GEORGIA DOT RESEARCH PROJECT 24-11

Final Report

ENHANCING THE SAFETY OF GEORGIA'S SENIOR DRIVERS AND PEDESTRIANS BY ANALYZING CRASH CHARACTERISTICS AND BEHAVIOR

Georgia Department of Transportation

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16. Abstract:
Georgia has triggered the Federal Highway Administration's Older Drivers and Pedestrians Special Rule for two consecutive comparison periods. As a result, the State is required to incorporate strategies addressing senior road user safety into its Strategic Highway Safety Plan. This report responds directly to this requirement. The objective of this study was to improve the safety of Georgia's senior drivers and pedestrians by developing a comprehensive understanding of the challenges they face on the roadway and translating those findings into targeted countermeasure recommendations. To achieve this, the study first conducted a comprehensive literature review and then utilized three data sources for in-depth data analysis: a statewide crash data analysis, a preliminary roadway safety survey of Georgia residents, and a preliminary eye-tracking based driving behavior analysis. The synthesized findings identify four priority areas for action based on these analyses. For senior drivers: 1) left-turn angle crashes at intersections driven by reaction-time failures are the most critical crash pattern. Among all fatal and severe angle crashes in Georgia, over 40 % are senior-related, the highest involvement of any crash type, and reaction time accounts for 79 % of older driver left-turn crashes. The eye-tracking study showed that seniors exhibit slower saccades, consistent with the reaction-time deficit observed in the crash data. 2) nighttime driving conditions present greater challenges for older drivers, with more than 50 % of older adults rating their visual acuity at night as fair or poor, and the eye-tracking study showing consistently higher fixation duration (high attention) at night across all curves studied. For senior pedestrians: 1) Wide signalized crossings present challenges for seniors, with 44 % citing insufficient crossing time as a concern at crosswalks; 2) Driver failure to yield represents a key safety concern, with over 65 % of older adults reporting this concern at crosswalks. The report further translates these findings into a set of countermeasures for intersection left-turn movements, nighttime visibility, wide pedestrian crossings, and driver yielding behavior.

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Final Report

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By

Yichang (James) Tsai, Ph.D., P.E.
Professor of Civil and Environmental Engineering

Shiwei Luo, Ph.D. Student, Graduate Research Assistant
Reid Cabe, MS Student, Graduate Research Assistant

Georgia Tech Research Corporation

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In cooperation with
U.S. Department of Transportation
Federal Highway Administration

July 2026

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003)

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LIST OF ABBREVIATIONS

ACS	American Community Survey
ANOVA	Analysis of Variance
DARE	Dynamic All-Red Extension
FD	Fixation Duration
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
GPS	Global Positioning System
HSIP	Highway Safety Improvement Program
IIV	Intra-Individual Variability
IMU	Inertial Measurement Unit
IRB	Institutional Review Board
LPI	Leading Pedestrian Interval
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
P2V	Pedestrian-to-Vehicle
PC	Point of Curvature
PT	Point of Tangency
ROM	Range of Motion
RRFB	Rectangular Rapid Flashing Beacon
SA	Saccade Amplitude
SHSP	Strategic Highway Safety Plan
SMS	Saccade Main Sequence
SPV	Saccade Peak Velocity
SSR	Sum of Squared Residuals
UTC	Coordinated Universal Time

EXECUTIVE SUMMARY

Georgia has met the criteria of the FHWA Older Drivers and Pedestrians Special Rule (the Special Rule) for two consecutive comparison periods: Georgia's rate of traffic fatalities and serious injuries for drivers and pedestrians aged 65 and older, defined as the five-year rolling rate of fatalities and serious injuries per 100,000 older adults, increased from 45.8 for the period ending in 2020 to 51.2 for the period ending in 2022, and from 48.5 to 52.8 for the period ending in 2021 and in 2023. As a result, the Special Rule requires the State of Georgia to incorporate strategies addressing senior road user safety into its Strategic Highway Safety Plan. This report responds directly to that requirement.

The objective of this study is to enhance the safety of Georgia's senior drivers and pedestrians by developing a comprehensive understanding of the challenges the seniors face on the roadway, and translating that understanding into targeted countermeasure recommendations. To achieve this objective, the following tasks will be performed based on the existing literature and three data resources: 1) Conduct a comprehensive literature review on age-related characteristics that may affect the driving and walking safety of older adults; 2) Perform crash data analysis to identify the most critical crash patterns in which Georgia’s seniors are disproportionately involved in fatal and serious injury crashes; 3) Explore the use of eye-tracking technology as a method for investigating age-related differences in driving safety; 4) Conduct a survey focused on driving and walking experiences in Georgia. The survey aims to gather feedback from residents across the state and examine age-related walking and driving behavior; 5) Synthesize the findings from the three main analyses to develop practical and evidence-based countermeasures. By combining insights from the literature review, crash data analysis, eye-

tracking study and survey, this task aims to identify effective strategies that can enhance the safety of Georgia's senior drivers and pedestrians.

Synthesizing the findings from literature review, crash data analysis, eye-tracking study and survey, the report identifies four areas for action.

For senior drivers in Georgia:

1. Left-turn angle crashes at intersections driven by reaction time failures are the most critical crash pattern for senior drivers in Georgia. Among all fatal and severe angle crashes in Georgia, over 40 % are senior-related, the highest involvement of any crash type. Within angle crashes, left-turn movements represent the largest share. Reaction time accounts for 79% of older driver left-turn crashes. The intersections are the primary setting for over 82% of those left-turn crashes. The eye-tracking study showed that seniors exhibit slower saccades, implying that the visual scanning required to locate oncoming vehicles, signals, and pedestrians during a left-turn maneuver takes longer to complete. This is consistent with the reaction-time deficit observed in the crash data.
2. Nighttime driving conditions present greater challenges for older drivers. The survey showed that more than 50 % of older adults rated their static visual acuity at night as fair or poor. The eye-tracking study confirmed that nighttime driving imposes greater visual processing demand on drivers of all ages. Mean fixation duration was consistently higher at night than during the day across all curves studied, indicating that low-light conditions increase the time required to extract and interpret visual information from the roadway.

For senior pedestrians in Georgia:

1. Wide signalized crossings present challenges for seniors; the literature documents that older pedestrians walk more slowly than younger and middle-aged pedestrians, with mean gait speeds of 1.33 m/s compared with 1.44 m/s for younger walkers. The survey confirmed this challenge from the user side in Georgia. Feeling rushed when crossing wide intersections was the most pronounced senior-specific challenge, and seniors more often than other groups cited long crossing distances (cited by 35 % of seniors) and insufficient crossing time (cited by 44 % of seniors) as concerns at crosswalks.
2. Driver failure to yield represents a key safety concern for seniors. The literature documents that older pedestrians are disproportionately represented in pedestrian fatalities, accounting for roughly 21% of all fatal pedestrian crashes in 2023 despite making up only 17.7% of the U.S. population [1]. In the survey conducted for this study, failure to yield by drivers emerged as a shared concern across all age groups, with more than 65% of older adults reporting this issue at crosswalks.

The corresponding countermeasures, recommended based on these synthesized findings, are presented in Chapter 6.

CHAPTER 1. INTRODUCTION

PROJECT BACKGROUND

Georgia is facing a sustained rise in fatal and serious injury crashes involving residents aged 65 and older. Georgia's rate of traffic fatalities and serious injuries for drivers and pedestrians aged 65 and older (defined as five-year rolling rate of fatalities and serious injuries per 100,000 older adults) increased from 45.8 for the period ending in 2020 to 51.2 for the period ending in 2022, and from 48.5 to 52.8 for the comparable 2021 and 2023 windows. Georgia's combined fatality and serious injury rate for the 65-and-older population has increased across two consecutive two-year comparison periods.

According to the FHWA Older Drivers and Pedestrians Special Rule, the Rule applies if a State's rate of traffic fatalities and serious injuries for drivers and pedestrians aged 65 and older increases during the most recent two-year period. As the detailed crash statistical evaluation shown in Chapter 3, Georgia meets this criterion. If the Older Drivers and Pedestrians Special Rule applies to a State, that State shall include strategies to address the increase in the older driver and older pedestrian fatal and serious injuries rate, taking into account the treatments listed in the 2014 FHWA publication, "Handbook for Designing Roadways for the Aging Population" and a secondary analysis to determine whether the increase is attributable to driver fatalities and injuries, pedestrian fatalities and injuries, or a combination of the two, in its subsequent Strategic Highway Safety Plan (SHSP) update.

Prior research on senior road safety has generally followed two complementary directions. The first uses crash data to objectively characterize, in statistical terms, the senior-related crash characteristics, such as the crash type that older road users are most exposed to. One of the findings is that turning maneuvers are the highest-risk scenario for older drivers, with driver fault probability during turning movements rising from below 60% for ages 45 to 64 to more than 80% for ages 85 and above [2]. The second direction focuses on senior driving behavior, using surveys and eye-tracking to identify patterns that are specific to older adults. For example, the survey-based research shows that senior drivers adapt their behaviors to prioritize safety, including avoiding nighttime driving, bad weather, and unfamiliar roads[3]. Eye-tracking studies provide a more direct behavioral view: older drivers (aged 50 and above) show a time-to-first-fixation on hazards of 0.4 to 0.7 seconds compared with 0.3 to 0.5 seconds for younger drivers and execute fewer correct primary and secondary glances at intersections[4].

OBJECTIVE AND TASKS

Thus, the objective of this research is to enhance the safety of Georgia's senior drivers and pedestrians by developing a comprehensive understanding of the challenges the seniors face on the roadway, and translating that understanding into targeted countermeasure recommendations. To achieve this objective, the following tasks will be performed based on the studies from four data sources:

1) Study to conduct a comprehensive literature review on age-related characteristics that may affect the driving and walking safety of older adults. This includes examining how age-related declines are associated with specific crash types, reviewing methodological approaches such as surveys, crash data analysis, and eye-tracking studies, as well as the emerging countermeasures designed to address safety risks for both older drivers and pedestrians.

2) Study to perform crash data analysis to identify the most critical crash patterns in which Georgia's seniors are disproportionately involved in fatal and serious injury crashes, such as left-turn crashes at intersections, rear-end collisions on highway facilities, etc. The findings will be linked back to the literature review to recommend countermeasures.
3) Study to explore the use of eye-tracking technology as a method for investigating age-related differences in driving safety. Using a curved route in Vogel State Park as the study environment, this task examines how older and younger drivers allocate attention and process visual information under real-world conditions.
4) Study to conduct a survey focused on driving and walking experiences in Georgia. The survey aims to gather feedback from residents across the state and examine age-related walking and driving behaviors, with a particular focus on how physical limitations among older adults affect their driving and walking performance in everyday situations.
5) Synthesize the findings from the findings from these four studies to develop practical and evidence-based countermeasures. By combining insights from the literature review, crash data analysis, eye-tracking study and survey, this task aims to identify effective strategies that can enhance the safety of Georgia's senior drivers and pedestrians. Recommendations on future research were also made.

REPORT ORGANIZATION

This report is organized into the following chapters:

- **Chapter 1 Introduction:** Presents the project background, research needs, and the objectives and tasks of the study.

- **Chapter 2 Literature Review:** Synthesizes prior research on the age-related physical and cognitive characteristics that affect driving and walking safety, the methodological approaches used to study senior road user behavior, and the countermeasures that have been documented for improving driving and pedestrian safety.
- **Chapter 3 Senior-Related Crash Characteristics Analysis Using Numeric Crash Data:** Documents Georgia's determination under the Special Rule and presents a statewide analysis of police-reported crashes from 2013 to 2023, comparing crash characteristics across age groups to identify the crash patterns most distinctive of senior drivers in Georgia and recommend the countermeasures.
- **Chapter 4 Behavioral Analysis of Senior Drivers Using Eye-Tracking and Smartphone Technology:** Presents the on-road behavioral study conducted at Vogel State Park, including the synchronization of curve inventory, smartphone GPS, and eye-tracking data, and the analysis of gaze distribution, visual metrics analysis, and the metric's correlation with crash frequency. Although this is an exploratory study, it provides lots of useful information.
- **Chapter 5 Roadway Safety Survey for Georgia's Roadway Users:** Describes the survey design, administration, and data analysis results of the survey distributed to Georgia residents.
- **Chapter 6 Effective Countermeasures Recommendations:** Consolidates the findings from the crash data analysis, eye-tracking study, and survey into a set of evidence-based countermeasure recommendations targeted at the safety challenges identified throughout the study. These recommendations include both evidence-based strategies that have demonstrated effectiveness in prior research and practice, as well as emerging and

exploratory concepts currently under investigation, such as flashing beacon designs, adaptive or automatic signal timing systems, and other innovative countermeasure ideas.

- **Chapter 7 Conclusions and Recommendations:** Summarizes the main findings of the research, presents the overall conclusions, and outlines recommendations for implementation and future work.

CHAPTER 2. LITERATURE REVIEW

OBJECTIVE OF THIS CHAPTER

The objective of the literature review is to:

1) Identify age-related characteristics that could potentially affect senior driving and walking safety, such as vision, neck mobility, cognition, and motor function.
2) Examine how these functional declines are associated with specific crash types, such as left-turn angle, right-turn angle, head-on, sideswipe, rear-end, and roadway departure.
3) Evaluate the methodological approaches (surveys, crash data, eye-tracking) used to study these age-related safety issues and assess their respective strengths and limitations.
4) Review existing and emerging countermeasures that address the identified age-related safety risks for both drivers and pedestrians.

THE TEMPORAL SEQUENCE OF PERCEPTUAL–COGNITIVE RESPONSE

The following summarizes the sequence of perceptual and cognitive events that occur between the moment a sign becomes visible and the moment the driver completes their response. It is visually summarized in Figure 1. The model also helps identify key driver-related functional abilities that influence driving performance, including visual capability, neck mobility, cognitive function, and motor function, such as shoulder and leg movement required for steering, braking, and other driving maneuvers.

1. Visual Availability: The sign becomes optically present in the driver's field of view. At this stage the sign is physically visible but not yet seen by the driver. The driver may still be in a saccade or visual transition, meaning there is no cognitive processing during this time.

2. Attentional Orientation: The eyes orient toward the sign's vicinity. This is when the driver first "lays eyes on it." Orientation is strongly affected by clutter, salience, predictability, and perceptual load. A sign may be optically available but never attract orientation if competing stimuli dominate the scene.
3. Fixation Initiation: The gaze enters the sign's Area of Interest (AOI). This is the first possible moment of perception, but there is still no semantic processing. It only means the eyes are pointing toward the sign.
4. Fixation Stabilization and Perception: This operates much like the shutter time on a camera. Under ideal laboratory conditions, where a participant anticipates needing to see and decode a sign directly in their fovea, a driver may be able to see an image for about half that time and remember it later. In naturalistic settings, these capacities are rarely, if ever, realized. Anything under approximately 100 ms is typically pre-attentive scanning rather than a fixation that can be subsequently processed neurologically. This is the stage that determines whether the driver actually perceives the sign long enough to decode it later during the processing stage.
5. Cognitive Processing / Interpretation: Once the image is acquired, the brain begins to interpret the sign's meaning, resulting in conscious perception that emerges around 250 to 300 milliseconds. Fixations that dwell longer than this are more likely to be subsequently remembered consciously, although memory is not necessarily essential for an appropriate response. Once meaning has been assigned to the image, the brain selects a response to the message based on a limited set of feasible choices, consistent with the concept of bounded rationality: drivers do not evaluate every possible option; they choose among a small subset constrained by expectations, environment, and time pressure.

6. Motor Execution (Driver Action): The driver physically performs the selected action: braking, releasing the accelerator, adjusting steering, or preparing for a potential conflict. This is the human motor output, distinct from the vehicle response. This also includes any time needed for a driver to verbally begin to report what was seen, even with a relatively simple trigger word.
7. Vehicle Maneuver Response: The vehicle responds to the driver's motor action, which could include movements like deceleration, lane-change trajectories, lateral positioning adjustments, or stability during a curve. The previous six steps must occur prior to a go/no-go minimum time for a safe, relatively comfortable maneuver to occur.

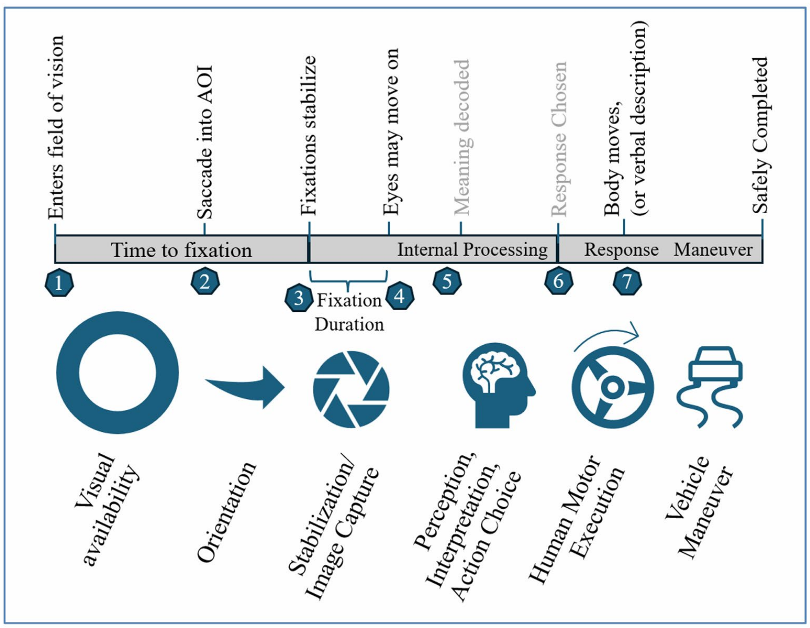


Figure 1. Graphs. Human Perception and Reaction Temporal Sequence

AGE-RELATED CHARACTERISTICS AND THEIR EFFECTS ON DRIVING AND WALKING SAFETY

This section describes common physical components that are affected by aging processes, with particular focus on components that are likely to impact driving ability, including vision, neck mobility, cognition, muscle strength, and imbalance. After describing how aging can negatively affect these physical characteristics, such characteristics are then connected to their impacts on driving ability using existing research studies.

Vision Capability

Aging significantly impairs visual capability, affecting multiple dimensions of visual performance. These declines are evident in visual acuity, spatial contrast sensitivity under challenging lighting conditions, and temporal sensitivity, which requires longer perception time to detect and process visual changes.

For example, studies estimate that up to 5.3% of older age groups are below the standard visual acuity for safe driving compared to only 0.5% among younger age groups, indicating the impact of age on vision[5].

Spatial contrast sensitivity, which measures the eye's ability to detect differences between light and dark regions, also worsens with age. Across adulthood, binocular summation data indicated substantial age-related declines of approximately 37% in contrast sensitivity and 59% in visual acuity[6]. Senior vision also worsens significantly under varying conditions, particularly under situations with low luminance (i.e., in the dark) and high glare where older individuals struggle to detect low-contrast objects. Under mesopic (dim light) conditions, age-related declines in reading vision are exacerbated as maximum reading speed decreases by 30 words-per-minute between ages 20 and 80, with similar decreases in other reading-based metrics including reading acuity[7].

Older individuals also exhibit reduced temporal sensitivity and motion perception, which impacts how effectively they can identify changes visually. For example, older adults require slower and larger visual changes to accurately process and respond to dynamic situations. Visual processing speed, which also relates to reduced cognitive capabilities, is also significantly slower among seniors, contributing to delayed response times[8].

Neck Mobility

Neck mobility and the body's overall Range of Motion (ROM) become more constrained amongst older individuals, with studies estimating an overall decrease in joint flexibility of around 25% due to age-related factors[9].

Among measures of joint flexibility, head rotation, a significant physical demand in driving, has been shown to be considerably lower for the senior age group when compared to younger drivers. Drivers under 30 demonstrated a mean maximum head rotation of 86°, whereas older drivers showed substantially reduced rotation. Among drivers aged 60–69, the mean maximum rotation decreases to 67°, and it declines further to 59° in drivers aged 70 and above[10]. In addition to head-specific rotation, younger drivers also demonstrated greater spinal flexibility than older drivers in general, with a mean baseline neck axial ROM of 78.1° compared to a mean of 63.48° among older drivers[11].

In addition to natural aging, health-related conditions further exacerbate these limitations. Cervical Degenerative Disc Disease (DDD) causes severe neck pain that inhibits the head movements required for blind-spot and mirror checks. DDD, though only detectable in 17% and 12% of young men and women, respectively, was detected in most men and women over the age of 60, with 86% and 89% of the individuals studied exhibiting symptoms[12-14]. A number of factors, attributable to natural aging and acquired health illnesses, therefore decrease senior neck mobility and range of motion.

Cognition Capabilities

Reduced cognitive capabilities among older adults affect several critical functional characteristics, including slower response times, greater variability in responses, and delayed physical movement. Together, these effects demonstrate that aging not only slows cognitive processing but also reduces its consistency and reliability.

Cognitive decline due to aging impacts response time to stimuli, with increased delays of around 2ms per additional decade in age of participants for overall Simple Reaction Times (SRTs). Further, in Choice Reaction Time (CRT) situations where time is taken to respond to a single stimulus from a set of multiple stimuli, more significant increases of up to 90-120ms were noted between age groups[15, 16].

Once responses are initiated, peak movement velocities have also been shown to be lower among seniors, with decreased accuracy and precision in rapid responses. This suggests that older individuals exhibit both slower and less stable reactions[17]. Intra-individual variability (IIV) in reaction time, which measures how much a person's reaction time varies across repeated trials and is correlated with cognitive decline, was also found to be higher among older adults in a study comparing them to younger adults[18].

Motor Function

In addition to major physical impairments relating to visual acuity, neck mobility and range of motion, and cognition, declines in other physical characteristics regarding motor functions and leg muscle strength are widespread among senior populations.

Motor function, defined as the physical execution of actions resulting from human decision-making, has been shown to both decrease strength and speed of movement with age. This includes decreases in muscle strength in areas that are crucial to driving, including the lower leg, as well as reduced speed of movement, which can be harmful in high-stress situations.

The Effects of Age-Related Characteristics on Driving and Walking Safety

Driving Safety Problems Arising from Age-Related Characteristics

Vision declines related driving safety issues

Declined vision capability among the older population leads to many unsafe situations for senior drivers and surrounding road users that can worsen under varying roadway and weather conditions. These risks arise because age-related visual impairments affect not only clarity of sight but also hazard detection and response.

Reduced visual acuity may require drivers to be closer to traffic signs or signals to read them clearly; in some cases, the required viewing distance may exceed standard design assumptions, potentially creating safety risks. Decreased contrast sensitivity can make it more difficult for older drivers to distinguish pavement markings, traffic signs, and signal indications, particularly at night or under adverse weather conditions. At intersections, these visual limitations become especially critical. For example, reduced visual capability may make it harder to detect pedestrians crossing the street, particularly when pedestrians are wearing low-contrast clothing or when lighting conditions are poor.

In addition, reduced temporal sensitivity and motion perception limit how quickly older adults can identify and interpret dynamic changes in the driving environment. Seniors typically require slower and more pronounced visual changes to accurately process surrounding events.

Seniors also exhibit slower visual processing speeds, with delays in response time, demonstrating how decreased visual acuity acts together with many other physical characteristics, like strained cognition, to reduce the capability of senior drivers to drive safely[8].

Constrained neck mobility related driving safety issues

Age-related reductions in neck mobility or ROM significantly affect driving performance, particularly during maneuvers that require wide visual scanning. These limitations restrict older drivers' ability to adequately observe areas outside their direct forward field of view, increasing the likelihood of missed hazards, such as failing to detect vehicles or pedestrians in blind spots.

For example, while younger drivers spotted 100% of targets during blind spot checks, lower trunk axial rotation by 8.2° among older drivers contributes to a lower target detection rate of 54%. Such a difference was largely due to seniors missing far left and far right targets, which were the objects furthest from the driver's forward view, demonstrating the impact restrained neck movement has on detecting hazards on the sides of drivers[11].

Inadequate blind spot checking has proven to be a common trend among older drivers, who fail to shift their gaze between regions of interest (far left, center, far right) as evenly as younger drivers do. Eye-tracking studies have also shown inadequate mirror and blind-spot checking among older drivers during lane changes: rearview-mirror and blind-spot checks occurred only 51% and 41% of the time, respectively, compared with 83% and 85% for younger drivers[1].

Cognitive decline related driving safety issues

Age-related declines in cognition, including longer and more variable reaction times, have been shown to decrease senior driver safety, especially at intersections. These impairments influence decision-making, and the ability to manage complex traffic environments.

One specific area of the intersection that poses a significant risk for older drivers is the "dilemma zone", where a vehicle approaching the intersection during the yellow phase can neither safely clear the intersection nor stop comfortably at the stop line. Findings indicate that, once a senior driver is within this zone, they are less likely to make the decision to stop when compared to younger drivers. Slower average driving speeds for seniors further increases the relative danger of not stopping, as they oftentimes are still within the bounds of an intersection at the onset of a red light[19, 20]. Other studies have also raised concerns over the ability of senior drivers to stop when prompted, with one experiment finding that lower acceleration and deceleration rates could contribute to lower proportions of seniors choosing to stop when compared to younger drivers[21].

Cognitive overload is also a prominent issue for senior drivers, as driving often requires the management of multiple tasks simultaneously. Studies have shown that seniors struggle to focus solely on prioritizing relevant information, instead of spending unnecessary time also processing irrelevant information, which can lead to cognitive overload. This is an issue enhanced in busy and complex environments such as intersections, where seniors are unable to successfully identify critical information[22].

Motor function decline related driving safety issues

Age-related declines in motor function and physical strength further compromise driving performance among senior drivers. As muscular strength, and movement speed deteriorate with age, older adults experience increasing difficulty executing rapid and forceful vehicle control maneuvers, particularly in emergency or unpredictable situations.

One important manifestation of this decline is slower braking responses. Weakened muscle strength and reduced speed of movement prolongs braking time[22]. Empirical evidence shows that older adults exhibited 17% slower braking times than middle-aged adults, alongside measured physical differences in lower-body strength and postural balance, further indicating a correlation between physical strength and driving ability[23].

In unpredictable situations, studies have also linked slower brake times in elderly drivers to lower limb muscle strength, agility, and low-contrast sensitivity. Such connections can be made through the many different physical components of driving; for example, reduced leg muscle strength can impact a driver's ability to control pedals effectively. This shift is outlined across age groups, with one study noting that younger drivers had significantly shorter break time in unpredictable situations when compared to elderly people, who also had poorer muscle strength[24].

Walking Safety Problems Arising from Age-Related Factors

Age-related physical and functional declines also significantly affect the safety of elderly pedestrians, who are disproportionately represented in pedestrian fatalities[1]. For example, while Americans aged 65 and older accounted for approximately 21.0% of all fatal pedestrian crashes in 2023, despite comprising only 17.7% of the U.S. population (NHTSA US Census) [1].

One major contributing factor is reduced walking speed. At intersections, older pedestrians face particular challenges due to slower walking speeds. While younger and middle-aged pedestrians were observed to have a similar mean gait speed of 1.44m/s, older adults walked more slowly, at 1.33m/s. Further, the current MUTCD-established standard for crossing speed of 1.2m/s has been found to exclude nearly two-thirds of older pedestrians based on walking speeds indicating the exclusion of seniors in pedestrian safety design[25].

In addition to slower walking speeds, older pedestrians also suffer from poor balance, which directly impacts walking ability. Pedestrians must exercise both static balance control and dynamic balance control when waiting and crossing intersections respectively, and studies have identified major deficiencies in both when compared to younger individuals[26].

The age-related characteristics and their effects on driving and walking safety are summarized in Table 1.

Table 1. Summary of Age-Related Characteristics Affecting Driving and Walking Safety

Age-Related Characteristic	Focused Area	Key Finding	Associated Crash Types
Vision Capability	Visual Acuity	5.3% of older adults fall below the safe-driving acuity standard vs. 0.5% of younger adults[5].	Degrades hazard detection, sign recognition, and pedestrian visibility across varying lighting conditions. Acts as an indirect risk amplifier across all crash types.
	Spatial contrast sensitivity	Across adulthood, binocular contrast sensitivity and visual acuity decline by approximately 37% and 59%, respectively[6].	
	Temporal sensitivity	Maximum reading speed decreases by ~30 words/min between ages 20–80 under dim-light conditions. Seniors struggle to detect low-contrast objects under glare.[7]	
Neck Mobility	Neck Range of Motion (ROM)	Overall joint flexibility decreases ~25% with age;[9] Mean max head rotation drops from 86° (under 30) to 59° (70+);[21] Mean neck axial ROM decreases from 78.1° to 63.48°.[11]	Limits ability to check blind spots and safe scanning while driving and walking. Potentially associated with left turn angle, angle, and sideswipe crashes, etc.
	Cervical Degenerative Disc Disease (DDD)	DDD detected in 86–89% of men and women over 60 vs. only 12–17% of young adults.[13]	
Cognition Capabilities	Simple and Choice Reaction Time	Simple Reaction Times increase ~2 ms per decade; Choice Reaction Times increase 90-120 ms between age groups under multi-stimulus conditions.[15, 16]	Slower reaction times and higher response variability reduce ability to respond promptly to sudden traffic changes. Potentially associated with rear end, left-turn, head on crashes, etc.
	Intra-Individual Variability (IIV)	Older adults show significantly higher variability in reaction time across repeated trials, indicating less reliable cognitive processing[18].	
Motor Function	Muscle Strength and Braking Speed	Older adults exhibit 17% slower braking times than middle-aged adults, with measured differences in lower-body strength and postural balance[23].	Slower braking response and reduced gait speed and balance increase stopping distances and crossing vulnerability. Associated with rear end and pedestrian related crashes, etc.
	Pedestrian Gait Speed	Mean gait speed: 1.33 m/s (older) vs. 1.44 m/s (younger); the MUTCD 1.2 m/s standard excludes ~two-thirds of older pedestrians based on walking speeds[25]	
	Static and Dynamic Balance	Older pedestrians show major deficiencies in both static (waiting at curb) and dynamic (crossing) balance compared to younger individuals[26].	

APPROACHES TO STUDYING AGE-RELATED CHARACTERISTICS IN DRIVING AND WALKING SAFETY

This section discusses two types of methodological approaches, qualitative and quantitative, used to examine how age-related characteristics affect senior pedestrian and driver safety. The qualitative approach encompasses the survey, which can be used to understand subjective insights into senior driving and pedestrian challenges, as well as the reasoning behind those insights. The quantitative approaches study crash characteristics using historical crash data, and study driver behavior using the data collected using eye-tracking technologies, which link objective data on where and when senior drivers and pedestrians struggle with gaze data that provides behavioral insights into why senior drivers and pedestrians struggle.

Subjective Approach: Survey

Survey-based insights into challenges faced by senior drivers

Surveys collect self-reported information on behavior, opinions, or knowledge and can yield qualitative responses or ordinal quantitative data for analysis. Commonly used in marketing, politics, and customer satisfaction studies, surveys are inherently subjective, relying on participants' memory, judgment, and biases. This can lead to response bias, where answers reflect what participants think is expected, and sampling bias, where the surveyed group may not represent the broader population[27]. Therefore, survey questions should be carefully designed to minimize bias and ensure they are appropriate for the target population.

The surveys presented that analyze the perceived challenges of senior drivers can be categorized into two groups: (1) self-reported errors and (2) perceived challenges. Surveys assessing self-reported errors among seniors found that seniors were more likely to report errors related to cognitive lapses than any other type of error. This means that senior driver's mishaps on the road are more related to cognitive function than reckless behavior. On the other hand, surveys assessing perceived challenges among senior drivers noted that most senior drivers faced age-related challenges while driving, including visual, cognitive, and physical challenges.

One commonly used driving study is the Driver Behavior Questionnaire (DBQ), which has seen multiple applications in driving behavior studies. The DBQ focuses on three types of driving mistakes: errors, mistakes that have potentially dangerous consequences, lapses, failure of a planned action to achieve desired consequences, and violations, risky driving behavior in which the driver engages in intentionally[28, 29]. In Parker et al., many older drivers reported some behavior related to lapses in attention, especially misreading signs on a roundabout and taking the wrong exit with a mean response rate of 2.40/6.00. This can be related to cognitive processing limitations in seniors, as they are required to complete several actions at once[30].

In Perez et al., a comprehensive survey evaluating senior drivers was conducted. Seniors were asked qualitative questions in tandem with ordinal quantitative questions on a scale of one to five (1 being never, 5 being always). Although 89% of participants rated themselves as exceptional drivers, respondents still reported difficulty related to visual, cognitive, and physical health constraints. Over 76% of participants struggled in some capacity while driving at night. This directly relates to declining contrast sensitivity in seniors, as contrast sensitivity is extremely important to the driving task, especially with detecting low-contrast objects under glare and limited illumination. Around 81% of respondents found that their reflexes weren’t the same as when they started driving, and over a quarter reported mobility issues while driving. This indicates that age-related physical and cognitive changes are directly affecting the driving task for seniors[31].

Survey-based insights into challenges faced by senior pedestrians

Surveys involving pedestrian studies primarily focused on two aspects: (1) locations and situations that undermine or bolster seniors' feeling of safety and comfort, as well as (2) age related challenges. Surveys focused on locations and situations, mainly found that complex environments and poorly maintained walkways undermined seniors' feelings of safety, causing them to make alternative decisions while choosing routes. Alternatively, the survey focused on age-related challenges among pedestrians found that mobility and visual related challenges are commonly faced among the senior population.

In Vine et al., 90-minute surveys were conducted for 12 respondents, who provided insight into what influences their walking decisions when navigating the urban environment. Respondents indicated that certain situations, such as high-density intersections, fast moving traffic, and overcrowded or poorly maintained pathways impacted pathfinding decisions, with participants choosing to avoid these locations or change routes if possible. This was due to these situations lowering their sense of safety, which in turn led to low levels of walking activity[32]. Another senior pedestrian survey conducted in high density urban areas indicated that seniors spent more time walking for transport if adequate pedestrian facilities, such as pedestrian crossings and outdoor parks were available[33].

Gonawala surveyed 75 elderly pedestrians regarding factors that exacerbate the difficulty of walking. Glare was indicated as an issue that was commonly cited as a difficulty in crossing intersections, with it being ranked between 7 and 8 on a ten-point scale in terms of difficulty, correlating to age-related decline in contrast sensitivity. Additionally, 58% of pedestrians interviewed reported neck range of motion constrictions when scanning at intersections[34].

Surveys are a useful tool for gaining insight into challenges seniors perceive they face, such as driving at night or what undermines their sense of safety as pedestrians, but they lack the empirical evidence that crash data, eye-tracking, and other studies provide. Without quantifiable metrics, it is impossible to distinguish between accurately reported information and inaccurate information, which is inherently due to the subjectivity of the survey. Additionally, senior pedestrian surveys inquiring about age-related challenges, such as mobility and visual issues while walking, are limited, with many surveys focusing on walkability and challenging locations for senior pedestrians. Finally, many of these surveys only focused on solely senior drivers and pedestrians, rather than comparing them with their younger counterparts. While this is essential for identifying problems that seniors face navigating transportation networks, it makes it harder to see the gap between the senior and younger population.

Quantitative Approach: Crash Data Analysis

Crash data consists of detailed, objective information collected from traffic accidents, typically through law enforcement reports. These data capture quantitative metrics such as crash frequency, severity, location, time, weather, and operational factors, and often include qualitative narratives that provide context for the collision. Stored in centralized databases, crash data are primarily collected at the local level, though variations in data entry systems and reporting practices can affect consistency and completeness, requiring state-level cross-referencing (GDOT). Despite these limitations, crash data are widely used in research to evaluate countermeasures, in traffic engineering to identify high-risk locations, and by the insurance industry to inform rate-setting.

Senior driver crash data analysis

For a general overview of senior driver crash statistics in 2022, in the U.S., 25 senior drivers are killed per day, while over 740 are injured in crashes[35]. The studies presented using crash data to examine senior-related issues can be broken down further into three separate categories; (1) location-based crash analyses, (2) studies examining types of driving errors, (3) situational based studies.

Lord et al. found seniors were disproportionally involved in angle crashes at roundabouts. [36]. High speed 2-lane roadways (50+ mph), multilane roadways with speed-limits from 40-45mph and stop-controlled intersections were all associated with higher senior driver crash involvement [37].

Cicchino and McCartt compared the critical errors for crashes between younger and senior drivers. For senior drivers, the most common critical error was inadequate surveillance, which represented 33% of all senior driver crashes involved in the study, compared to 22% of the middle-aged drivers. Of these crashes, 71% were considered "look but not seen errors," meaning they were scanning in the direction of the hazard, but they failed to cognitively process it. Misjudgment of the length of a gap between vehicles had the second largest difference in total crashes, 6% of all senior crashes, and 3% of all middle-aged driver crashes. This also can be correlated to a cognitive processing error, as senior drivers were able to see the gap, but were not able to process that it was not large enough to turn[38]. Additionally, 66% of inadequate surveillance errors and 77% of gap misjudgment errors for seniors happened on left turn movements, which is noted to be the most cognitively challenging movement.

Pae et al. found that the probability of the driver being at fault increased with age for certain movements at an intersection, such as merging, changing lanes, and turning movements. The difference was most pronounced in the turning movements, especially right turn movements. From ages 45-64, the probability of the driver being at fault during right turn related crashes was below 60%, while at ages 85 and over the probability of the driver being at fault was over 80%[2].

Senior pedestrian crash data analysis

Across the United States in 2021, 7,580 pedestrians aged 65 and older were injured. Seniors accounted for 18% of all pedestrian fatalities with known ages, despite representing only 15% of the total population [39]. Additionally, it is noted that senior pedestrians have a mortality risk two to eight times higher than their younger pedestrian counterpart[40] . While this is primarily due to an age-related decrease in physical resilience, crash severity risk for senior pedestrians can also be broken down further into (1) high complexity environments and (2) increased exposure to such environments.

Sultana Mimi et al. noted that higher-speed limits and more complex road situations, such as urban environments and intersections, increase fatal and severe injuries in senior pedestrians [40]. There is also an association with walkable facilities, or facilities within 1km of the residence of a pedestrian, necessary for the daily living of older adults and crash fatalities. This association is specifically noted at areas with a high density of older adult walkable destinations such hospitals, healthcare delivery venues, health services, senior centers, libraries, and community centers[41].

While crash studies are valuable for identifying characteristics of a crash, such as location, time, and roadway environments were present, they lack in the ability to tie these metrics to age-related characteristics, such as declines in physical, cognitive, or visual ability. Studies using alternative methodologies have had more success at combining these age-related characteristics to senior driving performance, such as controlled simulator studies and eye-tracking studies. These methods allow for the direct measurement of metrics such as reaction time, visual attention allocation, and other physical and behavioral characteristics that can be correlated to age-related factors.

Quantitative Approach: Eye-Tracking Technology

Eye tracking measures eye movements, positions, and gaze points using an infrared camera that illuminates the pupil to create a corneal reflection, enabling analysis of pupil size, eye rotation, and gaze direction. Data can be collected in two main ways: 1) screen-based eye tracking and 2) eye tracking glass. Screen-based eye tracking uses a fixed setup, typically on a computer, offering high accuracy due to individual calibration and minimal movement noise. Eye tracking glasses, by contrast, capture data in real-world environments but are harder to analyze because the moving scene introduces more noise into the data.

Senior driver eye-tracking data analysis

Eye-tracking research has been widely used to examine how age-related changes in visual attention and cognitive processing influence driving safety, particularly in: 1) hazard detection and 2) variations in scanning patterns.

For hazard detection, Yeung and Wong focused on evaluating reaction time for abrupt onset hazards found that an older driver age group, ages 50+, had a significantly longer time to first fixation (TTF) on hazards than two younger age groups, one with experience and one without. The average TTF for older drivers was around 0.4-0.7 seconds, which would most likely be longer in the field where there is a higher cognitive load. On the other hand, the younger driver's counterpart had an average TTF of 0.3-0.5 seconds[4].

Prior research has reported that older adults fixate more frequently on less-relevant stimuli and miss critical hazards, reflecting age-related cognitive constraints [42]. A similar study found that older drivers did not shift their gaze between regions of interest as evenly as younger drivers at intersections; in particular, they made fewer fixations toward the direction of turning [1]. Dukic and Broberg found that there was a significant difference in gaze distribution between older and younger drivers at intersections. Older drivers tended to focus on the markings along the intersection, trying to position themselves within the flow of traffic, while younger drivers were more focused on scanning dynamic objects, such as oncoming vehicles[43].

For scanning patterns, Ziv et al. examined primary and secondary glance behavior at intersections between senior and middle-aged drivers. The glances are defined as scanning to either side, while primary glances occur when drivers are approaching an intersection, and secondary glances occur when drivers are within the intersection. The study found that older drivers executed significantly fewer correct primary glances, fewer secondary glances, and fewer glances towards potential threats while turning at intersections compared to the middle-aged driver group. Finally, a study involving eye tracking for rearview mirror and blind spot checks found that younger drivers inspected their rearview mirror and blind spot during a lane change 83% and 85% of the time respectively, while older drivers inspected them 51% and 41% of the time[1].

Senior pedestrian eye-tracking data analysis

Primarily, studies used eye and head tracking devices in a simulator setting to assess differences in: 1) pedestrian behavior across ages at street crossings and 2) utilizing gaze distribution and observational methods to view where seniors are looking. These two categories can be interlinked, as seniors may exhibit riskier intersection crossing behavior since they are not focused on scanning the intersection wholly, but rather tend to fixate on the ground and the near lane on multilane roadways.

Zito et al. found that seniors exhibited riskier behavior when making crossing decisions over longer distance intersections and that senior pedestrians had more fixations towards the ground and their feet while crossing. The study argues that the riskier behavior exhibited by seniors at could be due to the limited visual acuity at longer distances, leading to difficulties analyzing the car, then further exacerbated by limited cognitive processing abilities under time pressure. Additionally, Additionally, older adults tend to direct more visual attention toward the ground and their feet, likely due to the increased time required to plan precise stepping movements. This behavior suggests potential links to age-related declines in balance and other physical limitations [44].

Other studies use similar methods to measure these characteristics. Dommes et al. measured gap judgement between senior and younger pedestrians using observational methods to determine where participants were looking. It found that older participants were more likely to misjudge the time gaps required to cross between vehicles on multilane roadways, creating more collisions with oncoming traffic. This was primarily due to older participants favoring the near lane when assessing gap judgment, failing to adequately assess the entire roadway[45].

Eye-tracking, while a useful tool in tying behavioral and physical components of the driving task to age-related challenges, has seen limited use in studies focusing on senior pedestrians. Additionally, eye-tracking usage in naturalistic senior driver and pedestrian studies is limited, partially due to the ethical considerations of having seniors driving and walking in the field, but also due to the difficulties in filtering out noise from the moving scene of reference.

All three data collection methods are necessary to enhance the understanding of age-related safety risks in driving and walking, as they provide different contexts that combine to strengthen the validity of the data collected.

The methodological approaches used to study senior driving and walking safety are summarized in Table 2.

Table 2. Summary of Methodological Approaches Used to Study Senior Driving and Walking Safety

Method	Population	Key Finding	Implication for Senior Safety
Survey (Qualitative)	Drivers	DBQ studies show cognitive lapses are seniors' most common self-reported error (e.g., misreading roundabout signs; mean 2.40/6.00)[30]. Despite 89% rating themselves capable drivers, >76% reported difficulty at night and ~81% acknowledged slower reflexes[31].	Cognitive lapses are the dominant self-reported error. Night driving and reflex decline directly reflect aging vision and reaction time.
	Pedestrians	1. High-density intersections, fast traffic, and poor pathway maintenance undermined seniors' safety and prompted route avoidance[33]. 2. Glare rated 7-8/10 in difficulty at crossings; 58% reported neck ROM restrictions when scanning[34].	1. Environmental complexity and physical discomfort jointly deter walking. Intersection design must account for the combined effect of visual impairment and neck mobility loss. 2. Adequate infrastructure partially offsets age-related limitations, reducing the cognitive and physical demands of navigation.

Method	Population	Key Finding	Implication for Senior Safety
Crash Data Analysis (Quantitative)	Drivers	1. In 2022, in the U.S., 25 senior drivers are killed per day, while over 740 are injured in crashes[35]. Overrepresentation concentrated on high-speed 2-lane roads (50+ mph), multilane roads (40-45 mph), and stop-controlled intersections[37]. 2.Inadequate surveillance accounted for 33% of senior crashes (vs. 22% for middle-aged); 71% were 'look but not seen' errors. Misjudgment of the length of a gap between vehicles were also overrepresented among seniors[38]. 3. Driver fault probability during turning movements rises from below 60% (ages 45-64) to over 80% (ages 85+), most pronounced for right turns[2]. 4. Even at roundabouts where left turns are eliminated, seniors were disproportionately involved in angle crashes, suggesting residual cognitive processing difficulties with complex geometry[36].	1. Seniors are disproportionately at risk in fast-paced or cognitively complex road environments. 2. The primary failure is cognitive registration, not visual scanning. Countermeasures must target processing speed, not just visual coverage. 3. Turning maneuvers are the highest-risk scenario for older drivers, especially at advanced ages. 4. Roundabouts reduce but do not eliminate senior crash risk; continuous yield judgements under time pressure remain challenging.
	Pedestrians	Senior pedestrians have a mortality risk 2–8 times higher than younger counterparts. Crash severity is elevated near high-density senior-use destinations (hospitals, community centers) and in urban, high-speed environments[40].	The locations where seniors most need to walk are often the most dangerous safety design.
Eye-Tracking (Quantitative)	Drivers	1. Older drivers (50+) showed a time-to-first-fixation (TTF) on hazards of 0.4-0.7 s vs. 0.3-0.5 s for younger drivers; seniors also fixated more on non-hazardous stimuli[4]. 2. Older drivers executed fewer correct primary and secondary glances at intersections[4]. 3.Rearview mirror and blind spot checks occurred only 51% and 41% of the time vs. 83% and 85% for younger drivers[1].	1. Delayed hazard detection and poor prioritization of visual attention increase collision risk at intersections. 2. Inadequate mirror and blind spot scanning leaves seniors unaware of critical nearby hazards during lane changes and turns. 3. Senior gaze behavior reflects a reactive rather than proactive scanning strategy, reducing hazard anticipation.

Method	Population	Key Finding	Implication for Senior Safety
	Pedestrians	1. Seniors exhibited riskier crossing decisions at longer intersections, with more fixations directed toward the ground and feet, likely reflecting the need to plan precise stepping movements due to balance concerns[44]. 2. On multilane roads, older pedestrians misjudged gaps more often by fixating primarily on the near lane and neglecting vehicles in the far lane[45].	1. Balance-related visual attention toward the ground diverts focus away from traffic assessment, increasing crossing risk. 2. Incomplete roadway scanning leads to collision risk with vehicles in far lanes. This is a particularly dangerous error on multilane crossings.

COUNTERMEASURES FOR IMPROVING DRIVING AND WALKING SAFETY

Countermeasures for Improving Driving Safety

This section aims to identify evidence-based countermeasures for six critical crash types: (1) left-turn angle, (2) right-turn angle, (3) head-on, (4) sideswipe, (5) rear-end, and (6) roadway departure. For each crash type, relevant countermeasures are described, and their mechanisms of risk reduction are explained.

Left-turn crashes often occur when drivers misjudge gaps in opposing traffic or have limited visibility. A protected left-turn phase removes the need for gap judgment by giving drivers an exclusive signal. With a crash modification factor of 0.3, left-turn controls are a significant and straightforward way of reducing crashes[46]. Adding a far left-side signal head improves visibility and helps drivers focus on the correct indication. Providing or widening a left-turn lane separates turning vehicles and improves sight distance by offsetting opposing traffic. Improving lighting and clearing sight triangles helps drivers better detect oncoming vehicles and pedestrians, especially at night or in visually cluttered areas[47, 48]. A dynamic all-red extension can further reduce conflicts by allowing more time for vehicles to clear the intersection[49].

Right-angle crashes are typically related to drivers failing to stop or recognize intersection control. Measures such as enhanced signing and larger or overhead stop signs make control devices more noticeable. Adding a stop bar helps position vehicles where drivers have better sight distance before entering the intersection. Flashing beacons can attract attention in locations with poor visibility or low compliance. Clearing sight triangles and improving lighting ensures that drivers can better see approaching traffic and intersection geometry[47, 48]. Dynamic all-red extension also helps by reducing red-light violations and providing additional clearance time[49].

Rear-end crashes often happen when drivers are not prepared to slow down or stop. In intersection settings, treatments that help drivers anticipate the need to decelerate, such as clear signage and improved lighting, can be effective. On higher-speed roadways, queue warning systems provide real-time alerts about downstream congestion, allowing drivers to react earlier. Variable speed limits can further smooth traffic flow by reducing sudden speed differences between vehicles[50].

Vehicle head-on collisions are the most harmful event in approximately 14 % of all U.S. traffic fatalities each year and 27 % of all roadway departure fatalities. Centerline rumble strips provide immediate auditory and tactile feedback when a driver drifts across the centerline. Enhanced pavement markings make lane boundaries more visible and easier to follow. Median cable barriers physically separate opposing traffic and prevent crossover crashes. Adding a centerline buffer area increases the space between directions of travel, which further reduces the likelihood of a collision[51].

Sideswipe crashes typically result from unintentional lane drifting or poor lane discipline. Centerline and shoulder rumble strips can alert drivers when they begin to leave their lane. These treatments provide a quick warning that helps drivers correct their position before a collision occurs.

Roadway departure crashes occur when vehicles leave the travel lane and encounter roadside hazards. Guardrails can reduce crash severity by shielding fixed objects. Shoulder rumble strips warn drivers as they begin to drift out of the lane. Enhanced curve delineation improves driver awareness of roadway alignment, especially on curves. Widening the roadside clear zone provides space for drivers to recover control. High-friction surface treatments improve tire grip, particularly in curves and wet conditions, which helps prevent loss of control[52].

Table 3 presents a consolidated summary of countermeasures for improving driving safety.

Table 3. Summary of Countermeasures for Improving Driving Safety

Crash Type	Countermeasure	Description
Left-Turn Crashes	Left-Turn Control (Protected Phase)	Provides an exclusive left-turn phase, eliminating the need for gap judgment[46].
	Add Far Left-Side Signal Head	Narrows driver field of view and improves signal visibility.[48]
	Add Left-Turn Lane	Separates turning traffic, reducing conflicts and improving maneuverability[48].
	Provide offset left-turn lanes at intersections	Improves sight distance by offsetting opposing left-turning vehicles[47].
	Lighting	Enhances nighttime visibility of signs, markings, and vehicle paths[47].
	Clear Sight Triangles	Removes obstructions (e.g., vegetation, parked vehicles) to improve visibility[47].
	Dynamic All-Red Extension (DARE)	Extends all-red phase to reduce violations and eliminate dilemma zone issues[49].
Right-Angle Crashes	Dynamic All-Red Extension (DARE)	Extends all-red phase to reduce violations and eliminate dilemma zone issues[49].
	Enhanced Signing and Delineation	Provides advance warning and improves driver awareness of intersections[47].
	Add Stop Bar	Positions vehicles to improve sight distance at intersections[48].
	Larger Stop Signs	Increases visibility and conspicuity of stop control[48].
	Overhead Supplementary Stop Signs	Improves stop sign visibility, especially in complex environments[47].

Crash Type	Countermeasure	Description
	Flashing Beacons	Alerts drivers using flashing lights, especially effective in rural or nighttime conditions[47].
	Clear Sight Triangles	Removes visual obstructions to improve intersection visibility[47].
	Lighting	Improves visibility of intersection geometry and control devices[47].
Rear-End Crashes	Dynamic All-Red Extension (DARE)	Extends all-red phase to reduce violations and eliminate dilemma zone issues[49].
	Enhanced Signing and Delineation	Warns drivers to slow down and anticipate stopping conditions[47].
	Queue Warning Systems	Uses real-time detection to warn drivers of downstream congestion[53].
	Variable Speed Limits	Adjusts speeds dynamically to reduce speed differentials and crash risk[50].
Head-On Crashes[51]	Centerline Rumble Strips	Provides auditory and tactile feedback when vehicles drift across centerline[47].
	Enhanced Pavement Markings	Wider centerlines and edge lines improve lane positioning and visibility[47].
	Median Cable Barriers	Physically separates opposing traffic streams to prevent cross-over crashes.
	Centerline Buffer Area	Increases lateral separation, significantly reducing head-on crash risk.
Sideswipe Crashes	Centerline Rumble Strips	Alerts drivers drifting out of lane, reducing unintended lane encroachment[54].
Roadway Departure Crashes[52]	Guardrails	Reduces severity of run-off-road crashes by shielding hazards.
	Shoulder Rumble Strips	Warns drivers when leaving the travel lane.
	Enhanced Curve Delineation	Improves driver awareness of horizontal curves.
	Roadside Clear Zone Widening	Provides recovery space for errant vehicles.
	High-Friction Surface Treatment	Improves skid resistance, especially in curves and wet conditions.

Countermeasures for Improving Walking Safety

Pedestrian safety countermeasures can be categorized into three groups: (1) signal timing strategies, (2) infrastructure treatments, and (3) sensor-based technologies. These approaches address different dimensions of pedestrian–vehicle interaction.

Signal timing strategies reduce conflicts by separating pedestrian and vehicle movements in time. Protected left-turn phases eliminate permissive turning conflicts by providing dedicated signal indications. Leading Pedestrian Intervals (LPIs) are one of the most cost-effective countermeasures available. They give pedestrians a brief head start before vehicles begin moving, making them more visible to drivers as they step into the crosswalk[55, 56]. Restrictions like no right turn on red[57] and pedestrian-only phases[58] take separation a step further by fully preventing vehicle-pedestrian interactions during certain phases. Adjusting assumed walking speeds in signal timing is another important consideration. Current MUTCD standards assume a walking speed of 1.2 m/s (4 ft/s), but studies have shown this is too fast for most senior pedestrians. Reducing the standard to 0.91 m/s (3 ft/s) would bring the proportion of pedestrians who can't finish crossing in time down to about 20%, making timed crossings much safer for older adults[25].

Other design-based improvements in enhancing walker safety include median refuges for pedestrian crossings, higher-visibility crosswalks, and Danish offsets. These relatively simple design changes improve pedestrian safety by increasing their visibility when crossing to drivers[59]. High-visibility crosswalks use enhanced markings, lighting, and signage to make crossings more conspicuous to drivers. Pedestrian refuge islands allow people to cross in two stages, giving them a safe place to wait in the middle of a wide road. Danish offsets, which are a set of bright-yellow pillars placed at crosswalks, encourage pedestrians to face oncoming traffic during their crossing and make the crosswalk easier for drivers to detect from a distance. Roadway diet can also help by narrowing the roadway, which slows vehicle speeds and shortens crossing distances. At uncontrolled crossings, devices like pedestrian hybrid beacons and rectangular rapid flashing beacons have been shown to significantly increase driver yielding rates. Raised crosswalks further improve safety by physically slowing vehicles and elevating pedestrians into the driver's line of sight.

Sensor-based technologies improve safety by detecting conflicts in real time and alerting drivers before a crash occurs. The Pedestrian-to-Vehicle (P2V) Warning System is a smartphone-based tool that sends alerts to drivers when a potential collision with a pedestrian is detected. By reducing brake reaction time, it provides significant safety benefits in environments with limited visibility or unpredictable pedestrian activity. Driving simulator studies show that forward collision and P2V warning systems can reduce crash rates by 56% to 97% under conditions involving distraction or unpredictable pedestrian behavior[60].

Table 4 presents a consolidated summary of countermeasures for improving walking safety.

Table 4. Summary of Countermeasures for Improving Senior Driving and Walking Safety

Type	Countermeasure	Description
Signal Timing	Left-Turn Control (Protected Phase)	Replaces permissive left turns with a dedicated green arrow, eliminating the need for gap judgment and reducing conflicts with pedestrians.[56]
	Leading Pedestrian Interval (LPI)	Provides pedestrians a 3–4 second head start before the parallel vehicle green, increasing their visibility to turning drivers.[55, 56]
	No Right Turn on Red	Restricts right turns during the red phase, eliminating conflicts between turning vehicles and pedestrians in the crosswalk.[57]
	Pedestrian-Only Phase	Stops all vehicular traffic and allows pedestrians to cross in all directions, fully separating pedestrian and vehicle movements[58].
	Consideration of Reducing Walking Speed	Adjusts signal timing (e.g., from 1.2 m/s to 0.91 m/s) to accommodate slower pedestrians, improving accessibility and safety for older adults[25].
Infrastructure[59]	High-Visibility Crosswalks	Uses ladder/continental markings, lighting, and signage to increase pedestrian visibility, especially under low-light conditions.
	Pedestrian Refuge Islands	Raised median islands allow pedestrians to cross in two stages, reducing exposure time and simplifying decision-making.
	Danish Offsets	Z-shaped refuge design that orients pedestrians toward oncoming traffic at the midpoint, improving awareness before completing the crossing.
	Roadway Diet	Reduces lane widths or lane count to lower vehicle speeds and shorten crossing distances while creating space for pedestrian facilities.
	Pedestrian Hybrid Beacons (PHBs)	Provide pedestrian-activated red signals at uncontrolled crossings, creating protected crossing opportunities.
	Rectangular Rapid Flashing Beacons (RRFBs)	Use high-intensity, irregular flashing amber lights to increase driver yielding rates at uncontrolled crossings.
	Raised Crosswalks	Elevate the crossing surface to function as a speed table, slowing vehicles and improving pedestrian visibility.

Type	Countermeasure	Description
Sensor Technology	Pedestrian-to-Vehicle (P2V) Warning System	Provides real-time alerts to drivers when a pedestrian conflict is detected, improving reaction time.[60]

SUMMARY OF THE LITERATURE REVIEW

This study provides a comprehensive understanding of how age-related physiological and cognitive changes influence the safety of seniors in both driving and walking. It integrates findings from existing literature to identify key functional declines including vision, neck mobility, cognition, and motor function, and systematically connects these impairments to increased safety risks.

1. Age-Related Functional Declines

   Aging significantly affects multiple physical and cognitive systems critical to safe mobility. Visual capability declines in terms of acuity, contrast sensitivity, and temporal processing, reducing the ability to detect hazards, particularly under low-light or high-glare conditions. Similarly, reduced neck mobility and range of motion limit the ability to perform essential visual scanning tasks, such as checking blind spots.

   Cognitive decline further exacerbates safety risks by increasing reaction time, reducing processing speed, and introducing variability in responses. These impairments hinder decision-making in complex traffic situations. Additionally, motor function deterioration, including reduced muscle strength and slower movement execution, affects braking performance and pedestrian mobility.

2. Impacts on Driving Safety

The interaction of these age-related declines leads to significant challenges in driving. Visual impairments reduce the ability to recognize traffic signs, detect pedestrians, and respond to dynamic changes. Limited neck mobility restricts hazard detection outside the forward field of view, contributing to missed blind spot hazards.

Cognitive limitations are particularly evident in high-demand environments such as intersections, where older drivers struggle with gap judgment and decision-making, especially in dilemma zone scenarios. Motor impairments further increase risk by delaying braking responses and reducing control in emergency situations. Overall, older drivers are disproportionately involved in crashes requiring complex cognitive processing, such as turning movements and multi-lane interactions.

3. Impacts on Walking Safety

Age-related declines also significantly affect pedestrian safety. Older adults exhibit slower walking speeds, poorer balance, and reduced environmental awareness, increasing vulnerability during road crossings. Current traffic design standards often fail to accommodate these limitations, leaving many older pedestrians unable to safely cross within allocated signal times.

Moreover, older pedestrians are overrepresented in fatal crashes, particularly in complex or high-density environments. Limitations in visual scanning and balance lead to unsafe crossing behaviors, such as inadequate gap judgment and increased focus on immediate walking tasks rather than surrounding traffic.

4. Methodological Approaches

   The study reviews both qualitative and quantitative methods used to analyze these safety challenges. Survey-based approaches provide subjective insights into perceived difficulties but are limited by bias and lack of empirical validation. In contrast, crash data analysis offers objective evidence of risk patterns, highlighting overrepresentation of older adults in complex driving scenarios.

   Eye-tracking studies bridge these approaches by directly linking behavioral patterns with underlying cognitive and visual limitations. These studies reveal delayed hazard detection, reduced scanning behavior, and inefficient gaze distribution among older drivers and pedestrians.

5. Countermeasures for Safety Improvement

   To address these challenges, the study proposes a range of engineering and technological countermeasures. For driving safety, interventions such as protected left-turn phases, improved signage, enhanced lighting, rumble strips, and dynamic signal timing can mitigate risks associated with cognitive and visual decline.

   For pedestrian safety, strategies include leading pedestrian intervals, pedestrian-only signal phases, reduced assumed walking speeds, high-visibility crosswalks, refuge islands, and sensor-based warning systems. These measures aim to reduce conflict, improve visibility, and accommodate slower movement and decision-making processes.

Overall, the study highlights that age-related declines in vision, cognition, mobility, and motor function collectively increase safety risks for older adults in transportation systems. These risks are particularly pronounced in complex and time-sensitive environments such as intersections. A multidisciplinary approach combining behavioral analysis, engineering design, and technological innovation is essential to develop effective interventions that enhance mobility safety for the aging population.

CHAPTER 3. SENIOR-RELATED CRASH CHARACTERISTICS ANALYSIS USING NUMETRIC CRASH DATA

OBJECTIVE OF THIS CHAPTER

The objectives of this chapter are as follows:

1. To determine whether the Older Drivers and Pedestrians Special Rule applies to Georgia;
2. To develop a systematic framework for identifying the most critical crash patterns in which older adults are disproportionately involved in fatal and serious injury crashes, such as left-turn crashes at intersections, rear-end collisions on highway facilities, etc. The ultimate objective is to translate the identified critical crash patterns into targeted, effective countermeasures, thereby supporting evidence-based transportation safety policies.

GEORGIA'S DETERMINATION UNDER THE FHWA OLDER DRIVERS AND PEDESTRIANS SPECIAL RULE

Introduction of the Special Rule

Per 23 U.S.C. 148(g)(2) [61], if the rate per capita of traffic fatalities and serious injuries for drivers and pedestrians age 65 and over in a State increases over the most recent 2-year period for which data are available, the Older Drivers and Pedestrians Special Rule requires a State to include strategies to address the increases in those rates in their SHSP. FHWA issued the HSIP Special Rules Guidance on February 2, 2022 to provide guidance and information on how to determine if the Special Rule applies in a State[62].

The FHWA guidance for making this determination is described as: "*The State should consider older drivers and older pedestrians collectively. If the rate of traffic fatalities and serious injuries for drivers and pedestrians aged 65 and older increases during the most recent 2-year period, then the Older Drivers and Pedestrians Special Rule applies.*"

Specifically, the State should:

- Add together the number of fatalities for older drivers and pedestrians from the Fatality Analysis Reporting System (FARS) Annual Report File and the number of serious injuries from a State's data system for drivers and pedestrians 65 years of age and older;
- Divide that combined amount by the population of State residents that are 65 years of age or older; and
- Compare the two time periods of 5-year rolling average rates of fatalities and serious injuries using a 2-year spread.

The following example illustrates this process, using a 2-year spread comparing the periods ending in 2014 and 2012:

- Step 1, Calculate the "Annual rate, year XXXX", as defined in Equation 1

$$AR, year\ XXXX = \frac{F\ +\ SI\ for\ drivers\ and\ pedestrians\ 65\ years\ of\ age\ and\ older, year\ XXXX}{Pop.of\ drivers\ and\ pedestrians\ 65\ years\ of\ age\ or\ older, year\ XXXX} \qquad \text{Equation 1}$$

- Step 2, Calculate 5-year rolling average rates for 2014 to two decimal places, then round to the nearest tenth, as defined in Equation 2

$$\text{5 year rolling average rates for 2014} = \frac{AR, 2014\ +\ AR, 2013\ +\ AR, 2012\ + AR, 2011\ + AR, 2010}{5} \qquad \text{Equation 2}$$

- Step 3, Calculate 5-year rolling average rates for 2012 to two decimal places, then round to the nearest tenth, as defined in Equation 3

$$\text{5 year rolling average rates for 2012} = \frac{AR,2012\ +\ AR,2011\ +\ AR,2010\ + AR,2009\ + AR,2008}{5} \qquad \text{Equation 3}$$

- Step 4, Compare 5-year rolling average rates for 2014 and 2012. If the rate for 2014 exceeds the rate for 2012, then the special rule applies.

Georgia's Special Rule Determination

The fatality and serious injury data for individuals aged 65 and older were extracted from Georgia's Highway Safety Improvement Program (HSIP) reports for 2022 and 2023. Population estimates for the 65-and-older demographic were obtained from the U.S. Census Bureau's American Community Survey (ACS) 1-Year Estimates (http://www.census.gov/acs/www).

As shown in Table 5, the analysis presents the annual raw data from 2016 through 2023. For each year, the number of fatalities and serious injuries among the 65+ population were combined and then divided by the corresponding population estimate, expressed as the annual rate per 100,000 persons. Table 6 shows the results of rolling five-year average rates for 2020, 2021, 2022 and 2023. The results were rounded to the nearest tenth for comparation.

As shown in Table 7, the State of Georgia's 5-year average rate of fatalities and serious injuries per capita for older drivers and pedestrians was 45.8 for the period ending in 2020 and 51.2 for the period ending in 2022, representing an increase of 5.4 points. Similarly, Georgia's 5-year average rate was 48.5 for the period ending in 2021 and 52.8 for the period ending in 2023, reflecting an increase of 4.3 points. Both sets of five-year rolling comparisons indicate that Georgia's combined fatality and serious injury rate for the 65-and-older population has increased across two consecutive two-year comparison periods. Therefore, the Special Rule applies to the State of Georgia.

Table 5. Annual Rate Calculation Results

Year	Fatalities (65+)	Serious Injuries (65+)	Fatalities + Serious Injuries Combined	Population 65+	Annual rate, year (per 100,000 people)
2016	229	314	543	1,359,134	39.95
2017	226	344	570	1,401,850	40.66
2018	207	406	613	1,456,428	42.09
2019	238	556	794	1,523,192	52.13
2020	234	557	791	1,459,361	54.20
2021	276	571	847	1,585,687	53.42
2022	263	625	888	1,644,275	54.01
2023	234	620	854	1,702,863	50.15

Table 6. 5-year Average Rate for Years 2020, 2021, 2022, and 2023

Year	5-Year Period	5-year Rolling Average Rate	5-year Rolling Average Rate (rounded)
2020	2016-2020	45.81	45.8
2021	2017-2021	48.50	48.5
2022	2018-2022	51.17	51.2
2023	2019-2023	52.78	52.8

Table 7. Special Rule Applies Checking

Comparison	Earlier Period	Later Period	Change	Special Rule Applies?
2020 vs 2022	45.8	51.2	+5.4	YES
2021 vs 2023	48.5	52.8	+4.3	YES

METHODOLOGY

Framework for Proposed Methodology

As shown in Figure 2, the proposed framework aims to systematically identify the most critical crash patterns in which older adults are disproportionately involved in fatal and serious injury crashes, such as left-turn crashes at intersections, rear-end collisions on highway facilities, etc. It does so by examining disparities in crash characteristics across different age groups, including crash type, location, and contributing factors such as reaction time, traffic violation, etc. The methodology integrates data acquisition, cleaning, aggregation, and advanced statistical analysis to generate actionable insights that can support more senior-inclusive transportation policies to promote the safety and quality of life of seniors. The proposed methodology is organized into four integrated components: (1) literature review, (2) data preparation, (3) data analysis, and (4) countermeasure recommendations.

Component 1: literature review

In chapter 1, the literature review synthesizes prior findings on how age-related physical, cognitive, and behavioral changes influence driving and walking safety outcomes. It also identifies proven countermeasures to enhance safety (in literature review component). The literature review provides the knowledge foundation for data interpretation and countermeasure recommendations.

Component 2: data preparation

- Data acquisition: Crash data is acquired from the Georgia Department of Transportation's AASHTOWare database, which includes all police-reported crashes in Georgia from 2013 to 2023. The dataset contains detailed information on driver age, crash severity, manner of collision, speed limit, contributing factors, environmental conditions, and crash locations.

- Data processing: Data cleaning is conducted to remove invalid records, including crashes with missing driver age (age = 0) or unlicensed drivers (age < 16). Crashes are then classified into younger drivers, older drivers, and non-age-related groups to support comparative analysis. Senior crashes are further separated into driver-involved and pedestrian-involved categories, and crash characteristics are aggregated to provide a holistic view of crash dynamics.

Component 3: Data analysis

- Step 1: Analyzing Temporal Trends in Senior-Related Crashes. The analysis examines temporal trends in senior-related crashes by separating them into three categories: older driver-involved crashes, older pedestrian-involved crashes, and combined cases. This step could support the Special Rule assessment by clarifying whether the fatal and serious injury's increase is driven by older drivers, older pedestrians, or both.
- Step 2: Quantifying Fatal and Severe Injury Risk with Age. In addition to understanding how crash rates change with age, it is also important to quantify the relationship between age and crash severity, with a focus on the likelihood of fatal and serious injury outcomes over all the severity levels. This step aims to establish whether older age is a statistically significant risk factor for more severe crash outcomes, providing the justification for deeper investigation in subsequent steps.
- Step 3: Analyzing Crash Characteristics by Age. The data aggregation in the previous step allows for a sophisticated statistical analysis by age, enabling a detailed examination of the differences in crash characteristics between various age groups. This analysis

analyzes crash characteristics across age groups, focusing on environmental conditions, contributing factors, and collision types to identify differences between younger, older, and non-age-related crashes. This step helps identify the crash characteristics that are unique to older adults and distinguish them from those of younger and non-older populations.

- Step 4: Diving down to critical crash patterns. Based on Step 3, the study aims to identify crash patterns that are unique to older adults and examines them in greater detail. Specifically, it seeks to determine where older adults are more likely to be involved in crashes, what types of driving behaviors are associated with these crashes, and the underlying factors that make them more susceptible to severe and fatal outcomes. Based on the identified critical crash patterns, the study will further inform the development of targeted safety countermeasures for older drivers.

Component 4: Countermeasure recommendations

The final component translates the empirical findings identified from Component 3 Data Analysis into evidence-based countermeasure strategies, while explicitly linking them back to the key insights identified in the literature review (Component 1).

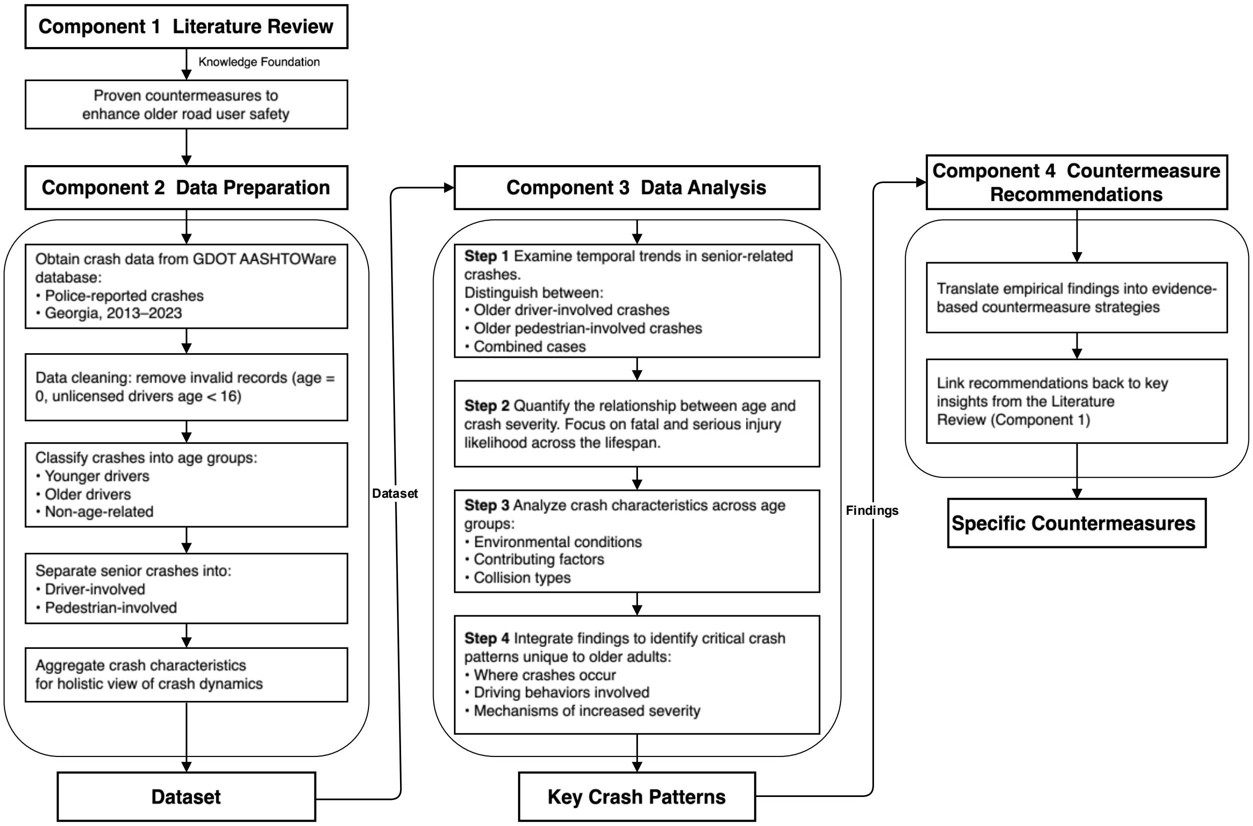


Figure 2. Illustration. Framework of the Proposed Senior Safety Analysis Methodology

Data Preparation

Data collection and cleaning

Data was collected from the Georgia Department of Transportation's AASHTOWare database, which contains information from every police report filed in the state from 2013 to 2023. Individual files include information on the ages of drivers involved, severity of the crash, collision ID, manner of collision, speed limit, contributing factors, weather conditions, surface conditions, and crash locations. A total of 3,444,404 crashes were reported.

Crashes where age is listed as zero indicate that the police officer did not fill out the driver's age in that instance, and drivers under 16 represent those without licenses. Therefore, crashes involving a driver whose age was listed as 0 or below 16 years old were also removed from the dataset.

Data aggregation

The crash reporting system aggregates data in a manner that does not specify the age of the driver at fault. Instead, it provides the ages of the drivers involved, and for crashes involving injuries or fatalities, it lists the age of the affected individuals. To address this limitation, two methods of data analysis were employed.

First, crash involvement was analyzed by creating a separate row for each driver listed in the crash reports. This approach allowed for the examination of crashes and the calculation of average severity based on the driver's age, facilitating the study of how crash severity varies with age.

Second, crashes were characterized into three groups including younger driver-related, older driver-related, and non-age related. If a crash involved a driver under the age of 25, it was classified as younger driver-related. If a crash involved a driver aged 65 or older, it was classified as older driver-related. Lastly, if all drivers involved in a crash were between the ages of 25 and 65, the crash was considered non-age-related.

Such categorization is based on previous research demonstrating distinct differences in crash rates to exist between these age groups. Younger drivers under the age of 25 more often engage in risky driving behavior such as speeding and distracted driving, which contributes to higher crash rates. On the other hand, older drivers aged 65 and above also demonstrate higher crash rates due to age-related declines in cognitive and physical abilities. Isolating age groups in this way can therefore indicate the unique risk factors and crash characteristics associated with each group, allowing for the development of tailored safety interventions.

While this approach allows for the comparison and analysis of crash percentages across different age groups, the magnitude of differences in crash characteristics may not fully reflect real-world conditions. This limitation arises from the way the data are aggregated: a crash is attributed to a driver within a given age group whenever that driver is involved, even if they were not responsible for causing the crash. As a result, this method of classification may include crashes that are not age-related, potentially skewing the distribution and reducing observed differences, as some crashes attributed to younger or older drivers may have been caused by drivers outside those age groups. Despite these limitations, the dataset still provides valuable insights that can inform improvements in transportation safety and equity.

DATA ANALYSIS RESULTS

Trends in Senior-Related Crashes

Figure 3 presents three panels tracking senior road user crash involvement as a percentage of all crashes from 2013 to 2023, where black lines represent all-severity crashes and red lines indicate fatal and serious injury crashes only. For all severity crashes, senior driver crashes across all severity levels exhibit a consistent upward trajectory, increasing from 13.74% in 2013 to 17.82% in 2023. A decline in 2020 likely reflects temporary distortions associated with the COVID-19 pandemic, which reduced overall travel and may have introduced short-term bias in crash patterns. Senior pedestrian involvement across all severity remains statistically minimal, fluctuating within a narrow range between 0.04% and 0.07%. Despite its low magnitude, this category also shows a slight upward trend over time. When categories of drivers and pedestrians are combined, the trend line confirms a gradual and sustained increase in the proportion of crashes involving seniors relative to the overall crash population.

Turning to the red lines, fatal and serious injury crashes involving senior drivers rose gradually from 0.24% in 2013 to 0.43% in 2023, representing 1.8 times increase over the twelve-year period. Among senior pedestrians, the proportion increased from 0.01% to 0.03%, representing 3 times increase over the twelve-year period.

Thus, both senior drivers and pedestrians warrant attention in Georgia.

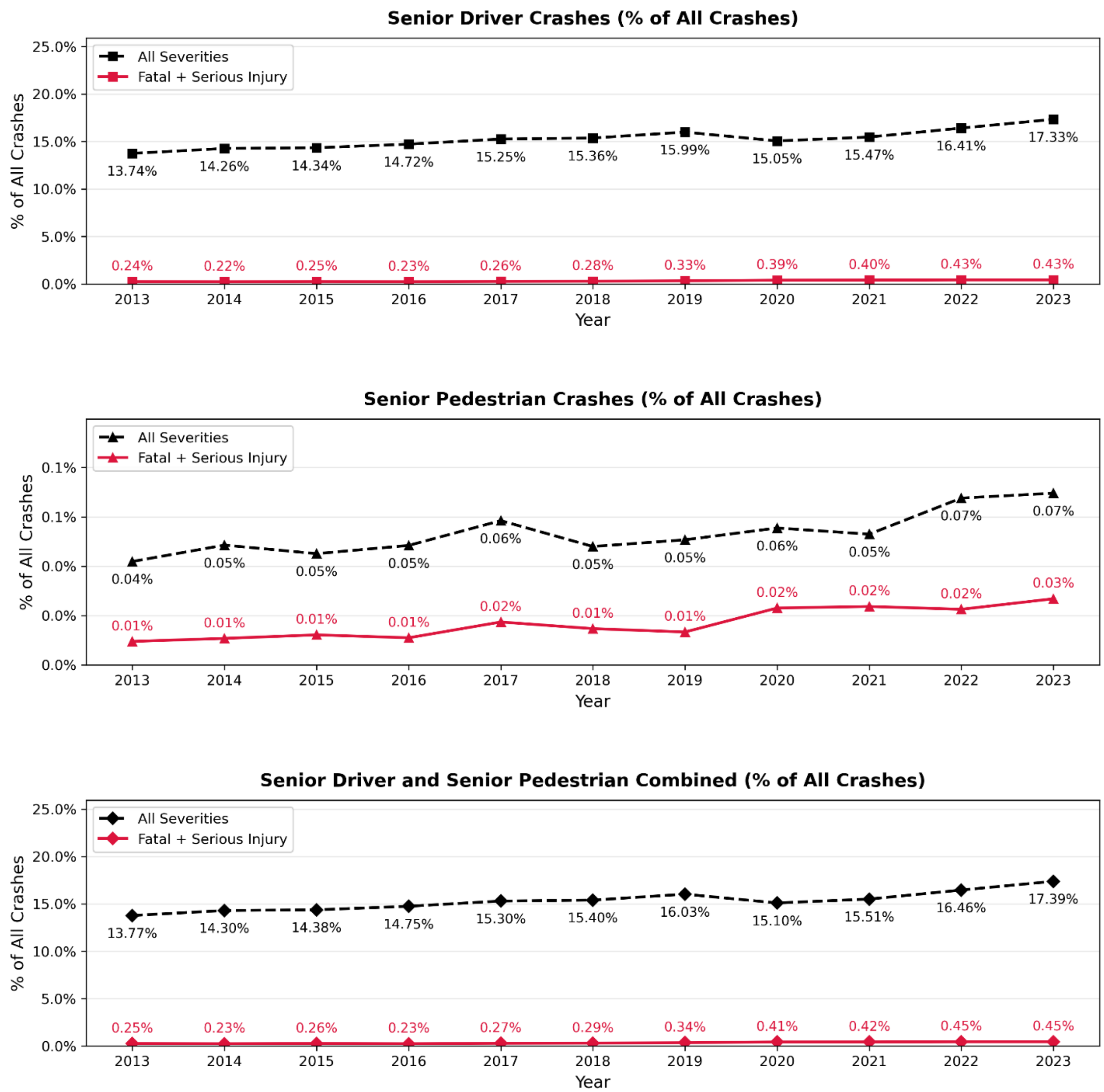


Figure 3. Graphs. Senior Driver and Pedestrian Crash Trends (2013–2024)

Crash Severity Across Age Groups

To gain a baseline understanding, the percentage of total crashes was plotted for each age group from 16 to 85. From this analysis, a clear trend emerged. It was observed that the percentage of crashes grew linearly up to around the age of 65. After this point, the percentage of crashes resulting in a fatal or serious injury began to increase exponentially. To test this hypothesis, the trend was plotted using equations where y represents the percentage of crashes resulting in a fatal or serious injury, x represents age, and the other variables are parameters to be fine-tuned by fitting the data. The equation to fit the data before age 65 linearly can be seen below in Equation 4.

$$y = mx + b \qquad \text{Equation 4}$$

The equation to fit the data after age 65 and account for exponential growth can be seen below in Equation 5:

$$y = mx + c(x - 64)^2 + b \qquad \text{Equation 5}$$

Optimizing these parameters resulted in the following values for each variable: b = 1.593, c = 0.0011, and m = 0.0045. To evaluate the quality of the model, the p-value was calculated. First, the standard error for each parameter was derived from the covariance matrix obtained during the curve-fitting process. This matrix provides estimates of the variance and covariance of the parameter estimates. Next, the t-statistic for each parameter was computed by dividing the parameter estimate by its standard error, resulting in the ratio shown in Equation 6:

$$t = \frac{estimate}{error} \qquad \text{Equation 6}$$

Finally, the p-value was calculated from the t-statistic using the cumulative distribution function (CDF) of the t-distribution. The CDF of the t-distribution is used to determine the probability that a given t-statistic would be observed under the null hypothesis, which assumes that the true parameter value is zero. Specifically, the CDF gives the probability that a t-statistic is less than or equal to a particular value. This can be done by using the below Equation 7:

$$p = 2(1 - CDF|t|) \qquad \text{Equation 7}$$

The two-tailed p-value assesses the likelihood of the parameter being significantly different from zero in either direction. It indicates the probability of observing a t-statistic as extreme as, or more extreme than, the one calculated if the null hypothesis were true. A low p-value suggests that the observed effect is unlikely to be due to random chance, providing evidence against the null hypothesis. In this analysis, each p-value was less than 0.0001, indicating there is less than a 0.01% chance that these values would occur by chance if the null hypothesis were true.

In addition to p-values, the R^2 value was calculated to measure the overall fit of the model. The R^2value, also known as the coefficient of determination, indicates the proportion of variance in the dependent variable that can be explained by the independent variable(s) in the model. It is calculated below in Equation 8**:**

$$R^2 = 1 - \frac{SSR}{SST} \qquad \text{Equation 8}$$

SSR (Sum of Squared Residuals) is the sum of the squares of the differences between the observed values and the predicted values from the model. SST (Total Sum of Squares) is the sum of the squares of the differences between the observed values and the mean of the observed values. In this analysis, the R^2 value provides an overall measure of how well the hybrid model explains the variation in the percentage of fatal crashes by age, complementing the p-values which assess the significance of individual parameters. The R^2 shows this model can explain 89% of the variance, demonstrating that it is a strong approximation of crash severity.

This analysis showed that the model fit the data well, supporting the hypothesis that the percentage of severe crashes (resulting in a fatal or serious injury) increases linearly from ages

16 to 64 and then rises exponentially from age 65 and older. The data, along with the severity models' projections, can be seen below in Figure 4.

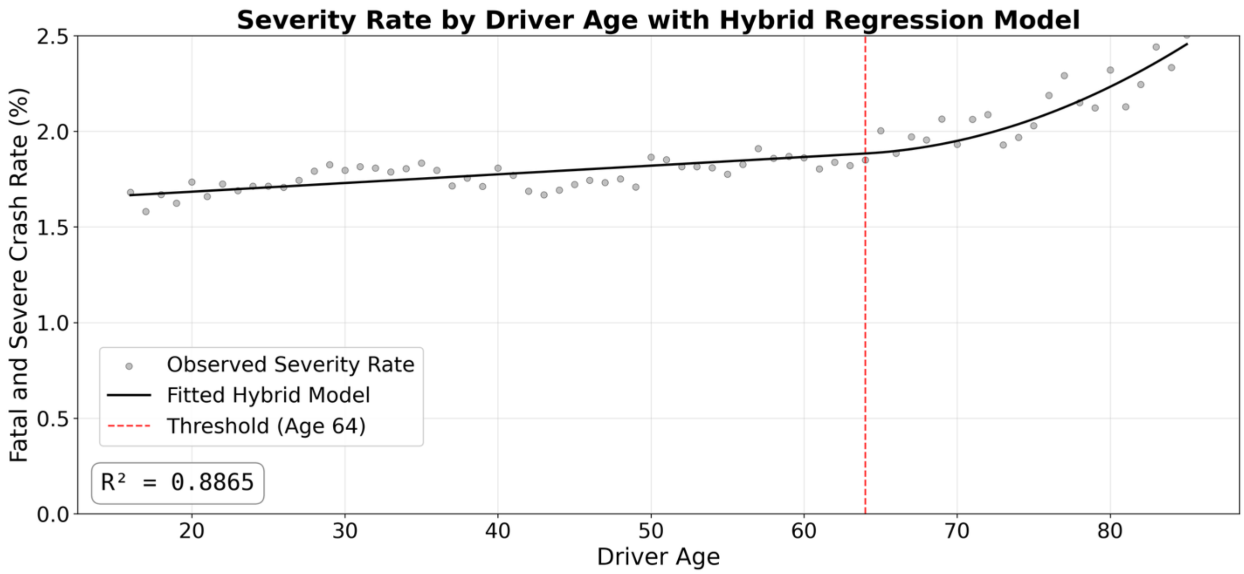


Figure 4. Graphs. Percentage of Crashes Resulting in A Fatal or Serious Injury by Age

Differences in Crash Characteristics

In response to these findings, the severe crashes (resulting in a fatal or serious injury) were each categorized as younger driver related (under 25), older driver related (65 and older), or non-age related (all drivers between the ages of 25 and 65) as described earlier. This was done to analyze the crash characteristics and determine whether there are statistically significant differences between the groups.

This section focuses on assessing the impact of environmental factors, such as weather and surface conditions, along with contributing factors to crashes (e.g., distracted driving), the manner of collision (e.g., head-on), and roadway locations (e.g., intersections).

To determine if these values varied statistically between the age groups, the analysis of variance (ANOVA) test was used. The p-values and F-values listed in the ANOVA table are crucial for determining whether the differences observed in the crash data across various factors, such as location, manner of collision, and contributing factors, are statistically significant. The F-value quantifies the extent of the variance between the groups relative to the variance within each group, providing a measure of the impact each factor has on the differences observed in crash occurrences.

Statistically significant results (p-value of less than 0.05) indicate that the observed differences in factors such as the location of the crash, manner of collision, and contributing factors are unlikely to have occurred by chance.

The results of the ANOVA test can be seen below in Table 8. The location of the crash, the manner of collision, and contributing factors are all statistically significant. However, surface conditions and weather conditions do not statistically differ across age groups. This indicates that older and younger driver-related crashes tend to occur in different locations, in different collision types, and for different reasons. The largest difference is manner of collision with an F-value of 5.69, followed by crash location and contributing factors, which have roughly equal effects.

It should be noted that although there were no statistical differences based on weather conditions, this does not necessarily mean that younger and older drivers are just as proficient in driving across all conditions. Instead, drivers often adjust their behavior according to their comfort levels, avoiding conditions that make them feel uncomfortable based on their age [63]. This suggests that younger and older drivers adjust their driving patterns to minimize exposure to challenging weather conditions.

Table 8. Results of ANOVA Test

Conclusion	Variable	ANOVA Results
Statistically Significant	Location of Crash	ANOVA F-value: 4.21
		ANOVA P-value: 0.04
	Manner of Collision	ANOVA F-value: 5.69
		ANOVA P-value: 0.01
	Contributing Factor	ANOVA F-value: 4.54
		ANOVA P-value: 0.02
Not Statistically Significant	Surface Conditions	ANOVA F-value: 0.70
		ANOVA P-value: 0.50
	Weather Conditions	ANOVA F-value: 1.00
		ANOVA P-value: 0.38

Difference in fatal and severe injury crash characteristics by age: manner of collision

Manner of collision has the largest F-value, indicating that manner of collision has the strongest impacts on the variance between the age groups. When analyzing the dataset, each collision was given a unique manner of collision based on the police report. The manner of collision is considered a 'Roadway Departure' if the crash is with a non-motorized vehicle (other than a pedestrian or animal) occurring off the roadway. The group "Angle" includes angle crashes that could involve left or right turns, or that are not classified as either type. Pedestrian-related crashes are crashes that involve at least one pedestrian. This analysis excluded any crashes where the manner of collision was not listed, or where the collision was with an animal.

As shown in Figure 5, roadway departure crashes are the most common manner of collision across all age groups, with prevalence in non-age-related crashes. This suggests that roadway departure crashes are widespread across all categories. However, because younger and older drivers have higher crash rates in other types of collisions, roadway departure crashes make up a smaller percentage of their total crashes.

The percentage of angle crashes is significantly higher for older driver-related crashes compared to younger driver-related and non-age-related crashes. Among all fatal and severe angle crashes in Georgia, over 40 % are senior-related. This suggests that older drivers might have difficulty with angle-related maneuvers. The proportion of pedestrian-related crashes is significantly lower among both older-driver-related and younger-driver-related crashes than among non-age-related crashes. This could be because older and younger drivers, aware of their challenges at intersections, may be more attentive and cautious, thereby reducing the likelihood of collisions involving pedestrians due to inattentiveness.

Overall, the data indicates that each age group exhibits distinct patterns in the manner of collision, underscoring the need for tailored interventions. By addressing the specific challenges faced by different driver age groups, policymakers can develop more effective strategies to enhance road safety for everyone.

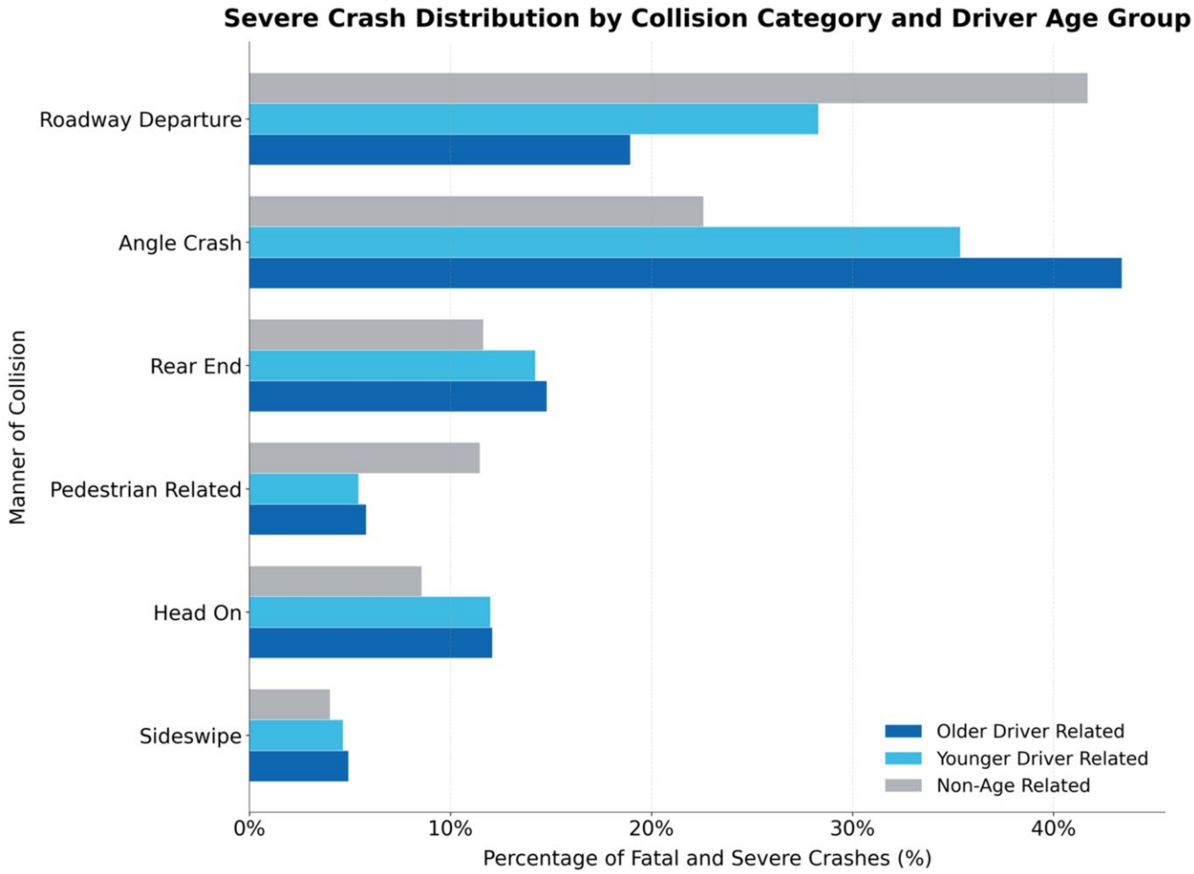


Figure 5. Graphs. Percentage of Fatal and Severe Crashes by Manner of Collision for Each Age Group

Difference in fatal and severe injury crash characteristics by age: location of impact

The location of a crash is included as a field on every crash report. Crashes can happen on roadways, at intersections, off roadways, on the shoulder of the road, or on the median of the road. Because both the median of the road and the shoulder of the road can be considered off roadway, this may lead to some confusion with the data. Furthermore, the default value is "on roadway" unless changed, which may result in some crashes being incorrectly classified. However, even with these potential issues in data quality, an in-depth analysis can still be performed.

The analysis of the data in Figure 6 reveals several key insights into the differences in crash locations between older driver-related, younger driver-related, and non-age-related severe crashes. Intersections are a critical point of concern for both older and younger drivers. Older driver-related crashes at intersections account for nearly 50% of severe crashes, significantly higher than the percentages for younger driver-related and non-age-related crashes. This highlights the importance of intersection safety measures for older drivers.

All groups have a high percentage of severe crashes occurring on the roadway. This makes sense, as most severe crashes are predicted to happen on the roadway since that is where most miles are driven. The percentage of severe crashes occurring off-roadway, on medians, and on shoulders is highest for the non-age-related group. Considering that older and younger drivers have higher crash rates, it follows that the percentages of severe crashes would be lower for these age groups. A likely explanation is that while off-roadway crash rates may be similar or even higher for younger and older drivers, these crashes constitute a smaller percentage of their total crashes due to the higher frequency of intersection-related crashes.

Overall, the findings highlight that each group is unique and that both older drivers and younger drivers have increased trouble with intersections.

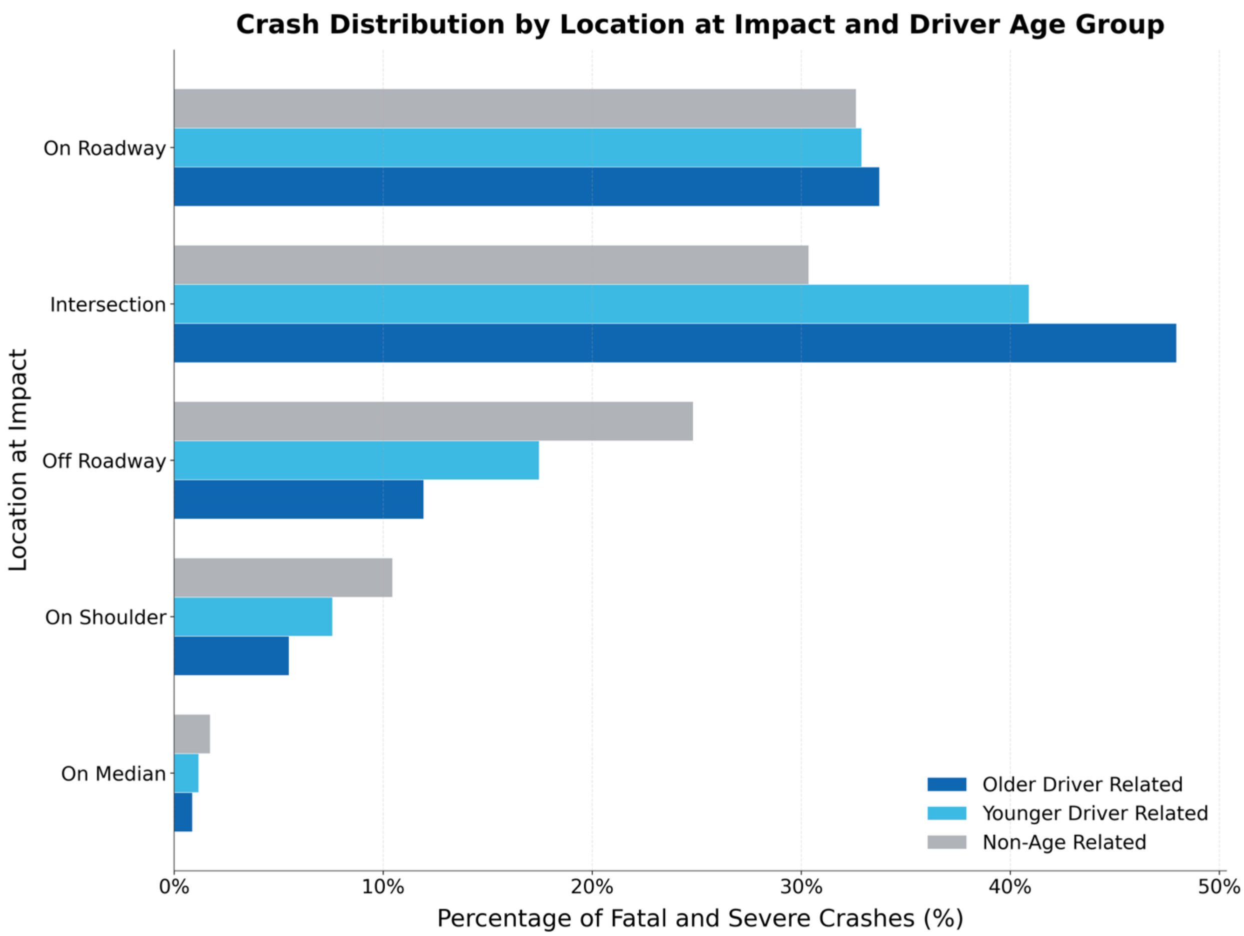


Figure 6. Graphs. Percentage of Fatal and Severe Crashes by Location of Impact for Each Age Group

Difference in fatal and severe injury crash: contributing factor

To assess data on contributing factors, each factor was prioritized based on crash type. The highest priority was given to 'Under the Influence' and 'Reckless Driving,' as they directly impair the driver. Next, 'Reaction Time' and 'Distracted Driving' were prioritized as they explain why the crash happened, followed by all remaining categories based on the order of the table below. Crashes without any listed contributing factors were excluded from this analysis. Furthermore, it is important to note that these factors contribute to the crash but do not necessarily indicate that the older or younger driver was at fault in an age-related crash, as the data aggregation does not provide that level of detail. The categories were determined manually by reviewing crash reports with the listed contributing factors and making categories based on that. The priority for these grouping and phrases can be seen below in Table 9.

Table 9. Categorization of Contributing Factors

Priority	Contributing Factor	Grouped Category
1	Reckless Driving	Reckless Driving
	Driver Lost Control	
	Too Fast for Conditions	
	Disregard Police	
	Evasion	
	Aggressive	
	Racing	
	Exceeding Speed Limit	
2	Under the Influence (U.I.)	Under the Influence
3	Failure to Yield	Reaction Time
	Following Too Close	
	Misjudged Clearance	
	Reaction to Object or Animal	
4	Distracted	Distracted Driving
	Cell Phone	
	Inattentive or Other Distraction (Distracted)	
5	Vision	Vision
	Visible	
6	Improper Turn	Traffic Violation
	Changed Lanes Improperly	
	Wrong Side of Road	
	Improper Backing	
	Improper Passing	
	Disregard Stop Sign/Signal	
	No Signal	
	Disregard Other Traffic Control	
	Parked Improperly	
7	Driver Condition	Driver Condition
8	Vehicle Failure	Other
	Surface Defects	
	Weather Conditions	
	Driverless Vehicle	
	Other	

After this categorization was done, it was possible to see how the categories varied among driver age groups by finding the averages and the confidence intervals. This method is effective because it allows for a detailed and structured analysis of contributing factors, ensuring that the specific impacts of various factors on different age groups are accurately assessed.

Contributing factors can also be categorized by external conditions (e.g., weather, road conditions) or by driver behavior (e.g., aggressive driving, inattention), each of which yields different analytical insights. For example, categorizing by external conditions could highlight how environmental factors affect crash rates among different age groups, while categorizing by driver behavior might better reveal how certain risky behaviors are more prevalent in specific age groups.

The chosen categorization method in this study was justified based on the direct impact of the factors on driver performance and the relevance to crash causation. By prioritizing impairing factors like 'Under the Influence' and 'Reckless Driving,' the analysis can focus on the most critical and preventable causes of severe crashes. This approach provides a clear understanding of the key areas where interventions can be most effective in reducing crash severity among different age groups.

As shown in Figure 7, the analysis of the contributing factors reveals distinct patterns in crash causes among different age groups. Notably, 'Reaction Time' related factors including 'Failure to Yield' and 'Following Too Close' are more prevalent among older drivers. This aligns with the known difficulties older drivers may face in reacting quickly to changing traffic conditions. This, combined with the fact that older drivers have higher overall crash rates, indicates that reaction time is a critical issue for older drivers leading to a higher cause of severe and fatal crashes among that age group. Furthermore, 'Reckless Driving,' 'Distracted Driving,' and 'Under the Influence' make up a smaller percentage of older driver related crashes. Given that younger drivers have such a higher crash rate, it can also be inferred that they are more likely to engage in risky behaviors. This suggests that younger drivers might be more prone to high-risk behaviors such as speeding, aggressive driving, and driving under the influence. Furthermore, vision, driver condition, and other similar categories account for a small percentage of fatal and severe injury crashes as the primary cause, according to this analysis.

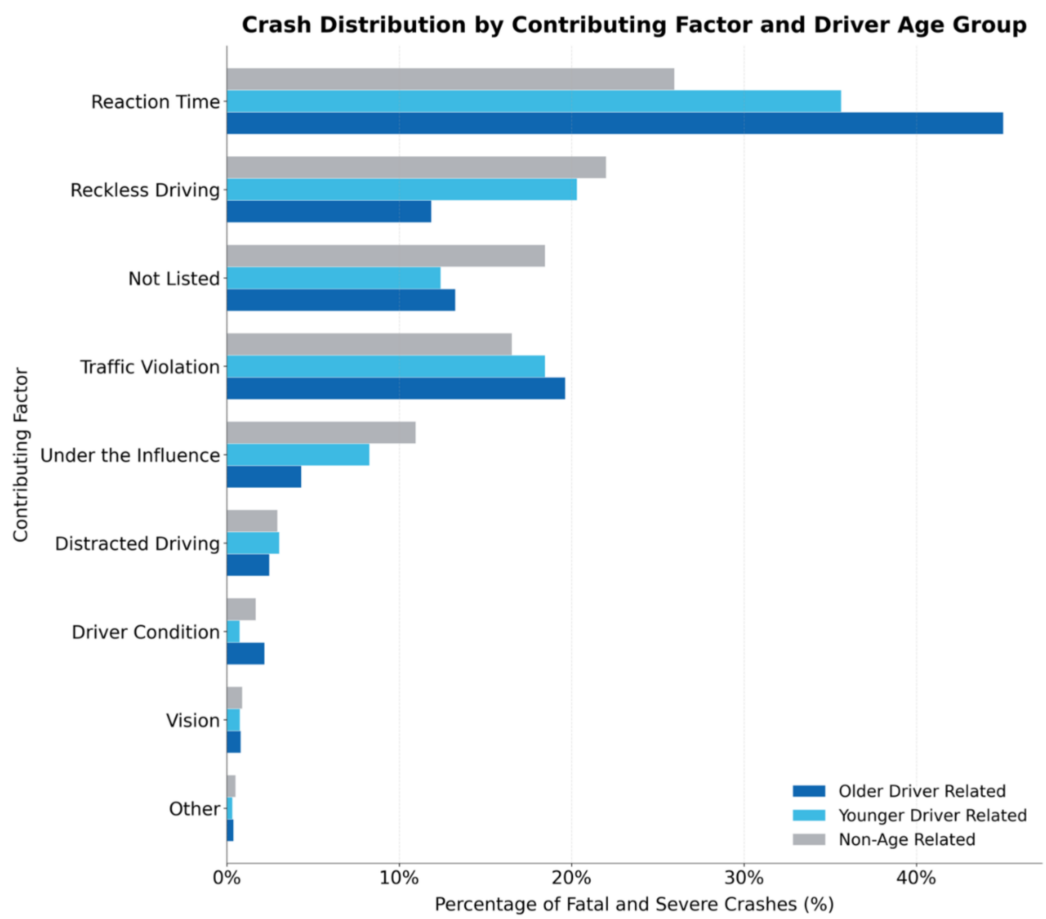


Figure 7. Graphs. Percentage of Severe Crashes by Contributing Factors for Each Age Group

Diving Down to Critical Crash Types

Based on the previous analysis, it was found that crashes which occur at intersections, happen at an angle, and happen due to a failure of reaction time are the most common for seniors. Therefore, an in-depth crash data analysis for angle crashes is conducted. As shown in Figure 8, older drivers show a consistently higher proportion of involvement across all turning-related crashes compared to both younger drivers and the non-age related group, indicating a greater overall risk for seniors in turning scenarios. “Angle (Unspecified)” is the largest turning-crash category for older drivers and includes crashes that cannot be distinguished as left-turn or right-turn events. Given the resolution of the available data, these crashes cannot be further disaggregated; thus, left-turn angle crashes should be interpreted as a lower bound of left-turn involvement, and the true share is likely higher. Right-turn angle crashes, while still elevated for older drivers relative to the other groups, account for a noticeably smaller percentage overall. Taken together, turning maneuvers in general, and left turns in particular, represent the highest-risk collision scenario for older drivers. In terms of contributing factors, reaction time stands out as the dominant cause across all turning crash types. Its impact is most pronounced in left-turn collisions, where it accounts for 79% of crashes involving older drivers (Figure 9). Regarding crash location, intersections are the primary setting for turning-related collisions, accounting for more than 82% of left-turn crashes (Figure 10).

In summary, given the quality and granularity of the available data, it can be reasonably concluded that left-turn crashes occurring at intersections, primarily attributed to insufficient reaction time, represent the most prevalent crash pattern among older drivers. Moreover, this crash pattern is consistent with the literature review findings, indicating that age-related declines in cognitive processing speed contribute to driving safety issues among older drivers.

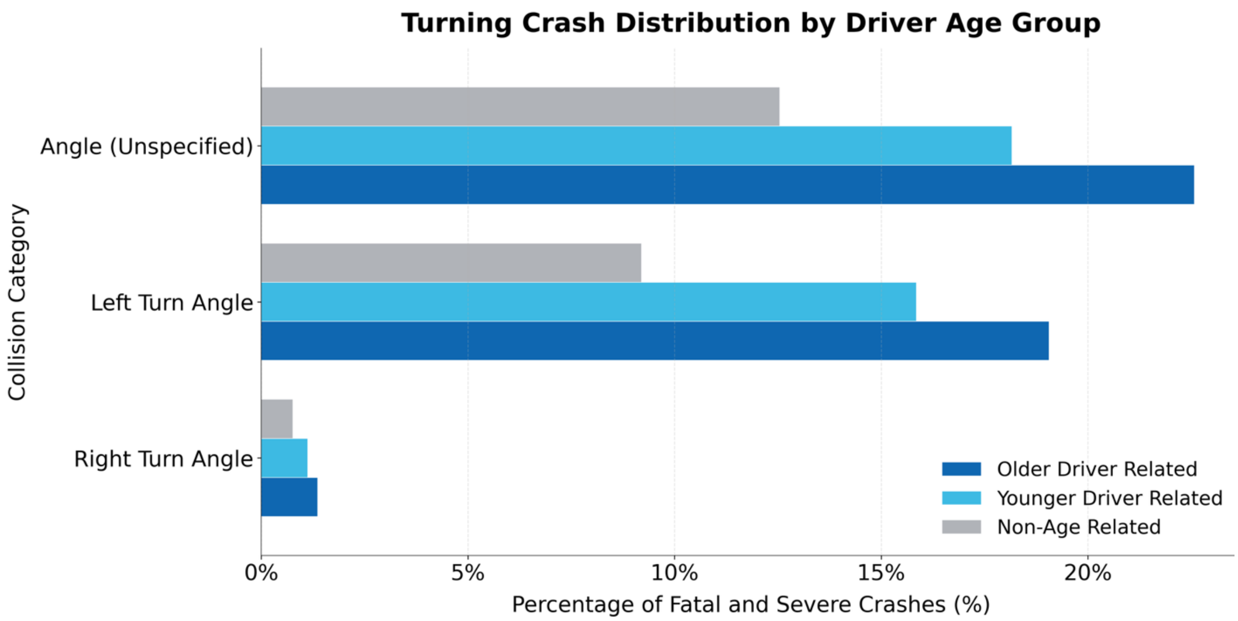


Figure 8. Graphs. Turning Crash Distribution by Age Groups

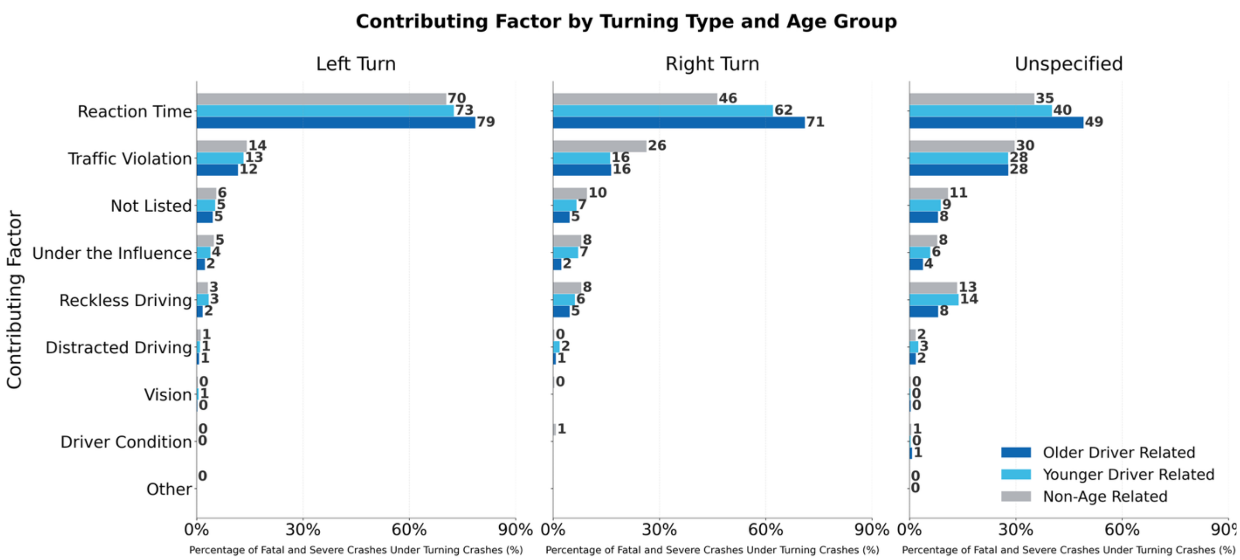


Figure 9. Graphs. Turning Crash Distribution by Contributing Factor

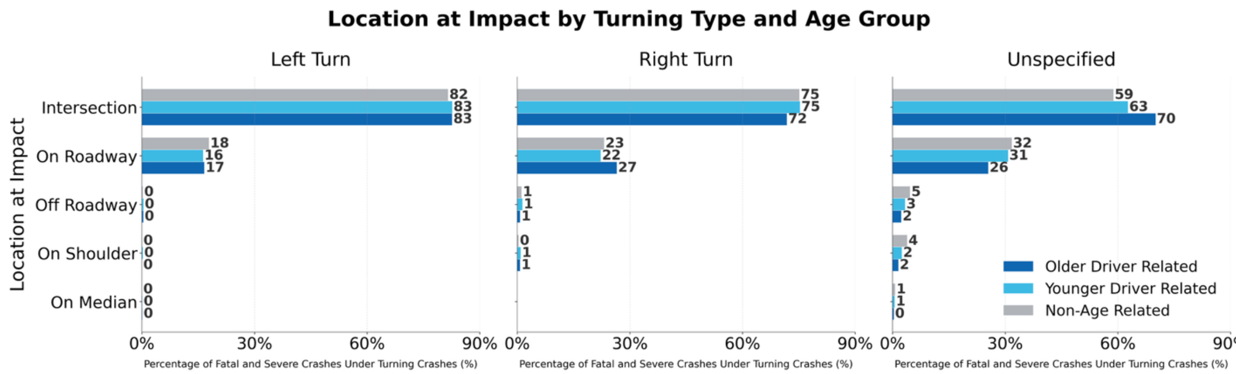


Figure 10. Graphs. Turning Crash Distribution by Location at Impact

RECOMMENDATION OF POTENTIAL COUNTERMEASURES

The data analysis in the preceding sections established that left-turn angle crashes occurring at intersections, primarily attributed to insufficient reaction time, represent the most prevalent and severe crash pattern among older drivers in Georgia. This section translates these empirical findings into evidence-based countermeasure strategies, while explicitly linking them back to the key insights identified in the literature review.

Key Findings

1. Manner of collision, crash location, and contributing factors differ significantly across age groups for fatal and serious crashes. An ANOVA test was conducted across five variables comparing older driver-related (65+), younger driver-related (under 25), and non-age-related (25–65) fatal and severe crashes. The results revealed that the manner of collision ($F = 5.69$, $p = 0.01$), contributing factor ($F = 4.54$, $p = 0.02$), and crash location ($F = 4.21$, $p = 0.04$) were statistically significant.
2. Turn angle crashes at intersections driven by reaction time failures are the most critical crash pattern that distinguishes seniors from other drivers in terms of fatal and serious crashes in Georgia. An in-depth analysis of turning crashes shows that older drivers have

the highest involvement across all turning crash types, with left-turn angle crashes representing the largest share. Reaction time accounts for 79% of older driver left-turn collisions, far exceeding other factors such as reckless driving or distraction. Regarding location, intersections are the primary setting for over 82% of those left-turn crashes.

Recommended Countermeasures

Based on the findings summarized above, the following countermeasures are recommended for left-turn crashes at intersections, sequenced by the degree to which they reduce the reaction time load on older drivers.

1. Protected left-turn signal phasing. A protected phase provides an exclusive green arrow that eliminates the need for gap judgment entirely, directly removing the reaction time demand that the data identified as the primary cause of these crashes. Since reaction time accounts for 79% of older driver left-turn collisions, this treatment addresses the root cause rather than mitigating its effects. The literature review identified a crash modification factor of 0.3 for this treatment, indicating a 70% reduction in left-turn crash frequency.
2. Add or widen the left-turn lane. Separating left-turning vehicles from through traffic reduces conflicts and minimizes delays for through movements. This separation improves overall traffic flow efficiency and provides clearer maneuvering space for turning drivers.
3. Provide offset left-turn lanes at intersections. Offsetting opposing left-turning vehicles extends the available sight distance, which extends the detection distance to evaluate oncoming vehicles before committing to the turn. This could potentially lengthen the reaction time window within which older drivers must make their gap judgment.

4. Clear sight triangles. Removing visual obstructions such as vegetation and parked vehicles at intersection approaches also extends the detection distance, providing additional time to make decisions.
5. Far left-side signal head. This reduces the cognitive load of the reaction by narrowing the required visual scanning area and making the signal indication easier to locate, so that less of the available reaction time is consumed by the act of finding and interpreting the signal.
6. Lighting. Enhanced intersection lighting improves the detection range of oncoming vehicles, signs, and pedestrians, particularly under nighttime and low-light conditions where age-related declines in contrast sensitivity and temporal sensitivity further compress the available reaction time.

CHAPTER 4. BEHAVIORAL ANALYSIS OF SENIOR DRIVERS USING EYE-TRACKING AND SMARTPHONE TECHNOLOGY

OBJECTIVE OF THIS CHAPTER

This chapter explores how eye-tracking technology can be used to investigate age-related differences in driving safety. Using a curved route in Vogel State Park as the study environment, it examines how older and younger drivers allocate attention and process visual information under real-world conditions. To achieve this objective, three main tasks are defined:

1. Understand where drivers look. Identify how older and younger drivers distribute their attention across the road environment using gaze heatmaps. This includes comparing attention to continuous features (like lane markings) and discrete features (like traffic signs) and examining how these patterns change with familiarity and lighting conditions.
2. Measure how drivers process information. Use eye-tracking metrics, such as fixation duration, saccade amplitude, and saccade peak velocity to evaluate how drivers process visual information. By comparing repeated drives on the same curves, the study examines whether older drivers show slower visual processing than younger drivers.
3. Link visual behavior to safety. Geospatially correlate these eye-tracking metrics with crash data (e.g. crash frequency), exploring whether gaze behavior can serve as an indicator of safety risk.

BACKGROUND KNOWLEDGE OF EYE-TRACKING TECHNOLOGY

Introduction to Eye-Tracking Technology

Eye-tracking technology provides direct measurements of how and when drivers detect and process targets within a visual field. Eye-tracking devices illuminate the eye with near-infrared light and use high-definition cameras to capture the corneal reflection pattern, from which real-time algorithms compute gaze direction. When synchronized with the forward-facing scene, this technology produces accurate spatiotemporal records of gaze points, fixations, and saccades, enabling detailed analysis of visual attention and perceptual changes. As shown in Figure 11, gaze points are the raw data recorded by an eye-tracking system that indicate where a person is looking at a specific moment in time. A fixation occurs when the eyes remain relatively stable on a single location long enough for visual information to be processed. Saccades are the rapid eye movements that shift gaze between fixations.

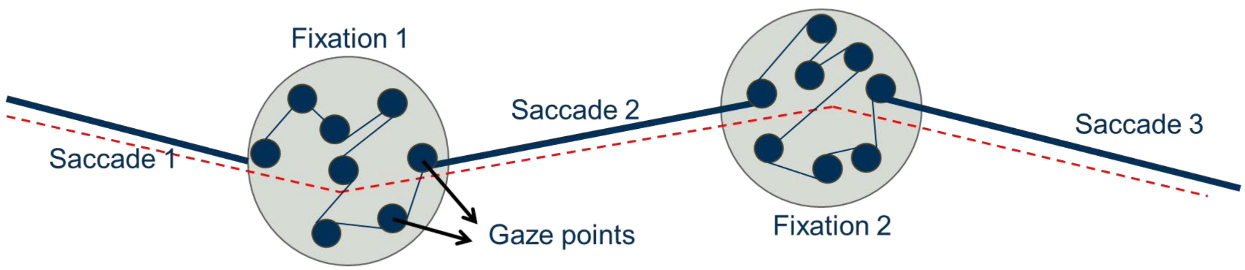


Figure 11. Illustration. Gaze Points, Fixations, and Saccades

As shown in Figure 12, wearable eye-tracking systems, which consist of small glasses with inward-facing and outward-facing cameras, provide naturalistic on-road measurements and support multimodal fusion with IMU, GPS, and other biosensors, allowing researchers to quantify fixation timing, gaze distribution, attention lapses, and the stability of head–eye coordination in real environments. Metrics such as fixation duration, first fixation distance, and recognition latency offer insight into the opportunities drivers have to perceive and interpret information in real time.

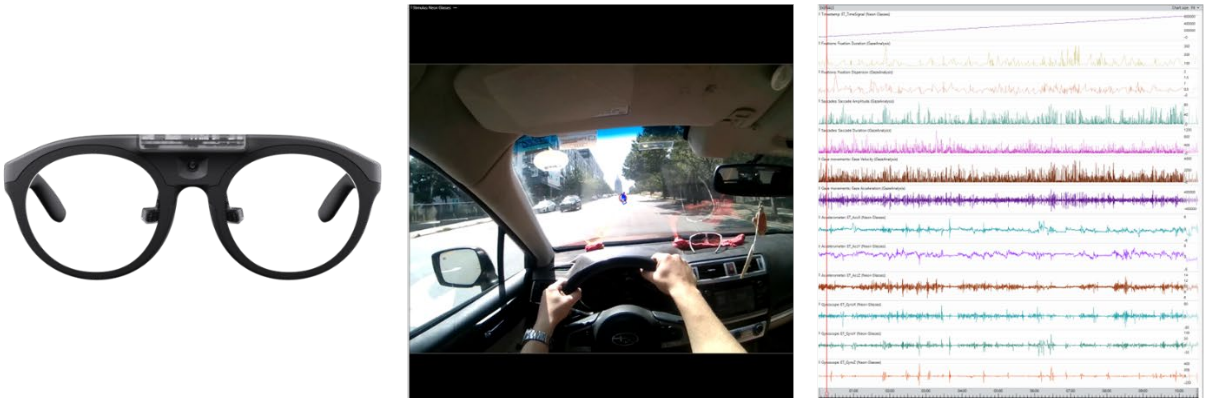


Figure 12. Illustration. Eye-Tracking Glasses, Data Collection Setup, and Sample Data (Image Source: I Can See Clearly Now - Neon Eye Tracking Glasses - iMotions)

Sequence of Driving Perceptual-Cognitive Response and the Related Eye-Tracking Metrics

Metric 1: Time to First Fixation (T1)

- Definition: Interval between when stimulus appears in visual field and when eyes settle on the object;
- What it measures: Visual search efficiency and attention allocation;
- Significance: Indicates how quickly drivers can locate relevant objects in their environment;
- Age differences: Seniors may take longer to locate objects in visual field.

Metric 2: Fixation Time (T2)

- Definition: Duration that eyes remain fixated on a specific object;
- What it measures: Time required for perception and comprehension;
- Significance: Longer dwell times may indicate need for more processing to understand object/situation;
- Age differences: Seniors may require longer dwell times to process the same information.

Metric 3: Verbal Response Time (T3)

- Definition: Time from first fixation to beginning of vocalization;
- What it measures: Internal cognitive processing speed. This measures whether drivers consciously processed the information, not just whether their eyes landed on it;
- Measurement point: Start of word articulation (not completion). Participants say short words like "pet" (pedestrian), "stop" (stop sign), "light" (traffic signal);
- Significance: Reveals conscious perception and cognitive processing delays.

Metric 4: Motor Response Time (Physical Action)

- Definition: Time from first fixation to physical action execution (e.g., time from seeing red light to actually pressing brake pedal);
- What it measures: Motor processing and physical response capability. CAN bus data showing brake pedal activation or we can use brain signal detection devices;
- Significance: Tests whether motor movement is impaired vs. cognitive processing.

Metric 5: Overall Response Time

- Definition: Composite measure from stimulus appearance through complete response;
- Components: Combines elements of all above metrics;
- Significance: Provides holistic view of driver response capability.

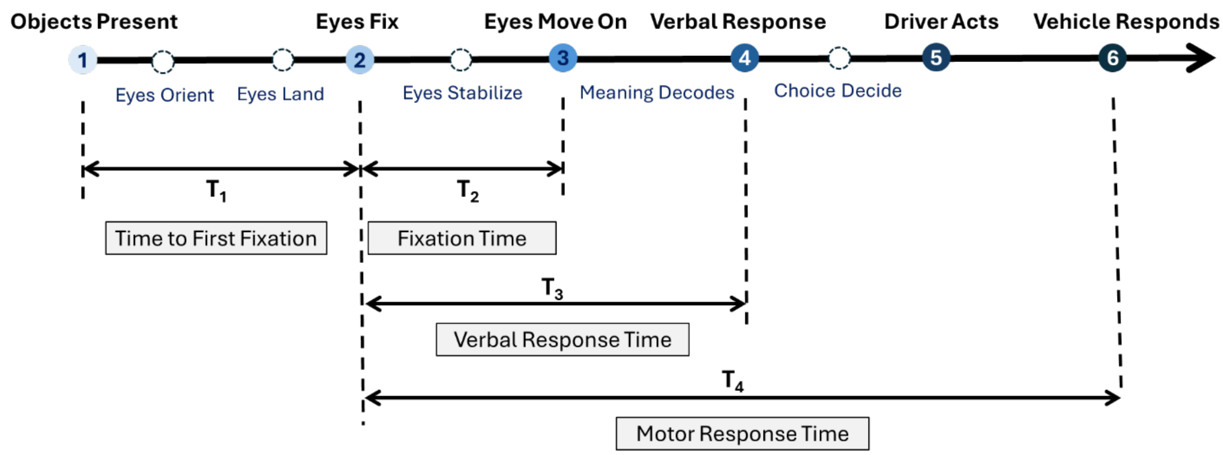


Figure 13. Illustration. Temporal Sequence of Perceptual-Cognitive Response and the Related Eye-Tracking Metrics

METHODOLOGY

Figure 14 presents the framework of the methodology, organized into three components. Component 1 covers data collection, including the study route, participants, testing variables, devices, and the three data streams gathered (curve inventory, smartphone GPS, and eye-tracking metrics). Component 2 describes the spatial-temporal data synchronization process, which links curve-level geometry with GPS locations and eye-tracking observations through spatial buffering and UTC timestamp matching. Component 3 outlines the three-step data analysis: gaze distribution analysis using heatmaps, visual cognition metrics analysis using fixation and saccade measures, and safety risk correlation linking gaze behavior to crash locations. Each component is detailed in the sections that follow.

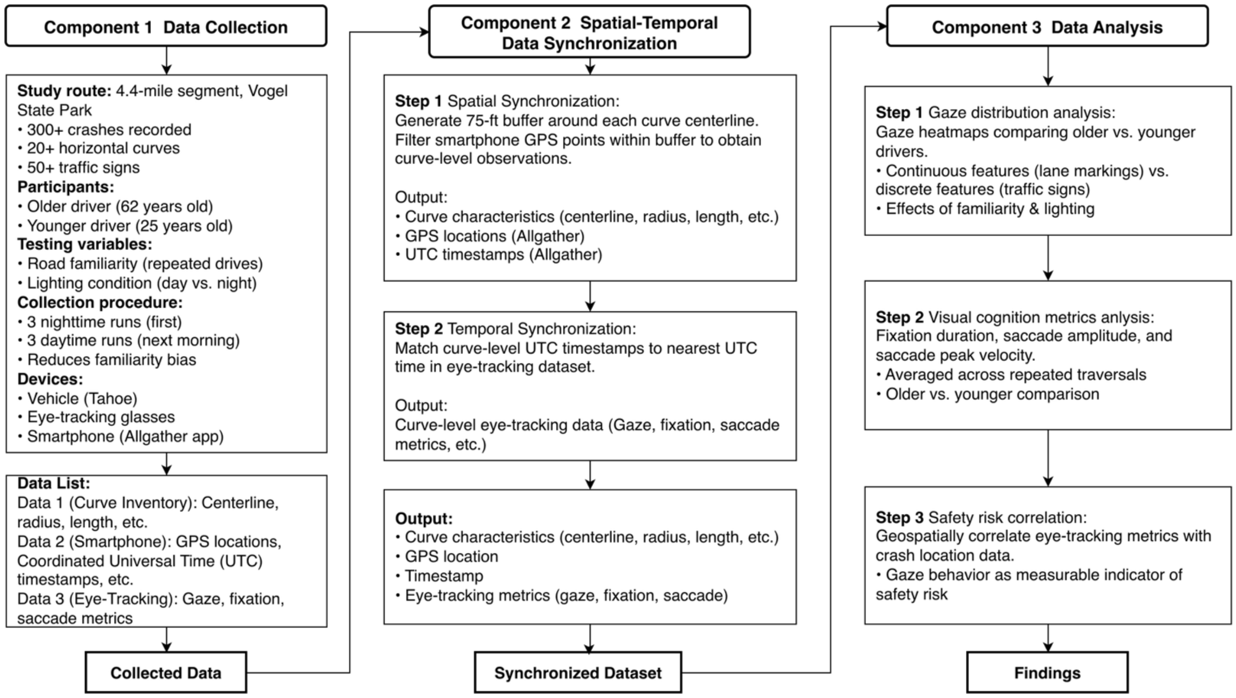


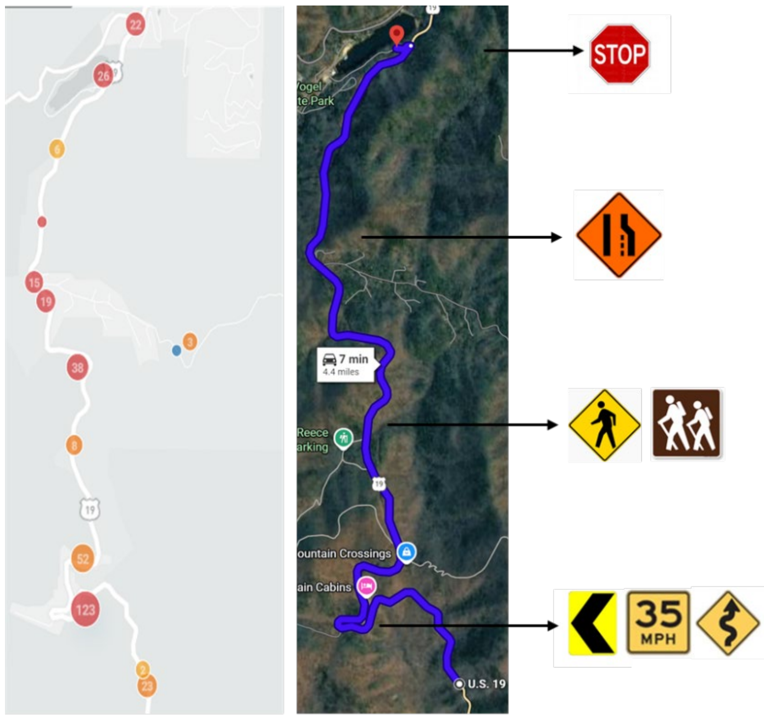
Figure 14. Illustration. Framework for the Proposed Methodology

Component 1: Data Collection

As shown in Figure 15, the data collection was conducted along a 4.4-mile route within Vogel State Park, with an average driving time of approximately 14 minutes per round trip. This route was selected based on several key characteristics:

1) It has a high crash frequency, with over 300 crashes recorded along the 4.4-mile segment, making it a meaningful setting for safety analysis.
2) The route contains a high density of horizontal curves, with 35 curves identified, including one particularly hazardous curve associated with 123 crashes. These geometric features create complex driving conditions and increase the likelihood of driver error.
3) A comprehensive inventory identified more than 50 traffic signs along the corridor, including regulatory signs, curve warning signs, and other supplementary signage. This

dense signage environment contributes to the overall visual complexity and plays an important role in guiding driver behavior along the winding roadway.



Crash Map Route Signs

Figure 15. Illustration. Data Collection at the Vogel State Park Route Characteristics

The data collection plan was developed to support the study objective of examining age-related differences in drivers' visual behavior, with a particular focus on how older and younger drivers allocate attention and process visual information.

- Participants: Due to Institutional Review Board (IRB) requirements and considerations regarding the vulnerability of older adult participants, the data collection process relied on trained lab members as drivers to ensure safety. Thus, two lab members were included as drivers in this study: one 62-year-old driver representing the older group and one 25-year-old driver representing the younger group.

- Testing variables: Two contextual factors were considered as potential moderators of visual behavior: road familiarity and lighting condition. Road familiarity was operationalized through repeated drives along the same route, while lighting condition distinguished between daytime and nighttime driving. Both factors were expected to interact with age in shaping how drivers perceive and respond to roadway environments. In particular, dim light driving has been shown in prior literature to present greater challenges for older drivers
- Collection procedure: Each participant first completed three consecutive runs under nighttime conditions. The data collection was then repeated the following morning under daytime conditions. This design reduced familiarity bias by conducting the initial sessions at night before any daytime exposure.
- Devices: Data were collected using Ford Tahoe, eye-tracking glasses, and a smartphone. This integrated system allowed synchronized collection of spatial, temporal, and visual behavior data for subsequent analysis.

The collected data list:

- Data 1 (Curve Inventory): Contains curve geometric characteristics such as radius and length, along with the GPS coordinates of the point of curvature (PC) and point of tangency (PT), as well as the curve centerline.
- Data 2 (Smartphone Data): Recorded by the Allgather smartphone application, provides continuous GPS locations and Coordinated Universal Time (UTC) timestamps captured during driving.
- Data 3 (Eye-Tracking Data): Includes gaze metrics, fixation metrics, and saccade metrics, together with their associated timestamps.

Component 2: Spatial-Temporal Data Synchronization

The data synchronization process integrates the above three independent data sources into a unified, curve-level dataset through a two-stage matching procedure based on spatial and temporal proximity. The smartphone, specifically the Allgather APP, serves as a spatiotemporal bridge between the other two sources, leveraging its continuously recorded GPS coordinates and UTC timestamps to establish both spatial and temporal linkages. The flowchart of the spatial-temporal data synchronization was illustrated in Figure 16.

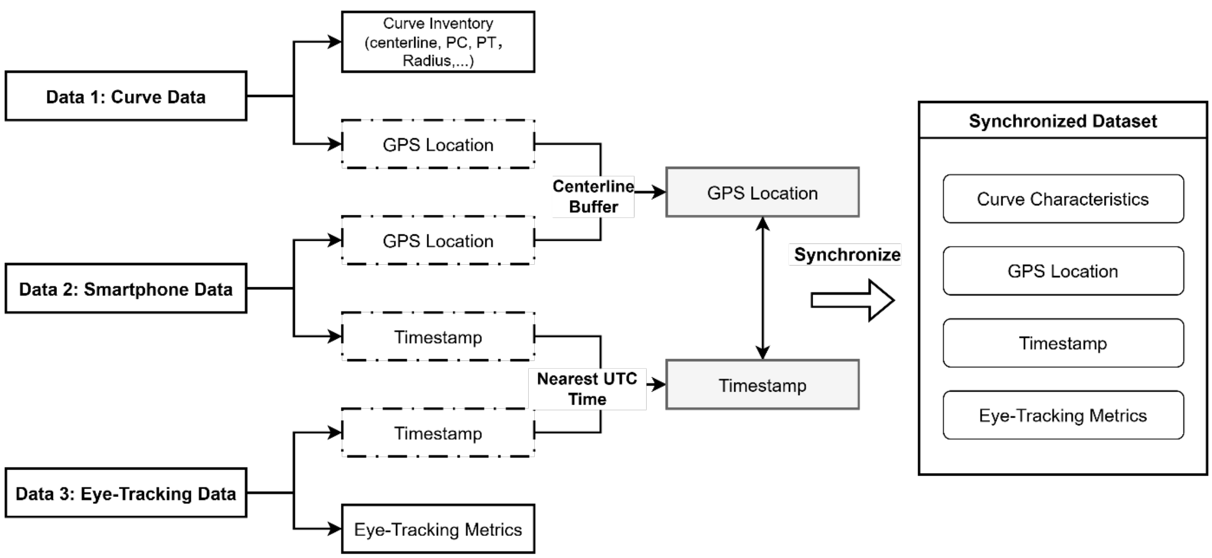


Figure 16. Illustration. Flowchart of Spatial-Temporal Data Synchronization for Curve Inventory, Smartphone Sensing, and Eye-Tracking Sensing

The detailed data processing steps using the data collected from Vogel State Park in Component 1 are listed below and shown in Figure 17:

- Step 1: Spatial Synchronization. To link smartphone GPS data with specific horizontal curves, a geospatial buffering method is used. Since the roadways examined in this study were primarily two-lane facilities, a 50-foot threshold was sufficient to capture GPS points within the curve while minimizing points from adjacent roadway segments. Any smartphone GPS points falling within this buffer are identified as belonging to that curve and are assigned accordingly. As shown in Figure 17 (left panel), the route contains 35 curves in total. The middle panel zooms in on Curve 8091 as an example. Here, GPS points from both travel directions are distributed on either side of the curve centerline within the buffer zone. This process produces curve-level records that merge geometric information from the curve inventory (such as radius and length) with smartphone data, including GPS location and UTC timestamps.

- Step 2: Temporal Synchronization. Using the curve-level UTC timestamps obtained in Step 1, a time-window approach is applied to align eye-tracking data with the corresponding curve-level results. For each curve, the earliest and latest GPS timestamps define a time window representing the vehicle's traversal period. Since each curve is driven in two directions, two separate time windows are generated per curve. All eye-tracking samples whose UTC timestamps fall within these windows are retained, preserving the full sampling frequency of the eye-tracking system (~200 Hz). Each eye-tracking sample is matched to the nearest GPS record using nearest-timestamp matching to provide spatial context, including latitude, longitude, and speed. No interpolation is applied to the GPS data. As a result, approximately 200 eye-tracking samples share the same GPS point. As shown in Figure 17 (right panel), Curve 8091 is used as an example. The GPS data span approximately 21 seconds, resulting in 21 GPS observations at ~1 Hz. During the same period, about 4,000 eye-tracking samples are recorded at ~200 Hz. Therefore, each GPS point corresponds to roughly 200 eye-tracking samples.

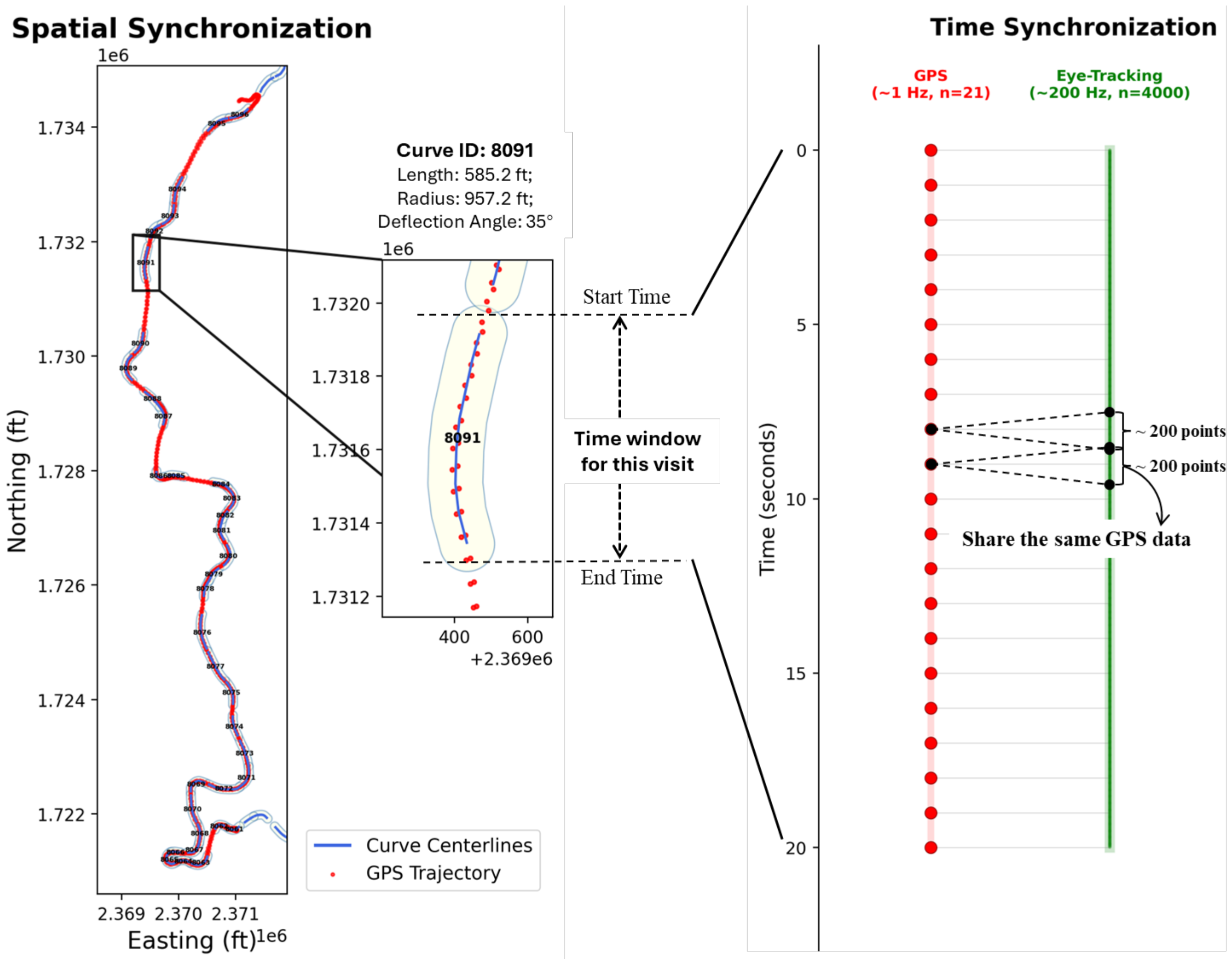


Figure 17. Illustration. Spatial-Temporal Data Synchronization at Vogel State Park

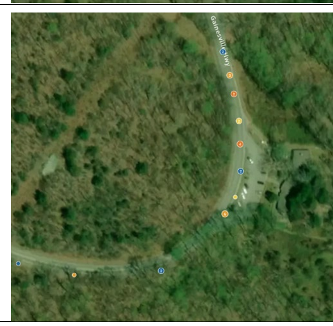
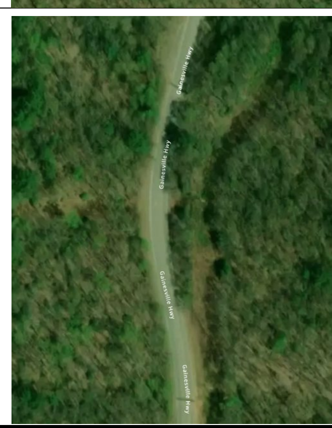
The resulting synchronized dataset encompasses 35 horizontal curves, collected from two participants during both daytime and nighttime conditions, across three runs in two travel directions. The dataset contains four categories of curve-level information:

1) Timestamps;
2) Curve characteristics from the geometric inventory, including curve ID, radius, deviation angle, and curve length.
3) GPS location data at 1 Hz resolution, including latitude, longitude, altitude, and speed;
4) Eye-tracking metrics at full ~200 Hz resolution, including gaze position, gaze velocity, fixation parameters, and saccade parameters.

Component 3: Data Analysis

This study further selected 3 representative curves for in-depth data analysis. The selected curves represent a broad spectrum of horizontal curve characteristics, with radii ranging from 100 ft to 957.2 ft, deflection angles from 35.0° to 223.6°, and lengths from 388.0 ft to 585.2 ft, as presented in Table 10. In addition, the selected curves are associated with different levels of crash frequency, allowing for a more comprehensive comparison of safety-related patterns across varying curve conditions.

Table 10. The Selected Representative Curves

Curve ID	Radius (ft)	Deflection Angle (°)	Length (ft)	Crash Map	Crash Frequency
8065	100	223.6	388		39
8071	311.5	77.3	420.8		20
8091	957.2	35	585.2		1

To support the objective of this study, the data analysis includes the following steps:

Step 1: Gaze distribution analysis

Characterizes where older and younger drivers direct their gaze across the environment using gaze heatmaps, with particular emphasis on differences between continuous features (e.g., lane markings) and discrete features (e.g., traffic signs), and how these patterns vary with familiarity and lighting condition.

Step 2: Eye-tracking metrics analysis

Quantify how older and younger drivers process the environment, using metrics including fixation duration, saccade amplitude, and saccade peak velocity. By averaging these measures across repeated traversals of the same curves, the analysis assesses whether older drivers exhibit slower visual cognition relative to their younger counterparts.

The eye-tracking metrics are categorized into two dimensions including infrastructure cognitive demand and human visual search efficiency to provide a comprehensive framework for understanding how eye-tracking data can be used to investigate age-related differences in driving safety.

- Infrastructure cognitive load dimension. These metrics capture how heavily the driver's cognitive resources are being consumed by demands of the road environment. Therefore, they may serve as indicators of curve complexity in this study. Fixation duration metrics are selected to quantify the cognitive load of driving. Fixation Duration (FD) is the time interval during which the gaze remains relatively stationary on a single location, defined as Equation 9. Equation 10 defined the fixation duration normalized by curve length, reflecting the spatial density of visual attention allocation. Longer mean fixation duration within a curve segment indicate that the driver needs more time to extract and interpret visual information from the scene.

$$FD_i = t_{end,i} - t_{start,i} \qquad \text{Equation 9}$$

The mean fixation duration within a curve segment:

$$FD_{mean} = \frac{1}{L_{curve}} \times \sum_{i=1}^{N} FD_i \qquad \text{Equation 10}$$

Where:

- FD_{mean} is the mean fixation duration for a specific curve segment across i fixations;
- FD_i is the duration of the i-th fixation;
- N is the total number of fixations within the segment;
- $t_{start,i}$ is the start timestamp of the i-th fixation;
- $t_{end,i}$ is the end timestamp of the i-th fixation.
- L_{curve} is the length of the curve.

- Human Visual Search Efficiency Dimension. These metrics capture how quickly drivers scan and interpret the roadway environment. Saccade Main Sequence (SMS) is selected as the primary metric. SMS describes the robust physiological relationship between Saccade Amplitude (SA) and Saccade Peak Velocity (SPV). In healthy individuals, saccade peak velocity increases systematically with amplitude, typically following a linear or power-law relationship. For each curve segment, the Main Sequence model is constructed by fitting a linear regression to all the saccade points. The linear relationship for the Main Sequence can be modeled as Equation 11:

$$V_{peak,i} = \beta_1 \cdot A_i + \beta_0 \qquad \text{Equation 11}$$

Where:

- $V_{peak,i}$ is the Saccade Peak Velocity of the i-th saccade;
- A_i is the Saccade Amplitude;
- β_1 is the Main Sequence Slope. If the slope β_1 for the older driver is lower than that of the younger group, it demonstrates that for a saccade of the same required distance, older drivers exhibit slower eye movement speeds.
- β_0 is the intercept constant. It represents a baseline offset in peak saccade velocity when extrapolated to zero amplitude.

Step 3: Correlation analysis between eye-tracking metrics and crash data

Geospatially correlate these eye-tracking metrics with crash location data, exploring whether gaze behavior can serve as a measurable indicator of safety risk.

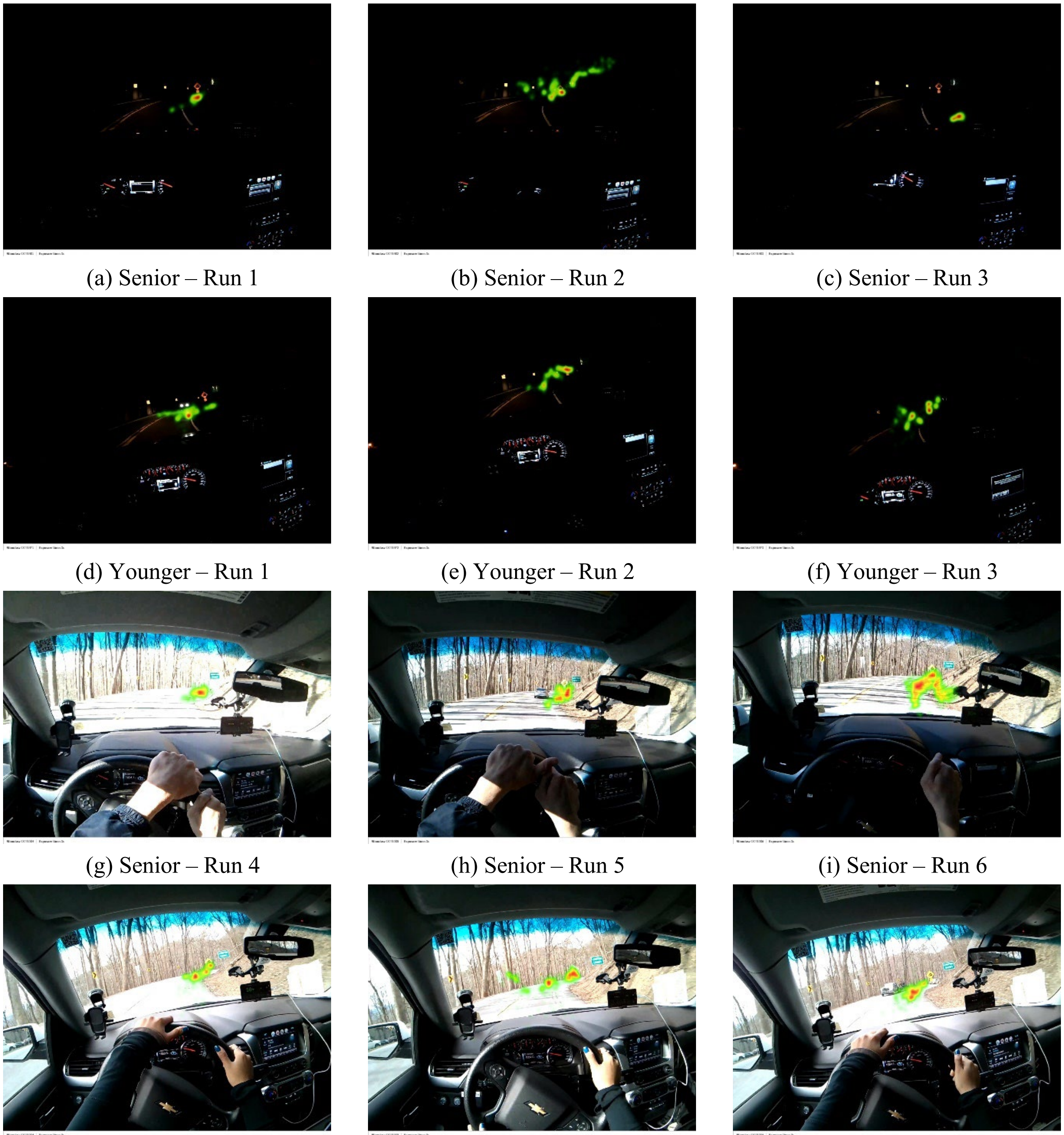
RESULT

Due to the requirement of Institutional Review Board (IRB) at Georgia Tech related to the vulnerability of older adult participants, trained laboratory members were used as drivers during data collection to ensure safety. As a result, only two participants were included in the study. Therefore, the results are descriptive only and should not be used for statistical inference.

Gaze Distribution Analysis

Figure 18 and Figure 19 illustrate the drivers' dynamic gaze maps while traversing a given curve. For Curve 8071, the time window is 3 seconds (with signs). For Curve 8091, it is 2 seconds (without signs). The images shown correspond to the first frame within the selected time window. The following listed three key findings:

- In the scenario with signs, both older drivers initially glance at the sign located at the beginning of the curve. As they enter the curve, their attention shifts to the road markings, and they subsequently maintain a steady gaze at these markings while driving. Notably, the chevron signs receive little to no attention. This pattern is consistent across both older and younger drivers, and it remains relatively stable as the number of runs increases.
- For the segment without signs, drivers tend to focus even more on the road markings. This pattern is consistent across both older and younger drivers, and it remains relatively stable as the number of runs increases.
- When driving within the curve, continuous road markings along the curve serve as the primary source of visual guidance for drivers, playing a more influential role than discrete features such as chevron signs. However, signs still provide an important alerting function: drivers tend to glance at them when approaching or entering the curve, using them as an initial cue before relying on the continuous markings.



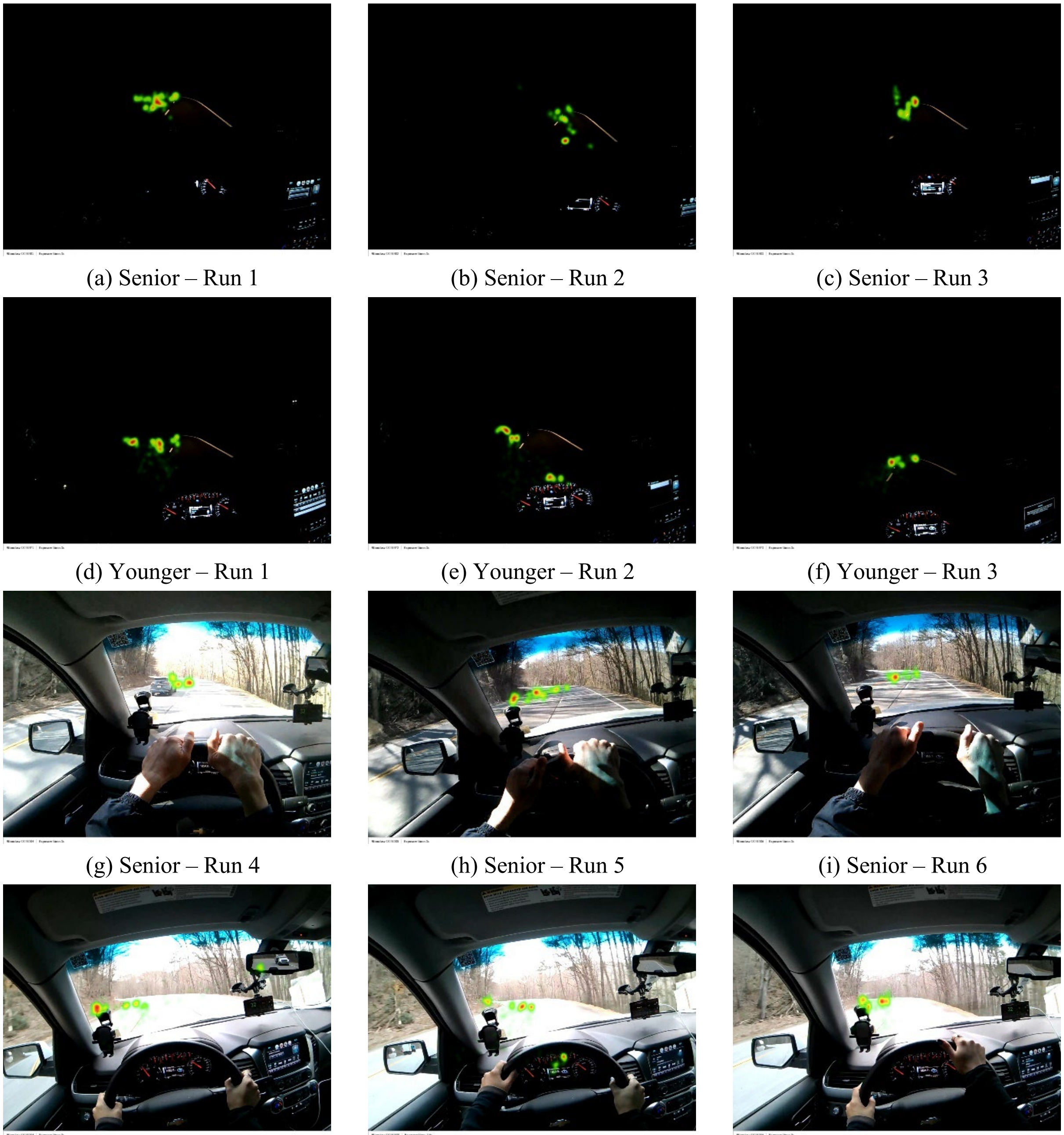
(a) Senior – Run 1 (b) Senior – Run 2 (c) Senior – Run 3

(d) Younger – Run 1 (e) Younger – Run 2 (f) Younger – Run 3

(g) Senior – Run 4 (h) Senior – Run 5 (i) Senior – Run 6

(j) Younger – Run 4 (k) Younger – Run 5 (l) Younger – Run 6

Figure 18. Illustration. Gaze map of Curve 8071



(a) Senior – Run 1 (b) Senior – Run 2 (c) Senior – Run 3

(d) Younger – Run 1 (e) Younger – Run 2 (f) Younger – Run 3

(g) Senior – Run 4 (h) Senior – Run 5 (i) Senior – Run 6

(j) Younger – Run 4 (k) Younger – Run 5 (l) Younger – Run 6

Figure 19. Illustration. Gaze Map of Curve 8091

Eye-Tracking Metrics Analysis

Mean fixation duration analysis.

Figure 20 (a)–(c) present the trend of mean fixation duration per unit length across six runs (R1–R6) under nighttime (R1–R3) and daytime (R4–R6) conditions for both younger and older drivers, across four representative curves with varying geometric characteristics. Several consistent patterns emerge.

- Mean fixation duration shows a roughly decreasing trend with increasing runs for both age groups. This suggests that as drivers become more familiar with the roadway, the visual processing demand declines.
- Mean fixation durations during nighttime are roughly higher than those during daytime across all curves. This indicates that low-light conditions impose greater perceptual and cognitive demands on drivers, likely due to reduced visibility and increased uncertainty in interpreting roadway features.
- Curve geometry plays a significant role. Sharper curves (e.g., 8065 and 8071) are associated with higher mean fixation durations compared to gentler curves (e.g., 8091). This pattern suggests that sharper curves increase visual demand, requiring more sustained attention and processing time to negotiate safely.
- There is no consistent or substantial separation between the two age groups in terms of mean fixation duration. This implies that, in this dataset, this metric is more sensitive to curve characteristics than to age-related differences in visual behavior. This finding is consistent with the functional role of fixation duration, which primarily reflects the processing demand of the visual environment.

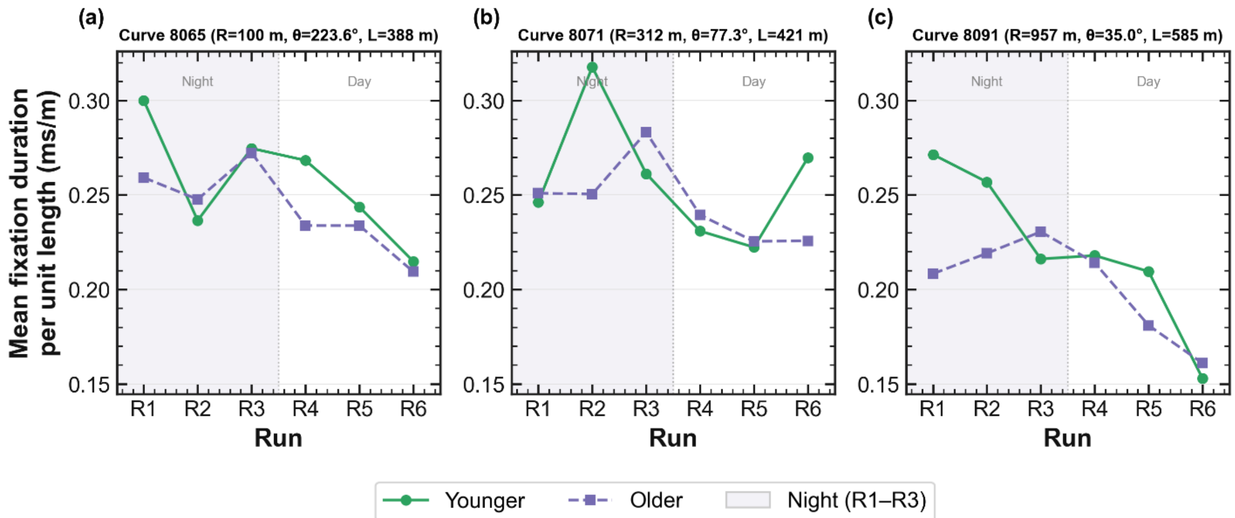


Figure 20. Graphs. Trend of Mean Fixation Duration per Unit Length across Six Runs

Saccade main sequence

Figure 21 (a)–(c) present the saccade main sequence under daytime (aggregated from R4 to R6) and nighttime (aggregated from R1 to R3) conditions for both younger and older drivers across four representative curves with varying geometric characteristics.

- The main sequence slope (β_1), is consistently higher for younger drivers than for older drivers during daytime conditions. This indicates that, for a given saccade amplitude, older drivers exhibit lower peak saccade velocities, reflecting slower oculomotor responses. In addition, the baseline offset of peak saccade velocity is also lower in older drivers compared to younger drivers, further suggesting reduced overall eye movement speed.
- The difference in saccade speed between younger and older drivers appears more pronounced in gentler curve (e.g., 8095) compared to sharper curves (e.g., 8065 and 8071).

- Under nighttime condition, neither the main sequence slope nor the baseline offset shows a consistent difference between younger and older drivers. Given the current limited dataset, no stable or reliable conclusions can be drawn for nighttime driving at this stage.
- Together, the main sequence slope appears to be more sensitive in distinguishing younger and older drivers during daytime conditions, than curve characteristics. This finding aligns with the role of the main sequence slope as a metric that captures differences in human eye movement performance.

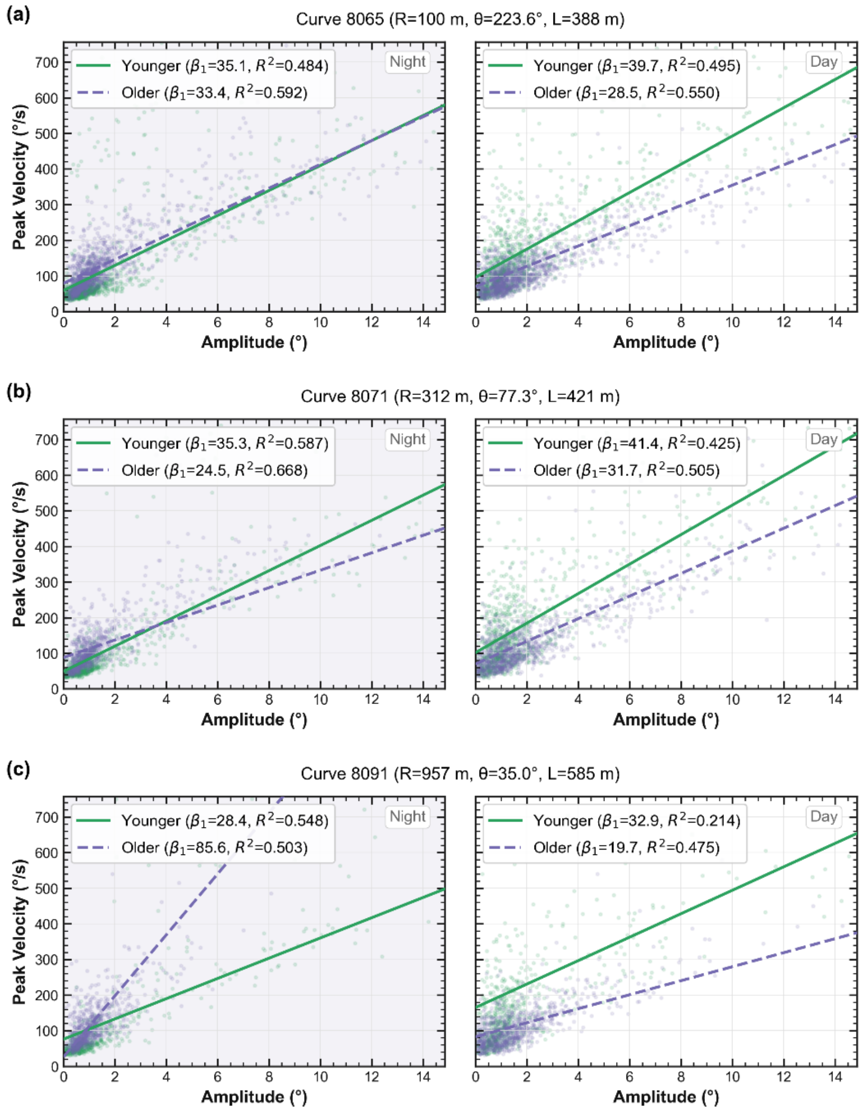


Figure 21. Graphs. Saccade Main Sequence under Daytime and Nighttime Conditions across Representative Curves

Correlation Analysis Between Eye-Tracking Metrics and Crash Data

Figure 22 (a)–(e) present the spatial comparison of eye-movement metrics and crash frequency along the three selected curves. For both the older and younger driver, six runs were recorded for each curve, and the corresponding data were then averaged to obtain a single representative value.

- As shown in Figure 22 (a), (b) and (e), For both older and younger drivers, FD mean shows a positive correlation with crash frequency. As the number of accident-prone scenarios increases, FD mean also rises. This suggests that curves with higher visual demand are more likely to be associated with crashes.
- As shown in Figure 22 (c), (d) and (e), in the older group, β_1 demonstrates a clear negative relationship with crash frequency: as the number of crashes increases, oculomotor efficiency declines. This pattern is not evident in the younger group. These findings suggest that reduced eye movement efficiency may be a potential factor associated with increased crash risk among older drivers.

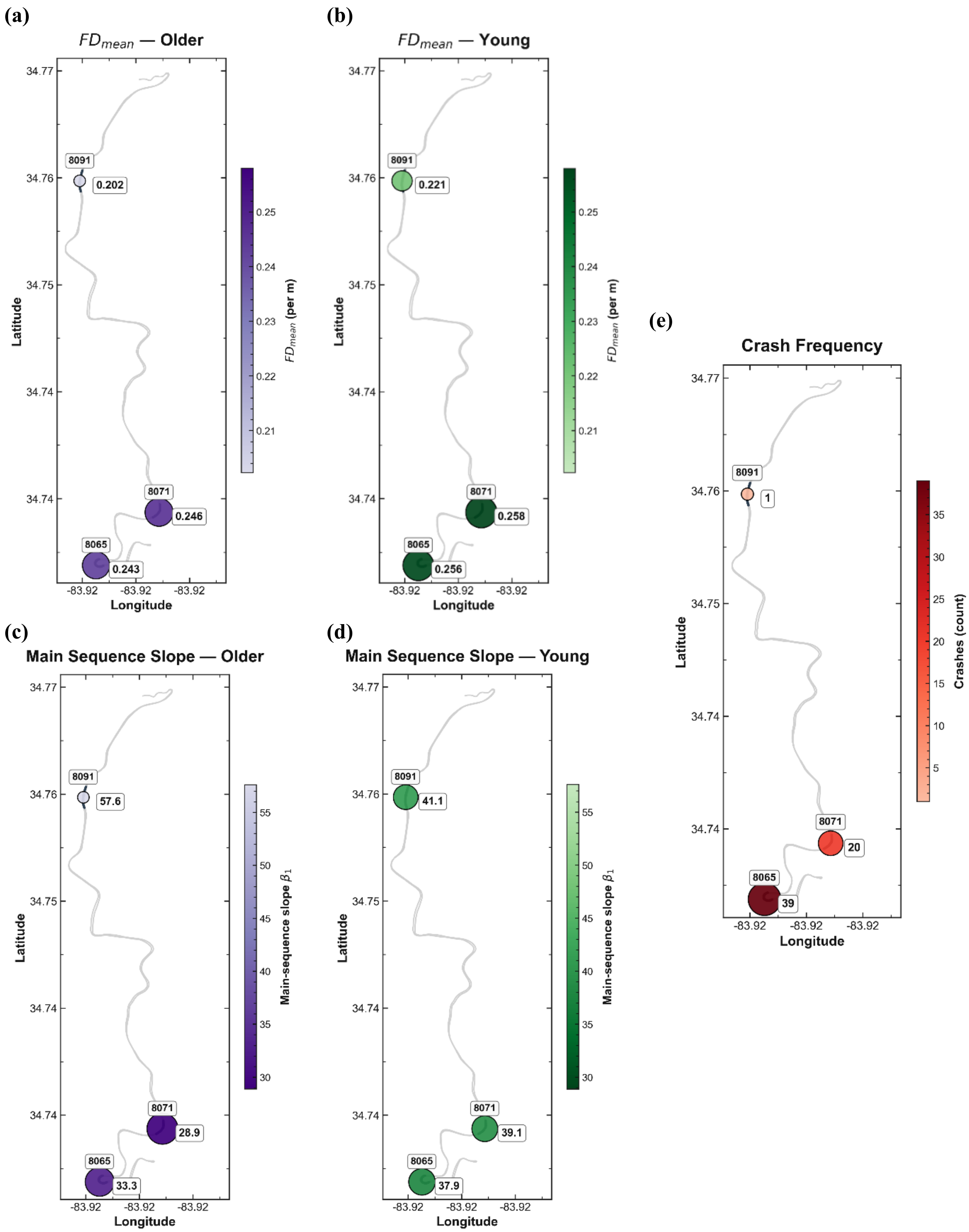


Figure 22. Graphs. Correlation Between Eye-Tracking Metrics and Crash Data

SUMMARY OF FINDINGS

- Spatial-temporal synchronization. The methodology successfully achieved spatial-temporal synchronization of three data sources including curve inventory, smartphone GPS, and eye-tracking metrics. The integrated dataset enabled curve-level integration of roadway geometry, vehicle trajectory, and driver visual behavior for in-depth data analysis.
- Gaze distribution on curves. Both older and younger drivers rely primarily on continuous road markings for visual guidance within curves, while discrete signs (e.g., chevrons) receive little attention. However, signs serve as initial alert cues when approaching the curve, as drivers tend to glance at the sign at the entrance before entering the curve.
- Mean fixation duration is environment-driven, not age-driven. Mean fixation duration is larger at sharper curves with higher visual demand. It also decreases as drivers become familiar with the road and increases at night. However, mean fixation duration showed no substantial difference between older and younger drivers.
- Saccade main sequence slope reveals age differences. During daytime, older drivers show consistently lower saccade velocities (lower β_1 and baseline offset) than younger drivers, indicating slower oculomotor responses. For nighttime, however, the dataset is limited and no reliable interpretation can be drawn.
- Eye-tracking metrics' linkage to crash risk. Mean fixation duration positively correlates with crash frequency for both groups. For older drivers specifically, reduced saccade efficiency shows a negative correlation with crash frequency, suggesting oculomotor decline is a potential risk factor unique to seniors. These results indicate that age-related

decline in oculomotor performance is a behavioral mechanism consistent with the reaction-time deficit observed in the crash data.

CHAPTER 5. ROADWAY SAFETY SURVEY FOR GEORGIA'S ROADWAY USERS

PURPOSE OF THE SURVEY

This survey aims to examine age-related driving behaviors, with particular focus on identifying potential roadway environmental barriers that affect the driving and walking safety of older adults in Georgia. Due to the relatively small sample sizes collected from both the senior and younger adult groups, this chapter primarily serves a supporting role by providing supplementary behavioral insights that complement the broader crash analysis, eye-tracking data analysis, and countermeasure development presented in this study.

Specifically, the study investigates the following hypotheses and designed the corresponding questions.

- Hypothesis 1: Declined Visual Capability
  - Reduced Visual Acuity
  - Decreased Contrast Sensitivity
  - Delayed Hazard Detection
- H2: Constrained Physical Mobility
  - Limited Neck/Head Range of Motion
  - Limited Arm Range of Motion
  - Limited Leg Range of Motion
  - Reduced Walking Speed
- H3: Delayed Cognitive Processing and Response Time
  - Information Overload at Intersections
  - Difficulties in Making Time-Critical Decisions

SURVEY QUESTION DESIGN

The survey is designed in 4 main sections to systematically capture participant background information, driving experience, and walking experience in Georgia.

Section A: Eligibility And Consent Confirmation

This section ensures that responses come from qualified participants. The consent form verified that the respondent is at least 18 years old, currently holds a valid driver's license, currently the residence of Georgia, and acknowledges that participation is voluntary and may be withdrawn at any time.

Section B: Demographics

This section collects basic background information used for subgroup analysis, particularly comparisons between senior and younger drivers. It collects basic demographic characteristics of participants, including age, gender, and education. It also asks about the type of vehicle usually driven, driving frequency, outdoor walking frequency for exercise or transportation, and the typical driving environment.

Section C: General Driving Experience

Before the hypothesis-driven items, respondents answer a set of warm-up questions drawing on their everyday experience. They are asked to list up to three Georgia intersections they find problematic and up to three they find well-designed, with the same paired structure repeated for crosswalks and for road curves. For each location type, checklist items help identify contributing factors (for example, confusing lane markings, poor signal timing, faded crosswalk markings, missing guardrails), and an open-ended field invites suggestions for improvement.

Section D: Hypothesis-Driven Questions

- Hypothesis 1: Declined Visual Capability
    - Reduced Visual Acuity. Assessed using self-reported static visual acuity ratings and dynamic visual acuity for sign legibility at varying speeds (25–35 mph, 35–65 mph, and 65+ mph). Participants also evaluated their ability to scan and interpret different sign arrangements (side-by-side, top-to-bottom, overhead, and roadside).
    - Decreased Contrast Sensitivity. For drivers, this was measured through reported difficulty in reading traffic signs under nighttime conditions across six color categories (red, black, yellow, green, blue, and brown), as well as recognizing pavement markings (four types) and pedestrians. For pedestrians, questions focused on nighttime visibility of traffic signals and approaching vehicles.
    - Delayed Hazard Detection. Measured by the frequency of being startled by pedestrians or vehicles while driving or walking, under both daytime and nighttime conditions.
- Hypothesis 2: Constrained Physical Mobility.
    - Limited Neck/Head Range of Motion. Assessed by self-reported difficulty in turning the head to check surrounding traffic.
    - Limited Arm Range of Motion. Measured through reported arm or shoulder strain during driving and difficulty fully turning the steering wheel during tight maneuvers (e.g., U-turns, parking, and sharp turns).

    - Limited Leg Range of Motion. Evaluated based on difficulty performing rapid transitions between the accelerator and brake pedals
    - Reduced Walking Speed. Assessed through self-reported walking speed limitations, particularly in wide intersections.
- Hypothesis 3: Delayed Cognitive Processing and Response Time
    - Information Overload at Intersections. Measured by the extent to which participants feel overwhelmed by clustered roadway elements at intersections, along with identification of specific contributing factors (e.g., signs, signals, pedestrians, pavement markings, and vehicles).
    - Difficulties in Making Time-Critical Decisions. Assessed through reported difficulty in judging safe gaps for maneuvering, particularly when making unprotected left turns at signalized intersections.

METHODOLOGY

Component 1: Data Collection

The survey was built and administered using Qualtrics, a widely used online survey platform that supports a broad range of question types, conditional branching logic, and automated data export. Respondents were recruited through Prolific; an online participant recruitment platform designed specifically for academic research. Prolific maintains a large, pre-screened participant pool with verified demographic information, which allows this project to target specific groups by age, driving licensing status, and residency.

Component 2: Data Preparation

- Step 1: Screen for eligible and complete responses. Only responses where the consent and eligibility field are confirmed and the “Finished” flag is “True” will be retained. Incomplete submissions will be excluded from all analyses.
- Step 2: Derive participant age and define age groups. Participant age will be calculated from the date of birth and the survey completion date. The grouping variable will then be created, classifying respondents as Younger Adults (18–25 years), Middle-aged adults (26–64 years) or Seniors (≥65 years). The continuous age variable will be retained for regression analyses.
- Step 3: Recode survey responses into analyzable formats. Likert-scale items will be recoded as integers (1–5 or 1–4) according to their response labels. For multi-select questions, each answer option will be coded as a separate variable (1 = selected, 0 = not selected) to enable frequency counting. Demographic variables such as gender, education, and driving environment will be recoded as categorical factors.

Component 3: Data Analysis

Descriptive statistics for sample characteristics

The descriptive analysis focuses on summarizing and visualizing the key demographic and behavioral characteristics of the survey respondents, providing an overview of the sample before moving into hypothesis-driven analyses. The variables examined include age, gender, highest level of education, vehicle type, typical driving environment, driving frequency, and walking frequency.

Hypothesis-driven analysis

The hypothesis-driven analysis section aims to systematically test the core research hypotheses proposed in this study. Specifically:

- Declined Visual Capability
    - Reduced Visual Acuity
    - Decreased Contrast Sensitivity
    - Delayed Hazard Detection
- Constrained Physical Mobility
    - Limited Neck/Head Range of Motion
    - Limited Arm Range of Motion
    - Limited Leg Range of Motion
    - Reduced Walking Speed
- Delayed Cognitive Processing and Response Time
    - Information Overload at Intersections
    - Difficulties in Making Time-Critical Decisions

RESULTS

Sample Characteristics

The samples collected by age group are summarized in Figure 23. The participants' ages range from 18 to 80, consisting of 112 middle-aged adults, 39 younger adults, and 34 seniors. Education levels mostly sit at a high school diploma or bachelor's degree. Most of the participants prefer SUVs and sedans, and most of their driving happens in urban or suburban areas. Regarding driving frequency, over half of the participants in each age group reported driving daily. As for walking behavior, 21% of older adults reported never walking outdoors for exercise, leisure, or transportation, which is higher than the proportion observed in the other two age groups.

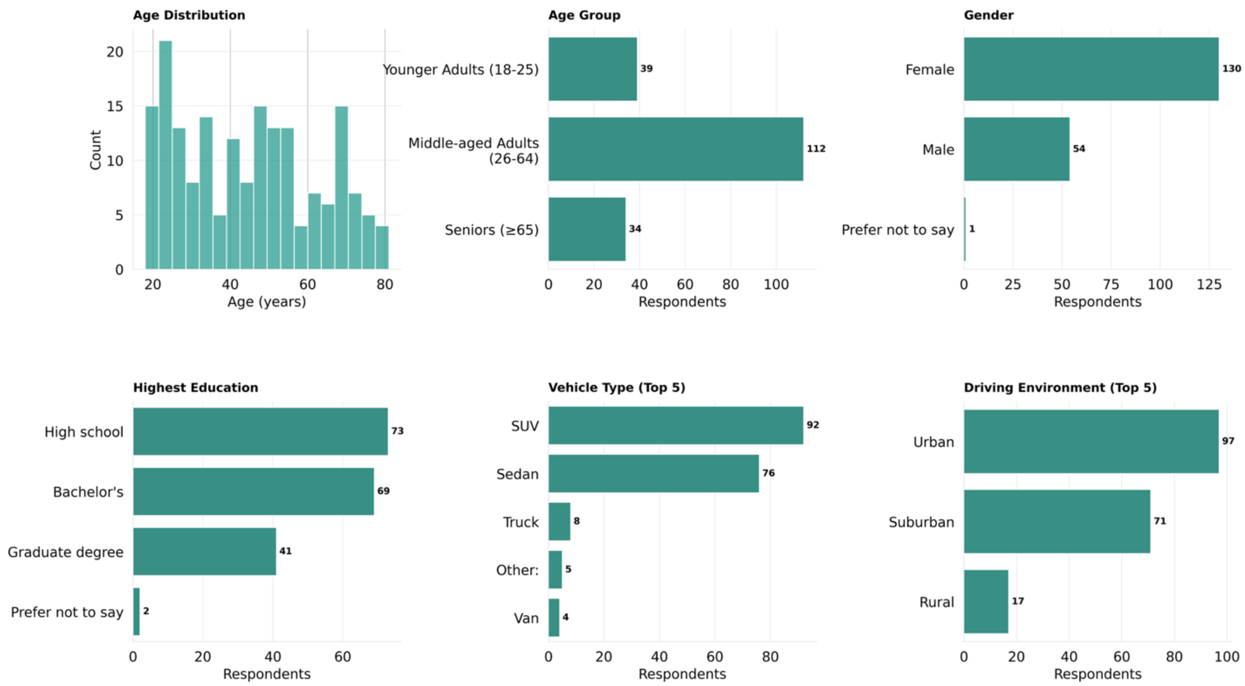


Figure 23. Graphs. Demographics of the Participants

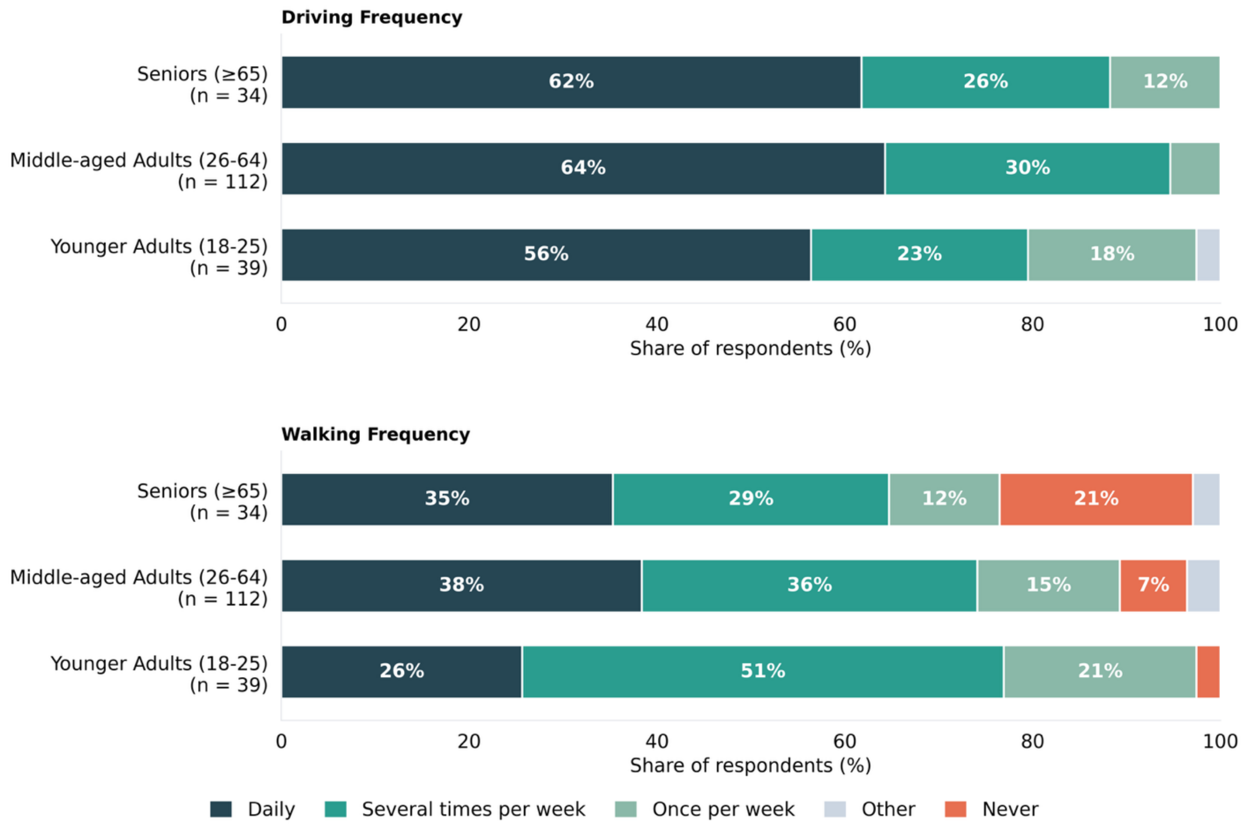


Figure 24. Graphs. Driving and Walking Habits of the Participants

Due to the relatively small sample sizes in the senior and younger adult groups, inferential statistical testing (i.e., between-group significance testing) was not conducted. As a result, the findings presented in this study are based on descriptive comparisons only, and should be interpreted as indicative trends rather than statistically validated group differences.

General Driving and Walking Experience

Intersection driving experience

The survey first asked participants to identify 1–3 intersections in Georgia where they had experienced the most problematic and the most positive conditions. Based on these examples, participants were further asked to explain what made those intersections good or bad. Responses about problematic intersections help reveal what different age groups find challenging, while feedback on positive intersections highlights their needs and the factors that support them. The results are shown in Figure 25.

- When discussing the most problematic intersections, participants across all age groups showed strong agreement: traffic congestion was identified as the primary issue, with 87% of respondents in each group reporting it as a major concern. Notably, older adults did not identify any specific issue that stood out uniquely for them compared to other age groups.
- In terms of positive intersections, all age groups tended to prioritize clear pavement markings, indicating that visible and well-defined markings are a key consideration for users when navigating intersections. However, older adults placed greater emphasis than other groups on sight distance, the presence of a dedicated left-turn lane with sufficient queue storage, and proper lighting. This suggests that older individuals have higher visual and perceptual needs. In this context, "adequate turning lanes" refers to the presence of dedicated turning lane or sufficient queue storage within the turning lane.

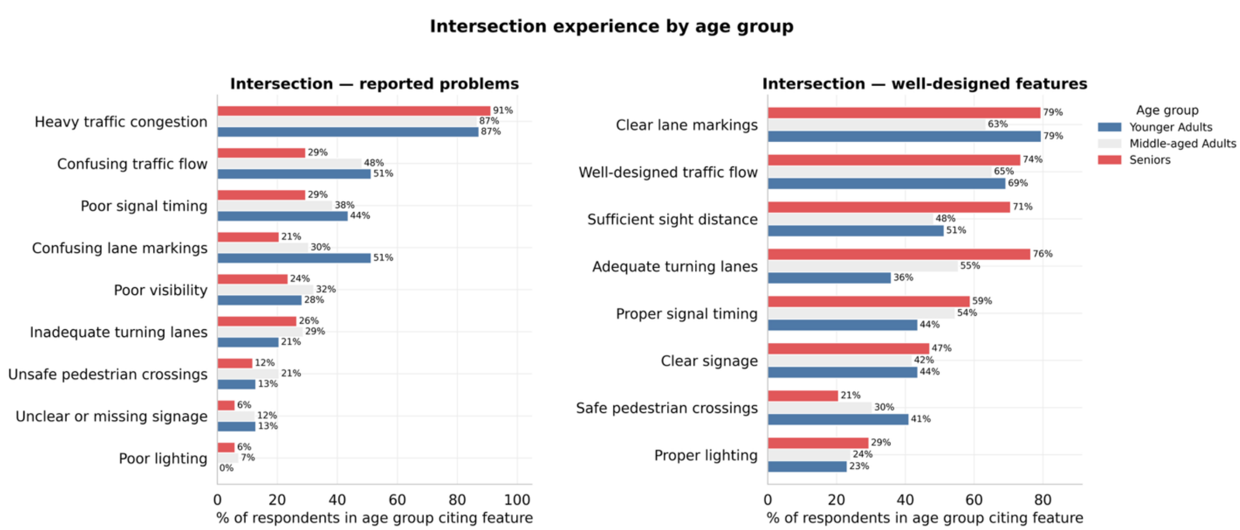


Figure 25. Graphs. Intersection Driving Experience in Georgia

Curve driving experience

Using the same approach as for intersections, participants were first asked to identify 1–3 curves they perceived as most problematic and 1–3 that they considered positive. Follow-up questions then explored the reasons behind their choices. The results are shown in Figure 26.

- For curve driving, participants across all age groups consistently identified insufficient sight distance as a key problem, while good visibility was seen as a feature that improves their driving experience. These two findings are closely aligned, underscoring that sight distance is a critical factor for drivers when navigating curves.
- Compared to the other age groups, senior participants highlighted additional concerns, including missing guardrails or barriers and a lack of reflective markers. They also expressed a stronger preference for clearly posted speed limits and well-defined markings. This further suggests that older drivers place greater importance on features that enhance guidance and visibility.

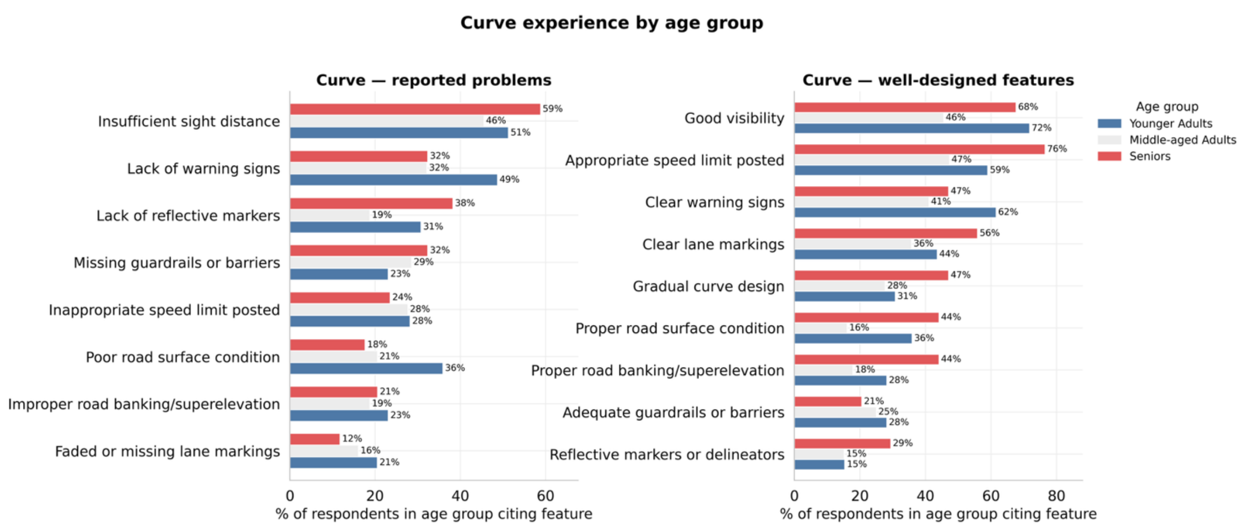


Figure 26. Graphs. Curve Driving Experience in Georgia

Crosswalk walking experience

Same as the intersection and curve question design, participants were first asked to identify 1–3 crosswalks they perceived as most problematic and 1–3 that they considered positive. Follow-up questions then explored the reasons behind their choices. The results are shown in Figure 27.

- For walking conditions, a common issue identified across all age groups was that drivers often fail to yield to pedestrians, with older adults reporting this problem more frequently than others. In addition, seniors more often noted challenges such as long crossing distances and the absence of adequate pedestrian signals.

- In terms of positive features, participants across all age groups emphasized the importance of clear crosswalk markings and adequate crossing time. Older adults, in particular, indicated that raised crosswalks can be beneficial for improving their walking experience.

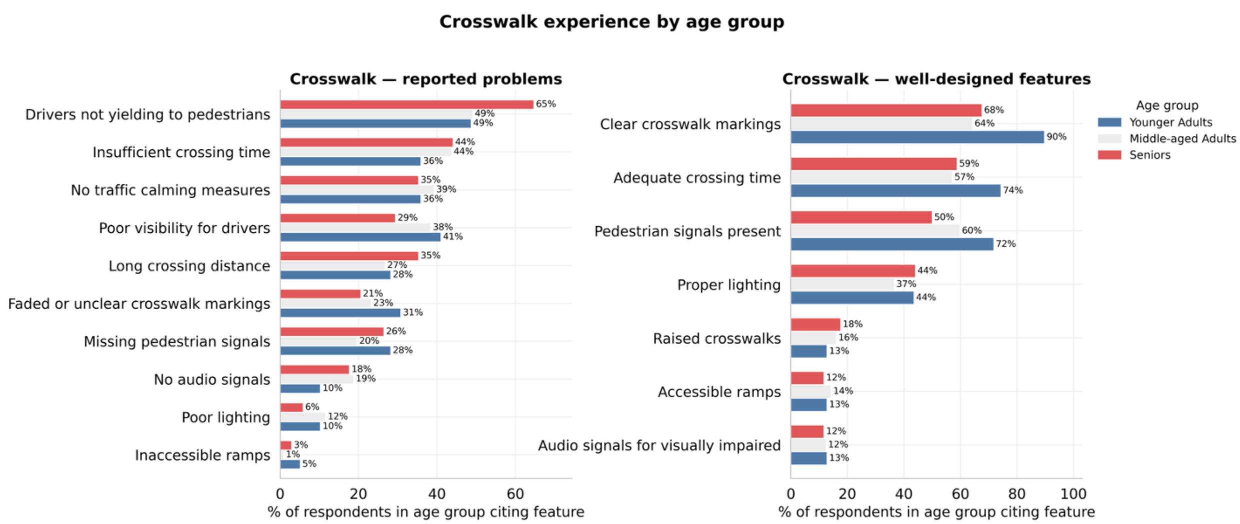


Figure 27. Graphs. Crosswalk Walking Experience in Georgia

Visual Capability

Visual acuity

The survey results of visual acuity are shown in Figure 28, the main findings are as follows:

- Across all age groups, static visual acuity during daytime is generally better than at night. Age-related differences are more pronounced under nighttime conditions, where over 50% of older adults reported their vision as “fair” or “poor.”
- Dynamic visual acuity was assessed based on participants’ perceived ease of reading road signs at different driving speeds, where lower mean ratings indicate greater difficulty in reading signs. The results show that as driving speed increases, the mean ease-of-reading ratings decrease across all age groups, suggesting a general decline in dynamic visual performance under higher-speed conditions. At all tested speeds, older adults reported lower mean ratings than the middle-aged group, indicating that they perceived their dynamic visual acuity to be poorer than that of middle-aged participants.
- Frequency of interpretation was used to capture age-related differences in perceiving various sign arrangements. A higher score (i.e., “always easy to interpret”) indicates that the sign arrangement poses little to no reading difficulty. Across all four sign arrangements, no significant differences were observed between age groups. Most mean ratings clustered around 3, suggesting that, in general, the signs were considered easy to read most of the time.

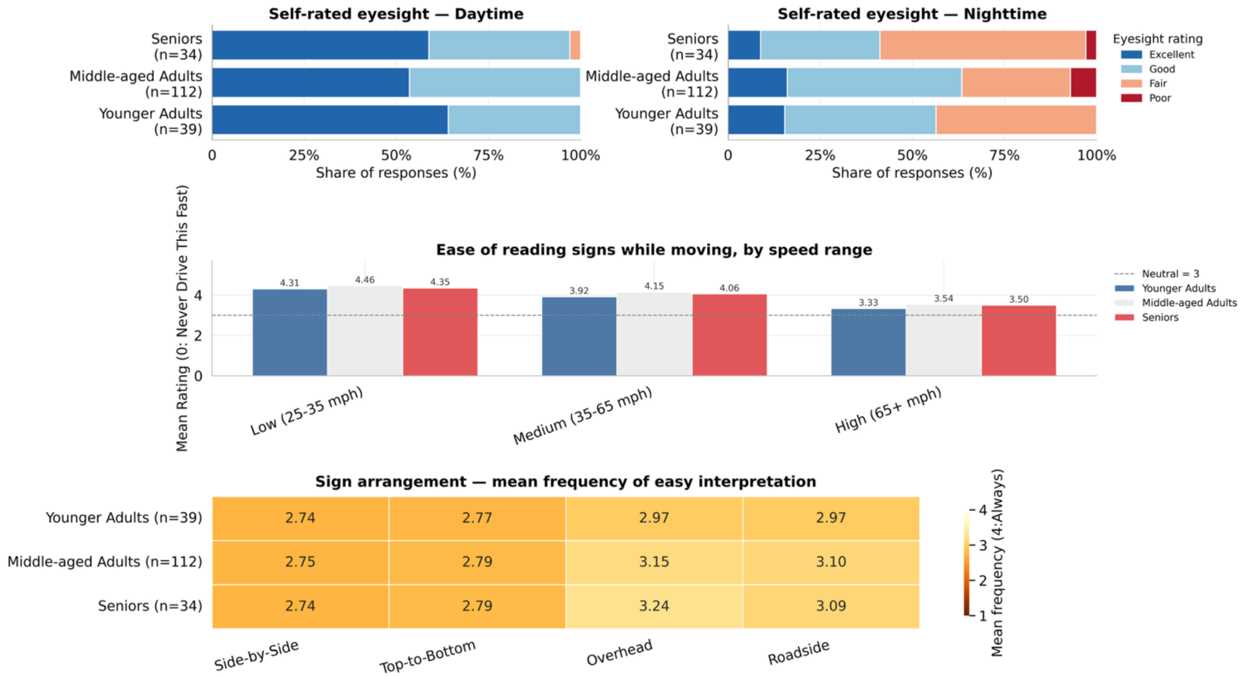


Figure 28. Graphs. The Survey Results of Visual Acuity

Contrast sensitivity

- Contrast sensitivity was primarily assessed by examining participants' perception of sign colors, pavement markings at night, and their ability to detect pedestrians and vehicles under different roles (as drivers and as pedestrians).
- As shown in Figure 29, for sign color perception, there were generally no substantial differences across age groups for most color combinations. Participants across all groups reported little to no difficulty in recognizing red/white and yellow/black signs. However, a slight age-related difference was observed for brown/white signs: older adults were more likely to rate them as neutral or somewhat difficult to perceive, whereas the younger and middle-aged groups tended to report them as easy to see.
- No significant differences were found across age groups in perceiving pavement markings at night, with all participants reporting minimal difficulty.

- In terms of situational perception, detecting pedestrians at night while driving was rated as more difficult than perceiving vehicles or traffic signals while walking. Older adults reported slightly greater difficulty in detecting pedestrians compared to the other two groups, although the difference was relatively small.

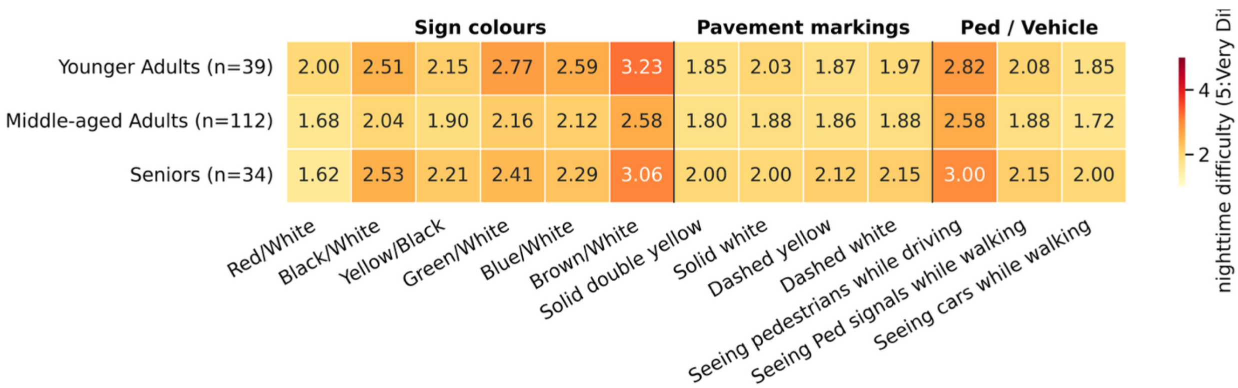


Figure 29. Graphs. The Survey Results of Visual Contrast Sensitivity

Hazard detection

- Hazard detection was measured using the frequency of being startled in two situations:
    - While driving, participants reported how often they were startled by pedestrians or vehicles that they did not notice in time.
    - While walking, participants reported how often they were startled by bicycles or vehicles that they did not notice sooner.
- As illustrated in Figure 30, overall, the frequency of being startled was higher in nighttime scenarios compared to daytime conditions. Across age groups, both older adults and younger adults reported being startled more frequently than middle-aged participants, with young adults showing the highest overall frequency of being startled.

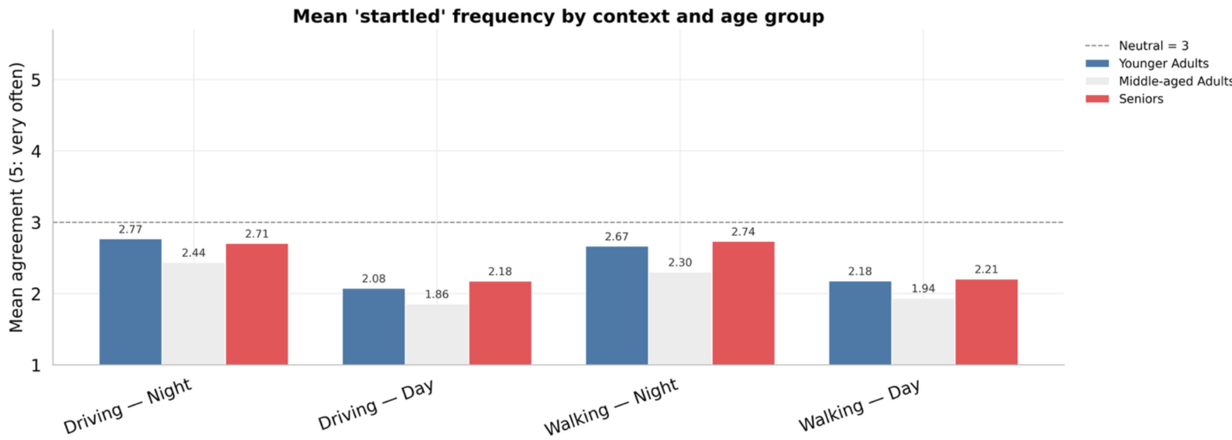


Figure 30. Graphs. The Survey Results of Hazard Detection

Physical Mobility

- As shown in Figure 30, the neck mobility differs across age groups, with older adults reporting the highest proportion of constrained neck movement. In contrast, arm and shoulder strain shows relatively similar distributions across all age groups, although the middle-aged group reported one case of significant restriction.
- Overall, limitations in neck and arm mobility did not appear to substantially affect driving performance in tasks such as over-the-shoulder checks, steering, or pedal operation. However, participants across all age groups reported feeling rushed when navigating wide intersections, with this perception being most pronounced among older adults.

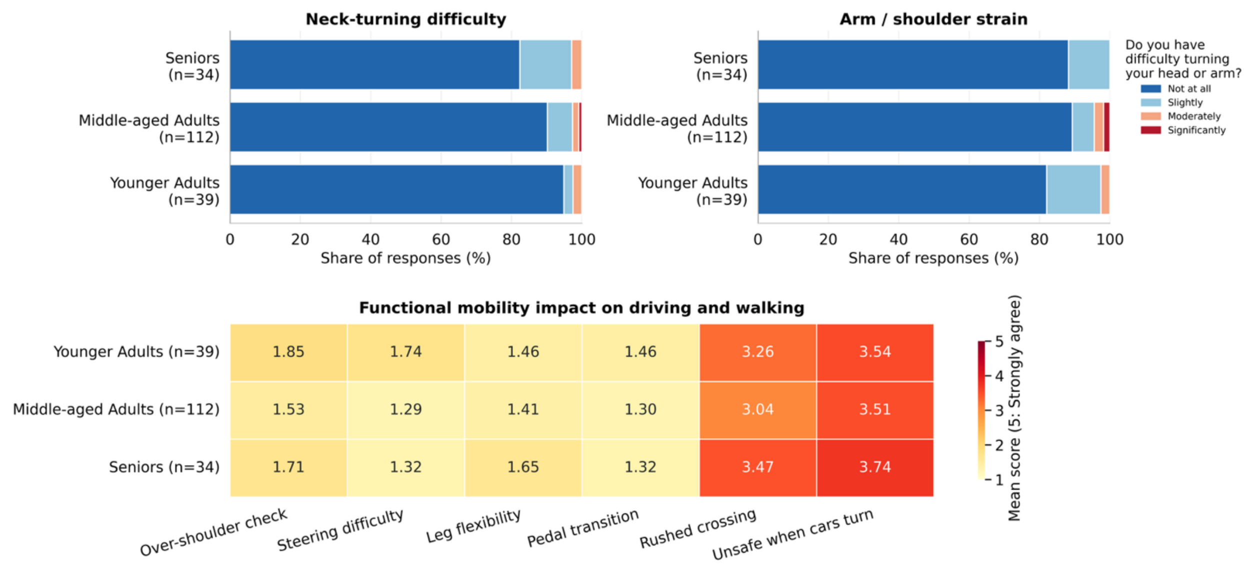


Figure 31. Graphs. The Survey Results of Physical Mobility

Cognitive Processing and Response Time

The survey results of cognitive processing are shown in Figure 32, the main findings are as follows:

- Perceived information overload at intersections was assessed using agreement with the statement “intersection signage is overly clustered.” More than half of both the younger and older adult groups selected “Agree” or “Strongly agree,” indicating a prevalent perception of excessive visual complexity at intersections among these groups.
- Regarding perceived sources of information overload during driving, “other vehicles” was consistently the most frequently reported factor across all three age groups, accounting for 61–64% of responses. Intergroup differences were minimal for this factor. The distribution of all contributing factors varied modestly across age groups.
- For left-turn safety gap judgment, self-reported difficulty was highest among younger adults and lowest among older adults.

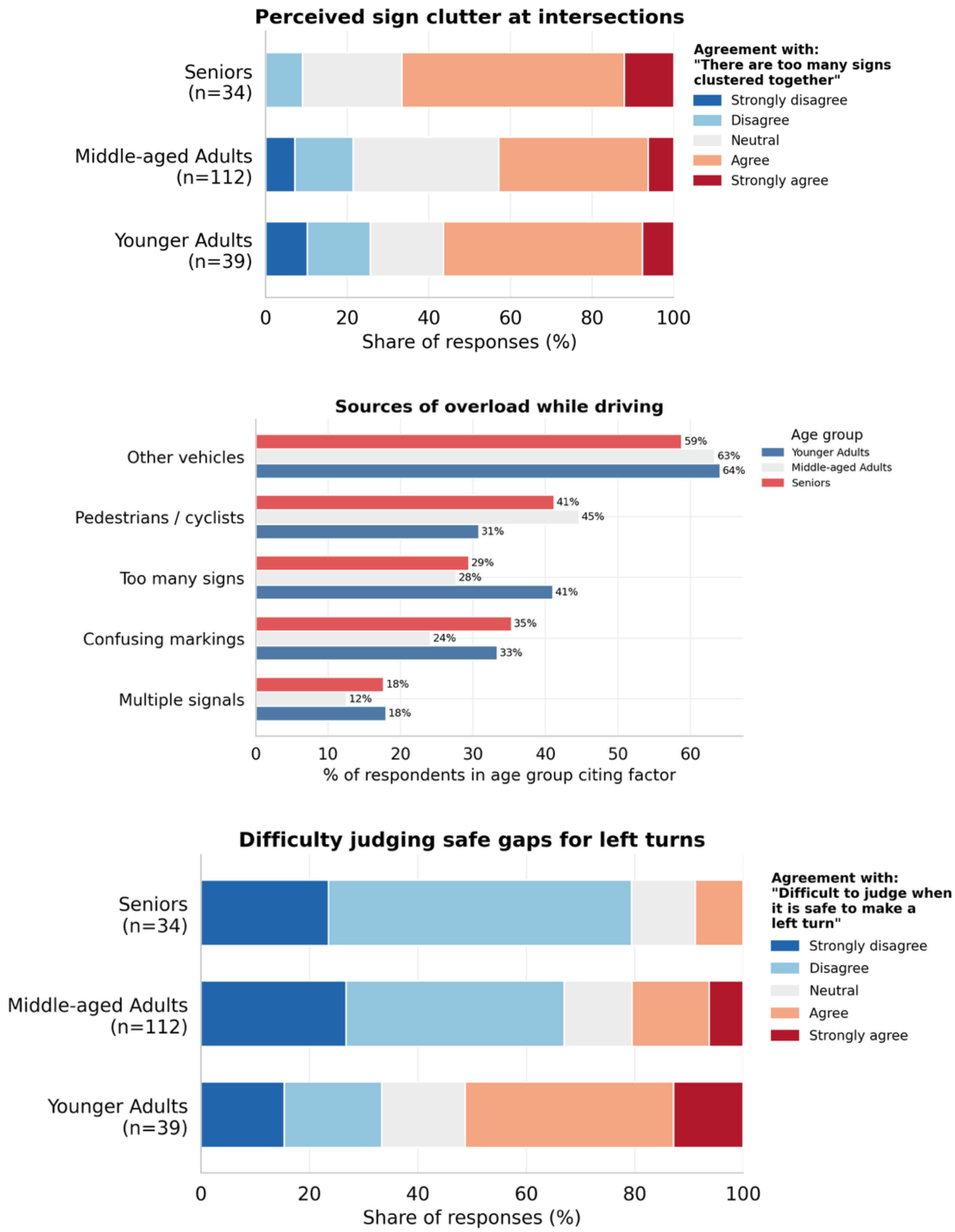


Figure 32. Graphs. The Survey Results of Cognitive Processing

SUMMARY OF FINDINGS

Due to the relatively small sample sizes in the senior and younger adult groups, inferential statistical testing (i.e., between-group significance testing) was not conducted. As a result, the findings presented in this study are based on descriptive comparisons only, and should be interpreted as indicative trends rather than statistically validated group differences.

- General driving and walking experience.
    - *Intersections.* Traffic congestion was the dominant concern across all age groups, reported by roughly 87% of participants in each group. When identifying positive intersections, all groups valued clear pavement markings, but older adults placed distinctly greater emphasis on sight distance, adequate turning lanes, and proper lighting.
    - *Curves.* Insufficient sight distance was consistently identified as the key problem across all groups, while good visibility was the most valued positive feature. Seniors raised additional concerns, including missing guardrails or barriers and a lack of reflective markers. They also showed a stronger preference for clearly posted speed limits and well-defined markings.
    - *Crosswalks.* Drivers failing to yield to pedestrians was a shared concern across all age groups, but was reported most frequently by older adults. Seniors also more often cited long crossing distances and the insufficient crossing time. While all groups valued clear crosswalk markings and adequate crossing time, older adults uniquely highlighted raised crosswalks as beneficial to their walking experience.
- Hypothesis examination. As shown in Table 11, three hypothesis-driven items were supported by the survey data, representing the areas where older adults differed most clearly from younger and middle-aged participants. These three findings center on seniors are facing challenges in nighttime visibility, neck mobility, and walking speed at wide intersections.

Table 11. Summary of Hypothesis-Driven Findings

Hypothesis	Items	Support Level	Description
Reduced Visual Acuity	Static visual acuity	Supported	**Age-related differences were more pronounced under nighttime conditions, where over 50% of older adults rated their static visual acuity as “fair” or “poor.”**
	Dynamic visual acuity	Not Supported	Older adults reported higher mean ratings than both younger and middle-aged participants across all tested speeds.
	Sign arrangements	Not Supported	No significant age-group differences were observed across the four sign arrangements.
Decreased Contrast Sensitivity	Sign color combinations at night	Partially Supported	Differences across age groups were generally modest. **Older adults reported slightly greater difficulty with brown/white signs and detecting pedestrians at night while driving.**
	Pavement markings at night	Not Supported	Most comparisons involving colors and pavement markings showed no consistent age-related effect.
	Detecting pedestrians at night while driving		Older adults reported slightly greater difficulty than the other two groups, though the difference was relatively small.
	Nighttime visibility of traffic signals and approaching vehicles while walking		No substantial age-group differences were observed in pedestrian-side perception of signals and approaching vehicles.
Delayed Hazard Detection	Frequency of being startled by pedestrians while driving (daytime and nighttime)	Not Supported	Younger adults reported the highest frequency of startle responses, followed by older adults, with middle-aged adults reporting the lowest. Across all groups, startle events were more frequent at night than during the day.
	Frequency of being startled by vehicles while walking (daytime and nighttime)		Across all groups, startle events were more frequent at night than during the day, but no senior-specific pattern emerged.
Limited Neck/Head Range of Motion	Turning the head to check surrounding traffic	Supported	**Older adults reported the highest levels of neck movement limitations, compared to other age groups.**
Limited Arm Range of Motion	Turning the steering wheel during tight maneuvers	Not Supported	Arm and shoulder strain was distributed similarly across all age groups, with no pronounced senior-specific limitation.
Limited Leg Range of Motion	Performing rapid transitions between the accelerator and brake pedals	Not Supported	Pedal-transition difficulty (accelerator-to-brake) was similar across age groups, with no clear age-related limitation.
Reduced Walking Speed	Walking speed limitations, particularly at wide intersections	Supported	**Feeling rushed when crossing wide intersections was most pronounced among older adults, directly relevant to pedestrian signal-timing countermeasures.**
Information Overload at Intersections	Agreement with the statement “intersection signage is overly clustered”; identification of contributing factors (signs, signals, pedestrians, pavement markings, vehicles)	Not Clearly Supported	More than half of both younger and older adults agreed signage is overly clustered, while middle-aged adults were less likely to agree. “Other vehicles” was the top reported source (61–64%) across all groups with minimal intergroup differences.
Difficulties in Making Time-Critical Decisions	Making unprotected left turns at intersections	Not Supported	Contrary to expectation, self-reported difficulty judging safe gaps for unprotected left turns was highest among younger adults and lowest among older adults, suggesting driving experience may offset age-related processing delays.

CHAPTER 6. EFFECTIVE COUNTERMEASURES RECOMMENDATIONS

This chapter synthesized the findings from the three analytical components of the study and translates them into a set of countermeasure recommendations for Georgia's senior drivers and pedestrians.

SYNTHESIZED FINDINGS AND RECOMMENDED COUNTERMEASURES FOR SENIOR DRIVING SAFETY

Synthesized Finding 1: Left-Turn Angle Crashes at Intersections Driven by Reaction Time Failures Are the Most Critical Crash Pattern for Senior Drivers in Georgia

The crash data analysis identifies the left-turn angle crash at an intersection caused by insufficient reaction time as the most prevalent and most distinctive senior-specific crash pattern in Georgia. Reaction-related factors account for 79 % of older-driver left-turn collisions. The eye-tracking study provides indirect support for this finding from the behavioral side. Older drivers show consistently lower saccade main sequence slopes and lower baseline saccade velocities than younger drivers during daytime conditions. Slower saccades imply that the visual scanning required to locate oncoming vehicles, signals, and pedestrians during a left-turn maneuver takes longer to complete. This is consistent with the reaction-time deficit observed in the crash data.

Recommended countermeasures:

The following countermeasures are recommended for left-turn crashes at intersections, sequenced by the degree to which they reduce the reaction time load on older drivers.

1. Protected left-turn signal phasing. A protected phase provides an exclusive green arrow that eliminates the need for gap judgment entirely, directly removing the reaction time demand

that the data identified as the primary cause of these crashes. Since reaction time accounts for 79% of older driver left-turn collisions, this treatment addresses the root cause rather than mitigating its effects. The literature review identified a crash modification factor of 0.3 for this treatment, indicating a 70% reduction in left-turn crash frequency.

2. Add or widen the left-turn lane. Separating left-turning vehicles from through traffic reduces conflicts and minimizes delays for through movements. This separation improves overall traffic flow efficiency and provides clearer maneuvering space for turning drivers.
3. Provide offset left-turn lanes at intersections. Offsetting opposing left-turning vehicles extends the available sight distance, which extends the detection distance to evaluate oncoming vehicles before committing to the turn. This could potentially lengthen the reaction time window within which older drivers must make their gap judgment.
4. Clear sight triangles. Removing visual obstructions such as vegetation and parked vehicles at intersection approaches also extends the detection distance, providing additional time to make decisions.
5. Far left-side signal head. This reduces the cognitive load of the reaction by narrowing the required visual scanning area and making the signal indication easier to locate, so that less of the available reaction time is consumed by the act of finding and interpreting the signal.
6. Lighting. Enhanced intersection lighting improves the detection range of oncoming vehicles, signs, and pedestrians, particularly under nighttime and low-light conditions where age-related declines in contrast sensitivity and temporal sensitivity further compress the available reaction time.

Synthesized Finding 2: Nighttime Driving Conditions Present Greater Challenges for Older Drivers

The survey and eye-tracking study both indicate that nighttime conditions present challenges for older drivers, and these findings are consistent with the broader literature on seniors' declined visual capability. The survey showed that more than 50 % of older adults rated their static visual acuity at night as fair or poor. The eye-tracking study confirmed that nighttime driving imposes greater visual processing demand on drivers of all ages. Mean fixation duration was consistently higher at night than during the day across all curves studied, indicating that low-light conditions increase the time required to extract and interpret visual information from the roadway.

The crash data analysis did not isolate nighttime conditions as a separate variable, so this finding is supported primarily by the survey, eye-tracking evidence, and existing literature rather than direct statistical crash records. Even so, the consistency across multiple sources suggests that nighttime visibility should be treated as an important safety priority for seniors.

Recommended countermeasures:

The following countermeasures are recommended for improving lighting conditions, sequenced by potential cost from lowest to highest.

1. Maintain high-visibility, well-defined pavement markings. The eye-tracking study showed that drivers of all ages rely primarily on continuous road markings for visual guidance, and the survey showed that senior respondents express a stronger preference for well-defined markings on intersections and curves. Maintaining marking visibility is particularly important under nighttime conditions.

2. Maintain retroreflectivity of signs. The eye-tracking study showed that signs at curve entrances and intersection approaches serve as initial alert cues, and the survey showed that seniors specifically cited a lack of reflective markers as a concern. Routine retroreflectivity inspection and timely replacement of faded signs keep these cues visible at night.
3. Flashing beacons. Flashing beacons draw driver attention to specific features such as stop signs, curve warnings, and pedestrian crossings, which directly addresses the reduced contrast sensitivity and slower oculomotor responses identified in the survey and eye-tracking study.
4. Installation of lighting. Full lighting at intersections, curves, and crossings provides the strongest improvement in nighttime visibility. Because of the higher capital and operating cost, lighting should be deployed selectively at locations identified through senior crash data.

SYNTHESIZED FINDINGS AND RECOMMENDED COUNTERMEASURES FOR SENIOR WALKING SAFETY

Synthesized Finding 1: Wide Signalized Crossings Present Challenges for Seniors

For senior walking safety, the integrated findings draw primarily on the literature review and the roadway safety survey. The literature documents that older pedestrians walk more slowly than younger and middle-aged pedestrians, with mean gait speeds of 1.33 m/s compared with 1.44 m/s for younger walkers, and that the current MUTCD assumed walking speed of 1.2 m/s excludes nearly two-thirds of older pedestrians. The survey confirmed this challenge from the user side. Feeling rushed when crossing wide intersections was the most pronounced senior-specific finding in the physical mobility section, and seniors more often than other groups cited long crossing distances and insufficient crossing time as concerns at crosswalks. The two sources point out that wide signalized crossings are challenging for them.

Recommended countermeasures:

The following countermeasures are recommended for improving wide signalized crossings, sequenced by potential cost from lowest to highest.

1. Consideration of Reducing Walking Speed in Signal Timing. Adjusting the assumed walking speed used in pedestrian signal timing from 1.2 m/s to 0.91 m/s accommodates slower pedestrians and addresses the survey finding that older adults feel most rushed at wide intersections. This is a low-cost adjustment implemented through existing signal controllers.
2. Pedestrian Refuge Islands. Raised median islands allow pedestrians to cross in two stages, reducing exposure time and simplifying the gap-judgment task. This treatment directly addresses the long crossing distances reported by senior respondents and supports older walkers with reduced balance [59].
3. Danish Offsets. Z-shaped refuge designs orient pedestrians toward oncoming traffic at the midpoint of the crossing, improving awareness before the second stage. This treatment is well-suited to wide crossings where two-stage crossing is being introduced.
4. Roadway Diet. Reducing lane widths or lane count lowers vehicle speeds and shortens crossing distances, responding to the senior-specific concern about long crossings.

Synthesized Finding 2: Driver Failure to Yield Represents a Key Safety Concern for Seniors

The literature documents that older pedestrians are disproportionately represented in pedestrian fatalities, accounting for roughly 21 % of all fatal pedestrian crashes in 2023 despite making up only 17.7 % of the U.S. population. In the survey, drivers failing to yield was a shared concern across all age groups, but was reported most frequently by older adults at crosswalks.

Recommended countermeasures:

The following countermeasures are recommended to improve driver yielding, sequenced by potential cost from lowest to highest.

1. Signal Optimization.
    a. Leading Pedestrian Interval (LPI). A three to four second head start increases pedestrian visibility to turning drivers.
    b. No Right Turn on Red. Eliminates conflicts between turning vehicles and pedestrians. Requires only signage and controller updates.
    c. Pedestrian-Only Phase. Fully separates pedestrian and vehicle movements at complex intersections. Implemented through signal-timing changes.
    d. Left-Turn Control (Protected Phase). Eliminates turning-vehicle conflicts with pedestrians and also supports the driver-side benefit identified in section 6.3. Requires controller and possibly signal-head changes.
2. Rectangular Rapid Flashing Beacons (RRFBs). Increase driver yielding at uncontrolled crossings.
3. Pedestrian Hybrid Beacons (PHBs). Provide pedestrian-activated red signals at uncontrolled crossings.
4. Raised Crosswalks. Slow vehicles and elevate pedestrians into the driver's line of sight. The survey produced a senior-specific finding that older adults uniquely identified raised crosswalks as beneficial. Cost reflects localized pavement reconstruction.
5. Pedestrian-to-Vehicle (P2V) Warning System. Sensor-based real-time driver alerts. Highest cost as an emerging technology, most appropriate for pilot deployment.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Using the number of fatalities and serious injuries among those aged 65+ and the corresponding population estimates in Georgia from 2016 through 2023, the following conclusion can be drawn:

1. **Georgia has met the criteria of the FHWA Older Drivers and Pedestrians Special Rule.** Georgia's rate of traffic fatalities and serious injuries for drivers and pedestrians aged 65 and older (defined as five-year rolling rate of fatalities and serious injuries per 100,000 older adults) increased from 45.8 for the period ending in 2020 to 51.2 for the period ending in 2022, and from 48.5 to 52.8 for the comparable 2021 and 2023 windows. Georgia's combined fatality and serious injury rate for the 65-and-older population has increased across two consecutive two-year comparison periods.

Using the crash dataset of over 3.4 million police-reported records from GDOT's AASHTOWare database covering 2013 to 2023, the following conclusion can be drawn:

2. **Crash severity rises sharply after age 65.** A hybrid linear and exponential model confirmed that the share of crashes resulting in a fatal or serious injury increases approximately linearly between ages 16 and 64 and then grows exponentially beyond age 65.
3. **Left-turn angle crashes at intersections driven by reaction time failures are the most critical crash pattern for senior drivers in Georgia.** The ANOVA tests showed that older drivers differ from other age groups in manner of collision, crash location, and contributing factor. Among all fatal and severe angle crashes in the State, over 40 % are

senior-related, the highest involvement of any crash type. Within angle crashes, left-turn movements represent the largest share. Reaction time accounts for 79% of older driver left-turn collisions, far exceeding other factors such as reckless driving or distraction. Regarding location, intersections are the primary setting for over 82% of those left-turn crashes.

The on-road eye-tracking study at Vogel State Park, which synchronized curve inventory data, smartphone GPS, and eye-tracking metrics across 3 representative horizontal curves under both daytime and nighttime conditions, found that:

4. **Road markings function as continuous visual guidance, while signs serve as initial alert cues.** Both older and younger drivers rely primarily on continuous road markings for visual guidance within curves, while discrete signs (e.g., chevrons) receive little attention. However, signs serve as initial alert cues when approaching the curve, as drivers tend to glance at the sign at the entrance before entering the curve.
5. **Mean fixation duration is environment-driven, not age-driven.** Mean fixation duration is larger at sharper curves with higher visual demand. It also decreases as drivers become familiar with the road, and increases at night. However, mean fixation duration showed no substantial difference between older and younger drivers.
6. **Saccade main sequence slope reveals age differences.** During daytime, older drivers show consistently lower saccade velocities (lower β_1 and baseline offset) than younger drivers, indicating slower oculomotor responses. For nighttime, however, the dataset is limited, and no reliable interpretation can be drawn.
7. **Age-related decline in oculomotor performance appears to be a key behavioral risk factor for crashes among older drivers.** Mean fixation duration positively correlates

with crash frequency for both groups. For older drivers specifically, reduced saccade efficiency shows a negative correlation with crash frequency, suggesting oculomotor decline is a potential risk factor unique to seniors. These results indicate that age-related decline in oculomotor performance is a behavioral mechanism consistent with the reaction-time deficit observed in the crash data.

The roadway safety survey, which collected responses from 167 Georgia residents (38 seniors, 34 younger adults, and 112 middle-aged adults), identified that:

8. **Intersections:** Traffic congestion was the dominant concern across all age groups, reported by roughly 87% of participants in each group. When identifying positive intersections, all groups valued clear pavement markings, but older adults placed distinctly greater emphasis on sight distance, adequate turning lanes, and proper lighting.
9. **Curves**. Insufficient sight distance was consistently identified as the key problem across all groups, while good visibility was the most valued positive feature. Seniors raised additional concerns, including missing guardrails or barriers and a lack of reflective markers. They also showed a stronger preference for clearly posted speed limits and well-defined markings.
10. **Crosswalks**. Drivers failing to yield to pedestrians was a shared concern across all age groups, but was reported most frequently by older adults. Seniors also more often cited long crossing distances and insufficient crossing time. While all groups valued clear crosswalk markings and adequate crossing time, older adults uniquely highlighted raised crosswalks as beneficial to their walking experience.

11. **Seniors face challenges in nighttime visibility, neck mobility, and walking speed at wide intersections**, as supported by three hypothesis-driven survey items in Table 11 where older adults differed most clearly from younger and middle-aged participants.

Chapter 6 synthesizes the findings from the three analytical components of the study together with the literature review, and translates them into a set of countermeasure recommendations for Georgia's senior drivers and pedestrians. The following synthesized findings can be drawn, and their corresponding countermeasures are recommended in Chapter 6.

For the senior drivers:

12. Synthesized finding 1: left-turn angle crashes at intersections driven by reaction time failures are the most critical crash pattern for senior drivers in Georgia.
13. Synthesized finding 2: nighttime driving conditions present greater challenges for older drivers.

For the senior pedestrians:

14. Synthesized finding 1: wide signalized crossings present challenges for seniors.
15. Synthesized finding 2: driver failure to yield represents a key safety concern for seniors.

RECOMMENDATIONS FOR FUTURE WORK

The limitations of this study point to several directions for future research:

1. In the current study, a crash is attributed to a driver within a given age group whenever that driver is involved, regardless of whether they were responsible for causing the crash. As a result, the classification may include crashes that are not truly age-related, which can skew the distribution and reduce the observed differences between age groups, since

some incidents attributed to younger or older drivers may have been caused by drivers outside those age groups. Future work could address this limitation by restructuring the crash data around each individual involved in a crash, tracing their ages, injury outcomes, and fault designation. This person-centered organization would allow for a more objective analysis of age-related crash characteristics.

2. Identify and extract intersections with high frequencies of senior driver and pedestrian crashes, and conduct a detailed analysis of their roadway characteristics, including number of lanes, traffic volume, pavement width, sight distance, and signal timing. The study should also prioritize identifying roadway characteristics that are most strongly associated with crash occurrence in order to support the development and application of effective countermeasures. In addition, the potential impact of intersection signal timing on senior driver and pedestrian safety should be further investigated.
3. A similar analytical approach can be applied to the survey study, with greater emphasis on perceived environmental and roadway factors, such as cluttered signage, limited sight distance, roadway complexity, and driver workload. The objective is to better understand how these perceived factors influence senior driver behavior, comfort, and safety.
4. Compute eye-tracking metrics in both spatial and temporal dimensions to derive meaningful quantitative measures for correlation analysis. The selected metrics should have clear physical interpretations and be directly related to driver attention, visual scanning behavior, reaction patterns, and situational awareness.
5. The recommended countermeasures highlight the maintenance of signs and pavement markings as an important direction for improving senior road user safety, particularly under nighttime conditions. Investigating intelligent, cost-effective approaches for the

condition assessment of signs and markings represents a promising area for future research.

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