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Pedestrian Safety in Compact and Mixed-Use Urban Environments: Evaluation of 5D Measures on Pedestrian Crashes

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Abstract: This study examined the impact of density, diversity, design, distance to transit, and destination accessibility, five measures, known as the 5Ds, that characterize the built environment, on pedestrian–vehicle crashes in Seoul, Korea. Using spatial analysis based on 500-m grid cells, this study employed negative binomial regression models on the frequencies of three specific types of pedestrian–vehicle crashes: crashes causing death, major injury, and minor injury to pedestrians. Analysis shows that compact and mixed-use urban environments represented by 5D measures have mixed effects on pedestrian safety. Trade-off effects are found between a higher risk for all types of pedestrian crashes, and a lower risk for fatal pedestrian crashes in 5D urban environments. As a design variable, a higher number of intersections is more likely to increase some types of pedestrian crashes, including fatal crashes, a finding which warrants policy attention to promote pedestrian safety near intersection areas. This study also confirms an urgent need to secure the travel safety of pedestrians near public transit stations due to the higher risk of pedestrian crashes near such facilities. Various destinations, such as retail stores, traditional markets, and hospitals, are associated with pedestrian crashes. Pedestrian safety measures should be implemented to reduce the likelihood of pedestrian crashes near major destination facilities.

Keywords: pedestrian safety; pedestrian–vehicle crash; built environment; compact development; land-use mix; urban form

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1. Introduction

From the discourse on how to resolve transportation problems in Western cities, particularly the car-oriented cities of the United States (US), the concept of compact development has emerged. Since the late twentieth century, the vicious cycle of automobile-dependent transport systems and urban sprawl has led transportation planners and policymakers to frame a progressive concept of smart growth by promoting high-density and compact development in US cities. More recently, certain cities in Europe, Asia, and Africa with heavy traffic congestion and degrading environments have made the discourse on compact development even more important [1–4].

Though measures to design and implement compact urban development and environmental improvements have been diverse, they mainly aim to adopt high-density planning and efficient land-use. Such measures invariably address the "five Ds" (5Ds) of the urban built environment: density, diversity, design, distance to transit, and destination accessibility [5,6]. Some previous research indicates the potential of compact urban development for improving traffic safety by creating pedestrian-friendly urban environments, and promoting high urban density and mixed land-use [7–9]. For instance, planning strategies to reduce automobile dependence, and increase walking and biking, facilitate mixed land-use and job–housing balance, thereby lowering pedestrian–vehicle crash rates in urban environments [8]. In contrast, urban sprawl is related to higher numbers of traffic fatalities [10].

However, compact and mixed-use development may increase the frequency of vehicle-pedestrian crashes by increasing the volume of pedestrians in more compact and mixed-use urban environments [11]. In other words, as the number of pedestrians on roads increases, the potential risk exposure of pedestrians to traffic accidents may increase, despite there being less automobile travel [12]. For instance, one study [13] identifies that the number of pedestrian-involved crashes increased in counties with a high proportion of people whose primary travel mode is walking (the US and Italy). Furthermore, another study reports an increasing number of pedestrian–vehicle crashes as urban density increased, despite the opposite relationship between pedestrian fatality rates and urban density [14,15]. These results imply that higher density is associated with the possibility of a higher number of traffic accidents (due to increased risk for pedestrians), but that the higher density may lower the occurrence of pedestrian fatalities through other channels in dense urban environments, such as lowering traffic speeds [16]. These complex and mixed findings can increase concerns about the role of physical environments in promoting physical activity [17].

This line of recent research implies an urgent need for empirical validation and exploration to further refine the complex relationships between compact urban environments and pedestrian–vehicle crashes, especially by analyzing more diverse urban contexts. This is the primary motivation of our study. This study examines how urban built environments influence pedestrian safety by analyzing pedestrian injuries in a highly dense and mixed-use Asian city, Seoul, Korea. More specifically, this study examines relationships between pedestrian–vehicle crashes and various measures of urban developments, based on 500-m grid cells as the spatial analytical unit. Furthermore, this study investigates relationships according to different severities of pedestrian injuries and fatalities caused by accidents between pedestrians and cars in the urban environment.

2. Literature Review

Much of the previous research uses the idea that the 5D components of urban built environments are valuable strategies to support compact urban development and transit-oriented development (TOD) [6,18,19]. In addition, the benefits of 5D planning have been empirically reported in a wide range of areas, including improvements in local and regional accessibility, environmental conditions, and human health [20–32].

Despite numerous studies reporting the benefits of 5D compact development, its impacts on transportation safety have been less clearly identified [33–35]. A reduction in traffic accidents has been traditionally addressed by focusing on observed improvement in the geometric structures of road segments and traffic crash hotspots. These "traditional" and post-prescription approaches, however, are considered neither optimal nor preventive insofar as they are reactive, following traffic accidents that have already occurred [36]. Another new approach focuses on the prevention of traffic accidents by decreasing the total travel demand, and changing the travel patterns of vehicles, such as trip frequency, mode choice, and travel distance. Fundamentally, changes in travel patterns are heavily influenced by land-use patterns, density, and urban accessibility. This is where the relationships between transportation safety, urban environments, and development patterns promoting high-density and compact development become crucial.

Especially when pedestrians are involved, efforts to reduce traffic volume and alleviate traffic problems by redefining urban environments impact the intensity of the risk for vehicle–pedestrian crashes, and moderate personal travel behaviors [37,38]. This so-called "population approach" aims to reduce vehicle travel on roadways by fundamentally restructuring urban built environments. In particular, traffic volume and vehicle speed are closely associated with urban 5D characteristics.

Empirical evidence that supports compact urban development shows that mixed land-use, job–housing balance, and a reduction of automobile dependence lower traffic accidents, whereas urban sprawl is related to higher numbers of fatalities [10]. Overall, urban features to promote high-density environments, walking, and shorter durations of vehicle travel are expected to protect the safety of pedestrians exposed to vehicles in high-risk hotspots [7,9]. Nevertheless, conflicting evidence also exists [12,39]. For example, a higher volume of pedestrians in a more compact and denser environment increases the frequency of vehicle–pedestrian crashes [13]. Despite reduced vehicle travel, a higher number of pedestrians increases the potential risk of traffic crashes. In addition, one study [14] reports a higher number of pedestrian–vehicle crashes as urban density increased, whereas another study [15] finds that the pedestrian fatality rate was shown to decrease as urban density increased. For instance, retail employment density has been positively associated with pedestrian crashes in urban and rural areas [40]. Similarly, more pedestrian crashes have been found in commercial areas in Austin, Texas [41].

Overall, these results imply that higher density is associated with the possibility of more traffic accidents (due to increased risk commensurate with the increased number of pedestrians), but that higher density may lower the possibility of pedestrian fatalities, partly due to reduced vehicle speeds [42]. Another potential reason for conflicting findings on the relationship between the built environment and traffic safety is that the risk exposure for the traffic population might not be adequately measured [12]. For instance, different studies introduce different exposure units into their dependent variables by dividing traffic accidents by the number of residents [43], the land area [44], the number of traveling vehicles [45], or the vehicle kilometers traveled [46].

Land-use diversity can be another confounding factor in traffic safety. Greater land-use diversity has been shown to be negatively associated with pedestrian crash rates in Melbourne, Australia, which has comparatively more active transportation mode choices [47]. In contrast, land-use diversity has not been shown to consistently contribute to crash rates in the metro Detroit region of Michigan, USA [48]. One study reports that mixed land-use reduces the risk of pedestrian crashes for school-age children only in high-income neighborhoods, implying that greater land-use diversity does not necessarily promote pedestrian safety overall [49]. In addition, another study reports that greater mixed land-use was shown to be positively associated with an increased number of bicycle crashes in the San Francisco Bay area of California, USA [50]. These empirical studies suggest that land-use diversity might not be consistently associated with lowering crash rates.

Certain design measures seem to be closely related to pedestrian crashes. One study, for example, reports a belief among school-age children in a pedestrian crash risk due to the presence of crosswalks and more building entrances around intersections [51]. Another study finds that intersections with transit stops were positively associated with more pedestrian crashes [35]. In contrast, other research [38] shows that in Italy, road intersections have been proven to decrease the risk of pedestrian crashes (directly contradicting the results of other studies).

Transit access measures to promote pedestrian-friendly environments can also add unexpected costs that offset improved pedestrian safety [12]. Examining the causes of ward-level vehicle crashes in London, one study [52] finds that as the number of bus stops increased, the frequency of pedestrian crashes increased. Other studies report the same results, and demonstrate that intersections with transit stops have been shown to be positively associated with pedestrian crashes [46,53,54]. As a result, better transit accessibility tends to increase the frequency of pedestrian–vehicle crashes, despite encouraging people to walk and take public transit more often.

Destination accessibility, unlike the other 5D factors, is an index for which relatively few empirical studies have been conducted [12]. In TOD, facilities designed to enable passage near residential areas (that is, local accessibility) might be related to pedestrian crashes. For example, one study [55] reports that pedestrian–vehicle crashes in the city of Seattle in Washington, US, decreased as the distance from the city center increased, and in spots where there were no retail stores or neighborhood living facilities. In other words, that study shows that densely developed areas were more likely to be associated with a high frequency of pedestrian–vehicle crashes.

Indeed, the value of public transit and TOD can be undermined by perceived concerns about traffic safety [56]. Despite many benefits from TOD environments, concerns about its mixed effects on pedestrian safety can impede the successful adoption of TOD and pedestrian-friendly environments. Most previous research, though assessing some parts of the built environment according to 5D planning elements in the context of TOD, has only explored cities in Western countries as settings for case studies [57]. Reviewing comprehensive, extensive literature on spatial road safety approaches, one study [57] recommends further exploration of all physical environments as a direction for future research. In order to expand our understanding of the role of compact development measures in traffic accidents and pedestrian safety, the Asian city of Seoul, Korea, is a crucial study subject with a high-density, less dependence on automobiles, and well-developed public transit systems. In particular, the current study focuses on pedestrian crashes associated with Seoul's urban physical environment. The reason for this is, though pedestrians are a vulnerable user group on roads, they are a major measure to promote walking activity for desirable development, as well as sustainable transport systems [58].

3. Methodology

3.1. Study Area

Seoul is a megacity characterized by a high population density, mixed land-use, and public transit-oriented transportation systems [59]. Among comparable cities in other Organization for Economic Cooperation and Development (OECD) countries, Seoul reports a relatively high number of fatalities by traffic accidents [60,61], with 100 fatalities per million people in 2017. That figure is twice the average for OECD countries (56 fatalities per million people).

This study analyzes 31,999 cases of pedestrian–vehicle crashes out of a total of 120,329 traffic crashes in the Seoul metropolitan city over three years, spanning 2015 through 2017. For spatial analysis and regression models, this study aggregates crash data based on a 500-m grid cell unit. Our statistical models—specifically, negative binomial regressions—were designed to examine relationships between features of the urban physical environment and pedestrian crashes in Seoul.

3.2. Unit of Spatial Analysis

This study analyzes pedestrian–vehicle crashes based on a 500-m grid cell unit to test relationships between 5D measures of urban physical environments (the planning elements of TOD [21,62]) and pedestrian crashes. Previous empirical studies have adopted diverse spatial units with administrative boundaries, including states [63], metropolitan areas [64], and counties [13]. Other research has employed parameters according to census geographical boundaries, such as counties [13], census tracks [11,41,65,66], census blocks [36], traffic analysis zones (TAZs) [67], and voting districts (wards) [68], as well as road segments and intersections [57].

This study designates a 500-m grid cell as the spatial unit of analysis to determine homogeneous spatial characteristics of pedestrian–vehicle crash spots. Some studies have employed fixed distance grid cell units (instead of zonal or regional ones) for examination of road safety, such as 0.1 square miles [69], 1 square mile [70], or multiple units from 1 to 100 square miles [71]. For example, one study [72] identifies the range from 0.25 to 1.0 miles as an acceptable walking distance. Another study [11] describes an association between pedestrian safety and neighborhood characteristics by setting 400-m spatial units as walkable boundaries of neighborhoods. Notably, one study uses a 500-m grid cell as a spatial unit to analyze pedestrian–vehicle crashes in greater King County, Washington, USA [55]. That research analyzes the frequency of traffic accidents by 305-, 500-, and 1000-m units, respectively, finding that frequency by 500-m units was homogeneously distributed, and less dispersed across units in comparison to the other two spatial units. Another case study [73] in the city of Seoul uses a 500-m grid cell to analyze spatiotemporal patterns in pedestrian crashes. Accordingly, this study divides Seoul into 500-m grid cells. Furthermore, it is not uncommon in Korea to prescribe transit station areas with 500-m boundaries insofar as that distance is considered accessible through walking.

Pedestrian–vehicle crash spots in Seoul are illustrated by grid cells in Figure 1. After eliminating from analysis all the cells without buildings and inhabitants, we aggregated the values of the dependent and explanatory variables (Table 1) for a total of 2267 cells to analyze the relationship between 5D measures and pedestrian crashes.

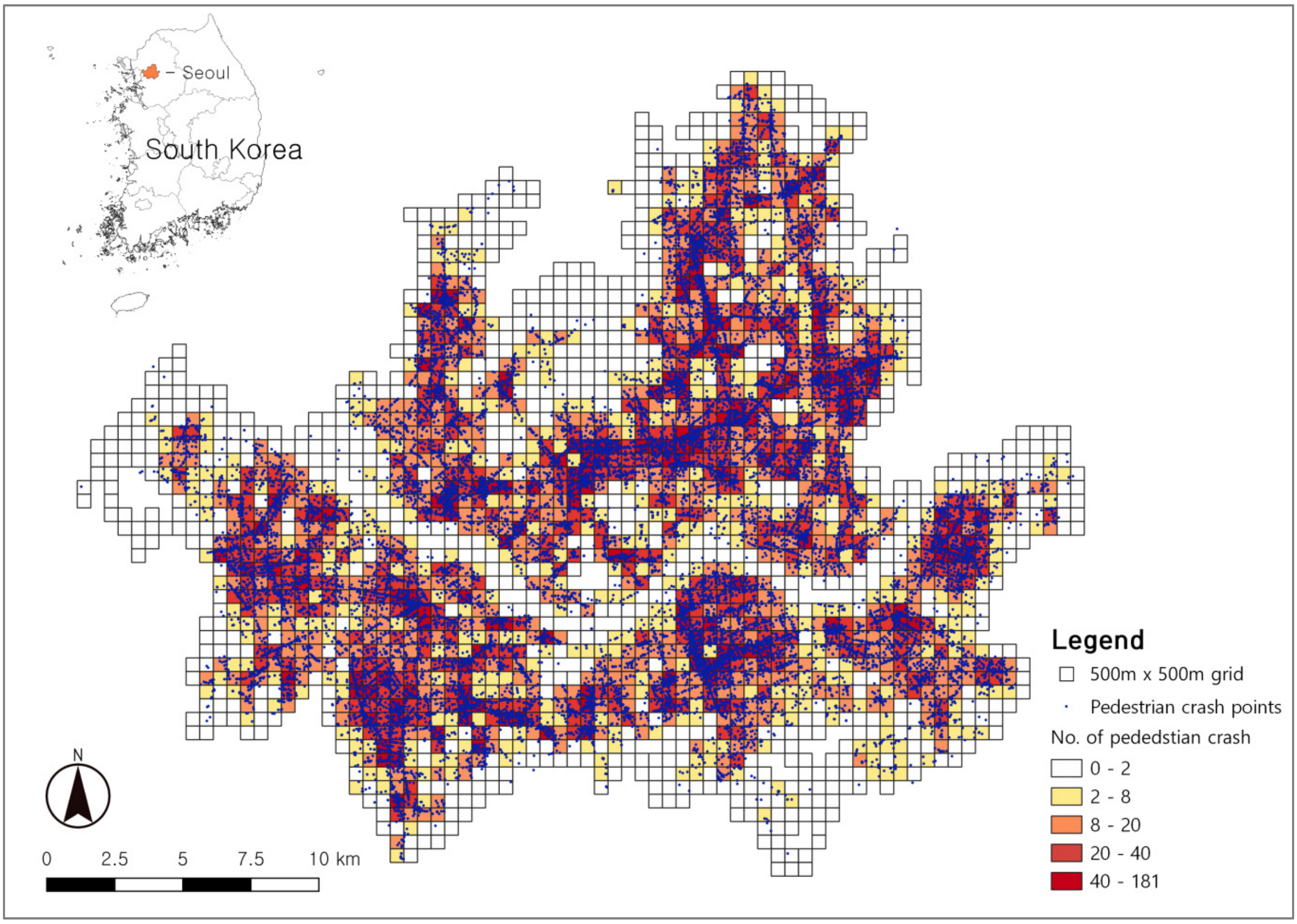


Figure 1. A number of pedestrian crashes (2015–2017) by 500-m grid cells in Seoul.

3.3. Variables and Models

Table 1 shows summary statistics of the dependent and independent variables used in our analysis, along with their descriptions and data sources. The dependent indicator is a counting variable—the frequency of pedestrian–vehicle crashes for the three years between 2015 and 2017 by 500-m grid cell. Crashes are counted by the seriousness of pedestrian injury—that is, fatality (death), major injury, or minor injury inflicted on pedestrians by vehicles. The number of crashes causing pedestrian death was much lower than the other two types of injuries (0.26 death per grid cell vs. 5.89 for major injuries vs. 8.22 for minor injuries per grid cell).

Table 1. Descriptive statistics of dependent and explanatory variables.

Variables		Description	Mean	S. D.	Source
Dependent variables	All	Number of total pedestrian crashes	14.12	18.37	Traffic Accident Analysis System
	Death	Number of pedestrian crashes causing death	0.26	0.57	
	Major injury	Number of pedestrian crashes causing major injury	5.89	7.23	
	Minor injury	Number of pedestrian crashes causing minor injury	8.22	11.90	
Density	SF_den	Total floor area of single-family housing (per 1000 m^2)	27.64	37.50	NSDI *
	MF_den	Total floor area of multi-family housing (per 1000 m^2)	101.63	118.70	
	Comm_den	Total floor area of commercial use (per 1000 m^2)	29.07	38.94	
	Office_den	Total floor area of office use (per 1000 m^2)	25.57	84.73	
Diversity	LUM	Entropy index of land-use mix: single-family housing, multi-family housing, commercial use, and office use	0.45	0.33	
	RNR	Residential-non-residential mix index for all of the buildings, RNR=1 − ∣(res − non_res)/(res + non_res)∣	0.49	0.30	
	Std_build_den	Standard deviation for all of the buildings (per 1000 m^2)	2.85	4.82	
Design	Intersect_3leg	Number of nodes of three-way intersections	4.92	5.33	Korea Trans. DB (KTDB)
	Intersect_4leg	Number of nodes of four-way intersections	1.23	1.75	
	No_U_turns	Number of nodes of U-turns	0.98	1.58	
Distance to transit	Dist_bus_stop	Average distance (m) from pedestrian crash points to closest bus stops	199.55	282.95	TOPIS **
	Dist_sub_stat	Average distance (m) from pedestrian crash points to closest subway stations	778.29	594.68	Seoul Metro
	No_bus_stop	Number of bus stops within a grid cell	4.88	4.59	TOPIS **
	No_sub_stat	Number of subway stations within a grid cell	0.17	0.48	Seoul Metro
Destination accessibility	No_school	Number of elementary, middle, and high schools	0.57	0.93	NSDI *
	No_college	Number of colleges	0.03	0.18	
	No_retail	Number of retail stores	1.63	3.00	
	Hosp_area	Total floor area of hospitals	3.56	14.30	Seumteo (E-AIS) †
	Relig_area	Total floor area of religious facilities	2.01	4.22	
	No_trad_ market	Number of traditional markets	0.15	0.60	Seoul open data plaza
Topography	Slope	Average slope based on land slope information (flat: below 7°, gentle: 7~15°, steep: above 15°)	1.58	0.76	NSDI
Exposure variables	Pop_den	Population number in the grid (per 1000 people)	4.12	3.51	SGIS ††
	Road_length	Total length of road networks (per 1000 m)	5.00	3.31	Seoul open data plaza
	Green_area	Total area of green and open spaces (per 1000 m^2)	44.80	73.43	
SAC factor		Spatial autocorrelation correction (SAC) factor	-		-

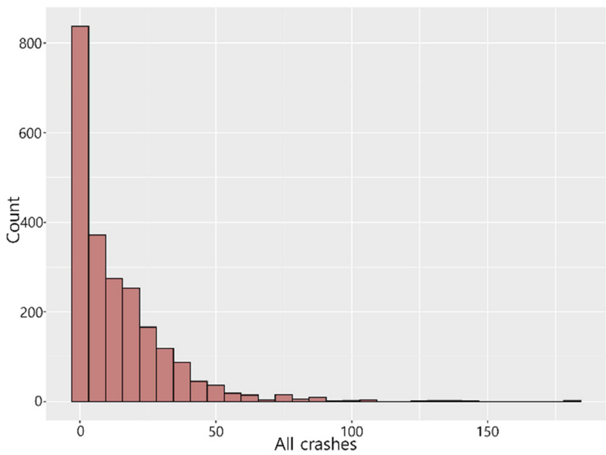
* NSDI: National Spatial Data Infrastructure Portal; ** TOPIS: Transport Operation and Information Service; † Seumteo (E-AIS): https://cloud.eais.go.kr (accessed on 1 March 2021); †† SGIS: Statistical Geographic Information Service.

For independent variables, we employed 5D urban environment measures for TOD, as well as topography slope and exposure variables, including total population density, total length of road networks, and total area of green space (see Table 1).

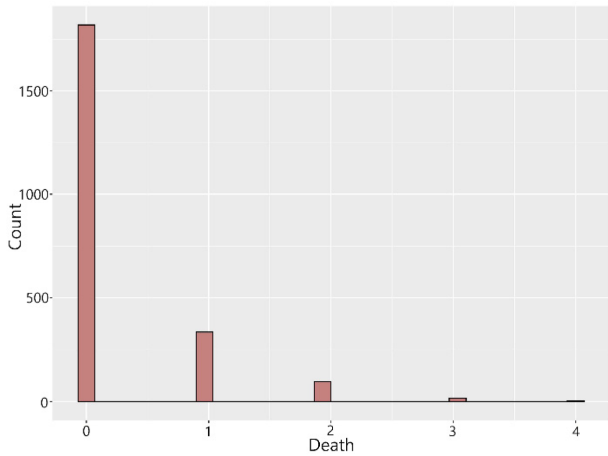
Here, each 5D category has its representative indicators as independent variables. First, density is represented by four specific floor area variables—namely, single-family housing (SF_den), multi-family housing (MF_den), commercial use, and office use. Second, diversity is composed of the land-use mix index (LUM), the residential/non-residential land-use mix index (RNR), and the standard deviations of total floor areas.

Third, the design category has three variables mainly associated with roadway design features—namely, the number of three-way intersections, the number of four-way intersections, and the number of U-turns. Fourth, this study considers four variables for distance to transit, including the average distance from the pedestrian crash point to the closest bus stop, the average distance from the pedestrian crash point to the closest subway station, the number of bus stops, and the number of subway stations. Fifth, this study considers six variable destination categories, including the number of elementary, middle, and high schools; the number of colleges; the number of retail stores; the total floor area of hospitals; the total floor area of religious buildings; and the number of traditional markets. Finally, this study considers three additional variables (i.e., population density, road length, and green area) to control for the effects of exposure variables on pedestrian crashes, together with one additional variable for the spatial autocorrelation correction (SAC) factor to control for spatial autocorrelation [74].

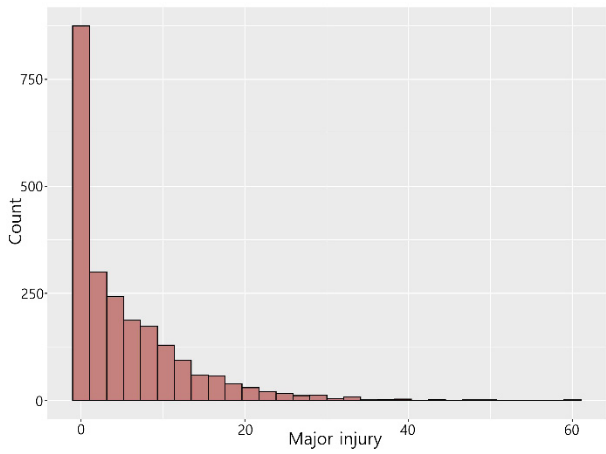
This study considers population density and total road length variables as proxy variables for ambient population and traffic volume, respectively. Most green space is characterized by mountains and rivers that are not developable in Seoul. Though the green space variable may typically be considered a "design" factor, this study considers design factors to be geometric components directly related to roadway design. Thus, the green space area in a 500-m grid cell indicates land-use characteristics herein. Traffic accidents are rarely occurring events [55]. Therefore, distributions of the three types of pedestrian-vehicle crashes counted within the 500-m grid cells are positively skewed (Figure 2).



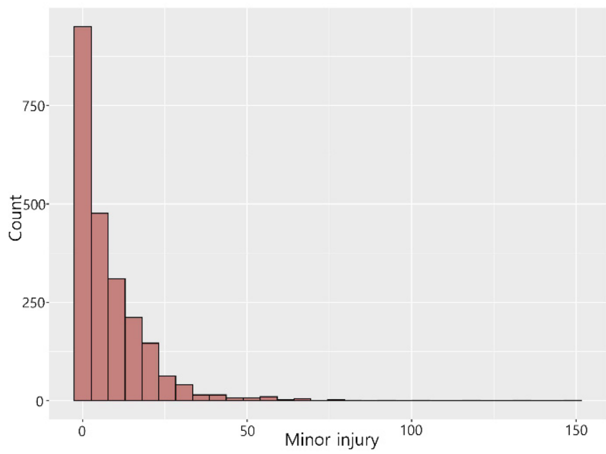
(**a**) All crashes



(**b**) Death crashes



(**c**) Major injury crashes



(**d**) Minor injury crashes

Figure 2. Distributions of pedestrian crashes (2015–2017) by injury type in 500-m grid cells.

This study uses a total of 2267 grid cells for analysis, excluding mountains and rivers. There are 476 (21.0%) grid cells with no pedestrian crashes, 1818 (80.2%) grid cells with no pedestrian crashes causing death, 633 (27.9%) grid cells with no pedestrian crashes causing major injury, and 618 (27.3%) grid cells with no pedestrian crashes causing minor injury. As shown in Table 1, the mean values are lower than the standard deviations for all types of injuries, which indicates an overdispersion. This overdispersion violates the homogeneity assumption for a general Poisson model. A negative binomial regression model (i.e., an extended model of the Poisson distribution) has been suggested to account for count scales, overdispersion, and unobserved heterogeneity in the data [75].

4. Analysis Results

Table 2 shows the results of negative binomial models for the four types of pedestrian crashes (i.e., all, death, major injury, and minor injury). We applied negative binomial models based on the characteristics of dependent variables, following some previous studies [11,55,68,72]. We tested the variance of error (α) and variance to mean ratio (VMR). Analysis confirmed that the negative binomial regression model was more appropriate than the Poisson model. We also tested a zero-inflated negative binomial model in model 2, which has many grid cells of no pedestrian crashes causing death. Because the zero-inflated negative binomial model had not been converged, we applied a negative binomial model for model 2. In addition, we confirmed no multicollinearity issues among independent variables. Lastly, we confirmed that the goodness of fit of each model is reasonable, based on pseudo R^2, the Akaike information criterion (AIC), and the Bayesian information criterion (BIC).

Table 2. Results of four pedestrian crash models.

	Variables	Model 1 (All)		Model 2 (Death)		Model 3 (Major Injury)		Model 4 (Minor Injury)	
		Coef.	z	Coef.	z	Coef.	z	Coef.	z
Density	SF_den	−0.002 ***	−3.36	−0.005 **	−2.02	−0.002 ***	−2.65	−0.002 ***	−2.90
	MF_den	1.6×10^{-4}	−0.91	−0.001 **	−2.04	2.3×10^{-4}	−1.11	-8.7×10^{-5}	−0.44
	Comm_den	0.006 ***	11.00	0.003 *	1.73	0.005 ***	8.56	0.006 ***	10.84
	Office_den	0.001 ***	3.44	0.001 **	2.34	0.000 ***	2.87	0.001 ***	3.66
Diversity	LUM	0.511 ***	7.15	0.655 **	2.42	0.564 ***	6.70	0.483 ***	5.83
	RNR	0.276 ***	3.01	0.850 **	2.28	0.176	1.55	0.248 **	2.26
	Std_built_den	0.017 ***	5.49	0.008	0.65	0.016 ***	4.46	0.016 ***	4.60
Design	Intersect_3leg	0.013 ***	4.96	0.028 ***	3.28	0.012 ***	3.96	0.012 ***	3.84
	Intersect_4leg	0.029 ***	3.61	0.008	0.30	0.038 ***	4.29	0.022 **	2.42
	No_U_turns	0.007	0.88	0.059 **	2.40	0.011	1.30	−0.005	−0.62
Distance to transit	Dist_bus_stop	−0.003 ***	−17.07	−0.004 ***	−3.86	−0.004 ***	−14.07	−0.003 ***	−12.64
	Dist_sub_stat	-2.2×10^{-4} ***	−6.08	-1.1×10^{-4}	−0.73	-1.9×10^{-4} ***	−4.35	-2.2×10^{-4} ***	−5.09
	No_bus_stop	0.014 ***	4.11	0.008	0.66	0.014 ***	3.43	0.015 ***	3.91
	No_sub_stat	0.110 ***	4.60	0.128 *	1.78	0.116 ***	4.45	0.107 ***	4.03
Destination accessibility	No_school	0.018	1.46	−0.125 **	−2.53	0.002	0.17	0.028 **	1.97
	No_college	0.020	0.32	−0.374	−1.23	−0.051	−0.69	0.096	1.36
	No_retail	0.016 ***	3.08	−0.019	−1.15	0.003	0.52	0.024 ***	4.19
	Hosp_area	0.003 ***	4.39	−0.001	−0.24	0.002 ***	2.69	0.004 ***	4.87
	Relig_area	0.005	0.66	0.000	−0.01	0.006	0.75	0.003	0.39
	No_trad_market	0.106 ***	6.17	0.079 *	1.83	0.108 ***	6.01	0.105 ***	5.69
Topography	Slope (flat) gentle slope	−0.067 **	−2.26	−0.100	−0.91	−0.089 **	−2.57	−0.046 ***	−1.35
	steep slope	−0.158 ***	−2.98	−0.255	−1.08	−0.148 **	−2.26	−0.166	−2.67
Exposure variables	Pop_den	0.070 ***	9.73	0.045 *	1.68	0.069 ***	8.35	0.070 ***	8.72
	Road_length	0.061 ***	6.76	0.072 **	2.37	0.053 ***	5.22	0.067 ***	6.65
	Green_area	−0.003 ***	−8.32	−0.006 ***	−3.02	−0.003 ***	−5.90	−0.004 ***	−7.15
	SAC factor	0.013 ***	10.53	0.292 **	2.39	0.032 ***	8.80	0.022 ***	10.19
	Constant	1.106 ***	13.81	−2.452 ***	−7.35	0.426 ***	4.28	0.474 ***	4.94
	No. obs.	2267		2267		2267		2267	
	Alpha (α)	0.163		0.102		0.147		0.175	
	Chibar2	2669.42 ***		1.19		614.97 ***		1604.15 ***	
	Variance to mean ratio (VMR)	23.90		1.28		8.60		17.22	
	Log-likelihood (null)	−8089.34		−1443.20		−6359.11		−6931.94	
	Log-likelihood (model)	−5997.64		−1192.02		−4567.09		−5066.96	
	Pseudo R^2	0.259		0.174		0.270		0.269	
	AIC	12,051.28		2440.04		9190.18		10,189.92	
	BIC	12,211.62		2600.37		9350.51		10,350.25	

* $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

4.1. Density

As shown in Table 2, four density variables were used, including single-family housing, multi-family housing, commercial use, and office use. Though the density of single-family housing shows significant negative associations with all three types of pedestrian crashes, the density of multi-family housing is not statistically significant, except in model 2 (death).

On the other hand, the densities of commercial and office buildings show relatively higher positive associations with all types of pedestrian–vehicle crashes. It also should be noted that the coefficient and level of statistical significance in model 2 (death) are lower than in model 3 (major injury) and model 4 (minor injury).

Overall, the analysis results indicate that the densities of commercial and office buildings are positively related to pedestrian–vehicle crashes. This result is in line with the results of previous studies [9,14,44]. However, the analysis results in Table 2 show mixed findings on the relationship between density and pedestrian crashes, depending on the dominant land–use. Though one study [15] claims that high–density development tends to reduce traffic on roadways, and decreases pedestrian–vehicle crashes with lower rates of fatal pedestrian crashes, our study confirms that the relationships between high-density development and pedestrian crashes are different according to land-use types in terms of total floor areas of residential, commercial, and office buildings.

4.2. Diversity

As shown in the models in Table 2, three variables were employed for diversity measures, including the entropy index of land-use mix (LUM), the land-use mix of residential and non-residential buildings, and the standard deviations of their total floor areas. Analysis results show that the land-use diversity indices are positively associated with pedestrian crashes. This result is consistent with findings from a previous study [76], claiming potential conflicts between pedestrian and vehicle movements. In addition, the standard deviations of total floor areas of buildings show a statistically significant, positive relationship with pedestrian–vehicle crashes, except in model 2 (death). In Seoul, the heights and volumes of buildings vary greatly, with high-story buildings located in close proximity on the main roadways, and low-story residential, commercial, and mixed-use buildings clustered on back streets. These areas are usually characterized by greater and more active interaction between pedestrians and vehicles, which might cause a higher rate of pedestrian–vehicle crashes.

4.3. Design

As shown in Table 2, three variables were adopted as design factors, including the number of three-way intersections, the number of four-way intersections, and the number of U-turn-permitted nodes in the models. A high intersection density (meaning a greater number of intersection nodes per unit area) indicates small block sizes, which tend to promote walking-friendly built environments, and thus, an increase in the number of pedestrians.

On the other hand, a high node density may lead to frequent vehicle stops, suggesting that pedestrian activities occur in a more complicated environment due to many intersections. Therefore, a narrow block design can be both beneficial and detrimental for pedestrians' safety. Analysis results indicate that the number of points of intersection is most likely to be positively associated with higher pedestrian crashes, with the exception of four-way intersections in model 2 (death). The main reason for this is because the risk is amplified by the higher number of intersection points [77], thus yielding a greater chance for pedestrians to encounter a vehicle.

Both U-turn-allowed intersections and elevated/underground passageways may also increase the chances of crashes causing major or minor injury to pedestrians. However, the number of U-turns is only positively associated with fatal pedestrian crashes in model 2. This result implies that proper design measures for U-turns are critical to prevent fatal pedestrian crashes.

4.4. Distance to Transit

Four variables were used to capture the distance to public transit in the context of the 500-m grid cell: the average distance from the pedestrian crash point to the closest bus stop, the average distance from the pedestrian crash point to the closest subway station, the number of bus stops, and the number of subway stations within each 500-m grid cell.

Overall, proximity to public transit systems was shown to be more likely to increase the number of pedestrian crashes. In particular, pedestrian crashes causing major or minor injuries show statistically significant and positive associations with nearby public transit systems, and negative associations with distant public transit. In addition, fatal pedestrian crashes are more likely to be associated with nearby bus stations and the presence of many subway stations. Although the existence of bus stops and subway stations obviously facilitates the usage of public transit, previous studies have suggested that more pedestrian–vehicle crashes happen in areas where transit stations are nearby and/or accessible to pedestrians [78], due mainly to there being more pedestrians in these areas [52,55,72]. Our results confirm that nearby bus stops and subway stations are positively related to pedestrian–vehicle crashes.

4.5. Destination Accessibility

As shown in Table 2, six variables were adopted for destination accessibility because they are closely related to pedestrian–vehicle crashes: number of elementary, middle, and high schools; number of colleges; number of retail stores; total floor area of hospitals; total floor area of religious buildings; and number of traditional markets. The presence of nearby schools is negatively associated with fatal crashes in model 2, and is positively associated with minor injuries in model 4. This result is in line with the two competing hypotheses around the effects of nearby schools in terms of pedestrian crashes. The presence of schools might result in a higher likelihood of pedestrian–vehicle crashes due to more students walking around schools [79]. On the other hand, we may assume a lower likelihood of crashes if traffic speed limit regulations are effective in designated "school zones" with very low speeds [80]. Our finding indicates that even though the high volume of pedestrians around schools increases the risk of pedestrian–vehicle crashes, lower speed limits and various other pedestrian safety measures in school zones counteract the pedestrian volume effect on fatal pedestrian crashes, thereby reducing the number of crashes that cause pedestrian fatalities.

This study finds similar results in the effects of the presence of retail stores on pedestrian–vehicle crashes. The number of retail stores is positively associated with pedestrian crashes in model 1 (all) and model 4 (minor injury), but not in model 2 (death). This finding is probably related to the locational characteristics of downtown or commercial districts where retails stores are found. The likelihood of a fatal crash within a downtown area with many retail stores is lower due to decreased traffic speed [8,35]. Similarly, the total floor area of hospitals showed positive associations with pedestrian crashes in all of the models, except for model 2 (death). In addition, the number of traditional markets showed positive associations with pedestrian crashes in all of the models. These results are related to the fact that hospitals and traditional markets attract many pedestrians.

4.6. Topography and Exposure Variables

As shown in Table 2, our findings indicate that gentle or steep slope areas are less likely to have pedestrian crashes than flat slope areas. Though this relationship is significant in model 1 (all) and model 3 (major injury), it is not significant in model 2 (death). Next, population density, one of the primary exposure variables, is positively associated with all types of pedestrian crashes. Nevertheless, it should be noted that the coefficient and the level of significance in model 2 (death) are relatively lower than the coefficient and the level of significance in model 3 (major injury) or model 4 (minor injury). Although higher density introduces higher exposure to pedestrian crashes, it leads to fewer cases of pedestrian crashes causing deaths or major injuries. This result is similar to the findings of previous research [15] identifying a lower rate of fatal crashes in highly dense areas.

The total length of road networks is another exposure variable; longer road networks in the unit of analysis might be associated with a higher risk of pedestrian crashes. According to analysis, the total length of road networks shows statistically significant and positive associations with all three types of pedestrian crashes.

Finally, this study also considers green space areas as an exposure variable. Green space areas are related to land-use diversity. Analysis results indicate that green space areas are negatively associated with all types of pedestrian crashes. In other words, more green space in a grid cell is related to a lower rate of pedestrian–vehicle crashes therein, mostly because a high ratio of green space in a grid cell can reduce exposure to pedestrian crashes by generating less traffic volume. This result is consistent with the findings of previous research [81] that reports a lower rate of pedestrian–traffic crashes in areas with more open spaces.

5. Discussion and Conclusions

5.1. Discussion

Many researchers and policymakers expect to see a lower risk for pedestrian–vehicle traffic accidents owing to compact and mixed-use urban environments and transit-oriented development, which are believed to have advantageous effects in lowering vehicle-dependent traffic inducement [7–10]. Previous studies [11–13], however, have reported that pedestrian–vehicle crashes have increased due to the tendency of more people to walk on streets because of pedestrian-friendly and transit-friendly physical environments. Taking a different point of view, other studies [14,15] have argued that TOD physical environments are effective in lowering the severity of pedestrian–vehicle crashes because of reduced vehicle speeds within the physical environments.

Thus, the relationships between TOD environments and pedestrian–vehicle crashes seem to be complex and cannot be easily generalized. In addition, most previous studies explore only some parts of the 5Ds (density, diversity, design, distance to transit, and destination accessibility) of TOD environments, focusing mainly on Western cities. Therefore, this study aims to identify evidence of the complex relationships in pedestrian–vehicle crashes with 5D measures in Seoul, a big city with a high-density mixed-use physical environment, and transit-oriented transportation systems.

Our findings lead us to conclude that TOD urban physical environments have the potential to increase the risk of pedestrian crashes without careful counterpart measures. Furthermore, although a TOD environment has positive effects in suppressing the frequency of automobile traffic, higher pedestrian volume means that more pedestrians may encounter more automobile traffic. Nevertheless, the results of this study demonstrate that the TOD environment of Seoul has positive effects in reducing the severity of pedestrian–vehicle crashes. More specific key findings are as follows.

First, this study confirms that though higher density in residential areas is associated with fewer cases of pedestrian crashes, higher density in commercial or office districts increases all three types of pedestrian crashes. This finding aligns with the findings of a few previous studies [9,14,44]. However, it should be noted that though a higher density is associated with higher exposure to pedestrian crashes, a higher density might lead to fewer cases of severe and/or fatal pedestrian crashes [15]. Next, this study indicates that mixed land-use is also strongly associated with a higher risk of all three types of pedestrian crashes. Greater mixed land-use is more likely to increase pedestrian crash risk across different severity levels [49,76]. This result may be related to the characteristics of a big city in Asia that has adopted diverse land-uses over most of its areas, thereby mitigating the other benefits of compact development. Therefore, integrating traffic-calming strategies into compact development principles and practices can effectively control fatal pedestrian–vehicle crashes, especially in high-density, mixed land-use areas of development.

Second, this study indicates that three-way and four-way intersections are highly associated with pedestrian crashes. In particular, a higher number of three-way intersections is more likely to increase all three types of pedestrian crashes, particularly fatal crashes. This finding is similar to the results of previous studies [72,73,78]. Most three-way intersections in the city of Seoul have non-signalized systems with lower direct visibility between automobiles and pedestrians. Higher numbers of pedestrian crashes and more severe pedestrian crashes near intersection areas should garner policy attention to promote pedestrian safety. This study also finds that the number of U-turns is highly associated with fatal pedestrian crashes. Therefore, mitigation measures should be implemented to reduce the likelihood of pedestrian crashes in places where cars frequently make U-turns.

Third, this study finds that distance to public transportation is highly associated with all three types of pedestrian crashes. In other words, pedestrian crashes are more likely to increase in spots with nearby transit stations, including bus and subway stops. This finding indicates that securing the traffic safety of pedestrians near public transit stations is an urgent matter. Although many Asian cities, such as Seoul, are hubs of public transportation with numerous bus stops and train stations, higher rates of fatal crashes around transit stations is a serious problem in need of solutions [73].

Finally, destinations are important factors in pedestrian crashes. For example, though the proximity of schools is positively associated with minor pedestrian crashes, it is negatively associated with fatal crashes. This finding indicates that mitigation measures near school zones have positive impacts on pedestrian safety in terms of fatal crashes. In contrast, retail stores, traditional markets, and hospitals are associated with many pedestrian crashes, resulting in major, as well as minor, injuries. This finding is consistent with the findings of previous research [82]. Therefore, pedestrian safety measures should be implemented to reduce the likelihood of pedestrian crashes near major destination facilities.

5.2. Conclusions

This study examines pedestrian safety issues in Seoul, South Korea, a TOD environment, with evaluations of 5D measures on pedestrian crashes. It is well known that the development of compact and mixed-use urban environments decreases car-oriented travel patterns, reduces traffic congestion, prevents air pollution, and supports healthier cities. However, this study confirms that compact and mixed-use urban development is more likely to be associated with pedestrian–vehicle crashes in concentration areas of commercial and office facilities. This finding indicates that pedestrian safety policies should be implemented to mitigate pedestrian–vehicle crashes in high-density and mixed-use urban environments. On the other hand, this study also finds that some adverse effects can be counterbalanced or offset by beneficial trade-offs generated through 5D measures. Accordingly, urban built environments promoting high-density and mixed-use development should be carefully monitored and planned to improve pedestrian safety, especially in the highly dense urban settings of Asian cities. Leveraging the approaches and findings of this study, future studies should attempt to answer fundamental policy questions, and garner real experience from diverse global urban contexts and settings regarding the risks, benefits, and trade-offs in pedestrian–vehicle crashes.

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