

Article

Investigating the Relationship Between Built Environment Characteristics and Pedestrian Risk Perception: A Comparative Analysis Across Urban Contexts

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Abstract

Understanding the built environment is essential for explaining road safety outcomes, particularly through individuals' perceptions of their surroundings, which are linked to perceived travel risk and play an important role in pedestrian decision-making. However, the heterogeneous effects of the built environment across contexts remain insufficiently understood and require further investigation. Thus, this study aims to investigate how perceived built environment attributes are associated with perceived travel risk and whether these associations differ across urban contexts, with specific variation in land-use contexts. Data were collected using questionnaires administered at pedestrian crossings in Bangkok, and ordinal regression was employed for the analysis. The results indicate that some factors are consistently significant across contexts, while others show significance in specific contexts. In particular, land use mix as diversity and traffic speed are among the variables that are consistently significant across multiple contexts. Overall, the findings suggest variation in the patterns of association between built environment attributes and perceived travel risk across contexts. These results provide useful insights for urban and transport planners regarding the role of environmental design and allocation in promoting safer pedestrian environments, thereby contributing to the development of a sustainable transport system by enhancing pedestrian safety and prioritizing pedestrians in planning.

Keywords: active transportation; built environment; pedestrian crossing; pedestrian safety



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1. Introduction

Pedestrian safety remains a persistent challenge in urban and transportation planning. Pedestrians account for approximately 21 percent of all road traffic fatalities worldwide. Although many regions have experienced a decline in pedestrian deaths compared with 2013, pedestrian fatalities in Southeast Asia have continued to increase [1]. This suggests that pedestrian safety remains a serious concern and requires further research. Pedestrian safety management not only helps reduce fatalities and injuries but also contributes to the development of sustainable transportation systems by prioritizing safe and inclusive environments for pedestrians. The built environment has been recognized as a critical determinant of pedestrian safety [2–4], as walking is a mode of transportation that is closely associated with its surrounding environment [5,6]. The characteristics of the environments through which pedestrians travel play a significant role in shaping activity

patterns, decision making of pedestrians and travel behavior [7,8]. Moreover, previous studies have shown that the built environment has a substantial impact on pedestrian safety. Built environment characteristics are multifaceted, encompassing factors such as land use patterns, pedestrian infrastructure, public transit facilities, and road characteristics [4,6,9]. Therefore, understanding the influence of built environment factors on road safety is crucial for urban and transportation planning aimed at creating safer walking environments. Improving pedestrian safety can also help address public health concerns associated with road traffic injuries. Previous studies have extensively examined the relationship between built environment characteristics and pedestrian safety outcomes. Existing studies have primarily emphasized objective environmental features [3,4,6,10]. However, some studies suggest that subjective perceptions of individuals regarding the built environment also play an important role in shaping safety outcomes for travelers [11]. This relationship is often mediated by pedestrians' perceptions of the walking environment, linking built environment characteristics to the decision-making of pedestrians [8]. This may ultimately influence behavioral and safety outcomes in travel.

However, the influence of the built environment on safety outcomes is heterogeneous across different contexts, reflecting the context-dependent effect [12,13]. Accordingly, examining such spatial heterogeneity in the effects of built environment factors remains an important research gap, indicating the need for further investigation. Although some studies have considered contextual variations in these effects, including behavioral contexts [13], locations [14], temporal and spatial contexts [15,16], land-use contexts [17,18], urban settings [19], and variations across states and regions [20,21]. For urban context studies, previous research has primarily focused on differences between urban, suburban, and rural areas [14,19]. In contrast, studies examining variations in effects across land-use contexts remain limited. Existing literature has mainly emphasized differences between residential and commercial areas [17] or mixed-use environments [22]. The heterogeneity of land-use patterns is evident, reflecting differences in activity characteristics and road users. However, understanding of the contextual differences in these land-use characteristics remains limited in terms of pedestrian safety outcomes. To fill this gap, this study examines whether the relationships between perceived built environment attributes and perceived travel risk vary across different land-use contexts. This approach provides important insights into the relationships linking physical environmental characteristics with travel risk perception under spatially varying contexts.

2. Literature Review

2.1. *The Interplay Between Built Environment, Perception and Travel Risk*

The built environment is closely associated with walking behavior and plays an important role in supporting active travel [7,8]. Built environments that are accessible, supported by appropriate infrastructure, and provide safe conditions for use are more likely to facilitate walking among individuals. Accordingly, most previous studies have focused on objectively measuring built environment attributes and examining their associations with walking behavior and road safety outcomes [4,6,10]. Within this body of literature, some studies have suggested that objective measures are more reliable than subjective measures [23], given their ability to capture relatively stable environmental characteristics. However, individuals do not always respond directly to objectively measured environmental conditions. Rather, their responses are often shaped by how they perceive and interpret their surroundings. Consequently, objective and subjective (perceived) measures may capture different facets of the same environment [24–26]. Given that individuals often respond to perceived rather than objective environmental conditions. Some studies have indicated that perception-based measures may be more influential than objective measures

in understanding responses of individuals to their environments. This is particularly evident in studies examining environment-related behaviors such as walking, cycling, and physical activity [27–29]. Importantly, previous research has highlighted the importance of perceptions of the built environment in influencing safety-related outcomes among pedestrians [11,30]. Although previous studies have demonstrated associations between perceived built environment attributes and travel-related behaviors, the present study shifts its focus to perceived travel risk. Perceived travel risk represents an important psychological construct through which individuals evaluate and interpret environmental conditions, and it may influence subsequent behavioral responses. In studies of pedestrian perceived travel risk, risk is understood as reflecting how individuals assess potential danger within the travel environment. The characteristics of the walking environment are considered an important determinant of risk perception because they constitute the physical setting in which pedestrian travel occurs. Measures of perceived built environment vary across studies and research contexts. For example, some studies have examined perceived environmental qualities, such as perceived safety, comfort, accessibility, and esthetics [18,31–33], whereas others have focused on perceived built environment attributes, including perceived street connectivity, land-use mix, signage and road markings, traffic-calming measures, and road surface quality [27,34].

With regard to perceived built environment attributes, these represent subjective assessments of physical environmental characteristics and may influence perceived travel risk and related decision-making. Given the mixed findings reported in previous studies and the growing recognition that individuals' perceptions of their surroundings play a critical role in shaping pedestrian activities and travel decisions, this study focuses on examining relationships within the context of individual perceptions. In particular, it examines the association between perceived built environment attributes and perceived travel risk.

2.2. Built Environment and Perceived Travel Risk: A Review of Contextual Variations

Previous studies have consistently highlighted that the effects of the built environment on traffic safety vary across spatial contexts, reflecting the spatial heterogeneity of built environment influences [12,13,20,35]. Perceived travel risk refers to the assessment of potential danger within a given travel environment by an individual. It has been widely recognized as an important mechanism for explaining safety outcomes and travel-related behaviors. While perceived risk may not always align with objective measures of risk, it remains an important consideration in safety research because individuals typically react to their own perceptions of safety when making travel-related decisions and behaviors [36,37]. However, such perceptions do not arise independently. Instead, they come from how individuals perceive and interpret their surrounding environment. This is particularly relevant in the context of walking, a travel mode that is closely associated with the built environment. Previous studies have shown that walking environments influence the perceptions of pedestrians regarding environmental qualities, such as safety and attractiveness [18]. Nevertheless, as noted earlier, the effects of the built environment are not uniform across spatial contexts. Some studies have attempted to examine environmental influences under different contextual settings. However, investigations that consider variations in land-use contexts remain limited. Existing research has primarily focused on residential, commercial areas and mixed-use settings [17,18,22,38].

Given the inconsistent findings reported in previous studies and the limited consideration of diverse land-use contexts. Therefore, further investigation is needed to examine how built environment perceptions influence perceived travel risk across different spatial settings. Such an understanding is important for pedestrian safety research, particularly

because recognizing the complex interactions between environmental conditions and human perceptions is a fundamental prerequisite for designing environments that support safe travel.

3. Materials and Methods

3.1. Study Setting

This quantitative study was conducted in Bangkok, Thailand, the capital city of the country, where urban development activities are highly concentrated due to intensive land-use patterns and extensive infrastructure development (Figure 1). Promoting pedestrian safety remains a key concern in Bangkok. Bangkok exhibits substantial variation in built environment characteristics, with previous studies indicating a high density of road networks in the central area of Bangkok [39]. Furthermore, pedestrian safety remains an important issue, based on statistics on pedestrian injuries and fatalities from road traffic crashes in Bangkok during 2020–2024 [40]. The data show that the number of fatalities decreased to 62 cases in 2024, but the number of injuries remained high at 4477 cases. The occurrence of pedestrian injuries and fatalities indicates that road traffic crashes continue to be a concern for pedestrian safety. Therefore, this study selected Bangkok as the study area because, besides pedestrian safety issues, the diverse characteristics of the city can reflect variations in spatial contexts.

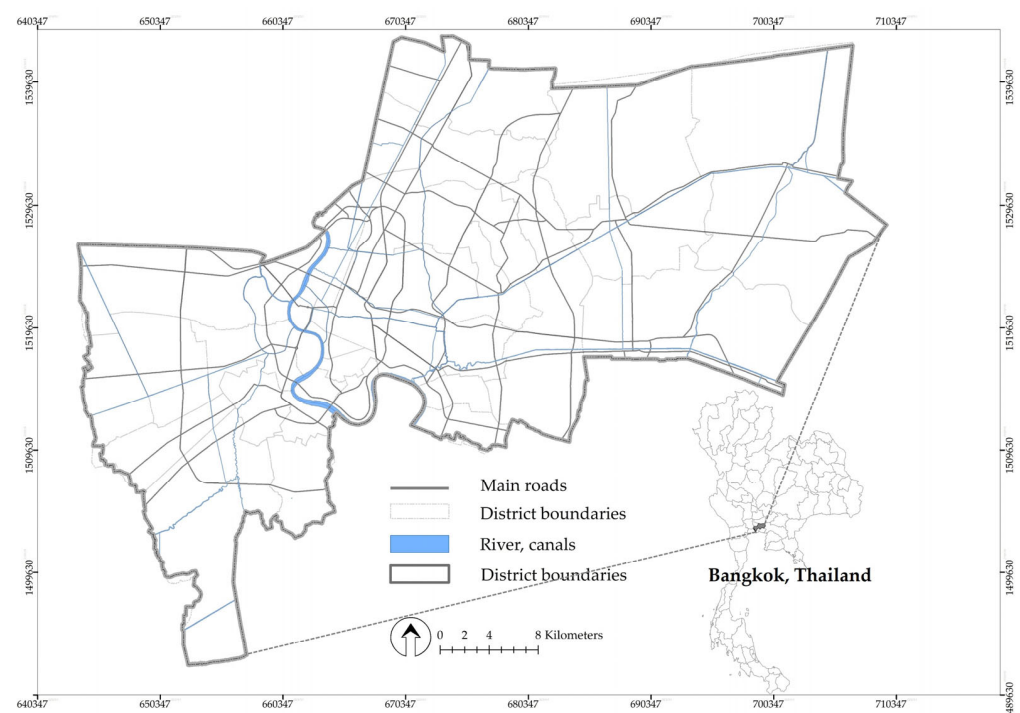


Figure 1. Study area.

In recent years, several initiatives have been undertaken to improve pedestrian crossings and sidewalks in order to facilitate walking that is convenient, connected, accessible, and safe. Nevertheless, pedestrian-related traffic crashes remain a persistent concern, highlighting the need for continued safety interventions due to their significant contribution to injuries and fatalities in the population. This study investigates how the relationships between perceived built environment attributes and perceived travel risk vary across different land-use contexts. Particular attention is given to signalized pedestrian crossings, which are widely regarded as an effective measure for improving pedestrian safety. By clearly allocating right-of-way to pedestrians and regulating interactions with vehicular

traffic, signalized crossings can reduce pedestrian–vehicle conflicts. Nevertheless, safety problems at pedestrian crossings continue to persist, highlighting the important interplay between the physical environment and pedestrian behavior. Although signalized pedestrian crossings are designed to improve safety, their effectiveness may also be influenced by the decisions made by road users [41–43].

3.2. Data Collection and Measurements

A questionnaire survey will be employed to collect data on perceived built environment attributes, perceived travel risk, and socioeconomic characteristics of individuals. The variables related to perceived built environment and perceived travel risk were developed and adapted based on a review of previous studies examining the relationships between the built environment and road safety. The perceived built environment variables were categorized into four main dimensions: road infrastructure and facilities (e.g., street/crosswalk width and pavement quality), pedestrian infrastructure and facilities (e.g., crossing visibility and crossing suitability), land use and planning (e.g., land use mix as diversity and population density), and traffic characteristics (e.g., pedestrian volume and crossing volume) [4,10,14,41–46]. Participants were asked to rate their perceived level of the physical environment. The questions were organized according to specific environmental factors, with each factor being assessed separately. Respondents' perceptions of the built environment at signalized pedestrian crossings were measured using a five-point Likert scale ranging from 1 (lowest level) to 5 (highest level). In addition, perceived travel risk was measured using items capturing respondents' perceptions of overall travel risk related to the likelihood of accidents. These items were also assessed using a Likert scale ranging from 1 (lowest level) to 3 (highest level). Data were collected through on-site questionnaire surveys at signalized pedestrian crossings. To account for differences in crossing contexts, the survey locations were classified into three land-use categories: residential areas, commercial areas, and vulnerable areas, including schools and hospitals. Data collection was carried out through face-to-face interviews with pedestrians selected using purposive sampling. Prior to participation, individuals were provided with information regarding the study objectives, procedures, potential benefits, anonymity, and their rights as participants, including the right to withdraw at any time. Individuals who verbally agreed to participate were subsequently invited to complete the questionnaire. Finally, a total of 384 valid questionnaires were included in the analysis, consisting of 96 questionnaires from residential areas, 96 questionnaires from commercial areas, and 192 questionnaires from sensitive areas (educational and healthcare settings), with 96 questionnaires collected from each sub-area. Additionally, this study was approved by the Human Research Ethics Committee of Thammasat University Social Sciences (Approval No. 063/2568) and all procedures adhered to established ethical guidelines.

3.3. Statistical Methods

Recent studies examining the effects of the built environment have generally assumed spatial uniformity, implying that the relationships between built environment characteristics and safety outcomes are consistent across different spatial contexts. However, an increasing body of literature has demonstrated that these relationships exhibit spatial heterogeneity, with the effects of built environment characteristics varying across locations. Such variations have been observed in a range of safety outcomes, including perceived risk, pedestrian–vehicle crash occurrence, and crash severity. Building upon the concept of spatial heterogeneity, the present study extends previous research by incorporating a broader range of land-use contexts, including residential areas, commercial areas, and sensitive areas such as education and healthcare. While previous studies have primarily

focused on conventional residential and commercial environments, this study explicitly considers sensitive contexts where pedestrian safety is of particular concern. This broader contextual framework represents an important contribution by providing a more comprehensive understanding of how the influence of built environment characteristics on pedestrians' perceived travel risk varies across different urban contexts. To examine these spatial variations, ordinal regression analysis was applied to evaluate the relationships between perceived built environment characteristics and pedestrian travel risk. Thus, three analytical frameworks were considered based on different spatial contexts. All analyses included the same set of explanatory variables, comprising perceived built environment attributes as the primary explanatory variables, along with socio-demographic characteristics, conformity traits, behavioral and experiential factors as control variables (Figure 2). The analyses differed only in the spatial context under investigation, namely residential areas (Model 1), commercial areas (Model 2), and sensitive areas, including educational and healthcare settings (Model 3).

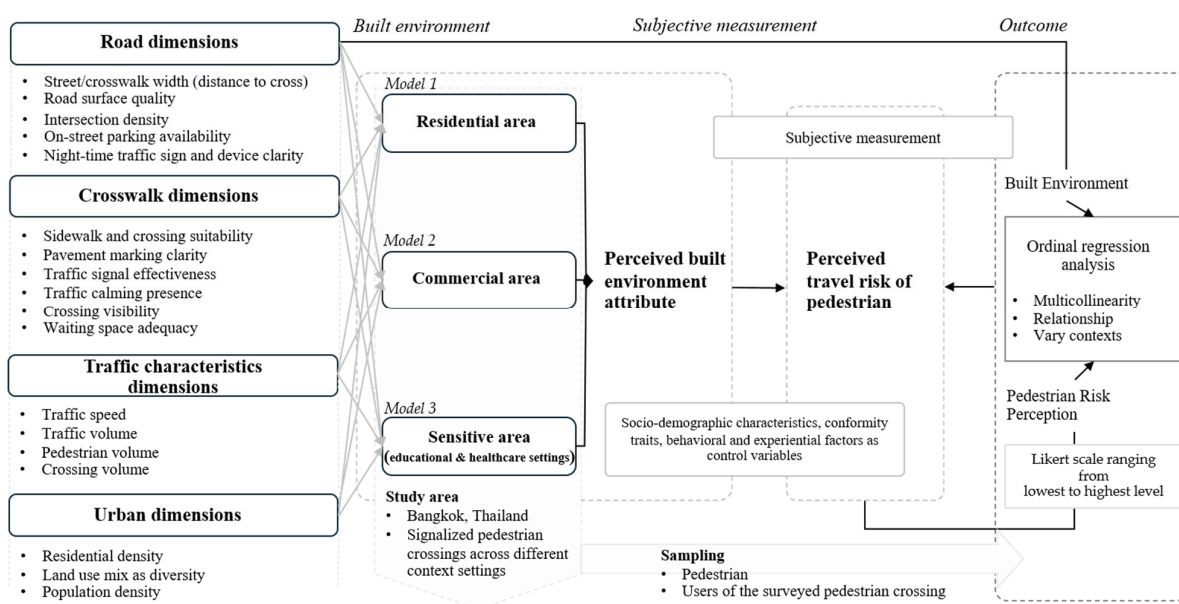


Figure 2. Process of study.

For data analysis, the characteristics of the participants were examined using descriptive statistics. While the relationship between the built environment and travel risk on subjective perspective was assessed using ordinal regression. Ordinal regression is designed to utilize the inherent ordering of the response categories to obtain simply structured models. The method is based on the assumption that the observed ordinal variable represents a categorized form of an underlying continuous latent variable [47]. The dependent variable, pedestrians' perceived travel risk, was measured on an ordinal scale. Therefore, the use of ordered regression is appropriate and consistent with the nature of the data. The data analysis was performed in SPSS version 23. The performance of the ordinal logistic regression models was evaluated based on model significance testing, goodness-of-fit tests, and the proportional odds (parallel lines) assumption [48]. The test of parallel lines was conducted to assess the proportional odds assumption. The non-significant result indicated that the assumption was satisfied, supporting the application of the ordinal logistic regression model. If the assumption is violated, alternative approaches may be considered. A significance level of 0.05 was utilized to determine which perceived built environment attribute variables were significantly correlated with perceived risk.

4. Results

4.1. Participant Characteristics and Differences in Perceived Built Environment Across Contexts

Participants were predominantly male (52%), with a mean age of 38 years (range 20–59 years). Regarding marital status, 50% were married, while 19% were single. In terms of education level, 65% held a bachelor's degree, followed by those with below a bachelor's degree at 20%, and those with above a bachelor's degree at 15%. For average monthly personal income, 54% earned between 20,000 and 40,000 baht, while only 6% earned more than 60,000 baht.

In this regard, differences in perceived built environment across urban contexts were examined to provide a preliminary understanding of the data characteristics (Table 1). The results indicated significant differences in the mean scores of perceived built environment attributes across different land use contexts. These attributes represent respondents' perceptions of specific built environment characteristics based on their experiences and observations. Among the factors, those related to traffic characteristics ($p = <0.001$), road dimensions ($p = <0.001$ to <0.05), and urban dimensions ($p = <0.001$ to <0.05) were found to be statistically significant, whereas some factors, such as waiting space adequacy ($p = 0.089$) under the crosswalk dimensions domain, were not statistically significant. The absence of significant differences in waiting space adequacy may be relatively similar across urban contexts, resulting in comparable perceptions among respondents. However, these results reflect only general differences in mean values. Therefore, further investigation is required to better understand the contextual relationships, as discussed in the following section. Overall, this finding suggests that pedestrians interpret the built environment differently depending on contextual settings.

Table 1. Differences in perceived physical environment across urban contexts.

Road Dimensions			Crosswalk Dimensions			Traffic Characteristics			Urban Dimensions		
Variables	F	Sig.	Variables	F	Sig.	Variables	F	Sig.	Variables	F	Sig.
Street width	31.65 **	<0.001	Sidewalk and crossing suitability	9.20 **	<0.001	Traffic speed	49.78 **	<0.001	Residential density	6.02 *	0.003
Road surface quality	41.22 **	<0.001	Pavement marking clarity	12.70 **	<0.001	Traffic volume	60.33 **	<0.001	Land use mix	61.42 **	<0.001
Intersection density	4.67 *	0.010	Traffic signal effectiveness	22.77 **	<0.001	Pedestrian volume	24.52 **	<0.001	Population density	29.78 **	<0.001
On-street parking	10.05 **	<0.001	Traffic calming presence	18.34 **	<0.001	Crossing volume	156.48 **	<0.001			
Night-time traffic sign and device clarity	21.11 **	<0.001	Visibility at crossings	22.09 **	<0.001						
			Waiting space adequacy	2.44	0.089						

Note: * $p < 0.05$; ** $p < 0.001$.

4.2. Investigating the Relationship Between Built Environment Characteristics and Pedestrian Risk Perception

Prior to model estimation, preliminary assumption testing was conducted, including assessments of multicollinearity. The multicollinearity results indicated that all models satisfied the recommended criteria, with variance inflation factor (VIF) values below 7. Most predictor variables exhibited VIF values below 5, while only one variable exceeded 5 but remained below the acceptable threshold of 10 [49,50]. Specifically, the VIF values ranged from 1.330 to 3.766 for Model 1, 1.193 to 6.279 for Model 2, and 1.154 to 2.428 for Model 3. These results indicate that the data are suitable for subsequent ordinal logistic regression analysis. Model evaluation was conducted prior to interpreting the ordinal logistic regression results. The overall model fit was evaluated using the likelihood ratio chi-square test based on the change in the -2 log-likelihood (-2 LL). The results indicated that all three models were statistically significant ($p < 0.001$), suggesting that each fitted model provided a significantly better fit than the intercept-only model. Model adequacy was further assessed using the goodness-of-fit test, which yielded non-significant results

($p > 0.05$) for all models, indicating an acceptable fit between the observed data and the estimated models. The proportional odds assumption was examined using the Test of Parallel Lines, which compares the proportional odds model with a model allowing non-proportional odds. The results showed that the chi-square values of the three models ranged from 8.591 to 25.971, while the Test of Parallel Lines indicated no significant violation of the proportional odds assumption, with p -values of 0.999, 0.780, and 0.409 for Models 1, 2, and 3, respectively. These findings indicate that the relationships between the predictors and the ordinal outcome were consistent across response categories.

Regarding the evaluation of predictor significance (Table 2 and Figure 3), Model 1, which represents the residential area context, identified four built environment perception variables that were significantly associated with pedestrians' perceived travel risk. Street/crosswalk width (Estimate = 0.823, $p < 0.05$), residential density (Estimate = 0.900, $p < 0.05$), and land use mix (Estimate = 1.197, $p < 0.05$) were positively associated with perceived travel risk, suggesting that increases in these perceived attributes were associated with an increased tendency to report higher perceived travel risk. In contrast, sidewalk and crossing suitability (Estimate = -2.191 , $p < 0.05$) showed negative associations. In Model 2, representing the commercial area context, intersection density (Estimate = 1.839, $p < 0.05$) and traffic speed (Estimate = 3.011, $p < 0.001$) were positively associated with perceived travel risk, whereas on-street parking availability (Estimate = -0.807 , $p < 0.05$) and pavement marking clarity (Estimate = -1.509 , $p < 0.05$) exhibited negative associations. For Model 3, representing sensitive areas (educational and healthcare areas), traffic speed (Estimate = 1.015, $p < 0.05$), pedestrian volume (Estimate = 0.656, $p < 0.05$), and land use mix (Estimate = 1.194, $p < 0.001$) were positively related to perceived travel risk, suggesting that increases in these perceived attributes were associated with an increased tendency to report higher perceived travel risk. Conversely, traffic calming presence (Estimate = -0.568 , $p < 0.05$), visibility at crossings (Estimate = -0.761 , $p < 0.05$), and waiting space adequacy (Estimate = -0.578 , $p < 0.05$) exhibited negative associations.

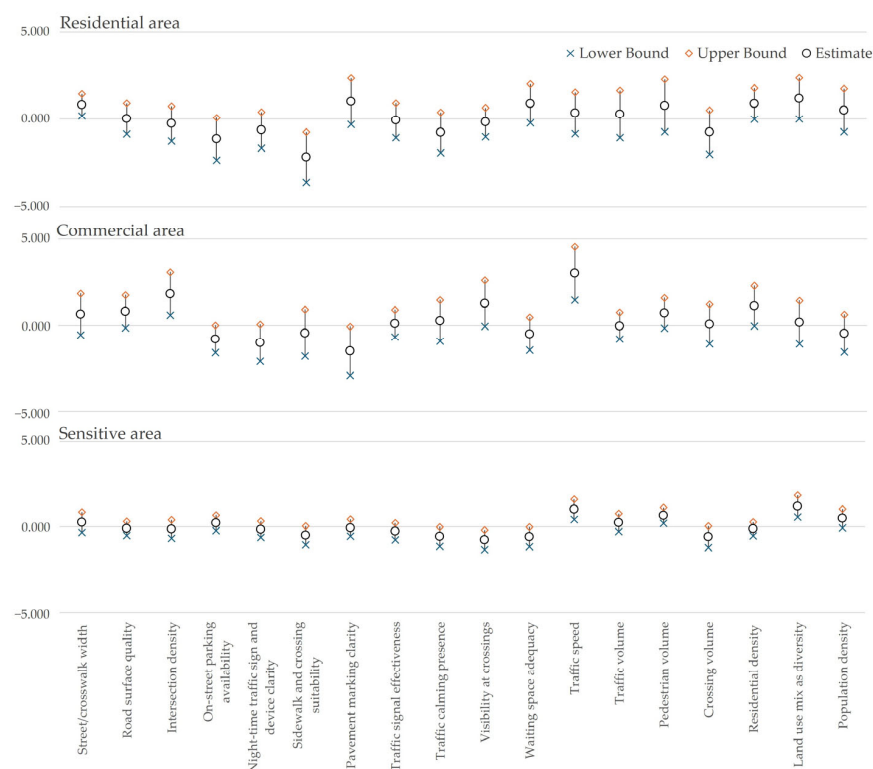


Figure 3. Estimated effects and 95% confidence intervals by urban context.

Table 2. Ordinal regression results.

Variables		Model 1			Model 2			Model 3		
		Estimate	S.E.	Sig.	Estimate	S.E.	Sig.	Estimate	S.E.	Sig.
Road dimensions	Street/crosswalk width	0.823	0.333	0.013 *	0.644	0.617	0.297	0.261	0.298	0.381
	Road surface quality	0.018	0.456	0.969	0.814	0.486	0.094	−0.095	0.212	0.655
	Intersection density	−0.263	0.514	0.609	1.839	0.634	0.004 *	−0.134	0.272	0.622
	On-street parking availability	−1.145	0.624	0.066	−0.807	0.409	0.048 *	0.228	0.231	0.323
	Night-time traffic sign and device clarity	−0.635	0.536	0.236	−1.020	0.551	0.064	−0.151	0.242	0.532
Crosswalk dimensions	Sidewalk and crossing suitability	−2.191	0.732	0.003 *	−0.447	0.693	0.519	−0.497	0.278	0.074
	Pavement marking clarity	1.024	0.688	0.136	−1.509	0.730	0.039 *	−0.054	0.251	0.829
	Traffic signal effectiveness	−0.074	0.511	0.886	0.104	0.400	0.794	−0.268	0.252	0.288
	Traffic calming presence	−0.774	0.596	0.194	0.268	0.615	0.663	−0.568	0.290	0.050 *
	Visibility at crossings	−0.185	0.430	0.668	1.271	0.681	0.062	−0.761	0.291	0.009 *
Traffic characteristics dimensions	Waiting space adequacy	0.899	0.580	0.121	−0.497	0.495	0.315	−0.578	0.291	0.047 *
	Traffic speed	0.360	0.615	0.558	3.011	0.787	0.000 **	1.015	0.302	0.001 *
	Traffic volume	0.287	0.698	0.681	−0.035	0.399	0.929	0.235	0.265	0.376
	Pedestrian volume	0.777	0.772	0.314	0.711	0.451	0.115	0.656	0.233	0.005 *
	Crossing volume	−0.758	0.648	0.242	0.061	0.596	0.919	−0.578	0.320	0.071
Urban dimensions	Residential density	0.900	0.466	0.053 *	1.133	0.597	0.058	−0.123	0.206	0.550
	Land use mix as diversity	1.197	0.611	0.050 *	0.169	0.647	0.794	1.194	0.325	0.000 **
	Population density	0.515	0.638	0.420	−0.468	0.561	0.405	0.484	0.275	0.079
Socio-demographic characteristics	Age	−0.012	0.035	0.733	0.103	0.034	0.002 *	0.019	0.016	0.238
	Gender (reference: male)	−1.730	0.729	0.018 *	−1.763	0.682	0.010 *	0.232	0.371	0.531
	Income (reference: >60,000)	3.081	1.929	0.110	7.255	1.998	0.000 **	−1.364	1.056	0.196
	Income (reference: >60,000)	2.971	1.902	0.118	5.717	1.590	0.000 **	−1.371	0.988	0.165
	Conformity traits (reference: yes)	−0.180	0.865	0.836	1.944	0.734	0.008 *	1.574	0.470	0.001 *
	Walk frequency (reference: >6 h/week)	−1.025	0.862	0.234	1.699	0.810	0.036 *	0.168	0.445	0.706
	Experience crash (reference: yes)	−4.025	1.218	0.001 *	0.638	1.007	0.527	0.261	0.629	0.678
Likelihood ratio test		<0.001			<0.001			<0.001		
Nagelkerke's R ²		0.577			0.734			0.394		
Test of Parallel Lines		0.999			0.780			0.409		

Note: * $p < 0.05$; ** $p < 0.001$.

Regarding the coefficients from the ordinal logistic regression models in Figure 3, with error bars representing 95% confidence intervals, the general pattern suggests that many coefficients have confidence intervals that cross zero. In contrast, traffic speed and intersection density in commercial areas show consistently positive effects, with confidence intervals entirely above zero. Meanwhile, sidewalk and crossing suitability in residential areas show consistently negative effects, with confidence intervals entirely below zero. Finally, Nagelkerke's R^2 values ranged from 0.394 to 0.734, with Model 2 demonstrating the highest explanatory power among the three models. The values suggest that Model 2 provided the best overall fit to the data, followed by Model 1 and Model 3.

5. Discussions

5.1. Contextual Variations in Built Environment Effects on Travel Risk Perception

Understanding perception plays a key role in shaping pedestrian travel behavior [51,52]. Therefore, examining the underlying reasons behind factors influencing perception is important for improving road safety outcomes. This study focuses on perceived travel risk in relation to the built environment. The results of this study support the hypothesis that certain built environment factors are associated across multiple spatial contexts, while others are context-specific. In this study, perceived speed emerged as a consistently associated factor across multiple spatial contexts, including commercial areas as well as vulnerable settings such as schools and hospitals. This finding is consistent with previous studies confirming that higher traffic speeds increase perceived travel risk. Some studies have also shown that road and traffic characteristics, particularly traffic volume and speed, are associated with perceived safety [50,53]. Accordingly, traffic calming measures that reduce speed are associated with lower perceived traffic risk [53].

When considering spatial contextual differences, in residential areas, factors associated with higher perceived travel risk are related to street and crosswalk width, residential density, and land use mix. These factors may reflect conditions such as higher building and residential density as well as greater land use diversity, which can be related to activity intensity and traffic volume within the area. This explanation aligns with previous findings indicating that an increasing number of motorized vehicles in residential neighborhoods may be associated with greater difficulties for pedestrians and may be associated with lower perceived safety when crossing streets under local traffic conditions [54]. Regarding street width, wider streets indicate longer crossing distances, which may be related to greater exposure to traffic. Longer crossing duration may increase exposure to moving vehicles, and pedestrians may therefore perceive a higher risk. In addition, factors that reduce perceived travel risk include sidewalk and crossing suitability. This finding is consistent with previous studies. For example, Yang et al. [55] examined the impact of the built environment on perceived traffic risk among children in residential neighborhoods and found that sidewalk availability is one of the built environment factors associated with risk perception, suggesting the importance of built environment interventions in residential neighborhoods. Overall, the findings of this study suggest that residential areas, which are generally intended to support walking and short distance travel rather than vehicle-oriented movement, may have traffic conditions and street designs that are not fully aligned with pedestrian needs. As pedestrians are exposed to vehicle movement, the potential for pedestrian-vehicle conflict may become more pronounced, which may be associated with higher perceived travel risk and feelings of insecurity while walking.

In commercial areas, perceived speed was a consistently significant factor, as discussed earlier. This finding is consistent with some previous studies emphasizing that pedestrian perceived travel risk is closely related to traffic volume and vehicle speed, particularly in commercial and mixed land use areas, which tend to have higher traffic density than residential areas. As a result, pedestrians may perceive higher levels of risk in these environments [18]. Intersection density is another factor that showed a significant positive association with perceived travel risk. This may be explained by the fact that areas with higher traffic volume and a greater number of intersections or crossing points are more likely to involve intersecting movement flows, which may be associated with higher perceived risk for pedestrians in commercial districts. In contrast, on-street parking availability and pavement marking clarity are associated with lower perceived travel risk, as indicated by their negative associations. On-street parking availability is statistically significant only in the commercial context, which may be related to curbside traffic management in the study area. As this study is conducted in Bangkok, commercial areas often include on-street parking and informal street vending. If not properly managed, these conditions may contribute to conditions that increase the likelihood of pedestrian-vehicle conflicts.

In sensitive areas, which include educational and healthcare settings, pedestrians are considered a vulnerable group, particularly children and older adults. Previous research has highlighted the importance of considering local context when addressing pedestrian safety, particularly in areas frequented by vulnerable groups such as children, older adults, and people with disabilities [56]. In this study, we therefore examined areas with more diverse land use patterns, with a particular focus on these sensitive contexts. The results highlight two main issues regarding the associations between the perceived built environment and perceived travel risk. The first emphasizes the general role of the built environment. In the context of perceived travel risk, the presence of traffic calming is generally associated with lower perceived risk, indicating a negative association. This finding is in line with several previous studies, across both general and context-specific settings, have highlighted the importance of traffic calming measures in reducing pedestrian travel risk [56,57]. However,

some studies suggest that the effects may be mixed depending on the type of measure, such as speed humps or school zones, which in some cases may have no significant effect on perceived risk or may be associated with higher perceived risk [58]. This evidence suggests that the design and implementation of traffic calming measures should consider their suitability and compatibility with the functional characteristics of the area. Another important issue is the factors positively associated with perceived travel risk in sensitive areas. In this context, perceived speed remains a key factor, which is consistent with previous studies indicating that high vehicle speed is one of the main reasons children feel unsafe when engaging in active travel [59]. In addition, land use mix as diversity and pedestrian volume were found to be associated with higher perceived travel risk. The association between land use mix diversity and perceived travel risk may not necessarily indicate higher risk due to activity patterns alone, but may instead be related to greater environmental complexity, which can affect risk perception. This is particularly relevant in healthcare settings, which are generally expected to be safe environments.

In addition, an important finding of this study is that perceived land-use diversity was positively associated with pedestrians' perceived travel risk in residential and vulnerable contexts, including educational and healthcare settings. Another interesting finding was the context-specific relationship between land use mix and perceived travel risk, with a positive association observed in residential and sensitive areas (i.e., educational and healthcare areas). Although this relationship has been discussed separately within each land-use context, the finding that land use mix was significant only in residential and sensitive areas suggests that its role in shaping pedestrians' perceptions of travel risk may vary depending on the surrounding land-use context. Areas with a higher degree of land use mix typically accommodate a wider range of daily activities. These diverse activities may create more complex movement patterns and increase interactions among different road users. This may influence pedestrians' perceptions of travel risk, particularly when increased interactions occur in areas with high pedestrian and traffic activity. In residential areas and sensitive areas, maintaining safe and comfortable living environments is particularly important. These areas often involve vulnerable pedestrian groups, including children, older adults, and individuals with reduced mobility. In these environments, increased interactions between pedestrians and vehicles associated with diverse land-use activities may further intensify perceptions of travel risk. This may be particularly the case when higher levels of land use mix are not accompanied by adequate pedestrian infrastructure and safety measures. At the same time, urban development concepts such as walkable and people-centered cities commonly emphasize compact development and mixed land use. However, this relationship may not consistently translate into reduced perceived travel risk across all urban contexts. This positive association observed in this research may be explained by increased pedestrian and activity intensity associated with higher land-use diversity, which can place greater demand on pedestrian infrastructure. When sidewalks and related facilities are not adequately designed or sufficiently available, this may contribute to higher perceived travel risk. This interpretation is supported by the significant effect of pedestrian volume, which also reflects increased activity intensity and is associated with higher risk perception. Nevertheless, these relationships are likely context-dependent. In urban environments with well-designed pedestrian infrastructure and appropriate facility provision, land-use diversity may not necessarily increase perceived risk and could potentially support safer pedestrian conditions. Overall, the findings highlight that the influence of land-use diversity on perceived travel risk is not uniform and should be interpreted in relation to surrounding infrastructure and urban context.

5.2. Implications for Built Environment and Safety

These findings suggest that the effects of the built environment on pedestrians' perceived travel risk vary across different land-use contexts and highlight the importance of context in shaping these relationships. In particular, the results indicate that some design elements may be more important in certain settings than in others, suggesting that environmental planning should be sensitive to spatial differences rather than relying on a generalized approach that does not account for contextual variation. This has implications for built environment planning and improvement. Residential areas should prioritize reducing traffic intensity and managing activity levels to enhance livability. Commercial areas should focus on providing sufficient physical space to accommodate pedestrian volumes. In more vulnerable environments such as schools and hospitals, greater emphasis should be placed on improving infrastructure quality and pedestrian facilities, given the presence of more vulnerable user groups such as children and older adults. Finally, traffic speed management emerges as an important consideration across all contexts, as it plays a key role in shaping perceived safety and may contribute to reducing perceived travel risk. However, additional measures should be considered alongside built environment factors because perceived risk is shaped by a combination of built environment characteristics and individual-level factors rather than being determined by spatial conditions alone. Environmental improvements should therefore also aim to reduce objective risks. For example, within the context of this study, pedestrian crossing facilities should be improved with greater emphasis on traffic-calming measures. These measures may include road narrowing approaches at crossing locations, which can reduce vehicle speeds while also decreasing pedestrian crossing distances. In addition, pedestrian crossings should be provided at accessible locations and equipped with facilities that support safer crossing conditions. Furthermore, appropriate roadside management measures should be implemented such as regulating roadside parking and establishing clear boundaries between roadway and pedestrian areas, particularly in locations with roadside commercial activities and sensitive areas. These measures may help improve pedestrian visibility, reduce conflicts between pedestrians and vehicles, and minimize pedestrians' exposure to traffic-related risks. Ultimately, improvements in perceived safety should be supported by physical design interventions that genuinely enhance safety.

5.3. Limitations and Future Studies

The findings of this study highlight the relationship between the built environment and perceived travel risk, with particular attention to variations across different land-use contexts. Nevertheless, several limitations should be acknowledged and considered in future research. First, this study focused on environment-related risk perception, referring to individuals' perceptions of accident risk associated with physical characteristics of the travel environment. However, risk perception is a multidimensional concept that may include behavior-related and other non-traffic risk dimensions. Future research could further examine differences across risk perception dimensions to better understand how each dimension influences decision-making and behavioral responses. In addition to variations in perceived travel risk, spatial contexts related to land-use characteristics may also differ considerably. In this research, land-use contexts were classified based on dominant activity patterns, with educational and healthcare-related areas grouped as sensitive areas to represent environments involving vulnerable pedestrian groups. Future studies could further examine more specific land-use categories such as educational, healthcare, recreational and industrial areas, to provide deeper insights into context-specific relationships between built environment characteristics and perceived travel risk. Further investigations should consider sufficient sample sizes and appropriate analytical approaches to enable

meaningful comparisons across different land-use contexts. Second, this study employed a cross-sectional design, which limits the ability to capture changes in perceptions over time. Individual perceptions are inherently dynamic and may vary across temporal contexts. Therefore, future research could adopt a longitudinal design to examine how pedestrians' perceptions of the built environment and travel risk change over time. In addition, future studies could compare different cities and further distinguish specific land-use categories within each city. They could also extend the investigation to broader geographical contexts, such as different regions. Expanding the scope of the study may require the adoption of advanced analytical approaches and emerging technologies, such as big data analytics or automated data collection techniques, to support large-scale data collection and analysis. This would provide a better understanding of whether the relationships between the built environment and perceived travel risk vary across cities and different land-use contexts. Third, built environment characteristics can be measured through both objective and subjective (perceived) approaches. This research focused on subjective measurements to capture pedestrians' interpretations and experiences of their surrounding environments. The absence of objective built environment measures limits the ability to compare the effects of objective and perceived characteristics on risk perception. Moreover, the analysis incorporated control variables related to socio-demographic characteristics and walking behavior to account for individual differences that may influence perceived travel risk. However, other behavioral factors, such as crossing violations, were not included in the current model. Future studies could incorporate objective built environment measures and other relevant control factors to provide a more comprehensive understanding of the relationships. Including these factors in future studies may help account for unmeasured influences and provide more robust findings. Finally, this study mainly considered perceptions of built environment characteristics and traffic conditions. However, environmental factors such as weather conditions may also influence travel decisions and perceived travel risk. Future studies could incorporate these factors to provide a more comprehensive understanding of perceived travel risk.

6. Conclusions

In the context of pedestrian travel, understanding how the built environment shapes the spatial setting in which walking occurs is important. The findings suggest that perceived built environment attributes are associated with perceived travel risk in different ways depending on their functional characteristics. Attributes related to exposure to traffic conditions, such as crosswalk width, intersection density, traffic speed, and pedestrian volume, are generally associated with higher perceived risk. By contrast, attributes associated with a negative effect on perceived risk such as road markings, and visibility conditions (e.g., absence of obstructions), as well as traffic calming measures. When considering spatial contextual differences, residential areas appear to be more sensitive to issues related to density and diversity, reflecting their role as living environments where reducing traffic congestion and prioritizing traffic calming features are essential. In contrast, commercial areas, which are characterized by high levels of human activity, tend to place greater emphasis on factors related to pedestrian perception such as intersection density, on-street parking availability, and pavement marking clarity, reflecting their capacity to accommodate pedestrian movement. In more vulnerable areas such as educational and healthcare settings, the relevant factors tend to be more influenced by environmental conditions and spatial provision for pedestrians, including traffic calming features, and visibility conditions. In addition, land-use diversity may also play a role, as higher levels of activity heterogeneity may reflect increased interaction intensity, which could contribute to higher perceived risk in vulnerable zones such as school environments. Overall, the findings indicate that

the effects of built environment attributes on perceived travel risk reflect the functional characteristics of activities within each context. Some factors, such as land use mix and traffic speed, appear to be relevant across more than one spatial context, suggesting that these elements represent general design features that are broadly applicable. Moreover, the findings suggest that the influence of the built environment on perceived travel risk may not occur directly. Instead, it may operate through individuals' perceptions and interpretations of the physical characteristics, activities and traffic conditions within the travel environment. The perceived built environment therefore serves as a mechanism linking the physical characteristics of the environment to perceived travel risk. Furthermore, the findings indicate that this mechanism varies across land-use contexts. This suggests that the influence of the built environment on perceived travel risk is context-dependent rather than being uniformly applicable across all urban environments. These findings also highlight the need for further investigation across broader contexts. Future research could extend this study by incorporating both objective and subjective measures and examining the relationships across diverse temporal, geographical, behavioral and land-use contexts. Longitudinal designs and advanced analytical approaches may also provide further insights into how these relationships evolve over time and vary across different settings.

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