian safety in urban transportation systems, which emphasise the importance of pedestrian safety at high-activity locations, such as safe pedestrian crossings near transit nodes [48]. Urgent safety strategies are needed to mitigate the situation and promote inclusive and sustainable mobility.

Specific bus stop features have been shown to influence pedestrian safety, although the evidence remains limited. Guardrails have been associated with lower pedestrian crashes, likely due to reduced pedestrian–vehicle conflicts [61]. Similarly, the absence of seating at sheltered stops has been linked to increased crashes, possibly because passengers wait in exposed locations [19], indicating that shelters alone may be insufficient to prevent such incidents.

Exposure is a critical determinant of pedestrian safety at bus stop environments. Higher traffic, pedestrian, and transit volumes increase the likelihood of crashes [16,18]. However, limited attention has been given to diverse pedestrian behaviour common in developing countries.

The surrounding environment also significantly influences pedestrian safety. Evidence on the effects of lighting is mixed, with both crash-reducing and crash-increasing effects reported [16,19]. Infrastructure elements such as wider sidewalks, crosswalks, and medians have demonstrated safety benefits by improving visibility and reducing exposure [16,17,19], particularly in high pedestrian-activity areas.

Despite emerging evidence, four critical gaps remain, particularly relevant to Africa and other developing regions:

1. **Assumed bus stop homogeneity**, overlooking the coexistence of formal and informal stops.
2. **Oversimplified exposure measures** failing to capture diverse pedestrian activities near bus stops.
3. **Limited integration of infrastructure and behaviour**, constraining practical application of findings.
4. **Scarcity of evidence from developing countries**, where infrastructure provision and road user behaviour differ substantially from developed contexts.

Based on the identified gaps, the study addresses the following research questions:

- RQ1: Does bus stop type (formal and informal) influence pedestrian crash occurrence?
- RQ2: How do various components of pedestrian exposure measures (passing, waiting, crossing) relate to crash outcomes in bus stop environments?
- RQ3: How do road design elements affect pedestrian crash frequency in bus stop environments?

Accordingly, the following hypotheses are tested based on the literature and contextual observations in Ghana:

- H1: Informal bus stops are associated with higher crash frequency compared with formal bus stops.
- H2: Higher pedestrian crossing volumes are associated with increased crash frequency.
- H3: Passing and waiting volumes are associated with reduced crash occurrence.

- H4: Wider carriageways and increasing lane counts are related to elevated crash counts.
- H5: The presence of medians is linked to reduced crash occurrence.

These hypotheses are tested using the Negative Binomial regression model in the methodology section.

The study focuses on Kumasi, Ghana's second-largest city, which is burdened by persistent pedestrian injuries. Crash data indicate a concentration of pedestrian crashes at bus stops. Approximately 32.6% (244) of the 782 pedestrian crashes that occurred in Kumasi (2019–2021) occurred within 50 m of bus stop environments [5], highlighting potential safety concerns at such locations.

Addressing these gaps, this study examines the relationship between bus stop environments and pedestrian safety in Kumasi, focusing on diverse exposure measures and infrastructure elements at both formal and informal bus stops. The findings aim to inform safer bus stop design and reduce pedestrian deaths and injuries in Ghana and other Sub-Saharan African countries.

By addressing these gaps, the study aligns with Ghana's road safety initiatives. Ghana has implemented several road safety initiatives over the past three decades to reduce traffic injuries, including Ghana's National Road Safety Strategy IV (2021–2030) [62], led by the National Road Safety Authority. These initiatives align with global efforts such as the United Nations Decade of Action for Road Safety and the Sustainable Development Goals (SDG 3, target 6) [63], which aim to halve fatalities and injuries by 2030. Despite these commitments, pedestrian injuries remain over-represented in crash data, particularly in urban areas such as Kumasi. This highlights the need for localised evidence to inform the implementation of targeted pedestrian safety interventions in high-activity environments such as bus stops.

2. Materials and Methods

This section outlines the data sources and procedure adopted for the study. It provides a detailed description of how primary and secondary data were collected and applied to investigate pedestrian safety around bus stops, with the ultimate goal of guiding safer planning and design of bus stop environments to prevent fatalities and serious injuries. A detailed description of how each step of the study was conducted is provided in the following sub-sections.

2.1. Description of Study Area: Greater Kumasi

The study was conducted in Greater Kumasi, located in the Ashanti Region, one of the current sixteen (16) administrative regions in Ghana [64] (Figure 1). Kumasi is Ghana's second-largest city, comprising six (6) districts, with an estimated population of about 3 million [65]. Its central location and dense road network make it a major commercial and transport hub. Urban mobility is dominated by largely unregulated intra-urban public transport services ("Tro-tro"), with commuters relying extensively on both formal and informal bus stops (Figure 2).

The city experiences a persistently high incidence of pedestrian injuries, indicating substantial vulnerability to pedestrian-related risks. However, existing local studies have primarily focused on intersections and road segments, identifying exposure and road design factors as key risks [42,43]. Rapid urbanisation, increasing motorisation, and population growth are expected to intensify these challenges, with Kumasi's population projected to reach 4.7 million by 2030 [66]. This context underscores the need for a targeted analysis of pedestrian safety in bus stop environments to inform the sustainable planning and design of safer bus stops in Ghana and other Sub-Saharan African cities.

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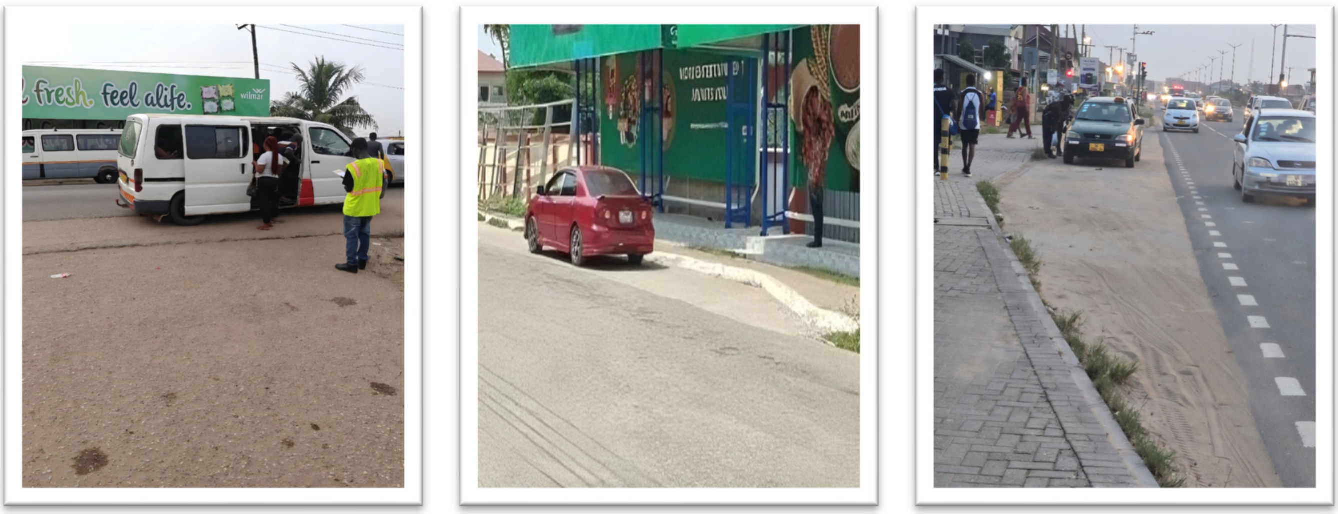
Figure 1. Map of Ghana, showing Kumasi.



Sheltered bus stop | Sheltered bus stop without seats | Bus stop without shelter

Figure 2. Representation of different bus stops in Kumasi, Ghana.

2.2. Data Sources

The data used in this study were obtained from diverse sources, including crash data, bus stop locations, and pedestrian exposure data from field observations.

2.2.1. Crash Data

This study used a three-year crash dataset (2019–2021) obtained from the Traffic and Transportation Division of the Building and Road Research Institute (BRRI), Kumasi, Ghana, the national repository of road crash data. Crash data are collected by the Ghana Police Service using standardised crash report forms, which allow recording of injury severity, crash date and time, road geometric characteristics, vehicle and road user characteristics, and crash location referenced using kilometre posts or nearby landmarks. The BRRI subsequently validates crash data.

Since crash data are referenced by kilometre posts and nearby landmarks rather than GPS coordinates, it was necessary to geocode the data to support the study's objectives, as in other countries such as Spain [25].

A comprehensive dataset of 782 crash events was thoroughly vetted and cleaned to correct misspelled landmark names and expand abbreviations. Eighteen (18) of the crash records lacked landmark information and were therefore excluded from the analysis, leaving 764 records for further examination.

A multi-stage hybrid geocoding approach combining a locally developed Lookup Table (containing GPS coordinates of landmarks), fuzzy matching, external geocoding services (OpenStreetMap Nominatim (version 5.2.0) and Google Maps API (accessed through the Google Maps Python client library (version 4.10.0))), and manual review of unsuccessfully geocoded crash records was implemented (Figure 3). A success rate of 97.91% was achieved, with 95.55% from the Local Lookup Table and fuzzy matching and 2.36% from external geocoding services, indicating reduced reliance on external geocoding sources. The success rate shows that a combination of local knowledge and external geocoding APIs can optimise geocoding results, particularly in developing countries where landmark-based address data is common.

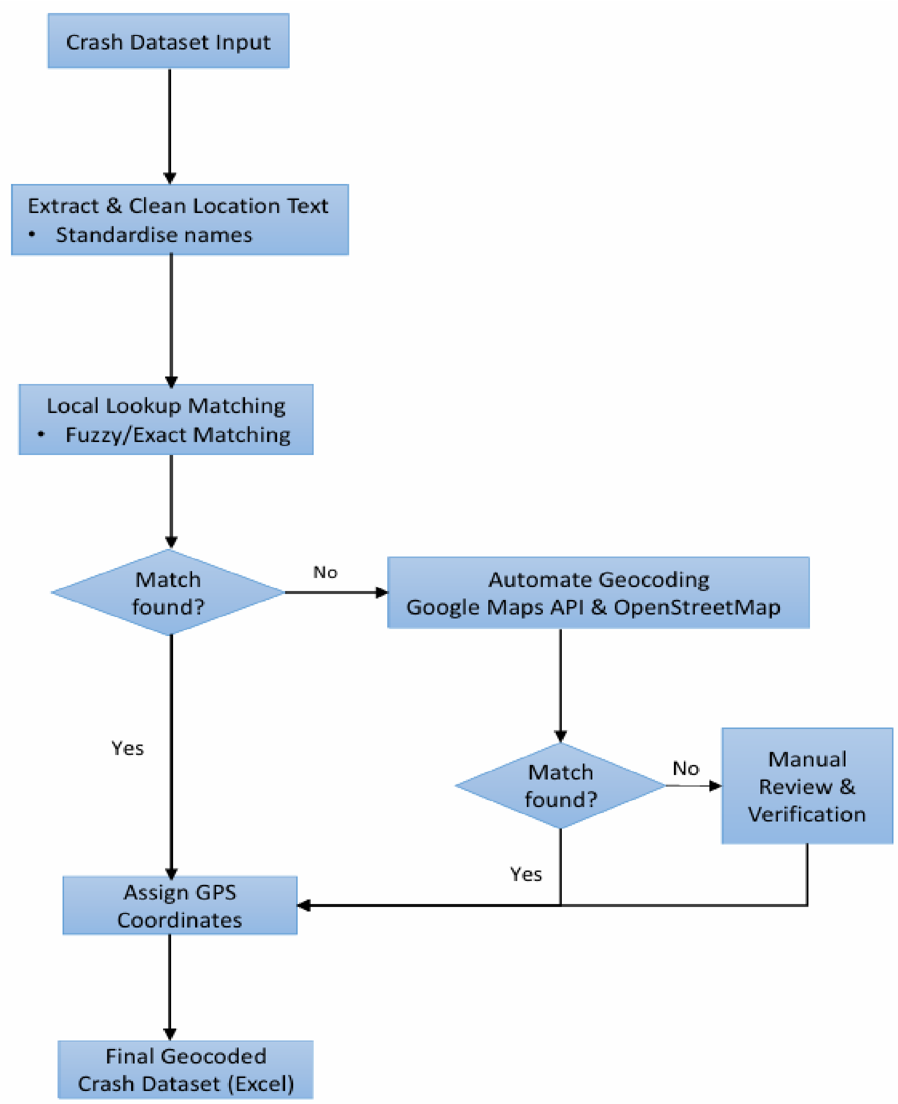


Figure 3. A Multi-tier Hybrid Geocoding Pipeline for Pedestrian Crash Locations.

2.2.2. Bus Stop Location Data

Formal bus stops' location information was obtained from the Ghana Highway Authority, whereas informal bus stops, which are unofficially planned, were identified from the offices of urban transport operators. Both were subsequently validated through site visits. Following [67], field surveys were conducted to map the locations of all identified bus stops using GPS equipment, and to record built environment characteristics (crosswalks, medians, and lane counts) and bus stop design features (seats, shelters, and guardrails). Roads that underwent significant infrastructure modifications during the crash data period (2019–2021) were excluded from the surveys to obviate potential bias in the built environment-safety relationship.

2.2.3. Integration of Crash Data and Bus Stops' Location Data

To examine pedestrian safety around bus stops, crashes, and the built environment, the bus stops were linked to crashes and the built environment using a combination of buffering and spatial join analysis. OpenStreetMap, Ghana's road network map, and crash data were imported into ArcGIS Pro 3.2 and projected onto Ghana's local coordinate system (Leigon/Ghana Metre Grid (EPSG:25000) for accurate distance-based measurement. The spatial distribution of bus stops (black dots) and pedestrian crashes (red dots) in Kumasi is shown in Figure 4.

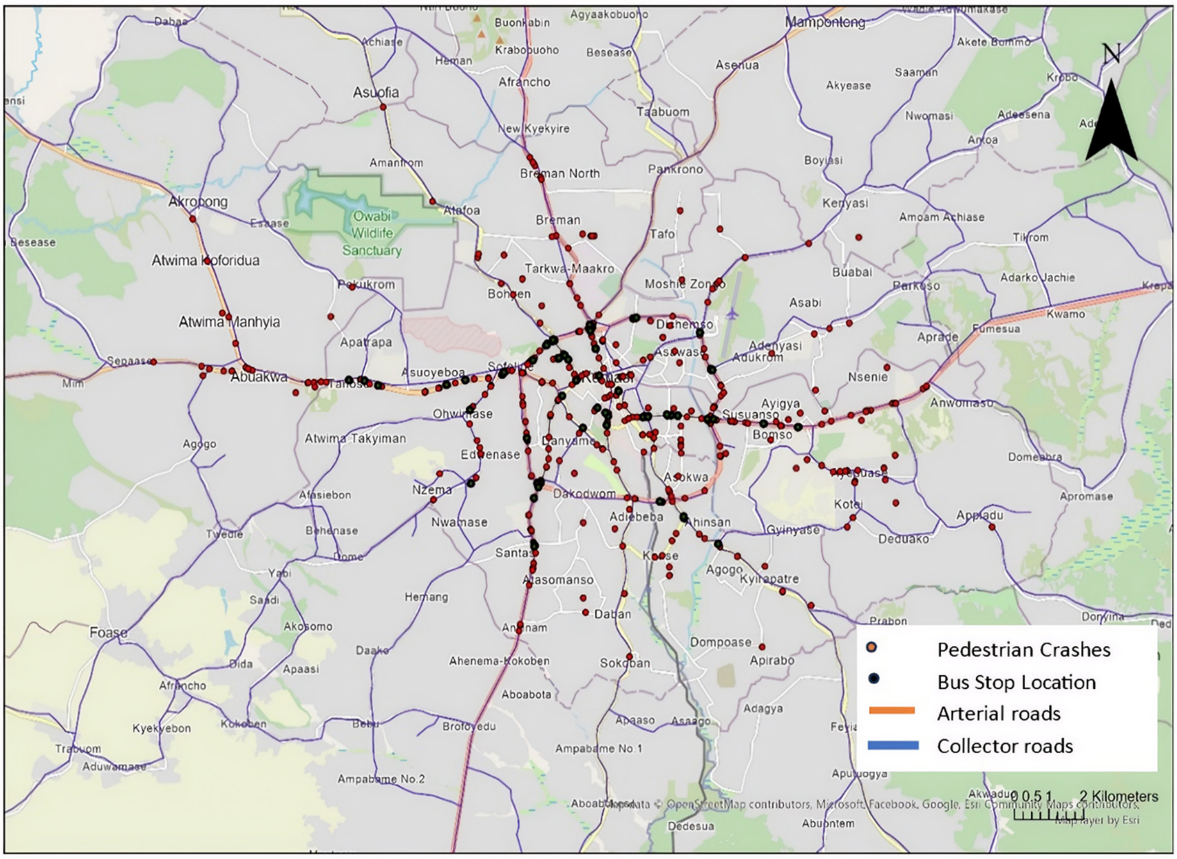


Figure 4. Spatial Distribution of Bus Stop Location and Pedestrian Crashes in Kumasi.

A 50 m buffer radius, based on a typical bus stop length of 60 m and pedestrian–vehicle interactions upstream and downstream of bus stops in Kumasi, was applied to capture pedestrian crashes linked to bus stops. This approach is in sync with earlier studies, which applied buffer radii of 30–100 m, taking into account their unique relative context [16–18,60,68]. After buffering, relevant features within the buffered areas were extracted using a spatial join, resulting in the successful integration of crashes and features within the bus stop environments within the 50 m buffer. This facilitated the subsequent regression analysis.

2.2.4. Pedestrian Exposure Data

Exposure, although critical for safety analysis, is often oversimplified to pedestrian and traffic volumes, density, or transit frequency. This narrow approach neglects diverse pedestrian behaviours around bus stops, such as crossing, walking past, or waiting in traffic-exposed areas, which are common in developing countries like Ghana and may subtly increase risk. Omitting these behaviours can lead to underestimation of risk and ineffective interventions.

In this study, pedestrian exposure at bus stops was defined as individuals: (1) crossing the road at or near the stop, (2) walking past along the shoulder or carriageway, or (3) standing in traffic-exposed areas, including informal waiting locations. Since exposure data were unavailable, observations were conducted manually within a 50-m buffer around each bus stop under clear weather conditions. Data were recorded at one-hour intervals over 12 h (06:00–18:00) on weekdays (Tuesday–Thursday) in May 2025, chosen for stable, representative conditions with good visibility and minimal disruption from events such as school vacations. Multiple trained observers conducted observations based on standardised protocols. To ensure data reliability, an inter-observer reliability test was conducted during the pilot stage. Two trained observers independently observed pedestrian movements using a standardised observation protocol that defined specific classification categories (passing, waiting, and crossing) at fixed observation time intervals. The validation was performed at 30 representative bus stops, making up 48% of the sample, and spanned locations with varying activity levels. The resulting pedestrian counts showed high agreement among observers, yielding a Pearson Correlation Coefficient (R) of 0.98, indicating strong internal consistency.

2.3. Data Analysis

Crash analysis is robustly done using count models. The Poisson regression model has traditionally been used for crash analysis based on the equi-dispersion assumption [12,30]. However, this assumption is often violated in crash data, which frequently exhibits overdispersion [69,70], requiring dispersion-sensitive statistical models for valid inference.

Although more advanced and sophisticated statistical modelling techniques exist, we opted for the Negative Binomial regression model as a relatively straightforward and well-established approach for analysing pedestrian safety at and around bus stops [71,72]. Our primary objective was to better understand the relationships between the identified risk factors and crash occurrence, rather than to push the boundaries of methodological complexity. Using this model also yields clear, interpretable results, which are essential for ensuring practitioners can easily understand the findings and translate them into practical, action-oriented safety recommendations.

The Negative Binomial regression model was used to examine the relationship between pedestrian crashes aggregated at each bus stop and features in the bus stop environments. The aggregated pedestrian crashes defined the dependent variable and features in the bus stop environments, as well as the independent variables. The independent variables used in the regression modelling were categorised into three groups as follows:

- Road design: median, crosswalks, lane count;
- Bus stop characteristics: formal and informal; and
- Exposure: waiting, passing, and crossing pedestrians.

The following variables were initially examined during field surveys for potential inclusion in the analysis: bus stop features (e.g., shelters and seating), bus stop facility type (bus-bays versus curbside), road geometric characteristics, and stopping position. However, these variables were later excluded due to insufficient variability and explanatory power.

For instance, most bus stop features observed during site visits lacked shelters and seating. In addition, bus stops in Kumasi are generally designed as bus-bay facilities rather than curbside stops. Additional roadway geometric characteristics, including curb geometry and stopping position, were systematically assessed during field surveys. However, these variables were excluded from the analysis because they exhibited negligible variation across bus stop locations and, therefore, could not contribute meaningful explanatory power to the model. Excluding variables with minimal variation ensures that the analysis emphasizes characteristics that can meaningfully explain differences in pedestrian crash risk and informs actionable design interventions.

The various variables included in the regression model, along with their corresponding definitions and sources, are provided in Table 2.

Table 2. Variables used in the Negative Binomial Regression Modelling.

Variable Type	Variable Name	Description/ Measurement	Data Source/Method	Statistic/Distribution
Dependent variable	Pedestrian crash counts	Number of pedestrian crashes within a buffer radius of 50 m at each bus stop (continuous)	Police data (BRRI, Ghana).	Mean = 3.7 (Min = 0, Max = 22)
		Independent variables		
Road Design	Lane count	Number of lanes along a road segment near bus stops (continuous)	Field survey	Mean = 3.8 (Min = 2, Max = 6)
	Median presence	Presence of medians around bus stops (categorical) (1 = yes, 0 = no)	Field survey	Yes: 46 (74.2%) No: 16 (25.8%)
	Crosswalk presence	Presence of crosswalks around bus stops (categorical) (1 = yes, 0 = no)	Field survey	Yes: 10 (16.1%) No: 52 (83.9%)
Bus Stop Characteristics	Bus stop type	Formal and informal (categorical) (Formal = 1 and informal = 0)	Field survey	Formal: 40 (64.5%) Informal: 22 (35.5%)
Pedestrian Exposure	Waiting pedestrian	Number of pedestrians waiting at the bus stops (continuous)	Manual counts	Mean = 250.0 (Min = 51, Max = 588)
	Passing pedestrians	Number of pedestrians passing near the bus stops (continuous)	Manual counts	Mean = 2078.0 (Min = 161, Max = 5389)
	Crossing pedestrians	Number of pedestrians crossing near the bus stops (continuous)	Manual counts	Mean = 545.0 (Min = 134, Max = 1609)

Before model fitting, multicollinearity among the independent variables was assessed using the variance inflation factor (VIF). All variables had VIF values below 5, indicating no significant multicollinearity [73,74]. Moreover, crash data exhibited mild overdispersion (1.20), justifying the use of the Negative Binomial regression model.

The model's outputs included coefficients, *p*-values, and 95% confidence intervals, with predictors considered significant at $p < 0.05$. These results informed subsequent analysis, providing insights into pedestrian safety and potential countermeasures in bus stop environments.

3. Results

This section presents the results of the Negative Binomial regression modelling that examined pedestrian crashes around bus stops as a function of three groups of independent variables: bus stop characteristics, road design features, and pedestrian exposure.

The regression results provide parameter estimates that shed light on the strength, direction, and statistical significance of the relationship between pedestrian crashes and the independent variables. To aid interpretation, the results are presented as Incident Rate Ratios (IRRs), obtained by exponentiating the model coefficients. The IRR represents the multiplicative change in the expected count of pedestrian crashes for a one-unit increase in the corresponding predictor. An IRR greater than 1 indicates an increase in the expected crash count, while an IRR less than 1 indicates a decrease. Table 3 provides details of the results.

Table 3. The Negative Binomial Regression Results for Pedestrian Crashes at Bus Stops in Kumasi.

Variable	Variable Type	Coefficient Estimate	Standard Error	*Z*	*p*-Value	IRR (exp(β))	95% Confidence Interval for IRR	
							Lower	Upper
Intercept		−7.2961	2.165	−3.371	0.001	0.0007	0.0000	0.0472
Median	Categorical (1 = present, 0 = absent)	−1.3253	0.536	−2.471	0.013	0.2657	0.0929	0.7601
Crosswalk	Categorical (1 = present, 0 = absent)	−0.2665	0.446	−0.598	0.550	0.7661	0.3199	1.8344
Lane count	Continuous	0.3290	0.193	1.709	0.088	1.3895	0.9527	2.0266
Bus Stop type	Categorical (Formal = 1 informal = 0)	0.3776	0.355	1.063	0.288	1.4588	0.7270	2.9275
Ln_Waiting pedestrians	Continuous	0.7677	0.350	2.194	0.028	2.1548	1.0853	4.2783
Ln_Passing pedestrians	Continuous	0.7109	0.315	2.258	0.024	2.0357	1.0984	3.7731
Ln_Crossing pedestrians	Continuous	−0.2483	0.444	−0.559	0.576	0.7802	0.3268	1.8624

The findings indicate that bus stop characteristics, road design features, and pedestrian exposure influence pedestrian safety in bus stop environments.

The study examined the relative risk of formal and informal bus stops, analysing 62 bus stops, comprising 40 (67%) formal and 22 (33%) informal. Formal bus stops were associated with a 45.9% increase in pedestrian crashes compared with informal bus stops, though the difference was not statistically significant (IRR = 1.4588, *p*-value = 0.288).

Bus stop road design features were then analysed. Each increase in lane count near bus stops was associated with a 40% increase in pedestrian crashes (IRR = 1.3895, *p*-value = 0.088), although the association was statistically marginal. Raised medians, in contrast, were significantly associated with a 73% reduction in crash incidence around bus stops (IRR = 0.2657, *p*-value = 0.013). Similarly, the presence of crosswalks was associated with a 23.4% reduction in crashes at bus stops (IRR = 0.7661, *p*-value = 0.550), although this difference was not statistically significant.

Finally, pedestrian exposure measures were examined. Higher levels of passing pedestrian activity were significantly associated with a higher incidence of crashes in bus stop environments (IRR = 2.0357, *p*-value = 0.020). A proportional increase in waiting activity at traffic-exposed areas was associated with an increased crash incidence (IRR = 2.1548, *p*-value = 0.024). In contrast, higher pedestrian crossing activity was associated with fewer pedestrian crashes. However, the association was not statistically significant (IRR = 0.7820, *p*-value = 0.576).

To assess the robustness of these findings, an extended model including traffic volume as an additional exposure variable was estimated (Table S1, Supplementary Materials). Traffic volume is positively and marginally significantly associated with pedestrian crash risk. However, its inclusion does not materially change the direction, magnitude, or statistical significance of the key explanatory variables, particularly the pedestrian exposure measures and the geometric characteristics of bus stop environments. Minor changes observed in some roadway variables are likely due to shared variance with traffic flow.

This supplementary analysis confirms that the main findings are robust while maintaining the primary model's focus on actionable design-related factors, consistent with the study's exploratory and intervention-oriented objectives. The lane count variable remains in the main model as a structural roadway characteristic reflecting broader operational context, rather than as a substitute for traffic exposure.

Together, the findings indicate that the combined effect of infrastructural and behavioural factors influences pedestrian safety in bus environments in Kumasi. While road design features, such as medians, showed significant safety benefits, unsafe pedestrian activity, such as passing near bus stops, increased crash risks.

4. Discussion

Pedestrian safety concerns in Kumasi motivated this study to examine pedestrian safety conditions near bus stops.

Previous studies have often treated bus stops as a homogeneous entity [16–19]. It was observed that formal bus stops were associated with a higher number of crashes than informal bus stops, although the difference was not statistically significant. The lack of statistical significance may stem from the limited sample size, particularly the small number of informal bus stops (22), limiting statistical power. Additionally, the effect of bus stop type may interact with other variables, such as road design features, temporal conditions, and traffic characteristics, warranting further investigations with a larger dataset. To the best of our knowledge, this is the first study to examine this distinction, and the disaggregation is worthwhile as formal and informal bus stops pose distinct risks that can guide context-specific interventions.

Several contextual factors may explain this observation. In Ghana, formal bus stops are delineated by raised platforms, located along high-speed arterial and collector roads, and placed in areas of high pedestrian concentration, thereby attracting large passenger volumes. In contrast, informal bus stops serve lower-demand areas and attract fewer passengers. A higher number of passengers at formal bus stops may increase exposure and contribute to the elevated pedestrian crashes observed there. These findings highlight the importance of design and infrastructure improvements for effectively managing the high pedestrian concentration at high-demand bus stops. In addition, the observed trend may be linked to risk adaptation theory [75], which suggests that a higher level of perceived safety associated with formal bus stops may influence pedestrians and drivers to modify their behaviours in many ways that offset the expected safety gains. Together, these perspectives may explain the observed safety pattern associated with bus stop environments.

Road design elements were also associated with pedestrian crash risk. The effect of carriageway width on pedestrian safety has received considerable attention in the literature, but remains understudied near bus stops. Higher crash rates were observed near bus stops with wider carriageways, although the relationship was marginally significant. This finding is consistent with broader pedestrian safety studies that report adverse effects of wider carriageways on pedestrian safety [10,22]. This suggests that the adverse effects of carriageway width may not be limited to intersections and midblock crossings but persist in bus stop environments.

Pedestrians take longer to cross wider carriageways. High traffic volumes and vehicle speeds on wider carriageways, combined with longer exposure times, increase the risk of crashes [9,35]. Therefore, road expansion projects near bus stops can increase crash risk, underscoring the role of exposure and vehicle speed in shaping pedestrian safety.

Medians enhanced pedestrian safety near bus stops. Similar findings have been observed in general safety studies [7,11,22]. Emerging studies on pedestrian safety near bus stops also confirm these findings [16,17]. Medians, by providing refuge areas for pedestrians during two-stage crossings, minimise exposure to traffic and pedestrian–vehicle conflict, highlighting their relevance to pedestrian safety improvement strategies, particularly in areas of high pedestrian concentration.

Crosswalks were associated with lower crash rates, although the difference was not statistically significant. The lack of statistical significance may be due to the relatively small number of crosswalks observed near bus stops, which reduces statistical power. Nonetheless, the findings suggest potential safety benefits of visible crosswalks in areas with high pedestrian traffic.

This observation is supported by broader safety studies, despite their limitations [33,76,77], and is also confirmed by bus stop-specific studies [16,17,19]. Crosswalks enhance pedestrian visibility and driver awareness, improving speed limit compliance and driver yielding rates, consequently minimising pedestrian–vehicle conflicts [78–80]. Given their cost-effectiveness, they are ideal for resource-constrained countries like Ghana [76,78].

Disaggregated pedestrian exposure measures influence crash risk, highlighting distinct crash risks and demonstrating a novel and valuable analytical approach. Passing pedestrians were at a higher crash risk, a finding consistent with evidence that increased walking frequency increases crash risk [81,82]. In Ghana, the regular use of pedestrian road shoulders and driver shoulder running to minimise rush-hour travel delays, although illegal [83,84], undermines the safety of passing pedestrians near bus stops [85]. Collectively, infrastructure conditions and driver behaviour influence pedestrian safety near bus stops.

Pedestrians waiting were also at significant risk near bus stops. This finding suggests that exposure is not exclusively mobility-related, such as walking in road environments, but may also emanate from immobility-related activities, a dimension rarely discussed in pedestrian safety analysis. The lack of seats and waiting areas compels pedestrians to wait for buses in traffic-exposed areas during peak times. Delays due to unscheduled intra-urban transport in Ghana and many other developing countries [86–88] heighten exposure in terms of duration and proximity, increasing pedestrian vulnerability. Taken together, bus stop design shapes play a critical role in shaping pedestrian safety around bus stops.

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Crossing pedestrians was associated with fewer crashes, although the association was statistically insignificant. This finding contrasts with general pedestrian safety studies, which have observed an increase in crashes associated with increased pedestrian crossing activity [9,12]. However, it aligns with other studies reporting an inverse relationship [36,37]. In Ghana, pedestrians often cross roads at traffic interruptions when there are no crosswalks along their desired paths. Slow-moving or momentarily stopped traffic due to alighting/boarding near bus stops enables pedestrians to employ an adaptive safety strategy by altering their crossing behaviour to find safe gaps in traffic and cross, thereby reducing crash risk.

Although this study focuses on Kumasi, the analytical framework adopted provides a transferable approach for assessing pedestrian safety at bus stops. By integrating pedestrian crash data with detailed bus stop environmental characteristics and disaggregated pedestrian exposure measures (e.g., passing, waiting, and crossing), the approach enables systematic identification of risk factors associated with public transport stop environments. These elements are not unique to Kumasi and can be adapted to other urban contexts where pedestrian activity interacts with public transport operations. Consequently, the proposed approach offers a practical framework to support safety assessments and infrastructure planning around bus stops in other cities, particularly in rapidly urbanising areas with similar pedestrian and public transport dynamics.

5. Practical Implications

Based on the analysis of pedestrian safety conditions near bus stops, the following are implications for pedestrian safety improvements. The analysis revealed that space utilisation is a critical risk factor, with waiting and passing pedestrians being the most vulnerable. Road agencies should prioritise developing safer bus stop environments by providing adequate waiting areas with guardrails and wider, obstruction-free sidewalks to reduce pedestrian exposure.

The analysis also revealed that an adaptive safe crossing strategy often emerged from natural traffic-calming conditions, providing insights into an effective strategy for enhancing pedestrian safety. Engineering-based traffic-calming measures, through design and operational strategies, should be implemented to maintain a maximum safe operating speed of 30 km/h, in accordance with the Safe System Principle.

Additionally, raised medians provided safe crossing opportunities around bus stops with wider carriageways. Clearly marked crossing facilities, medians, and raised pedestrian crossings will therefore be critical for pedestrian safety in areas with high exposure levels.

New insights emerged from exposure disaggregation, with different exposure measures exhibiting diverse crash risks. These non-traditional findings underscore the importance of incorporating exposure diversity in future safety analysis and long-term infrastructure planning to avoid potential risk underestimation and ineffective countermeasures.

Finally, formal bus stops present high-risk sites for pedestrians. Design and infrastructure improvements that effectively handle high pedestrian volumes, such as wide, continuous sidewalks, shelters, and staggered waiting areas, should be prioritised to limit pedestrian–vehicle conflicts. Additionally, an integrated transport planning and community engagement programme should be pursued to better regulate the siting and growth of informal bus stops, ensuring a balance between public transport accessibility and safety.

6. Limitations and Future Research

The study has some limitations. For instance, although the study incorporated disaggregated pedestrian exposure measures, it did not capture pedestrian–vehicle interactions and behavioural patterns such as jaywalking, which may compromise pedestrian safety in their entirety. Furthermore, the condition of infrastructure features such as crosswalks, sidewalks, and the visibility of bus stops, which are critical to safety conditions around bus stops, was not analysed in the study.

In view of these limitations, future studies should consider applying observational approaches, such as the traffic conflict technique, to capture pedestrian–vehicle interactions and pedestrian behaviours, including jaywalking and other risky behaviours, alongside assessments of infrastructure conditions to provide an in-depth understanding of pedestrian safety concerns in bus stop environments. Such evidence will be instrumental in planning and designing bus stop environments that promote pedestrian safety and sustainable mobility.

One important limitation of this study is the lack of temporal resolution in the crash data. Although pedestrian observations were conducted at multiple times of day, the crash records were aggregated and lacked time-specific information. Because boarding and alighting activities around bus stops are inherently time-dependent, this limits the ability to capture temporal variations in pedestrian crash risk. Future research should use temporally disaggregated crash data to more accurately assess the effect of time-dependent operational factors.

Apart from the aforementioned limitations, there are contextual limitations. Since the study focused on pedestrian safety near bus stops in Kumasi, Ghana, findings apply to other urban areas in Ghana and developing countries with similar contexts, particularly Sub-Saharan Africa. However, the findings may not be generalisable to contexts that differ in pedestrian behaviour, transport systems, or enforcement.

Crash data quality is another limitation worth noting. The study is based on police-recorded crash data, which often suffer from underreporting, particularly of slight-injury crashes, and may affect pedestrian crash risk estimates near bus stops. Future studies should consider integrating crash records with hospital data to enhance data quality.

7. Conclusions

This study investigated the relationship between pedestrian exposure measures, road design, bus stop characteristics, and pedestrian safety in Kumasi, an area with a high incidence of pedestrian fatalities in Ghana. To the best of our knowledge, this study presents one of the most detailed analyses of pedestrian safety in bus stop environments in developing countries, specifically Sub-Saharan Africa. The study integrated surrounding environmental elements, diverse pedestrian exposure measures, road design features, and bus stop characteristics, demonstrating that interactions among infrastructure, bus stop characteristics, traffic conditions, and pedestrian behaviour influence pedestrian safety near bus stops.

The effect of the interactions is evident in the observed safety outcomes. Wider carriageways near bus stops pose a significant risk to pedestrians, whereas raised medians mitigate this risk by reducing the frequency of pedestrian–vehicle interactions. Improved pedestrian infrastructure and exposure-reducing strategies are therefore critical near bus stops.

The disaggregation of pedestrian exposure into walking, waiting, and passing pedestrians yielded mixed findings. Heightened exposure and inadequate protection for pedestrians near bus stops increased the risk for waiting pedestrians and passing pedestrians. Interestingly, crossing pedestrians were associated with lower crash risk due to reduced exposure to traffic and adaptive crossing behaviour. All these emphasise and support the importance of exposure heterogeneity and the relevance of exposure disaggregation for robust safety analysis.

Taken together, pedestrian safety near bus stops is shaped by infrastructure and behavioural factors. Passing and waiting pedestrians, formal bus stops, and wide carriageways were associated with increased crashes. In contrast, the presence of medians, crosswalks, and adaptive crossing behaviour was associated with reduced crashes. These findings highlight the importance of exposure-reducing and visibility-enhancing interventions to minimise pedestrian–vehicle conflicts, underscoring the need for context-specific bus stop design within an integrated transport system that accounts for surrounding environmental features to support pedestrian safety and sustainable urban mobility.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18073437/s1, Table S1: Negative Binomial Model Including and Excluding Traffic Volume.

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