

Diagnosing double vulnerability in aging cities: A spatial coupling framework applied to elderly pedestrian crash risk and hospital accessibility in Seoul

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Abstract

As cities worldwide undergo rapid population aging, older adults face compounding spatial disadvantages when high pedestrian crash risk and poor healthcare accessibility converge in the same neighborhoods. Yet existing literature has largely examined these two dimensions separately, leaving the spatial co-occurrence of traffic danger and medical underservice — and its implications for urban governance — underexplored. Using Seoul, South Korea, as a case study, this research constructs an integrated framework encompassing risk identification, accessibility assessment, and spatial coupling analysis. This framework is evaluated using 9,190 elderly pedestrian crashes recorded between 2020 and 2024, alongside facility attributes from 59 general hospitals. The Gaussian two-step floating catchment area (Ga2SFCA) method is employed to evaluate potential medical access under 15-minute and 30-minute walking thresholds. The results demonstrate that both elderly pedestrian crash risk and hospital accessibility exhibit significant spatial heterogeneity across Seoul. High-risk areas are predominantly concentrated in the urban core and along major transport corridors, whereas zones lacking adequate medical access are widely distributed in the urban periphery. As the walking threshold is extended from 15 to 30 minutes, the service catchment improves and the number of medium-accessibility areas increases substantially; however, the overall pattern of spatial inequality remains largely unchanged. Further spatial coupling analysis identifies 10 administrative neighborhoods (dongs) that remain consistently classified as high-risk–low-accessibility (HL) under both threshold settings, representing typical zones of double vulnerability faced by older pedestrians. In contrast, only one dong is classified as high-risk–high-accessibility (HH) under the 30-minute threshold, suggesting that relatively high healthcare accessibility does not necessarily correspond to reduced collision exposure. Beyond the Seoul context, this study proposes a transferable spatial coupling framework for diagnosing double

vulnerability in aging cities, offering a replicable methodology for identifying priority intervention zones where traffic risk and healthcare underservice spatially converge.

1. Introduction

Rapid urbanization and population aging are reshaping the socio-ecological and spatial fabrics of megacities, thereby exacerbating governance challenges at the intersection of urban safety and healthcare provision (Luo and Qi, 2009). Within complex road environments, older pedestrians are highly susceptible to traffic collisions because of diminished perception, slower reaction times, and compromised physical recovery; consequently, the consequences of such crashes are often devastating (Roe et al., 2020; Wang et al., 2021). Following collisions, falls, or other acute emergencies, timely access to effective medical treatment is a critical determinant of survival chances and recovery outcomes for older adults (Cheng et al., 2020; Hassler and Ceccato, 2021). Healthcare accessibility, defined as the ability to obtain medical resources despite spatial impedance, has therefore emerged as an important factor shaping post-crash outcomes in this demographic and a central concern in both transport geography and health geography (Hansen, 1959; Handy and Niemeier, 1997; Perchoux et al., 2013).

However, existing studies have largely proceeded along relatively separate trajectories. One strand focuses on pedestrian crashes and their spatial variation (Lam et al., 2019; Smith and Ory, 2023; Xinyu et al., 2023), while another examines healthcare accessibility and its equity implications (Shen et al., 2021; Jiao et al., 2022). Systematic investigations exploring the spatial correlations between the two remain limited. This analytical divide may obscure an important reality: areas with high elderly pedestrian crash risk do not necessarily coincide with neighborhoods offering superior higher-level general hospital resources (Chen et al., 2023). Instead, certain communities may simultaneously face elevated crash risk and limited healthcare support, forming as-yet insufficiently identified zones of double vulnerability (Tang and Lai, 2019; Maresova et al., 2023; Lu et al., 2025).

Seoul provides a highly compelling case study to examine this spatial mismatch (Xiao et al., 2024; Du et al., 2026). As a megacity in East Asia characterized by intense transport activity and rapid population aging, Seoul exhibits pronounced internal disparities in built-environment intensity, road complexity, and public service provision (Kang, 2024). By the end of 2025, the proportion of residents aged 65 years and older in Seoul had exceeded 20% (Choi et al., 2025; Ministry of the Interior and Safety, 2026), and this demographic exhibits marked spatial differentiation across the city (Baek et al., 2022; Jeon and Woo, 2023; Jeon and Woo, 2024). For older adults who rely heavily on short-distance walking, the spatial relationship between crash-prone neighborhoods and nearby higher-level general hospitals directly dictates their potential access to medical support post-injury.

Overall, three major gaps remain in the existing literature. First, most studies address either healthcare accessibility or pedestrian safety separately, neglecting their combined spatial pattern within a unified analytical framework (Guida et al., 2022; Lee et al., 2020; Wang, 2020; Zhang et al., 2020; Cheng et al., 2020; Li and Wang, 2022;). Second, even when healthcare accessibility is considered, the focus is often placed on primary care or general service provision, while overlooking general hospitals that better represent advanced diagnostic and treatment capacity within the Korean healthcare system (Bauer et al., 2020; Kim and Kwon, 2022). Third, there remains insufficient identification of areas where high elderly pedestrian crash risk overlaps with low hospital accessibility, particularly concerning stable high-risk–low-accessibility areas across different threshold settings (Zhang et al., 2021; Yunus and Abdulkarim, 2022; Balawi and Tenekeci, 2024; Clemente et al., 2024).

Against this background, this study uses general hospitals as a proxy for higher-level healthcare resources and develops a three-step framework encompassing risk identification, accessibility assessment, and spatial coupling analysis to examine the spatial relationship between elderly pedestrian crash risk and healthcare accessibility in Seoul. Specifically, this study aims to: identify high-risk areas for elderly pedestrian crashes and their spatial clustering patterns; assess

accessibility to general hospitals under different thresholds using the Gaussian two-step floating catchment area (Ga2SFCA) method; identify high-risk–low-accessibility coupled areas; and provide a spatial basis for age-friendly urban governance, priority-area intervention, and the coordinated allocation of safety and healthcare resources.

2. Literature Review

2.1 Spatial mismatch between elderly pedestrian crash risk and healthcare accessibility to general hospitals

With the acceleration of population aging, post-crash medical support for older adults following traffic collisions and other acute events has gradually become a critical issue in research on urban safety and health equity (Roe et al., 2020; Wang et al., 2021). Compared with other age groups, older pedestrians are highly susceptible to traffic injuries in complex road environments because of diminished physical capacity, slower reaction times, and a stronger dependence on the walking environment. Consequently, the consequences of these collisions are often devastating (Lee et al., 2020; Hassler and Ceccato, 2021). At the same time, healthcare accessibility, defined as the ability of residents to obtain medical resources despite spatial impedance, has been widely used to evaluate the provision of urban public services and levels of health equity (Hansen, 1969; Handy and Niemeier, 1997; Perchoux et al., 2013; Cheng et al., 2020).

Existing studies on elderly pedestrian crashes have primarily focused on the spatial differentiation of crash risk and its relationship with the built environment, traffic exposure, and road network configurations. These studies demonstrate that elderly pedestrian crashes tend to cluster in high-density built-up areas, mixed-use districts, locations with intense traffic activity, and spatial settings characterized by complex road networks. In high-density cities such as Seoul, this spatial heterogeneity is particularly pronounced (Lee et al., 2020; Kim and Horner, 2025).

Concurrently, studies of healthcare accessibility have centered on facility coverage, supply–demand matching, and spatial equity. In the context of population aging, an increasing number of

studies have employed the two-step floating catchment area method and its extensions to assess the spatial convenience with which older adults can access healthcare services, and have shown that higher-level healthcare resources are typically concentrated in central areas, with relatively limited provision in peripheral locations (Cheng et al., 2020; Hu et al., 2020; Li and Wang, 2022; Kim and Kwon, 2022; Liu et al., 2023). For general hospitals with relatively strong comprehensive diagnostic and treatment capacity, uneven spatial distribution may directly compromise the level of potential healthcare support available to residents after acute injury events (Cheng et al., 2020; Bauer et al., 2020).

However, most existing studies have proceeded along two relatively separate trajectories: one emphasizes the identification of high-risk crash environments, while the other focuses on the coverage and equity of healthcare resources. Much less attention has been paid to whether high-risk areas can secure adequate support from higher-level healthcare resources within limited spatial thresholds. In other words, although previous studies have independently revealed pronounced inequalities in urban traffic safety and healthcare provision, there remains a lack of systematic and fine-grained analysis of whether these two dimensions are spatially matched. This gap is particularly concerning for older pedestrians, a vulnerable group that relies heavily on neighborhood walking environments (Zhang et al., 2020; Guida et al., 2022; Li and Wang, 2022).

2.2 Progress and gaps in research on spatial coupling

In recent years, some studies have begun to integrate risk exposure and facility accessibility into a common analytical perspective under broader frameworks of vulnerability or emergency response. The theory of compound vulnerability posits that vulnerability is not the outcome of a single risk, but rather the combined result of exposure, sensitivity, and coping capacity. This provides a crucial theoretical basis for identifying zones of double vulnerability formed by the overlap between elderly pedestrian crash risk and limited healthcare accessibility (Pelling, 2003).

Existing studies in this broader field can be roughly grouped into three strands. The first focuses on the static measurement of accessibility to public services or healthcare facilities, with

an emphasis on differences in service acquisition and spatial equity across groups (Cheng et al., 2020; Hu et al., 2020; Li and Wang, 2022; Kim and Kwon, 2022; Liu et al., 2023). The second examines the spatial distribution of elderly pedestrian crashes and their relationship with the built environment and traffic exposure, highlighting the pronounced spatial heterogeneity of crash risk within cities (Wang, 2020; Kim et al., 2025). The third incorporates accessibility into broader discussions of emergency response and spatial vulnerability; however, the research focus is usually placed on general emergency systems or broader vulnerable populations rather than older pedestrians as a specific group (Kim and Horner, 2025; Kotavaara et al., 2021; Radzimski, 2024; Zhang et al., 2024; Zhang et al., 2025).

Among the relatively limited number of coupling-oriented studies, Tian et al. (2025) incorporated a traffic crash risk layer into an analysis of pre-hospital emergency accessibility and applied a GP2SFCA model, thereby preliminarily illustrating a risk–accessibility coupling approach. However, that study focused on the pre-hospital emergency response system rather than higher-level general hospitals that possess more complex diagnostic and treatment capacity. In addition, it did not adopt threshold settings specifically tailored to elderly pedestrian walking scenarios, thus failing to adequately reflect the influence of walking environments on potential healthcare support.

Overall, three major limitations remain. First, methodologically, most existing studies still rely on static accessibility measures or single-risk analyses, and a systematic framework for examining the spatial mismatch between traffic risk and healthcare resources remains absent. Second, existing studies rarely incorporate elderly pedestrian crash locations, route safety, and risk-exposure factors into the accessibility assessment process, which obscures the true spatial constraints affecting medical access in hazardous environments. Third, coupling analyses specifically focused on older pedestrians remain limited, especially concerning the need for identifying stable high-risk–low-accessibility areas that constitute persistent zones of double vulnerability. These limitations form the primary point of departure for the present study.

3. Methods

3.1. Study area

This research designates Seoul, the capital of South Korea, as the primary empirical setting. As illustrated in Figure 1, general hospitals in Seoul are predominantly clustered within the urban core, whereas elderly pedestrian collisions recorded between 2020 and 2024 display clear spatial agglomeration in areas characterized by dense built environments and intense transport volumes. Functioning as a megacity with a high concentration of population, transport flows, and healthcare resources, Seoul had a resident population of approximately 9.3 million as of February 2026 (Ministry of the Interior and Safety, n.d.). The proportion of residents aged 65 years and older has already exceeded 20%, indicating that the city has entered a super-aged society. Concurrently, substantial intra-urban disparities exist in built-environment density, road network structure, population aging, and public service provision, making Seoul an ideal context for examining the spatial mismatch between elderly pedestrian crash risk and accessibility to higher-level healthcare resources.

3.2. Data acquisition and preprocessing

To rigorously investigate the spatial relationship between elderly pedestrian crash risk and hospital accessibility in Seoul, this study synthesizes multi-source datasets, including traffic collisions, healthcare facilities, demographics, and road network topologies. Crash data were retrieved from the Traffic Accident Analysis System (TAAS) (TAAS, n.d.), hospital data from the Health Insurance Review and Assessment Service (HIRA) (HIRA, n.d.), and population and road network data from the Seoul Metropolitan Government Open Data Platform (Seoul Metropolitan Government, n.d.). In detail, TAAS data were utilized to extract incident records and precise geocoded coordinates for collisions involving pedestrians aged 65 years and older between 2020 and 2024. HIRA data were processed to acquire the locations and service capacity information for 59 general hospitals across Seoul. Data from the Seoul Metropolitan Government Open Data Platform were employed to extract the elderly population and road network information at the

dong (administrative neighborhood) level. Given the relatively strong comparability of general hospitals in terms of service level and diagnostic and treatment capacity, they were treated as the primary supply nodes representing higher-level healthcare resources. To ensure spatial consistency and analytical reliability, all datasets were preprocessed under a unified coordinate system and then integrated through spatial overlay analysis. The definitions and descriptive statistics of all incorporated variables are summarized in Table 1 and Table 2.

3.3. Analytical framework

As illustrated in Figure 2, this study formulates a three-step analytical framework encompassing risk identification, accessibility assessment, and spatial coupling analysis to identify geographical zones exhibiting a spatial mismatch between elderly pedestrian crash risk and advanced healthcare resources represented by general hospitals in Seoul. First, the collision risk for elderly pedestrians is classified at the dong (administrative neighborhood) level. Second, potential accessibility to general hospitals is quantified using the Gaussian-based two-step floating catchment area (Ga2SFCA) model. Third, the derived crash risk tiers are spatially overlaid with accessibility levels to pinpoint high-risk–low-accessibility (HL) areas, and their intervention priority is systematically evaluated in terms of spatial extent, affected demographics, and crash density (Luo and Wang, 2003; Cheng et al., 2020).

3.4. Identification of elderly pedestrian crash risk levels

The analysis was conducted at the dong level, covering 424 dongs in Seoul. Based on the geocoded crash data extracted from TAAS, elderly pedestrian crashes recorded between 2020 and 2024 were spatially matched to dong boundaries, and the cumulative number of crashes in each dong, denoted as $Acc_i (i=1, \dots, 424)$ was calculated to represent the local level of elderly pedestrian crash occurrence.

To maintain consistency with the subsequent classification of healthcare accessibility, the Jenks natural breaks method ($K=3$) was applied to classify Acc_i into three levels of elderly

pedestrian crash risk: high, medium, and low ($RiskLevel_i \in \{H, M, L\}$). The classification procedure was implemented in ArcGIS 10.8.

3.5. Assessment of healthcare accessibility to general hospitals using Ga2SFCA

This research employs the two-step floating catchment area (2SFCA) method to evaluate potential access to advanced medical facilities and incorporates a Gaussian distance-decay function to accurately model the continuous decline in accessibility as spatial impedance increases within a given catchment area.

Considering the diminished physical stamina and daily mobility patterns of older adults, the average walking speed is calibrated to approximately 50 m/min (about 0.83 m/s). This aligns closely with the standard low walking-speed reference value of 0.8 m/s frequently applied in gerontological studies (de souza et al., 2025). Following established service-area configurations (Jiang et al., 2025), the walking distance thresholds (d_0) are set to 750 m and 1500 m, corresponding to 15-minute and 30-minute walking intervals, respectively. Travel cost is quantified using the shortest walking distance along the road network between each dong and each hospital.

Let hospital j denote a supply node and dong k denote a demand centroid. To distinguish the two computational steps of the 2SFCA method, k denotes dongs located within the service threshold of hospital j in the first step, whereas i denotes the target dong whose accessibility is being calculated in the second step. P_k represents the elderly population in dong k , and S_j represents the service capacity of hospital j , derived from a weighted combination of standardized bed and physician counts. d_{kj} and d_{ij} denote the shortest network walking distance from dong k or i to hospital j , respectively, and d_0 denotes the distance threshold.

Step 1: the supply-to-demand ratio of hospital j , denoted as R_j , is computed as:

$$R_j = \frac{S_j}{\sum_{k \in \{d_{kj} \leq d_0\}} P_k \cdot G(d_{kj}, d_0)} \quad (1)$$

Step 2, the healthcare accessibility index of dong, denoted as A_i , is calculated as:

$$A_i = \sum_{j \in \{d_{ij} \leq d_0\}} R_j \cdot G(d_{ij}, d_0) \quad (2)$$

A larger value of A_i indicates greater spatial convenience for elderly residents in dong to access healthcare services provided by general hospitals.

The Gaussian distance-decay function is defined as:

$$G(d_{ij}, d_0) = \begin{cases} \frac{e^{(1/2) \times (d_{ij}, d_0)^2} - e^{-(1/2)}}{1 - e^{-(1/2)}}, & d_{ij} \leq d_0 \\ 0, & d_{ij} > d_0 \end{cases} \quad (3)$$

Using $d_0=750\text{m}$ and $d_0=1500\text{ m}$, accessibility under the 15-minute and 30-minute walking thresholds was calculated as AI-15 and AI-30, respectively. To ensure consistency with the classification of crash risk, the continuous accessibility index was further classified into high, medium, and low accessibility levels using the Jenks natural breaks method ($K = 3$).

3.6. Spatial coupling analysis of crash risk and healthcare accessibility

To identify compound vulnerable areas where high elderly pedestrian crash risk overlaps with low healthcare accessibility, a spatial coupling model was constructed by overlaying the crash-risk layer and the healthcare-accessibility layer at the dong level. The coupling type of each dong i , denoted as C_i , is defined jointly by its crash-risk level R_i and accessibility level A_i :

$$C_i = (R_i, A_i), \quad R_i, A_i \in \{H, M, L\} \quad (4)$$

This procedure generates nine potential coupling types, such as HH, HL, and LL. Among them, this study focuses on the high-risk–low-accessibility (HL) type. To characterize its vulnerability and intervention priority, three descriptive indicators are constructed from the perspectives of spatial extent, affected population, and crash concentration:

$$N_{HL} = \sum_{i=1}^{424} I(C_i = (H, L)) \quad (5)$$

$$P_{HL} = \sum_{i \in \{C_i = (H, L)\}} P_i \quad (6)$$

$$Acc_{HL} = \frac{\sum_{i \in \{C_i=(H,L)\}} Acc_i}{9190} \times 100\% \quad (7)$$

Where N_{HL} denotes the number of dongs classified as HL, P_{HL} denotes the total elderly population residing in HL dongs, and Acc_{HL} denotes the proportion of historical crashes in HL dongs relative to the citywide total. $I(\cdot)$ is an indicator function that takes the value 1 when the condition is satisfied and 0 otherwise; P_i denotes the elderly population of dong i , and Acc_i denotes the cumulative number of crashes in dong i . This spatial coupling analysis makes it possible to identify spatial units under different risk–accessibility combinations and, in turn, to characterize the spatial relationship between elderly pedestrian crash risk and healthcare accessibility to general hospitals.

4. Results

4.1. Spatial pattern of elderly pedestrian crash risk

Drawing upon an extensive dataset of 9,190 elderly pedestrian–vehicle collisions recorded across Seoul between 2020 and 2024, the city's 424 dongs were categorized into three distinct risk tiers—high, medium, and low—using the Jenks natural breaks optimization algorithm. Figure 3 illustrates the spatial distribution of this classification, and the corresponding descriptive metrics are summarized in Table 3. The results reveal pronounced spatial heterogeneity in the collision exposure of older pedestrians throughout Seoul. Only 12 dongs emerged as high-risk zones, representing a mere 2.83% of all administrative neighborhoods, yet their localized collision rate reached 1.33%, substantially exceeding the citywide average of 0.61%. Medium-risk dongs numbered 155, comprising 36.56% of all dongs, with a corresponding rate of 0.74%, whereas 257 dongs (60.61%) were designated as low-risk, recording a crash rate of only 0.44%. Overall, the data demonstrate a pattern characterized by disproportionate agglomeration within a limited number of areas, while the vast majority of dongs remain in the low- or medium-risk categories.

From a spatial perspective, high-risk dongs are predominantly clustered in the urban core and around major transport nodes, particularly within Jongno-gu, Dongdaemun-gu, and

Yeongdeungpo-gu, with additional scattered occurrences in areas such as Gangseo-gu and Gangnam-gu. Notable high-risk donges include Jegi-dong, Yongsin-dong, Jongno 1, 2, 3, 4-ga-dong, Yeongdeungpo-dong, Mangubon-dong, and Jeonnong 1-dong. Among them, Jegi-dong recorded the highest number of incidents, with 169 collisions documented during the study period, accounting for 1.84% of the citywide total. In contrast, low-risk donges are primarily dispersed in peripheral areas and locations characterized by relatively weaker transport activity.

Overall, these findings confirm that crash vulnerabilities are not evenly distributed; rather, they are concentrated within core built-up areas and along major transport corridors characterized by intense traffic activity and complex road network structures.

4.2. Spatial pattern of healthcare accessibility to general hospitals

Leveraging the spatial locations and service capacities of 59 general hospitals, potential medical access was quantified at the dong level under 15-minute (T15) and 30-minute (T30) walking thresholds using the Gaussian two-step floating catchment area (Ga2SFCA) method. The resulting spatial patterns are illustrated in Figure 4, while descriptive statistics and class distributions are detailed in Tables 4 and 5, respectively.

As presented in Table 4, under the T15 scenario, the mean accessibility index is 0.100, with a standard deviation of 0.296. Under the T30 scenario, the mean and standard deviation decline to 0.035 and 0.065, respectively. This suggests that as the catchment threshold expands, hospital service coverage increases, while spatial inequalities in healthcare provision across neighborhoods are significantly mitigated.

In terms of accessibility categories (Table 5), under the T15 scenario, only 8 donges (1.89%) fall into the high-accessibility category, 33 donges (7.78%) into the medium-accessibility category, and 383 donges (90.33%) into the low-accessibility category. Under the T30 scenario, the number of high-accessibility donges increases to 11 (2.59%), the medium-accessibility group expands to 71 donges (16.75%), and the number of low-accessibility donges declines to 342 (80.66%). These

results indicate that broadening the walking threshold improves medical access in specific areas; nevertheless, low-accessibility donges still constitute the overwhelming majority.

Spatially, as depicted in Figure 4, the T15 scenario is characterized by a landscape predominantly lacking adequate access, punctuated by isolated high-accessibility enclaves, mainly concentrated around large general hospitals. Under the T30 scenario, high-accessibility areas expand outward, and medium-accessibility zones increase along the urban core and major transport linkages, forming transitional belts extending from the center toward the periphery. Overall, however, the spatial distribution of general hospital resources in Seoul continues to reflect a relatively stable core–periphery structure, characterized by robust agglomeration in central areas and diminished service provision in peripheral districts.

4.3. Spatial coupling between crash risk and healthcare accessibility

Through the spatial superposition of crash-risk and healthcare-accessibility tiers, nine spatial coupling types are delineated. The resulting spatial distributions are mapped in Figure 5, and the corresponding statistical summaries are detailed in Table 6. Overall, the coupling patterns under both threshold settings unveil a pronounced spatial mismatch: high-risk areas do not consistently coincide with high-accessibility zones, while coupling types associated with low accessibility prevail throughout the municipality.

Under the T15 scenario, the low-risk–low-accessibility (LL) type emerges as the predominant category, with 231 donges representing 54.48% of the total, followed by the medium-risk–low-accessibility (ML) type, with 142 donges comprising 33.49%. Under the T30 scenario, the number of LL donges decreases to 202 (47.64%), while coupling types associated with medium accessibility experience a notable expansion. In addition, one high-risk–high-accessibility (HH) dong appears under the T30 scenario, suggesting that a longer walking threshold enhances the alignment between risk and resources in localized areas, although the overall paradigm of spatial inequity remains largely unchanged.

The most salient observation pertains to the high-risk–low-accessibility (HL) type. This type remains remarkably robust under both the 15-minute and 30-minute thresholds, with 10 dongs consistently classified as HL, constituting 2.36% of all dongs in Seoul. The composition of HL dongs remains entirely invariant across the two thresholds. Collectively, these neighborhoods host 58,139 older residents and 764 collisions, corresponding to a localized collision rate of 1.31%, which is substantially higher than the citywide average of 0.61%. The 10 HL dongs are Jegi-dong, Yongsin-dong, Yeongdeungpo-dong, Mangubon-dong, Jeonnong 1-dong, Gil-dong, Siheung 1-dong, Mia-dong, Jangan 1-dong, and Yeoksam 1-dong. As shown in Figure 5, these zones of double vulnerability are not distributed as a continuous cluster, but rather as a combination of point concentration and scattered dispersion. The most pronounced clustering occurs in Dongdaemun-gu, while additional HL dongs appear in Yeongdeungpo-gu, Gangdong-gu, Geumcheon-gu, Gangbuk-gu, Jungnang-gu, and Gangnam-gu—built-up areas and transport corridors characterized by heavy vehicular flows but relatively limited healthcare support. This indicates that specific areas are subject to the persistent intersection of high crash exposure and inadequate healthcare accessibility.

By contrast, the high-risk–high-accessibility (HH) type appears only under the 30-minute threshold and includes just one dong, Jongno 1, 2, 3, 4-ga-dong, where the collision rate reaches 2.18%, the highest among all coupling types. This finding suggests that even in areas with relatively high accessibility to general hospitals, high crash risk may persist because of complex road networks and intense transport volumes.

Overall, the relationship between crash risk and healthcare accessibility at the dong scale in Seoul epitomizes a structurally entrenched pattern of spatial inequality: high-risk areas are disproportionately aligned with low-accessibility types, whereas high-accessibility areas are predominantly correlated with low- or medium-risk types.

5. Discussion

By synthesizing elderly pedestrian crash risk and hospital accessibility into a unified analytical framework, this study uncovers a pronounced risk–service spatial mismatch at the dong level in Seoul. In particular, the 10 dongs categorized as high-risk–low-accessibility remain remarkably consistent under both the 15-minute and 30-minute thresholds, signifying that some areas are chronically subjected to high crash risk while experiencing a deficit in proximity to higher-level healthcare resources. These areas therefore represent quintessential zones of double vulnerability, where transport-related exposure and inequitable medical service allocation overlap spatially.

First, the spatial provision of advanced medical facilities in Seoul manifests a distinct core–periphery pattern, characterized by dense agglomeration in central areas and weaker coverage in peripheral districts. This finding largely corroborates previous studies which demonstrate that higher-level healthcare resources tend to predominantly agglomerate in urban cores rather than being evenly distributed across metropolitan space (Cheng et al., 2020; Li and Wang, 2022; Kim and Kwon, 2022; Liu et al., 2023). More importantly, the present study shows that even when the walking threshold is broadened from 15 minutes to 30 minutes, this overall structure remains virtually unaltered. In other words, a wider catchment enhances superficial service coverage in some dongs, but does not fundamentally alter the underlying geography of higher-level healthcare provision. This implies a deeply entrenched structural rigidity regarding the uneven allocation of general hospitals in Seoul, and underscores that accessibility inequality cannot be comprehensively resolved by threshold expansion alone.

Second, high-risk dongs for elderly pedestrian crashes are predominantly clustered in core built-up areas and along major transport corridors, especially in Jongno-gu, Dongdaemun-gu, and Yeongdeungpo-gu. This pattern aligns with previous studies indicating that elderly pedestrian crashes are highly prone to cluster in areas with dense built environments, mixed land uses, and high levels of traffic exposure (Lee et al., 2020; Kim et al., 2025). The results therefore substantiate the premise that elderly pedestrian crash risk is not merely a byproduct of population size, but is

intricately linked to road complexity, traffic intensity, and the mobility exposure of older adults in everyday urban environments.

More importantly, the spatial coupling analysis demonstrates that crash risk and accessibility to higher-level healthcare resources do not possess an inherent spatial concordance. The high-risk–low-accessibility type exhibits structural persistence under both threshold settings, whereas the high-risk–high-accessibility type appears in only one dong under the T30 scenario. This finding advances earlier studies that have traditionally investigated crash environments or healthcare accessibility in isolation, by illuminating that the spatial overlap between transport risk and medical support is itself a critical dimension of urban inequality. In this sense, the geography of vulnerability is not solely attributable to either unsafe streets or insufficient healthcare provision; rather, it is dictated by the mismatch between where risk is concentrated and where higher-level care is most accessible.

The endurance of the HL type under both thresholds is particularly important from a geographical perspective. These dongs are not merely local hotspots identified under one arbitrary parameter setting, but spatial units that remain vulnerable even when the assumed walking catchment is expanded. Their stability implies that they epitomize a more deeply rooted configuration of urban structure, where chronic traffic hazards intersect with structurally deficient hospital accessibility. This also infers that the identified zones of double vulnerability are not merely methodological artifacts of threshold choice, and instead represent intervention spaces with stronger spatial robustness. From the perspective of applied geography, such stable mismatch zones are critically valuable because they highlight where multiple forms of urban disadvantage become spatially concentrated and where place-based intervention is most urgently mandated.

These findings also offer profound insights into age-friendly urban governance. In many policy discussions, improving healthcare coverage and improving road safety are treated as separate administrative silos. The results of this study indicate that such a separation is fundamentally inadequate in rapidly aging metropolitan contexts. In areas where crash risk is high

but healthcare accessibility remains low, expanding hospital access may bolster post-crash support, but cannot substitute for proactive traffic calming measures in risky walking environments. Conversely, improving road safety alone may still leave older residents in a weak position if higher-level healthcare resources remain difficult to access within everyday walking constraints. For age-friendly urban governance, the paramount imperative is therefore not simply to expand healthcare provision or reduce crash risk in isolation, but to identify and mitigate the spatial mismatch between the two through more holistic, place-based strategies.

The spatial mismatch pattern identified in Seoul resonates with findings from comparable aging cities. Studies in Chinese megacities such as Beijing and Shanghai have similarly documented a core–periphery concentration of higher-level healthcare resources alongside uneven distributions of pedestrian crash risk (Ma et al., 2023; Liu et al., 2025). In European contexts, research on cities such as Milan and Helsinki has demonstrated that older adults in peripheral neighborhoods face compounded disadvantages in both walkability and healthcare proximity (Guida et al., 2022; Tiitu et al., 2024). Taken together, these parallels suggest that the double vulnerability framework developed here is not Seoul-specific, but reflects a broader structural tension in aging cities between the spatial concentration of advanced medical infrastructure and the dispersed geography of everyday pedestrian risk (Lu et al., 2026).

Several limitations warrant acknowledgement. First, this study assesses potential healthcare accessibility to general hospitals rather than emergency-response accessibility in a strict sense, and consequently omits dynamic factors such as real-time traffic conditions, emergency response time, or fluctuating emergency ward capacities. Second, the analysis employs static walking thresholds to gauge localized medical proximities, but excludes multi-modal travel options such as public transit, private vehicles, or pre-hospital transport. Third, the study overlooks nuanced socio-demographic and localized individual susceptibilities, such as income level, household structure, or physical functioning. Future research should advance this paradigm by incorporating dynamic travel costs, multi-modal accessibility, and social vulnerability indicators, thereby providing a

more comprehensive account of how transport risk and healthcare access synergize in aging urban environments.

6. Conclusion

This study establishes an integrated framework of risk identification, accessibility assessment, and spatial coupling analysis, and utilizes Seoul as an empirical case study to investigate the spatial relationship between elderly pedestrian crash risk and hospital accessibility. The results show that both elderly pedestrian crash risk and healthcare accessibility demonstrate marked spatial heterogeneity. High-risk administrative neighborhoods are predominantly agglomerated in the urban core and along major transport corridors, whereas healthcare accessibility to general hospitals manifests a clear core–periphery pattern, with robust coverage in central areas and diminished availability in peripheral districts.

The most profound revelation is the pinpointing of 10 dongs that persistently emerge as high-risk–low-accessibility under both the 15-minute and 30-minute thresholds. Compared with approaches that delineate vulnerable zones strictly through the isolated lenses of crash risk or healthcare accessibility, the spatial coupling perspective adopted here affords a more nuanced comprehension of the compound vulnerability faced by older adults. This further underscores that the paramount challenge in Seoul transcends insufficient traffic safety and inadequate healthcare resources; rather, it is rooted in the absence of an effective spatial synergy between these two dimensions.

In contrast to prior literature that has compartmentalized elderly pedestrian crash risk or healthcare equity, the academic contribution of this research is twofold. First, it integrates elderly pedestrian safety and accessibility to higher-level healthcare resources within a unified analytical framework, thereby advancing the discourse on research on age-friendly cities and health equity. Second, through the comparative analysis of coupling paradigms across varying spatial thresholds, it identifies stable priority intervention areas and furnishes an actionable spatial methodology for

diagnosing zones of double vulnerability (Cheng et al., 2020; Guida et al., 2022; Lee et al., 2020; Li and Wang, 2022).

In terms of policy implications, these findings dictate that high-risk–low-accessibility areas warrant utmost priority within the framework of age-friendly urban governance. In such areas, the mere expansion of healthcare coverage is fundamentally inadequate to mitigate this compound vulnerability. Instead, synergistic interventions are imperative to improve both road safety and the provision of higher-level healthcare resources, thereby fortifying the safety net for the elderly across both the preventative and post-trauma continuum.

References

- Baek H, Leem Y, Lee S, Jo S. Analysis of expert perspectives on possible futures of the urban areas of South Korea. *Futures*. 2022; 141, 102990. <https://doi.org/10.1016/j.futures.2022.102990>
- Balawi M, Tenekeci G (2024) Time series traffic collision analysis of London hotspots: Patterns, predictions and prevention strategies. *Heliyon*. 10. <https://doi.org/10.1016/j.heliyon.2024.e25710>
- Bauer J, Brüggmann D, Klingelhöfer D, et al. (2020) Access to intensive care in 14 European countries: a spatial analysis of intensive care need and capacity in the light of COVID-19. *Intensive Care Med*. 46: 2026–2034. <https://doi.org/10.1007/s00134-020-06229-6>
- Chen L, Chen T, Lan T. et al. (2023) The Contributions of Population Distribution, Healthcare Resourcing, and Transportation Infrastructure to Spatial Accessibility of Health Care. *Inquiry*. 60: 00469580221146041. <https://doi.org/10.1177/00469580221146041>
- Cheng L, Yang M, De Vos J, Witlox F (2020) Examining geographical accessibility to multi-tier hospital care services for the elderly: A focus on spatial equity. *J Transp Health*. 19: 100926. <https://doi.org/10.1016/j.jth.2020.100926>

- Choi E, Seo HJ, Kim KH, Jung SY (2025) Gender-specific secular trends and related factors of high perceived stress level among Korean older adults: a nation-wide serial cross-sectional study. *BMC Public Health* 25: 450. <https://doi.org/10.1186/s12889-025-21644-4>
- Clemente GP, Della Corte F, Zappa D (2024) Hierarchical spatial network models for road accident risk assessment. *Ann Oper Res.* 1-36. <https://doi.org/10.1007/s10479-024-06049-7>
- de Souza AF, de Oliveira DC, Ramírez PC, et al. (2025) Low gait speed is better than frailty and sarcopenia at identifying the risk of disability in older adults. *Age Ageing.* 54: afaf104. <https://doi.org/10.1093/ageing/afaf104>
- Du SJ, Lee SH, Ban YU (2026) Interactive effects of COVID-19 social distancing policies and building density and their impact on GHG emissions in Seoul. *Landsc Urban Plan.* 266: 105535. <https://doi.org/10.1016/j.landurbplan.2025.105535>
- Guida C, Carpentieri G, Masoumi H (2022) Measuring spatial accessibility to urban services for older adults: an application to healthcare facilities in Milan. *Eur Transp Res Rev.* 14: 23. <https://doi.org/10.1186/s12544-022-00544-3>
- Handy SL, Niemeier DA (1997) Measuring Accessibility: An Exploration of Issues and Alternatives. *Environ Plan A.* 29: 1175–1194. <https://doi.org/10.1068/a291175>
- Hansen WG (1959) How Accessibility Shapes Land Use. *J Am Inst Plann.* 25: 73–76. <https://doi.org/10.1080/01944365908978307>
- Hassler J, Ceccato V (2021) Socio-spatial disparities in access to emergency health care—A Scandinavian case study. *PLOS ONE.* 16: e0261319. <https://doi.org/10.1371/journal.pone.0261319>
- HIRA, n.d. HIRA Health Map: General Hospital Information [WWW Document]. Health Insurance Review & Assessment Service. URL <https://www.hira.or.kr/ra/hosp/getHealthMap.do?tabgbn=03&WT.ac=HIRA%EA%B1%B4%EA%B0%95%EC%A7%80%EB%8F%84%EB%B0%94%EB%A1%9C%EA%B0%80%EA%B8%B0#a> (accessed 3.21.26).

- Hu S, Song W, Li C, Lu J (2020) A multi-mode Gaussian-based two-step floating catchment area method for measuring accessibility of urban parks. *Cities*. 105: 102815. <https://doi.org/10.1016/j.cities.2020.102815>
- Jeon J, Woo A (2023) Deep learning analysis of street panorama images to evaluate the streetscape walkability of neighborhoods for subsidized families in Seoul, Korea. *Landsc Urban Plan*. 230: 104631. <https://doi.org/10.1016/j.landurbplan.2022.104631>
- Jeon J, Woo A (2024) Uneven geography of health opportunities among subsidized households: Illustrating healthcare accessibility and walkability for public rental housing in Seoul, Korea. *PLOS ONE*. 19: e0306743. <https://doi.org/10.1371/journal.pone.0306743>
- Jiang Z, Wu C, Chung H (2025) The 15-minute community life circle for older people: Walkability measurement based on service accessibility and street-level built environment – A case study of Suzhou, China. *Cities*. 157: 105587. <https://doi.org/10.1016/j.cities.2024.105587>
- Jiao W, Huang W, Fan H (2022) Evaluating spatial accessibility to healthcare services from the lens of emergency hospital visits based on floating car data. *Int J Digit Earth*. 15: 108–133. <https://doi.org/10.1080/17538947.2021.2014578>
- Kang CD (2024) Measuring Urban Form and Its Effects on Urban Vitality in Seoul, South Korea: Urban Morphometric Approach. *J Urban Plan Dev*. 150: 05024019. <https://doi.org/10.1061/JUPDDM.UPENG-4718>
- Kim K, Horner MW (2025) Integrating People in Place-Based Accessibility Measures: Design and Application of a Mode Choice Accessibility Model. *Ann Am Assoc Geogr*. 115: 854–875. <https://doi.org/10.1080/24694452.2025.2461760>
- Kim K, Kwon K (2022) Time-varying spatial accessibility of primary healthcare services based on spatiotemporal variations in demand, supply, and traffic conditions: A case study of Seoul, South Korea. *J Transp Health*. 27: 101531. <https://doi.org/10.1016/j.jth.2022.101531>

- Kim S, Choi S, Kim BHS (2025) Analysis of factors affecting pedestrian safety for the elderly and identification of vulnerable areas in Seoul. *Accid Anal Prev.* 211: 107878. <https://doi.org/10.1016/j.aap.2024.107878>
- Kotavaara O, Nivala A, Lankila T, et al. (2021) Geographical accessibility to primary health care in Finland – Grid-based multimodal assessment. *Appl Geogr.* 136: 102583. <https://doi.org/10.1016/j.apgeog.2021.102583>
- Lam C, Chen CI, Chuang CC, et al. (2019) Improving the timeliness and accuracy of injury severity data in road traffic accidents in an emerging economy setting. *Int J Qual Health Care.* 31: 140–146. <https://doi.org/10.1093/intqhc/mzy115>
- Lee S, Yoon J, Woo A (2020) Does elderly safety matter? Associations between built environments and pedestrian crashes in Seoul, Korea. *Accid Anal Prev.* 144: 105621. <https://doi.org/10.1016/j.aap.2020.105621>
- Li C, Wang J (2022) A hierarchical two-step floating catchment area analysis for high-tier hospital accessibility in an urban agglomeration region. *J Transp Geogr.* 102: 103369. <https://doi.org/10.1016/j.jtrangeo.2022.103369>
- Liu Z, Li S, Cheng L, Shen Z, Witlox F (2025) Exploring accessibility to medical facilities for older adults: Potential vs. Revealed accessibility. *J Transp Health.* 40: 101952. <https://doi.org/10.1016/j.jth.2024.101952>
- Liu Z, Li S, Zhao X, et al. (2023) Examining Accessibility to Medical Resources for Urban Older Adults with Common Diseases Using Multisource Data: A Case Study of Beijing. *J Urban Plan Dev.* 149: 05023031. <https://doi.org/10.1061/JUPDDM.UPENG-4347>
- Lu G, Wang L, Jiao Y, Du P (2026) Evaluation and optimization of spatial equity in elderly care facilities: a case study of Dalian, China. *Hum Soc Sci Commun.* 13, 168. <https://doi.org/10.1057/s41599-025-06468-2>

- Lu Y, Shang Z, Zhang W, et al. (2025) Global, regional, and national burden of spinal cord injury from 1990 to 2021 and projections for 2050: A systematic analysis for the Global Burden of Disease 2021 study. *Ageing Res Rev.* 103: 102598. <https://doi.org/10.1016/j.arr.2024.102598>
- Luo W, Qi Y (2009) An enhanced two-step floating catchment area (E2SFCA) method for measuring spatial accessibility to primary care physicians. *Health Place.* 15: 1100–1107. <https://doi.org/10.1016/j.healthplace.2009.06.002>
- Luo W, Wang FH (2003) Measures of spatial accessibility to healthcare in a GIS environment: synthesis and a case study in Chicago region. *Environ Plan B.* 30: 865–884. <https://doi.org/10.1068/b29120>
- Ma W, Wang N, Li Y, et al. (2023) 15-min pedestrian distance life circle and sustainable community governance in Chinese metropolitan cities: A diagnosis. *Hum Soc Sci Commun.* 10: 364. <https://doi.org/10.1057/s41599-023-01812-w>
- Maresova P, Krejcar O, Maskuriy R, et al. (2023) Challenges and opportunity in mobility among older adults – key determinant identification. *BMC Geriatr.* 23: 447. <https://doi.org/10.1186/s12877-023-04106-7>
- Ministry of the Interior and Safety (MOIS) [WWW Document], 2026. URL <https://jumin.mois.go.kr/> (accessed 2.8.26).
- Ministry of the Interior and Safety, n.d. Resident registration population statistics [WWW Document]. Ministry of the Interior and Safety. URL <https://jumin.mois.go.kr/> (accessed 3.21.26).
- Pelling M (2003) The vulnerability of cities: natural disasters and social resilience. Earthscan Publications, London ; Sterling, VA.
- Perchoux C, Chaix B, Cummins S, Kestens Y (2013) Conceptualization and measurement of environmental exposure in epidemiology: Accounting for activity space related to daily mobility. *Health Place.* 21: 86–93. <https://doi.org/10.1016/j.healthplace.2013.01.005>

- Radzimski A (2024) Accessibility of Vulnerable Populations to Essential Opportunities: a Multimodal Approach with Application to Four Polish Cities. *Netw Spat Econ.* 1-28. <https://doi.org/10.1007/s11067-024-09660-0>
- Roe J, Mondschein A, Neale C. et al. (2020) The Urban Built Environment, Walking and Mental Health Outcomes Among Older Adults: A Pilot Study. *Front Public Health.* 8: <https://doi.org/10.3389/fpubh.2020.575946>
- Seoul Metropolitan Government, n.d.. Seoul Open Data Plaza. URL <https://data.seoul.go.kr> (accessed 3.21.26).
- Shen Z, Gao G, Wang Z (2021) Accessibility Assessment of Prehospital Emergency Medical Services considering Supply-Demand Differences. *J Adv Transp.* 2021; 1925354. <https://doi.org/10.1155/2021/1925354>
- Smith ML, Ory MG (2023) Multi-directional nature of falls among older adults: A rationale for prevention and management. *Front Public Health.* 11: <https://doi.org/10.3389/fpubh.2023.1117863>
- TAAS, n.d. TAAS [WWW Document]. Korea Road Traffic Authority. URL https://taas.koroad.or.kr/gis/mcm/mcl/initMap.do?menuId=GIS_GMP_STS_RSN (accessed 3.21.26).
- Tang P, Lai S (2019) A framework for managing public security risks with complex interactions in cities and its application evidenced from Shenzhen City in China. *Cities.* 95: 102390. <https://doi.org/10.1016/j.cities.2019.102390>
- Tian F, Lu S, Yang Z, et al. (2025) Spatial analysis of prehospital emergency medical services accessibility: a comparative evaluation of the GAUSS-probability two-step floating catchment area model in Handan City. *Front Public Health.* 13. <https://doi.org/10.3389/fpubh.2025.1548462>
- Tiitu M, Heikinheimo V, Karjalainen LE, Helminen V, Lyytimäki J, Lehtimäki J, Paloniemi R (2024) A spatially explicit comparison of walkability within city-centre and suburban

- contexts in Helsinki, Finland. *Landsc Urban Plan.* 252: 105196.
<https://doi.org/10.1016/j.landurbplan.2024.105196>
- Wang C, Sierra Huertas D, Rowe JW, et al. (2021) Rethinking the urban physical environment for century-long lives: from age-friendly to longevity-ready cities. *Nat Aging.* 1: 1088–1095.
<https://doi.org/10.1038/s43587-021-00140-5>
- Wang F (20202) Why public health needs GIS: a methodological overview. *Ann GIS.* 26: 1–12.
<https://doi.org/10.1080/19475683.2019.1702099>
- Xiao R, Murayama Y, Qin K, et al. (2024) Urban expansion in highly populous East Asian megacities during 1990–2020: Tokyo, Seoul, Beijing, and Shanghai. *Ecol Inform.* 83: 102843.
<https://doi.org/10.1016/j.ecoinf.2024.102843>
- Xinyu Q, Xiongwu X, Xinyan Z, et al. (2023) 6Ds-HLM: Hierarchical models of road traffic crash influencing factor analysis considering the urban built environment of intersection visibility. *Int J Appl Earth Obs Geoinf.* 123: 103472. <https://doi.org/10.1016/j.jag.2023.103472>
- Yunus S, Abdulkarim IA (2022) Road traffic crashes and emergency response optimization: a geo-spatial analysis using closest facility and location-allocation methods. *Geomat Nat Hazards Risk.* 13:1535–1555. <https://doi.org/10.1080/19475705.2022.2086829>
- Zhang S, Ma Y, Ren J, et al. (2025) Research on the spatial allocation of fundamental medical facilities utilizing multi-objective optimization—a case study on Tianjin. *J Asian Archit Build Eng.* 1–23. <https://doi.org/10.1080/13467581.2025.2527286>
- Zhang S, Song X, Zhou J (2021) An equity and efficiency integrated grid-to-level 2SFCA approach: spatial accessibility of multilevel healthcare. *Int J Equity Health.* 20: 229.
<https://doi.org/10.1186/s12939-021-01553-9>
- Zhang S, Wang L, Shen Y, et al. (2024) What causes Emergency Medical Services (EMS) delay? Unravel high-risk buildings using citywide ambulance trajectory data. *Habitat Int.* 153: 103198. <https://doi.org/10.1016/j.habitatint.2024.103198>

Zhang T, Sodhro AH, Luo Z, et al. (2020) A Joint Deep Learning and Internet of Medical Things Driven Framework for Elderly Patients. IEEE Access. 8: 75822–75832.
<https://doi.org/10.1109/ACCESS.2020.2989143>

Figure legends

Figure 1. Spatial patterns of elderly pedestrian crashes and general hospitals in Seoul.

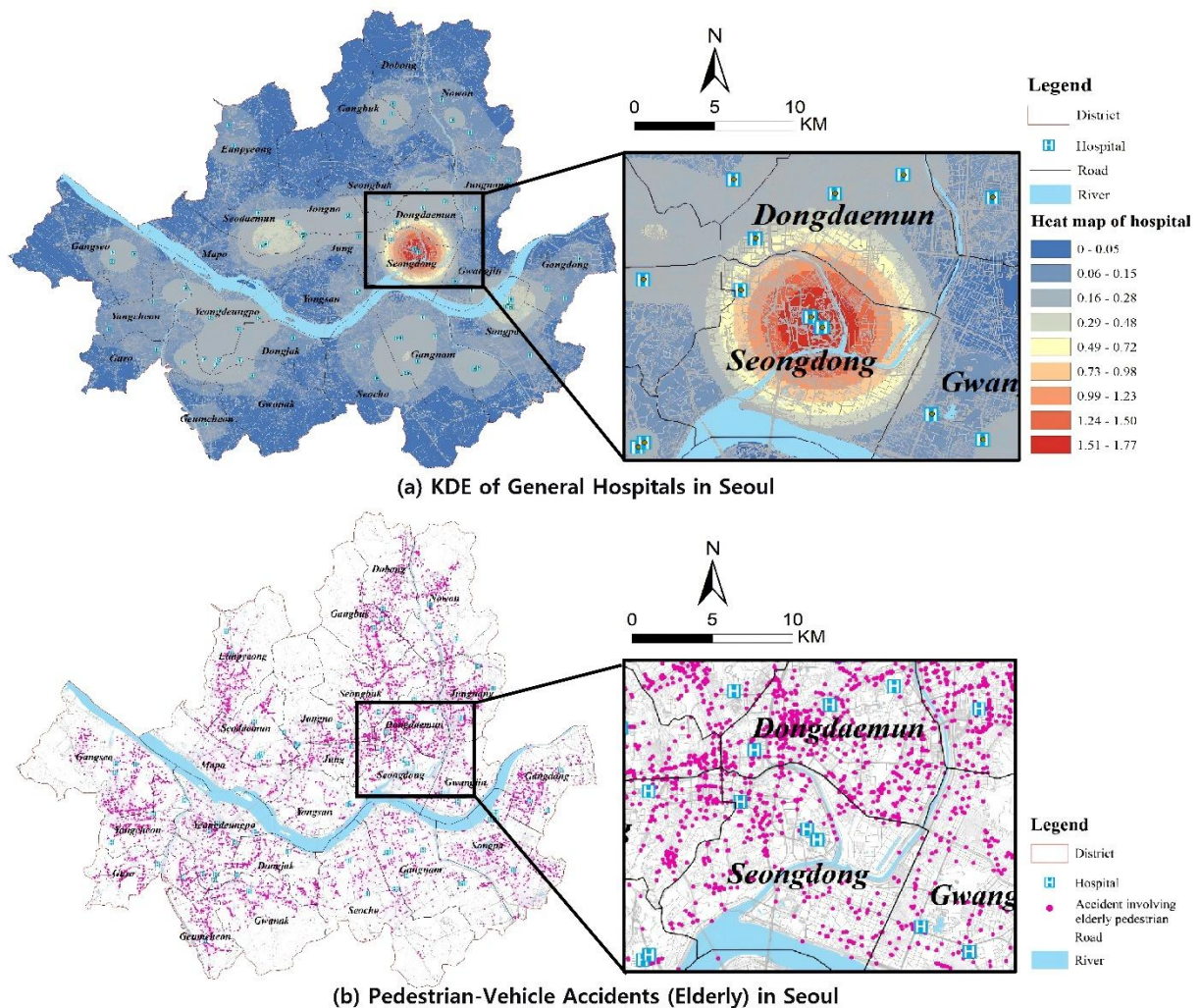


Figure 2. Analytical framework and methodological workflow.

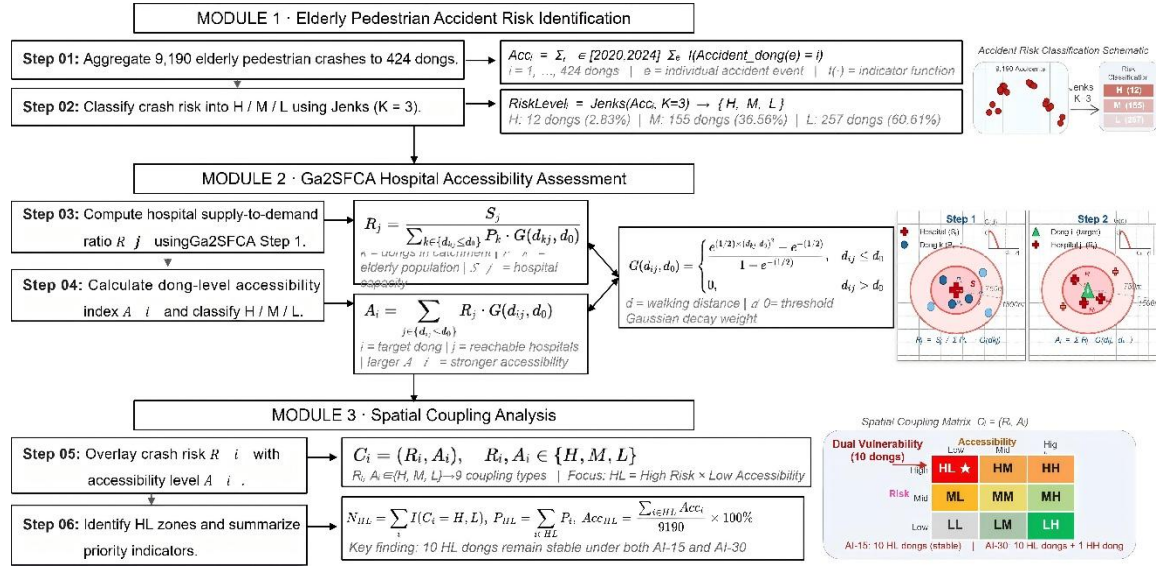


Figure 3. Classification of elderly pedestrian crash risk by dong.

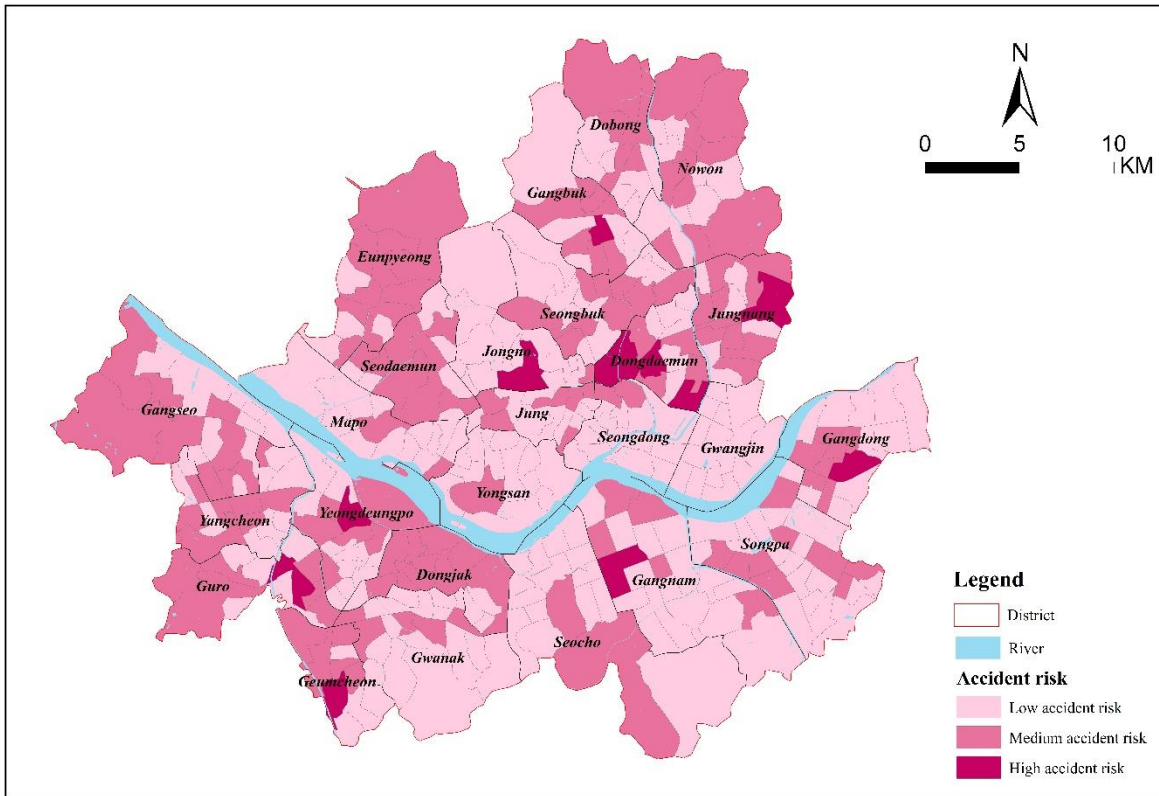


Figure 4. Spatial pattern of healthcare accessibility to general hospitals in Seoul.

Table 1. Descriptive statistics of service capacity of general hospitals in Seoul.

Hospital Category	No. of Hospitals	Average No. of Doctors	Average No. of Beds
All Hospitals	59	257.9	539.8
Level 2 Hospitals	45	102.0	289.4
Level 3 Hospitals	14	664.9	1,364.6

Table 2. Indicators and data sources used in the evaluation framework.

Category	Code	Variable	Definition	Unit	Data source	Analytical role
Crash risk variables	Acci	Cumulative crashes	Cumulative number of elderly pedestrian crashes from 2020 to 2024	Dong	TAAS	Identifying crash risk levels at the dong scale
	Acc_Spatial	Spatial distribution of crashes	Geocoded crash locations and their distribution across dongs	Dong	TAAS	Supporting the analysis of spatial patterns of crash risk
	(Ri)	Crash risk level	High, medium, and low crash risk classified using the Jenks natural breaks method	Dong	TAAS (derived)	Serving as the risk classification basis for spatial coupling analysis
Healthcare accessibility variables	(Sj)	Hospital service capacity	Composite service capacity derived from standardized numbers of doctors and beds	Hospital	HIRA	Serving as the supply indicator in the supply-to-demand ratio
	AI_Dis	Distance-threshold accessibility	Accessibility levels under 750 m and 1500 m distance thresholds	Dong	HIRA + Seoul road network data	Comparing accessibility differences under alternative distance thresholds
	AI-15 / AI-30	Walking-time-threshold accessibility	Accessibility index and classification under 15-min (d0=750m) and 30-min (d0=1500m) walking thresholds	Dong	HIRA + Seoul road network data	Forming the basis for accessibility classification and spatial coupling analysis
	Hospit	Spatial	Hospital	Hospi	HIRA	Calculating

	al_Spa tial	distribution of hospitals	coordinates and spatial distribution	tal		network walking distances between dongs and hospitals
Population variables	(Pk/Pi)	Elderly population	Resident population aged 65 years and over in each dong	Dong	Seoul Metropol itan Governm ent Open Data Platform	Calculating crash rates and supply-to- demand ratios
	Total_ Pop	Total population of Seoul	Total population of Seoul in January 2026	City	Seoul Metropol itan Governm ent Open Data Platform	Describing the demographic background of the study area
Supporting variables	Road_ Net	Road network data	Road hierarchy, crosswalk distribution, and related road attributes	Dong	Seoul Metropol itan Governm ent Open Data Platform	Supporting network-based walking distance estimation
	Dong_ Info	Basic dong information	Dong name, code, and district affiliation	Dong	Seoul Metropol itan Governm ent Open Data Platform	Supporting multi- source data matching and spatial aggregation

Table 3. Statistical summary of elderly pedestrian crash risk.

Risk	Dongs (%)	Elderly (k / %)	Accidents (n / rate, %)	Representative Dongs	Spatial pattern
H	12 (2.83)	68,419 (4.57)	908 (1.33)	Jegi, Yongsin, Jongno1·2·3·4Ga, Yeongdeungpo, Mangubon, Jeonnong 1(il), etc.	Central districts and transport corridors
M	155 (36.56)	667,06 7(44.56)	4,945 (0.74)	Bangi 2(i), Sinwol 1(il), Jongam, Eungam 3(sam), Sangdo 3(sam), etc.	Main urban road corridors
L	257 (60.61)	761,601 (50.87)	3,337 (0.44)	Haengdang 1(il), Seongsu 2(i)-ga1(il), Jeongneung 4(sa), Jangwi 1(il), Dunchon 1(il), etc.	Peripheral and low-traffic areas
Total	424 (100.00)	1,497,087 (100.00)	9,190 (0.61)		

Table 4. Descriptive statistics of the accessibility index (AI) to general hospitals under different threshold settings.

Thres hold	AI n = 424				H				M				L			
	Ma x	M in	Me an	SD	M ax	M in	Me an	S D	M ax	M in	Me an	S D	M ax	M in	Me an	S D
T15	2.2 71	0	0.1 00	0.2 96	2.2 7	1. 55	1.8 8	0. 28	0.9 3	0. 30	0.5 5	0. 20	0.2 8	0	0.0 2	0. 05
T30	0.5 75	0	0.0 35	0.0 65	0.5 8	0. 23	0.3 3	0. 10	0.2 1	0. 06	0.1 1	0. 04	0.0 5	0	0.0 1	0. 01

Table 5. Distribution of donges and crash statistics across accessibility classes under T15 and T30 thresholds.

T	Class	Dongs(%)	Elderly (k / %)	Accidents (n / rate, %)	Representative Donges	Spatial pattern
T 15	H	8 (1.89)	36,769 (2.46)	174 (0.47)	Balsan1, Jingwan, Sinchon, Pungnap 2(i), Dunchon 2(i), etc.	Concentrated around general hospitals
	M	33 (7.78)	120,592 (8.05)	747 (0.62)	Jongno1·2·3·4Ga, Guro 2(i), Yeoui, Sinnae 1(il), Heukseok, Suseo, Hwigyeong 2(i), etc.	Distributed in the urban core and secondary healthcare clusters
	L	383 (90.33)	1,339,726 (89.49)	8,269 (0.62)	Myeonmokbon, Cheongnyangni, Doksan 1(il), Hoehyeon, Myeonmok3·8, Seokgwan, etc.	Widely distributed in peripheral low-coverage areas
T 30	H	11 (2.59)	46,271 (3.09)	274 (0.59)	Jongno1·2·3·4Ga, Suseo, Jingwan, Sinchon, Pungnap 2(i), etc.	Concentrated around general hospitals and in the urban core
	M	71 (16.75)	247,741 (16.55)	1,419 (0.57)	Guro 2(i), Dongseon, Yeoui, Sinnae 1(il), Noryangjin 1(il), etc.	Expanded toward the periphery, forming transitional belts
	L	342 (80.66)	1,203,075 (80.36)	7,497 (0.62)	Jegi, Yongsin, Yeongdeungpo, Jeonnong 1(il), Mangubon, etc.	Mainly distributed in peripheral edge areas
Total		424 (100.00)	1,497,087 (100.00)	9,190 (0.61)		

Table 6. Distribution of spatial coupling types between crash risk and healthcare accessibility.

T	Type	Dongs (%)	Elderly (k / %)	Accidents (n / rate, %)	Representative Dongs	Spatial pattern
T 15		—	—	—	—	
T 30	HH	1 (0.24)	3,766 (0.25)	82 (2.18)	Jongno1·2·3·4Ga	High-accessibility, high-risk warning area
T 15	HM	2 (0.47)	10,280 (0.69)	144(1.40)	Jongno1·2·3·4Ga, Guro 2(i)	High-exposure transitional area
T 30		1 (0.24)	6,514 (0.44)	62 (0.95)	Guro 2(i)	
T 15	HL	10 (2.36)	58,139 (3.88)	764(1.31)	Jegi, Yongsin, Yeongdeungpo, Mangubon, Jeonnong 1(il), etc.	Zones of double vulnerability
T 30		10 (2.36)	58,139 (3.88)	764 (1.31)	Jegi, Yongsin, Yeongdeungpo, Mangubon, Jeonnong 1(il), etc.	
T 15	MH	4 (0.94)	21,980 (1.47)	109(0.50)	Balsan1, Jingwan, Pungnap 2(i), Sinchon	Resource-rich transitional area
T 30		4 (0.94)	21,921 (1.46)	106 (0.48)	Suseo, Jingwan, Pungnap 2(i), Sinchon	
T 15	MM	9 (2.12)	38,947 (2.60)	279(0.72)	Yeoui, Sinnae 1(il), Heukseok, Suseo, Hwigyeong 2(i), etc.	Balanced risk– resource area
T 30		21 (4.95)	92,746 (6.20)	648 (0.70)	Dongseon, Yeoui, Sinnae 1(il), Noryangjin 1(il), Balsan1, Deungchon 3(sam), etc.	
T 15	ML	142 (33.49)	606,140 (40.49)	4,557 (0.75)	Bangi 2(i), Sinwol 1(il), Jongam, Sinjeong 4(sa), Eungam 3(sam), etc.	Potentially vulnerable area
T 30		130 (30.66)	552,400 (36.90)	4,191 (0.76)	Bangi 2(i), Sinwol 1(il), Jongam, Eungam 3(sam), Sinjeong 4(sa), etc.	
T 15	LH	4 (0.94)	14,789 (0.99)	65 (0.44)	Dunchon 2(i), Ihwa, Hyehwa, Irwonbon	Ideal match area
T 30		6 (1.42)	20,584 (1.37)	86 (0.42)	Dunchon 2(i), Ihwa, Hyehwa, Irwon 1(il), Irwonbon, Jamsil 4(sa)	

T 15	LM	22 (5.19)	71,365 (4.77)	324 (0.45)	Banpo 4(sa), Yeoksam 2(i), Euljiro, Anam, Hannam, etc.	Beneficiary area of accessibility improvement
T 30		49 (11.55)	148,481 (9.92)	709 (0.48)	Haengdang 1(il), Yeoksam 2(i), Euljiro, Banpo 4(sa), Daerim 1(il), etc.	
T 15	LL	231 (54.48)	675,447 (45.11)	2,948 (0.44)	Suyu 1(il), Nonhyeon 2(i), Hwagok 2(i), Jangwi 1(il), Jeongneung 4(sa), Haengdang 1(il), Seongsu 2(i)-gal(il), Singil 7(chil), etc.	Resource- deficient background area
T 30		202 (47.64)	592,536 (39.58)	2,542 (0.43)	Suyu 1(il), Nonhyeon 2(i), Hwagok 2(i), Jangwi 1(il), Jeongneung 4(sa), Seongsu 2(i)-gal(il), Singil 7(chil), etc.	
Total		424 (100.00)	1,497,087 (100.00)	9,190 (0.61)		

Data availability

All datasets used in this study are publicly accessible through open government platforms. Elderly pedestrian crash data (2020–2024) were retrieved from the Traffic Accident Analysis System (TAAS) operated by the Korea Road Traffic Authority, available at: <https://taas.koroad.or.kr>. General hospital location and service capacity data were obtained from the Health Insurance Review and Assessment Service (HIRA) Health Map, available at: <https://www.hira.or.kr/ra/hosp/getHealthMap.do>. Elderly population statistics and road network data at the dong level were sourced from the Seoul Open Data Plaza, operated by the Seoul Metropolitan Government, available at: <https://data.seoul.go.kr>. Resident registration population statistics were obtained from the Ministry of the Interior and Safety (MOIS), available at: <https://jumin.mois.go.kr>. All datasets were accessed in March 2026. No additional datasets were generated during this study.

Ethics approval and consent to participate

This study used only publicly available, aggregated crash records and hospital location data. No human participants or personally identifiable information were involved. Therefore, ethical approval and informed consent were not required.

Consent for publication

Not applicable.

Conflict of Interest

The authors declare no competing interests.

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