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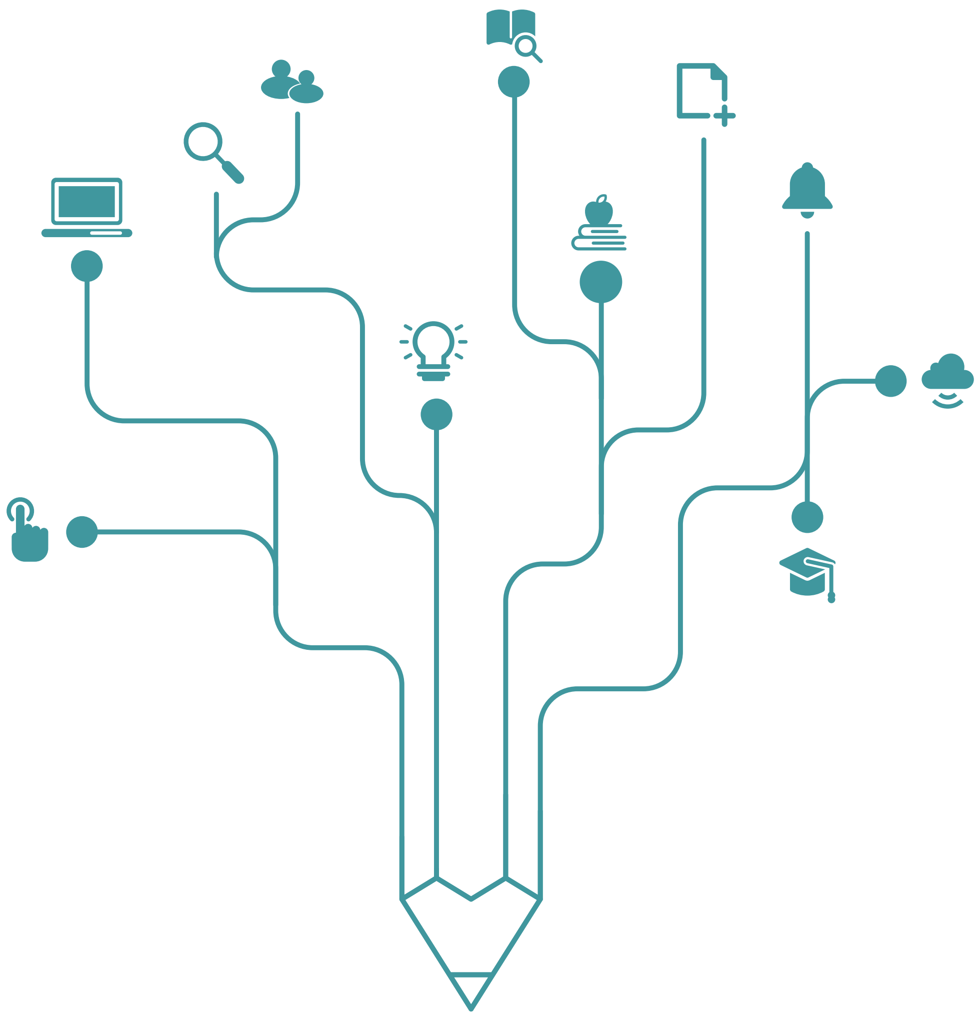
Heeyoung Cho (Public Safety and Traffic Department, Korea National Policy Agency)
Joeun Kim (KDI School of Public Policy and Management)



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Heeyoung Cho[1¶], Joeun Kim[2¶]

[1]Public Safety and Traffic Department, Korea National Policy Agency, Seoul, South Korea

[2] KDI School of Public Policy and Management, Sejong, South Korea

*Corresponding author

E mail: joeunkim@kdischool.ac.kr(JK)

Abstract

Pedestrian-vehicle crashes have been a leading cause of non-disease-related hospitalization, disability, and mortality among the elderly across the globe. Despite this, interventions addressing elderly pedestrian-vehicle crashes have received limited attention. This study examines the association between the Silver Zone program, a government initiative to enhance road safety for elderly pedestrians, and elderly pedestrians' safety outcomes in Seoul, South Korea. Using longitudinal data from multiple government sources spanning 2007 to 2022, we analyzed within-district changes in the number of crashes, severe injuries, and fatalities following Silver Zone installations across dong-districts. The findings reveal significant reductions in pedestrian crashes and severe injuries among the elderly in districts with additional Silver Zones, though outcomes varied by gender. Female elderly pedestrians experienced substantial safety improvements, while results for male pedestrians were mixed. The study underscores the importance of tailored safety measures for elderly pedestrians and calls for further research to explore more gender-specific responses to these interventions.

Keywords: Car Crash, Elderly Pedestrian, Silver Zone, Random Effect

Introduction

The rapidly aging populations across high-income countries across the globe have compelled scholars and policymakers to develop preventative measures to reduce health and mortality risks among the elderly (aged 65 or more). While public health research has extensively covered chronic and non-communicable diseases in older populations, less attention has been paid to improving road safety for this demographic. This oversight is significant given pedestrian-vehicle crashes constitute a leading cause of non-disease related hospitalization, disability[1,2], and mortality of the elderly [3]. Moreover, pedestrian-vehicle crashes are more likely to result in fatalities, severe injuries for elderly pedestrians compared with other road users and pedestrians of younger age groups [4–8]. The urgency to improve elderly pedestrian safety continues to grow, as population projections and traffic injury trends project a dramatic increase in elderly pedestrian deaths worldwide, from 83,183 in 2021 to over 130,000 by 2050 (see S1 table), with especially high-density urban areas are expected to face the steepest rise [9].

Public health concerns regarding elderly pedestrian car crashes are growing, prompting policymakers to consider targeted interventions. South Korea (Korea hereafter) introduced the Silver Zone in 2007, reducing speed limits and enhancing safety facilities in areas frequently visited by elderly pedestrians [10]. Similar initiatives, such as Singapore's Silver Zone, Green Man Plus system, and the United States' Safe Routes for Seniors program, have been implemented elsewhere [10]. However, the effectiveness of these interventions in reducing crashes, injuries, and mortality—and to what extent—remains unclear. In South Korea, prior research has shown limited effectiveness of the silver zone in reducing road collisions[10] , but these analyses were restricted to short time periods and small geographic areas, indicating a need for more comprehensive analyses.

This study aims to address this gap by examining the impact of the Silver Zone on all the car crashes, severe injuries, and mortalities among elderly pedestrians in Seoul, South Korea. Korea serves as a compelling case study, with a rapidly aging population and persistently high elderly pedestrian car crash rate, with older adults accounting for nearly 60 percent of all pedestrian crashes [11] . While overall injury-related hospitalization and mortality rates among the elderly have declined in recent decades[12], transport-related injuries, particularly pedestrian injuries, remain stubbornly high, placing Korea among the highest in elderly pedestrian fatalities among OECD nations[13]. Seoul's elderly population is particularly vulnerable, given the city's exceptionally high population density and rapidly aging demographic[14].

This study analyzes data from multiple administrative sources, including the Seoul city government and the Korea Road Traffic Authority. Focusing on the Dong district level—the smallest administrative unit in South Korea—we examine associations between Silver Zone installations and incident rates of car crashes, severe injuries, and deaths among elderly pedestrians and whether these associations vary by gender. Analyzing within-district changes from 2007 (the program's inception) to 2022, this study provides the comprehensive assessment of Silver Zone safety patterns, offering valuable insights for policymakers seeking to enhance road safety interventions and improve the health and well-being of aging populations in urban settings.

Background

Pedestrian-Car Crashes: Major Cause of Hospitalization and Deaths among the Elderly

Pedestrian-vehicle crashes represent one of the most significant non-disease threats to elderly health and mortality. These incidents are a leading cause of hospitalization, disability [1,2], and death among the elderly population[3]. Research consistently shows that older adults face disproportionate risks in traffic crashes, with elderly pedestrians experiencing particularly high rates of fatal outcomes compared to both younger pedestrians and other road users[15–17].

The health consequences of these crashes are particularly severe for elderly pedestrians. A comprehensive meta-analysis of 60 studies involving one million pedestrians revealed that elderly victims face significantly higher risks of critical injuries and require longer hospitalization periods, including extended intensive care stays, compared to younger pedestrians [18]. These prolonged recovery periods often lead to additional health complications, further compromising elderly independence and well-being.

The unique vulnerability of elderly pedestrians arises from a combination of age-related factors that affect their ability to navigate traffic safely. In complex traffic environments, older pedestrians frequently encounter difficulties with crucial decision-making tasks, such as accurately judging vehicle speeds and interpreting traffic signals [19]. Street crossing poses challenges, as it requires simultaneous processing of multiple stimuli, quick decision-making, and precise physical control—abilities that typically diminish with age[17]. These cognitive challenges are compounded by physical limitations that further increase accident risk. Reduced mobility, slower walking speeds, and diminished balance recovery abilities make elderly pedestrians more susceptible to accidents and less capable of avoiding sudden collisions. Age-related sensory decline, particularly in vision and hearing, further compromises their ability to detect approaching vehicles or respond to warning signals [20].

The scope of this challenge is expected to expand globally due to several converging trends. First, population aging is increasing the absolute number of elderly pedestrians. Second, growing awareness of walking's health benefits has encouraged more elderly individuals to engage in pedestrian activity. Third, as aging makes driving more challenging, many elderly individuals shift to walking and public transportation as primary mobility options. Fourth, rising elderly labor force participation and social engagement are increasing their exposure to traffic risks. These patterns are particularly evident in South Korea, where elderly pedestrians now account for 60% of all pedestrian fatalities in vehicle collisions—a proportion that continues to rise [11]. This disproportionate impact reflects both Korea's rapid population aging and the high mobility patterns of its urban elderly population.

In response to these challenges, policymakers have begun implementing various preventative measures for elderly road safety. However, despite the urgency of this issue and the range of policy interventions being deployed, evidence regarding the effectiveness of these safety measures remains limited and inconsistent, highlighting the critical need for rigorous evaluation of existing programs.

Gender differences in pedestrian behavior

The impact of Silver Zone installations on elderly pedestrian safety may vary by gender, though the direction and magnitude of these differences remain unclear. Several factors suggest potentially different effects for elderly men and women.

Silver Zones might yield greater safety benefits for elderly women for several reasons. First, transportation patterns differ substantially by gender: elderly women are more likely to be pedestrians than drivers, while men more frequently drive vehicles and travel longer distances [21]. Second, elderly women engage in more leisure walking compared to men [22], potentially increasing their exposure to traffic risks. Third, gender differences in mobility patterns are reflected in walking speeds—elderly men average 1.14m/s compared to 1.10m/s for elderly women [23]—suggesting women may spend more time in crossing zones. Additionally, female pedestrians over age 20 face higher risks of serious injuries in pedestrian-vehicle collisions compared to their male counterparts [24].

Conversely, several factors suggest Silver Zones could yield greater safety improvements for elderly men. Male pedestrians typically exhibit riskier road behaviors, including shorter waiting times at crosswalks, faster walking speeds, and a higher likelihood of conflicts with motor vehicles [25]. These behavioral patterns may make men more responsive to safety infrastructure improvements. Supporting this possibility, men are found to face significantly higher odds of severe injuries, particularly in situations conducive to risky behavior such as rural areas or nighttime travel where speeding is more common [26]. By implementing physical changes to road design and reducing vehicle speeds, Silver Zones might be particularly effective in mitigating these risk-taking behaviors.

Silver Zone Program in South Korea

South Korea introduced the Silver Zone program in 2007 as a comprehensive infrastructure intervention to enhance elderly pedestrian safety. In 2022, 2,673 zones have been designated across the country [27], reflecting the program's substantial expansion over less than two decades.

Since the program was initiated, areas within 300 meters of elderly welfare facilities, parks, and recreational sports facilities were primarily eligible to be designated as the Silver Zones. However, designation tends to concentrate on elderly leisure welfare facilities, such as senior welfare centers and senior community centers, which accounted for 2,333 out of 2,673 zones (87.3%) [28]. Meanwhile, academia and the media have continuously pointed out that Silver Zones legislation failed to include areas with higher demand for design improvement, such as traditional markets, where elderly pedestrian-car crashes occurred with higher frequencies and often resulted in fatalities. Along with the ongoing request and criticism, Seoul started to include traditional markets in the eligible areas to be designated as the Silver Zones in 2021 by legislating its own municipal ordinance [29].

The Silver Zone designation enables multiple layers of road design and traffic infrastructure improvements. First, traffic signals within these zones are encouraged to be calibrated to accommodate the slower walking speeds of elderly pedestrians. Second, a maximum speed limit of 30 km/h can be imposed throughout the zone, marked by prominent "Elderly Protection Zone" signage. Third, parking restrictions are strictly enforced, with violations incurring double the fines compared to non-Silver Zones. Other measures, such as the installation of speed bumps and raised crosswalks, implementation of road narrowing and traffic calming features, enhanced lighting systems for better visibility, installation of median refuges for safer road crossing, additional warning signals and road markings, automated speed enforcement cameras, and modifications to intersection geometry are encouraged to be adopted according to needs.

Previous evaluations of South Korea's Silver Zone program have found limited evidence of effectiveness. Choi et al. [10] analyzed Silver Zones in Seoul (2007-2014) and found no significant reduction in elderly pedestrian-vehicle crashes within designated zones, noting that zones were often not strategically located in high-crash areas. The program's limited impact may stem from inadequate implementation. For instance, one study [30]'s assessment of Busan's Silver Zones (2008-2014) revealed substantial gaps between government standards and actual implementation, including insufficient road facilities (speed bumps and enforcement cameras) and improper engineering specifications (traffic signal timing and sidewalk width). Similarly, another study [31] found no significant reduction in elderly pedestrian crashes attributable to Silver Zones when controlling for other safety measures.

This study advances our understanding of Silver Zone effectiveness in several important ways. First, we provide a more comprehensive assessment by analyzing within-district changes at the Dong level (the smallest administrative unit) over an extended period (2007-2022), offering greater precision in estimating program effects. Second, we examine whether Silver Zone effectiveness varies by gender, with particular attention to elderly women who face elevated risks of severe injuries in vehicle-pedestrian collisions. This gender-specific analysis can inform more targeted safety interventions. Finally, our longitudinal approach enables us to assess whether implementation quality and effectiveness have improved over time, addressing limitations identified in earlier studies.

Materials and Methods

Data and Sample

We used multiple datasets from government agencies to examine the impact of the Silver Zone on elderly pedestrian crashes, injuries, and mortalities.

First, we utilized data from the Traffic Accident Analysis System (TAAS), an open-source platform providing comprehensive car crash statistics for South Korea (https://taas.koroad.or.kr/web/shp/ine/initTaas.do). We collected data from 2007, when the Silver Zone program was initiated, through 2022. TAAS provides detailed information on each case, including location (at the Dong district level), victim and perpetrator characteristics, injury severity, and fatalities. We filtered the dataset to include only crashes involving pedestrian victims aged 65 or older (N=29,898), then aggregated the data to create Dong-level yearly records. Each record represents a unique Dong-year combination, containing the number of elderly pedestrian-car crashes, injuries, and fatalities.

Second, we obtained information on Silver Zone implementation from the Seoul City government's official data portal (data.seoul.go.kr). This publicly accessible database provides annual data on newly installed Silver Zones at the Dong (neighborhood) level. We aggregated this data to create a variable representing the cumulative number of Silver Zone areas for each Dong from 2007 to 2022. This approach allows us to examine how changes in Silver Zone coverage over time within Dong districts correlate with fluctuations in elderly pedestrian-car crashes.

Lastly, to account for potential confounding factors, we incorporated various control variables. Population data was obtained from the Resident Registration Population Statistics portal(https://jumin.mois.go.kr/) provided by the Ministry of the Interior and Safety of Korea. Data for the other covariate variables were sourced from Seoul City's official data portal(data. Seoul.go.kr). These control variables include registered population registered population, elderly population (65+), elderly population rate, School Zones, population, area, number of crosswalks, number of recipients of Basic Livelihood Security Benefits from the government, car crashes that occurred one year before the observation year, and number of any types of car crashes within Gu district, over the years from 2007 to 2022.

A unit of analysis needs to be created by combining two types of districts called Dong: the administrative Dong(n=455) and the legal Dong(n=425), and 86 of them have overlapping values. The legal district Dong, which is traditionally passed down over time and used as an official address for legal actions, and the administrative Dong, which is more flexible and changeable based on the demand of the residents and administrative tasks (Seoul Metropolitan Government, 2024). As of November 2024, a total number of 426 administrative Dong and 467 legal Dong exist. In this study, former administrative and legal Dongs that are no longer in use are also included to ensure comprehensive coverage of the data. Certain data, such as the number of residents, is collected and managed by administrative Dong (Seoul city, 2024), while other data, such as road crashes, are handled by legal district Dong.

As data collected for the variables are managed by either type of district depending on the data provider's needs, we created a new unit of analysis (PID) by concatenating district Gu, legal Dong, and administrative Dong and obtained a total of 733 units. In this manner, a total number of 23,456 (733 units × 12 years × two genders) observations were created. Of the 23,456 observations, the majority (17,694 or 75.43%) did not include Silver Zones. These observations were excluded, leaving a final dataset of 6,679 observations for analysis.

Meanwhile, it should be noted that TAAS data is exclusively sourced from police reports, potentially underestimating total incident occurrences due to unreported road crashes.

Measures

Outcome Variables

This study included three dependent variables to measure the traffic safety of elderly pedestrians. The first variable includes the number of elderly pedestrian-car crashes. The second variable includes the number of severe injuries, defined as injuries that require more than 3 weeks of medical treatment, caused by pedestrian crashes. The third variable is the number of fatalities of elderly pedestrian-car crashes. We use a one-year lead measure (t+1) for each dependent variable to identify a more accurate association between them.

Independent Variable (The Silver Zone)

To quantify the implementation of Silver Zones, we measure the total number of Silver Zones installed in each Dong (neighborhood) since 2007. We calculated the cumulative amount of Silver Zones since the program's inception in 2007 by aggregating the number of newly installed Silver Zone areas each year. This cumulative approach was feasible and appropriate because once a Silver Zone was established in an area, it remained in place throughout the study period.

Covariates

We considered various control variables, including traffic safety infrastructure and socio-economic factors were considered as covariates. To improve the model’s accuracy, we included various covariates.

Analytic Strategy

Random Effect Poisson (REP) Model / Random Effect Negative Binomial (RENB) Model

This study employs both Random Effect Poisson (REP) and Random Effect Negative Binomial (RENB) models to analyze our dependent variables: counts of elderly pedestrian-car crashes, severe injuries, and fatalities. These models are chosen for several key reasons.

First, since our dependent variables are discrete, non-negative count data with relatively low arithmetic means (typically <10), Poisson regression is more appropriate than standard OLS regression [32]. However, the Poisson model assumes equality between mean and variance, which can be problematic when data exhibits overdispersion [33]. In such cases, the Negative Binomial model may be more suitable as it accounts for unexplained variability among individuals with the same predictions [32].

Second, we incorporate random effects into both models to account for location-specific variations over time, which neither standard Poisson nor Negative Binomial models adequately capture [34]. Random effects are particularly appropriate for evaluating vehicle-pedestrian collisions as these incidents typically exhibit location-specific patterns [34,35]. We opted for random effect over fixed effect despite the Hausman test result suggesting that fixed effects would be a better fit for our dataset. The fixed effect is expected to better explain Dong-level location-specific patterns in the results. Nevertheless, for robustness, we report fixed effects results in S2 Table.

Results

Table 1 presents descriptive statistics of the sample of the original 23,456 observations. Dependent variables, including car crashes, severe injuries, and fatalities, are count data that occurred one year after the Silver Zone data was tallied. The mean number of car crashes is 4.35, with a standard deviation of 6.34, which indicates that 4.35 elderly pedestrian-car crashes occurred within Dong district on a yearly basis but with higher variability as it ranges from 0 to 43. Female elderly pedestrians are more likely to fall victim to car crashes, with a mean of 5.64 crashes, which is higher than 3.06 for male elderly pedestrians. Severe injuries, with a mean of 2.58, follow a similar pattern, as the mean for the female is 3.54, which is higher than the 1.63 of their male counterparts. Fatalities, which occur with comparably less frequency, display a mean of 0.19 and range from 0 to 4. Regarding the gender difference, the mean for the female is 0.24, which is higher than the 14 of the males.

The Independent variable, the Silver Zone, ranges from 0 to 7 within the Dong district, with a mean of 0.38 and a standard deviation of 0.90. Most observations are clustered around 0 counts of the Silver Zone (75.43%). In comparison, School Zones for children are more prevalent across the Dong district, with a mean of 10.88, a standard deviation of 8.62, and a range from 1 to 39.

Table 1. Descriptive Statistics of Samples

Dependent Variables	All(n=21,990)			Female(n=10,995)			Male(n=10,995)		
	Mean(SD)	Median(IQR)	Min-Max	Mean(SD)	Median(IQR)	Min-Max	Mean(SD)	Median(IQR)	Min-Max
Frequency of Crashes (1 year lead)	4.35(6.34)	2.00(6.00)	0-43	5.64(7.68)	2.00(8.00)	0-43	3.06(4.26)	1.00(4.00)	0-29
Severe injury (1 year lead)	2.58(4.00)	1.00(4.00)	0-26	3.54(4.93)	1.00(5.00)	0-26	1.63(2.42)	1.00(2.00)	0-17
Fatality (1 year lead)	0.19(0.51)	0.00(0.00)	0-4	0.24(0.57)	0.00(0.00)	0-4	0.14(0.43)	0.00(0.00)	0-3
Independent Variable	**All(n=23,456)**								
	Mean(SD)	Median(IQR)	Min-Max	Mean(SD)	Median(IQR)	Min-Max	Mean(SD)	Median(IQR)	Min-Max
Silver Zone	0.38(0.90)		0-7	-	-	-	-	-	-
Covariates	All			Female			Male		
	Mean(SD)	Median(IQR)	Min-Max	Mean(SD)	Median(IQR)	Min-Max	Mean(SD)	Median(IQR)	Min-Max
Population(n=21,712)	9901.03 (5316.45)	9,948(7,378)	29-30,612	10051.77 (5473.37)	10,113(7,652)	29-30,612	9750.29 (5150.61)	9,804(7,214)	35-28,438
Elderly population(n=21,712)	1293.80 (707.63)	1,192(871)	5-4,995	1448.50 (771.13)	1,347(972)	5-4,995	1139.09 (599.18)	1,044(719)	6-3,868
Elderly rate*(n=21,712)	0.14 (0.04)	0.135(0.06)	0.032-0.465	0.158 (0.050)	0.150(0.06)	0.053-0.465	0.127 (0.04)	0.120(0.05)	0.032-0.32
School Zone(n=12,673)	10.88 (8.62)	9(11)	1-29	-	-	-	-	-	-
Crosswalk(n=21,259)	388.79 (424.63)	230(526)	1-2,097	-	-	-	-	-	-
Area(n=15,988)	1.54 (1.70)	1.01(0.88)	0.23-12.68	-	-	-	-	-	-
Basic livelihood security recipients(n=17,779)**	244.91 (310.67)	240(313)	0.46/9788.96	245.09 (317.32)	229(326)	0.48-9788.96	244.73 (303.89)	259(292)	0.46-9607.03
Number of any type of car crashes (Gu district)	1598.73 (610.96)	1,442(540)	522-3970	-	-	-	-	-	-
Number of severe injuries by any type of car crash (Gu district)	2245.73 (901.89)	2018(833)	705-5,686	-	-	-	-	-	-
Number of fatalities by any type of car crash (Gu district)	14.29(6.92)	13(9)	2-41	-	-	-	-	-	-

Tables 2, 3, and 4 present the varying effects of Silver Zones on pedestrian-car crashes using Random Effect Negative Binomial and Random Effect Poisson models. The results of the two models are compared by their log-likelihood values, with more appropriate models being identified by a lower log-likelihood figure. The result is explained with Incident Rate Ratio (IRR) to display the relationship between the intervention and the outcome more intuitively. If the IRR of the outcome variable is less than 1.0, the increase in the Silver Zone is associated with the reduction in car crashes, severe injuries, or fatalities. Conversely, if the IRR is higher than 1.0, the addition of the Silver Zone is related to the increase in those three types of outcome variables.

Frequency of Elderly Pedestrian-Car Crashes

Table 2 illustrates the impact of Silver Zones on the number of car crashes involving elderly pedestrians. In both the Random Effect Poisson (REP) and Random Effect Negative Binomial (RENB) models, a consistent decreasing trend in car crashes involving female elderly pedestrians is observed. Districts with two or more Silver Zones show an estimated reduction of 18% (REP) and 19% (RENB) in crash cases compared to districts without Silver Zones. These findings highlight the potential positive effect of Silver Zones for this demographic.

Conversely, for male elderly pedestrians, the analysis reveals a slight increase of approximately 6% in car crashes across districts with one or two or more Silver Zones in both models. However, this trend lacks sufficient evidence to suggest a meaningful association.

When comparing the two models, the Negative Binomial model appears to align more closely with the data characteristics, suggesting it may better account for variability in crash counts.

Table 2. The Impact of the Silver Zone on Frequency of Elderly Pedestrian-Car Crashes

Applied Model	Number of Silver Zones	Elderly Female Pedestrians (n=3,341)		Elderly Male Pedestrians (n=3,338)	
		IRR* (95% CI)	P - value	IRR (95% CI)	P - value
Random Effect Poisson Model (REP)	0 (reference)				
	1	0.95(0.90-1.00)	0.067	1.06(1.00-1.13)	0.047
	2(or more)	0.82(0.76-0.89)	0.000	1.06(0.97 1.16)	0.169
Random Effect Negative Binomial (RENB)	0 (reference)				
	1	0.95(0.90-1.00)	0.069	1.06(1.00-1.13)	0.044
	2(or more)	0.81(0.74-0.880	0.000	1.06(0.96-1.16)	0.225

*IRR, Incident Rate Ratio of frequency of elderly pedestrian-car crashes after the Silver Zones are installed within the district Dong

Severe Injuries

Table 3 examines the impact of Silver Zones on the number of severe injuries among elderly pedestrians, using both the Random Effect Poisson (REP) and Random Effect Negative Binomial (RENB) models. Consistent with the result of car crashes in Table 2, the findings indicate a reduction in severe injuries among female elderly pedestrians in districts with two or more Silver Zones. Specifically, reductions of 16% and 17% are estimated under the Poisson and Negative

Binomial models, respectively, underscoring the potential protective effects of Silver Zones for this group.

For male elderly pedestrians, the analysis shows a slight increase in severe injuries, but the evidence supporting this trend is weak, suggesting no clear association between the presence of Silver Zones and severe injuries for this demographic.

Similar to the findings for car crashes, the Negative Binomial model appears to better capture the variability in severe injury counts, making it a more suitable modeling approach for this analysis.

Table 3. The Impact of the Silver Zone on Severe Injuries of elderly pedestrian-car crashes

Applied Model	Number of Silver Zones	Elderly Female Pedestrians (n=3,341)		Elderly Male Pedestrians (n=3,338)	
		IRR* (95% CI)	P - value	IRR (95% CI)	P - value
Random Effect Poisson Model (REP)	0 (reference)	-	-	-	-
	1	0.95(0.90-1.01)	0.069	1.06(1.00- 1.13)	0.044
	2(or more)	0.84(0.77-0.92)	0.000	1.06(0.96-1.16)	0.225
Random Effect Negative Binomial (RENB)	0 (reference)	-	-	-	-
	1	0.95(0.88-1.01)	0.141	1.09(1.01- 1.19)	0.025
	2(or more)	0.83(0.75-0.91)	0.000	1.15(1.01-1.29)	0.023

* IRR, Incident Rate Ratio of severe injury of elderly pedestrian-car crashes after the Silver Zones are installed within the district Dong

Fatalities

Table 4 examines the impact of Silver Zones on fatalities among elderly pedestrians by gender, revealing varying patterns based on the number of Silver Zones and gender. For female elderly pedestrians, districts with one Silver Zone show a slight increase in fatalities compared to districts without Silver Zones, while districts with two or more Silver Zones show a marginal reduction in fatalities. However, these trends lack strong evidence to suggest a clear association.

For male elderly pedestrians, districts with one Silver Zone show a modest reduction in fatalities, whereas districts with two or more Silver Zones indicate an increase in fatalities. Similar to the results for females, these findings are not strongly supported by the data and should be interpreted with caution.

Overall, the analysis does not demonstrate consistent or statistically meaningful effects of Silver Zones on fatalities among elderly pedestrians for either gender.

Table 4. The Impact of the Silver Zone on Elderly Pedestrian's Fatalities

Applied Model	Number of Silver Zones	Elderly Female Pedestrians (n=3,341)		Elderly Male Pedestrians (n=3,338)	
		IRR* (95% CI)	P - value	IRR (95% CI)	P - value
Random Effect Poisson Model (REP)	0 (reference)	-	-	-	-
	1	1.06(0.91-1.23)	0.432	0.90(0.73-1.11)	0.349
	2(or more)	0.97(0.79-1.19)	0.829	1.37(1.07-1.76)	0.012
Random Effect Negative Binomial (RENB)[a]	0 (reference)	-	-	-	-
	1	1.05(0.90-1.22)	0.477	0.90(0.73-1.11)	0.349
	2(or more)	0.96(0.78-1.18)	0.728	1.37(1.07-1.76)	0.012

*IRR, Incident Rate Ratio of fatalities of elderly pedestrians by car crashes

[a] Among covariates, the elderly population rate was excluded to deal with non-convergence issues occurring in a RENB model.

Interaction Effect of Gender

Another noteworthy aspect of the analysis of the study is the interaction effect of the gender variable, particularly when the gender is female, on the impact of the Silver Zone. Table 5 shows how the IRRs of the three dependent variables transform when the interaction effect of the Silver Zone and the female gender is applied. If the IRR decreases with the interaction term (female) being applied, it suggests that Silver Zone is more effective for females, as a lower IRR indicates a reduced risk of car crashes. As described in Table 5, all the results of three dependent variables- case, severe injury, and fatality- appear in a similar direction. First, for Car Crash cases, IRR decreases from 1.01 to 0.93(7% decrease) for the districts with one Zones, while it remains at 0.91(9% decrease) for districts with two or more Zones. Second, the reduction effect-decrease in IRR- reinforces in severe injuries from 0.99 to 0.98(one Silver Zone) and from 0.97 to 0.89(two or more Silver Zones). Likewise, the decrease in fatalities was solidified when the interaction term of females was applied, as it decreased from 0.99 to 0.98(one Silver Zone) and from 0.99 to 0.89(two or more Silver Zones).

Overall, the application of the interaction term (female) highlights the more enhanced effectiveness of Silver Zones in reducing elderly pedestrian-car crashes across three different dependent variables. Additionally, the effects are more conspicuous in districts with two or more Zones, with higher statistical significance.

Table 5. Comparison of Non-interaction Model and Interaction Model for Dependent Variables

Interaction Effect	Number of Silver Zones	Frequency of Crashes		Severe Injuries		Fatalities	
		IRR (95% CI)	P - value	IRR (95% CI)	P - value	IRR (95% CI)	P - value
Non-interaction Model	0 (reference)	-	-	-	-	-	-
	1	1.01(0.96-1.06)	0.654	0.99(0.92-1.06)	0.816	0.91(0.75-1.10)	0.342
	2(or more)	0.91(0.84-0.98)	0.015	0.97(0.88-1.06)	0.574	1.17(0.92-1.47)	0.180
Interaction Model	0 (reference)	-	-	-	-	-	-

	1	0.93(0.89-0.98)	0.005	0.98(0.92-1.04)	0.515	1.08(0.88-1.33)	0.417
	2(or more)	0.91(0.866-0.96)	0.001	0.89(0.83-0.96)	0.003	0.80(0.63-1.02)	0.084

Additional Analyses

If the overall decrease rate of crashes (14.0%) and severe injuries (13.8%) – the IRR of frequencies of crashes(0.859) and severe injuries(0.861) are utilized - are applied together with the elderly population projection from 2025 to 2040 as explained in Table 5, Seoul city's elderly pedestrian-car crashes can be reduced by 371 on average annually, and severe injuries by 180 on average per year even after factoring in increased car crashes caused by the elderly population growths.

Table 5. Elderly population projection and the projected elderly pedestrian crashes in the Seoul City, South Korea (Seoul Metropolitan City Government, 2024*

Year	Estimated Elderly population (a)	Case			Severe Injury		
		Estimated (b)	Estimated (IRR applied) (c)	Effect (b-c)	Estimated (d)	Estimated (IRR applied) (e)	Effect (d-e)
2023	-	1,973	1,973		969		
2025	1,853,084	2,161	1,856	-305	1,061	914	-148
2026	1,937,948	2,260	1,941	-319	1,110	956	-154
2027	2,000,032	2,332	2,004	-329	1,146	986	-159
2028	2,073,950	2,419	2,078	-341	1,188	1,023	-165
2029	2,127,121	2,481	2,131	-350	1,218	1,049	-169
2030	2,187,977	2,552	2,192	-360	1,253	1,079	-174
2031	2,242,669	2,615	2,247	-369	1,284	1,106	-179
2032	2,293,458	2,675	2,297	-377	1,314	1,131	-183
2033	2,348,374	2,739	2,352	-386	1,345	1,158	-187
2034	2,415,472	2,817	2,420	-397	1,383	1,191	-192
2035	2,475,251	2,887	2,480	-407	1,418	1,221	-197
2036	2,539,264	2,961	2,544	-418	1,454	1,252	-202
2037	2,595,169	3,026	2,600	-427	1,486	1,280	-207
2038	2,646,821	3,087	2,651	-435	1,516	1,305	-211
2039	2,693,283	3,141	2,698	-443	1,543	1,328	-214

2040	2,727,774	3,181	2,733	-449	1,562	1,345	-217
Average				-371			-180

* Based on the population projection provided by the Seoul Metropolitan City Government In 2024, the frequency of elderly pedestrian-car crashes and severe injuries were estimated utilizing the coefficients of the Poisson Model.

Discussion

It is an indisputable fact that elderly pedestrians have been found to be the most vulnerable cohort among any type of road user, according to various previous studies and statistics. However, few intervention programs have been introduced to target this group to improve their road safety so far. In this regard, the Silver Zone should receive more attention, as its value and contribution have been underestimated or disregarded so far. Moreover, this study holds greater significance in the context of a rapidly shifting demographic landscape boosted by lower birth rates and higher life expectancy.

Under these circumstances, this study was initiated to investigate the effectiveness of the elderly-focused intervention program (Silver Zone) on elderly pedestrian's safety. We derive results from three types of car-pedestrian crash data – the number of cases, severe injuries, and fatalities in Seoul City- through a micro-level district at the Dong level for an extended period of time. We uncovered mixed results by gender and variables.

First, installation of Silver Zones predicted a decline in both car crash cases and severe injuries among elderly female pedestrians, though it showed no significant association with fatalities. In contrast, for elderly men, these installations were associated with increases in both crash cases and severe injuries. More concerning, areas with two or more Silver Zones showed a positive association with male fatalities. Overall, while the Silver Zone program has enhanced road safety for elderly female pedestrians in terms of crashes and severe injuries, it appears to be ineffective and potentially disadvantageous for elderly male pedestrians, raising important questions about gender differences in response to road safety interventions.

Gender differences in Silver Zone effectiveness can be potentially attributed to contrasting behavioral patterns and compliance with safety measures. Research shows that elderly women tend to be more risk-averse and have higher compliance with safety measures [36], making them more likely to utilize Silver Zone features such as designated crossings and traffic calming measures. In contrast, elderly men demonstrate a higher propensity for risk-taking behaviors, including crossing at riskier locations or jaywalking [37], and may be more reluctant to modify long-established walking patterns even when faced with new safety features. These behavioral differences are further influenced by physical and health factors: women's greater longevity often comes with more mobility limitations [38], potentially making them more responsive to and dependent on safety infrastructure.

The installation of multiple Silver Zones creates additional complexity that may amplify these gender-based differences in risk behavior and compliance. These zones introduce modified environments with complex traffic patterns, including changed road configurations, additional crosswalks, and new traffic signals, resulting in more decision points and potential confusion. While elderly women might adapt their behavior to these changes and take additional precautions, men's tendency to maintain their usual walking patterns despite the modified environment can lead to increased risks. This environmental complexity, combined with men's lower compliance with safety features and higher risk-taking propensity, could explain why women experience enhanced safety while men face increased risks in areas with multiple Silver Zones. Understanding these gendered patterns suggests the need for complementary safety strategies that better address elderly male pedestrians' distinct mobility patterns and behavioral tendencies.

The potential risk of elderly pedestrians as a road user is expected to increase in the next decades as walking will play a more vital role in elderly people's daily lives as a means of leisure, exercise, and even a mode of transportation, especially in an urban context, while the elderly population is expected to grow [39]. At this point, the study underscores the significance of implementing more detailed and meticulous policy measures to improve the road safety of susceptible road users, like female elderly pedestrians, because the effects of a policy can have multiple dimensions depending on the context and the characteristics of the expected recipients. Future road safety programs, particularly those for seniors, should consider the specific risks faced by elderly pedestrians to ensure that safety policies are equally effective for all.

This study has also several limitations. Firstly, it relies on car crash data aggregated at the Dong-level districts in Seoul. Since Silver Zones are implemented only in specific areas within these districts, this broad approach may not accurately assess their effectiveness. Conducting analyses at more micro levels, such as intersections or specific corridors, could provide more precise insights. Secondly, the possibility of reverse causality cannot be ruled out, as Silver Zones are more likely to be installed in areas with a higher frequency of elderly traffic crashes, though one-year lagged variables- crashes, severe injuries, and fatalities occurred one year before- were controlled. In other words, prior crash prevalence may have led to the implementation of the Silver Zones. Third, the study did not fully account for the impact of broader factors, such as the overall development of traffic conditions and infrastructure over the observation years. More detailed research should follow to address these limitations, utilizing more comprehensive data covering broader regions and accurate crash locations while controlling additional factors related to road traffic conditions. Future research may be investigated further by resolving those limitations.

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Supporting Information

S1 Table. World Elderly Population and Pedestrian Fatalities Projection

S2 Table. Housman Test Result

S3 Table. Fixed Effect Result