Age Differences in the Situation Awareness and Takeover Performance in a Semi-Autonomous Vehicle Simulator

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Research on young and elderly drivers indicates a high crash risk amongst these drivers in comparison to other age groups of drivers. Young drivers have a greater propensity to adopt a risky driving style and behaviors associated with poor road safety. On the other hand, age-related declines can negatively impact the performance of older drivers on the road leading to crashes and risky maneuvers. Thus, autonomous vehicles have been suggested to improve the road safety and mobility of younger and older drivers. However, the difficulty of manually taking over control from semi-autonomous vehicles might vary in different driving conditions, particularly in those that are more challenging. Hence, the present study aims to examine the effect of road geometry and scenario, by investigating young, middle-aged and older drivers' situation awareness (SA) and takeover performance when driving a semi-autonomous vehicle simulator on a straight versus a curved road on a highway and an urban non-highway road when engaged in a secondary distracting task.

Due to the impact of COVID-19, data from only the young (n=24) and middle-aged (n=24) adults were collected and analyzed. Participants drove a Level 3 semi-autonomous simulator vehicle and performed a secondary non-driving related task in the distracted conditions. The results indicated that the participants had significantly longer hazard perception times on the curved roads and autopilot drives, but there was no significant effect of driver age and road type. Their Situation Awareness Global Assessment Technique (SAGAT) scores were higher in the highway scenarios, on the straight roads, and in the manual drive compared to the autopilot with distraction drive. Young drivers were also found to have significantly higher SAGAT scores than middle-aged drivers. While there was a significant interaction effect between road type and road geometry on takeover time, there was no significant main effect of road geometry, drive type and driver's age. For the takeover quality metrics, road geometry and drive type had an effect on takeover performance. The resulting acceleration was higher for the straight road and in the autopilot drives, and the lane deviation was higher on the curved road and autopilot only drive compared to the autopilot with distraction drive. There was no significant main effect of road type and driver's age on resulting acceleration and lane deviation.

Overall, while there were age differences in some aspects of SA, young and middle-aged drivers did not differ in their takeover performance. The participants' SA was impacted by the road type and geometry and their takeover quality varied according to the road geometry and drive type. The outcomes of this research will aid vehicle manufacturing companies that are developing Level 3 semi-autonomous vehicles with appropriately designing the lead time of the takeover request to meet the driving style and abilities of

younger and middle-aged drivers. This will also help to improve road safety by reducing the crash rate of younger drivers.

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List of Abbreviations

ADAS	Advanced Driving Assistance System
AV	Autonomous Vehicle
HAD	Highly Automated Driving
ACC	Adaptive Cruise Control
DDT	Dynamic Driving Task
ODD	Operational Design Domain
ICWS	Intersection Collision Warning System
PDL	Property Damage Liability
TOR	Takeover Request
SAE	Society of Automotive Engineers
TTC	Time-to-Collision
SuRT	Surrogate Reference Task
CTT	Critical Tracking Task
IVIS	In-Vehicle Information Systems
SA	Situation Awareness
SAGAT	Situation Awareness Global Assessment Technique
SPAM	Situation Present Awareness Method

SART	Situation Awareness Rating Technique
ROR	Run-Off-Road
TMT	Trail Making Test
MSSQ	Motion Sickness Susceptibility Questionnaire
SSQ	Simulator Sickness Questionnaire
SDLP	Standard Deviation of Lane Position
CAS	Collision Avoidance System

Chapter 1

Introduction

1.1 Motivation

Several factors can affect the safety and takeover performance in a semi-autonomous vehicle such as age, situation awareness, road type, road geometry, and engaging in a distracting task. While these factors have been researched separately, they have not been combined into a single study to enable the examination of interaction effects which is the purpose of this research.

Young novice drivers contribute to a public health concern due to their number of crashes, rates of crash involvement, and the injuries and fatalities that result from those crashes. They have a greater propensity to adopt a risky driving style, lack skills and have higher rates of distracted driving than middle-aged drivers [2]. Studies on the characteristics of traffic crashes have shown that crashes among young drivers are more likely to involve a single vehicle, driving errors, have speed as a factor, and involve alcohol and drugs [3]. Moreover, unsupervised teen drivers have a higher risk of a crash with the presence of other teen or young adult passengers [4]. Furthermore, the literature indicates that the relationship between young drivers' lifestyle and their driving behavior is mediated by factors such as an overestimation of driving skills and underestimation of crash risk as well as sensation seeking that explains their deliberately dangerous risk-taking behavior. Psychosocial factors such as status, control and mobility also negatively contribute to their poor driving behavior [5]. In addition, young drivers have a higher sleep deprivation and fatigue crash rate in comparison to middle-aged drivers and they are more likely to be involved in a fatal crash during nighttime and weekend driving [6]. Young drivers are also an at-risk group for distracted driving and are least likely to understand the risks associated with cell phone use while driving and texting which increases their risk of crashing given their inexperience [7]. Additionally, in comparison to experienced drivers, young novice drivers tend to have higher incidences of misjudgment, errors, disregard traffic signs and rules, and adopt bad habits [8]. Hence, they could benefit from advanced driving assistance systems (ADAS) that might help to avoid collisions that occur from their poor driving style.

Senior adults aged 65 years and older, in Canada and other developed countries, represent a significant proportion of the overall population and are expected to steadily increase [9]. Thus, as one of the largest age cohorts, older drivers will be a large segment of the driving population [10]. With seniors driving more miles than previous generations it is important to be mindful of age-related declines in sensory, cognitive and psychomotor abilities that might negatively impair them on the road [11]. Trends in fatal crash involvements in the US also indicate that older drivers have higher crash death rates per mile driven than middle-aged drivers [12], and are more likely to be considered the at-fault driver in a two-vehicle crash [13]. However, research suggests that older adults need transportation to access healthcare [14], and independent mobility as there are social and psychological consequences of driving cessation that contribute to a variety of health problems such as social isolation, lack of independence and an increase in depressive symptoms [15, 16]. As such, ADAS and autonomous vehicles (AV) have been suggested to improve road safety and mobility of older adults [17, 18].

In the past decade, there have been rapid improvements in the design and manufacture of autonomous vehicles which are often categorized on a taxonomy of six levels that range from Level 0 having no driving automation to Level 5 having full driving automation with the human out of the loop. Levels 1 to 4 have automation with varying degrees of human involvement needed for driving [1]. These vehicles incorporate a variety of ADAS features such as adaptive cruise control (ACC), lane departure warnings, collision avoidance and autopilot-like driving capability [19]. As Level 3 (Conditional Driving Automation) vehicles are currently being driven on the roads and may increase in the near future, it is anticipated that these vehicles will bring several benefits to drivers, particularly in the old and young age groups. Since older adults experience cognitive declines in visual scanning, attention, speed of processing, executive function and memory, this may negatively impact driving leading to errors such as lane drift, incorrect driving speed, sudden stop and when performing left turns into oncoming traffic. Thus, automation features that warn against lane departure, blind spots, forward collisions and intersection identification, for instance, may assist older drivers that might struggle with these aspects of driving and prevent them from making errors and crashes. A review of studies that looked at the effect of ADAS on older drivers' convenience, comfort and safety also indicated that these technologies enhanced safety, mitigated age-related declines and might reduce cognitive workload [20]. On the other hand, autonomous vehicles might be a solution to reduce crashes that result from human error, particularly in the case of young drivers who are inexperienced, lack skills and are likely to engage in risky behaviors. Driving a semi-autonomous vehicle would allow young drivers to safely engage in mobile phone use and other distracting tasks while the vehicle is autonomously driven and then only focus on driving the vehicle after a takeover request.

Autonomous vehicles with Level 3 conditional automation can take full longitudinal and lateral control and can perform most driving tasks. However, when a system limitation occurs, the human driver is expected to take over manual driving when a takeover is requested. This is an important aspect of semi-autonomous vehicles as the amount of time needed for a safe takeover and transitioning from automated to manual driving depends on how quickly the driver can gather information from the environment and develop sufficient situation awareness [21]. Several studies have investigated the effects of the lead time of the takeover on driver performance which can also be influenced by other factors e.g. doing a non-driving task, environmental conditions and cognitive abilities. For instance, the reaction time of older adults is more delayed which makes takeover requests a concern for this group of drivers. This is seen in a study by Li et al. [22] that investigated the effects of age and driving disengagement on takeover control performance. Older adults took longer to respond and make decisions than younger drivers. The age effect was also observed in some aspects of takeover quality that relate to operating the steering wheel and pedals. Moreover, a complete disengagement from driving in highly automated driving (HAD) resulted in a longer takeover time and a poorer takeover quality in older drivers than younger drivers. Another driving simulation study also showed that older adults had longer takeover times and worse takeover quality in comparison to younger drivers which was more pronounced in adverse weather conditions [23]. Thus, more research is needed to determine the effects of age on takeover performance in semi-autonomous vehicles in various situations.

Situation awareness, which is the perception and understanding of what is happening in one's environment, is an essential aspect of driving that is a highly attention-demanding task [24]. Hence, when a driver engages in secondary activities, their attention is likely to be diverted from their primary task of driving which could impair their performance. This is often evidenced in real-life crashes on the road that are sometimes caused by distracted driving as well as simulator studies that have shown participants who were cognitively distracted had more driving infractions and decreased situation awareness which was worse for novice drivers in comparison to experienced drivers (e.g. [25]). In a semi-autonomous vehicle, since the human operator has no control over the vehicle while it is autonomously driven, their situation awareness may be impacted when they have to resume driving the vehicle after a takeover request. Automation can lower situation awareness and create performance deficits and poor vigilance as the human operator is out-of-the-loop when they no longer have to engage with the system [26]. As the findings of several studies have indicated, this is likely to be further worsened in a semi-autonomous vehicle as drivers are likely to engage in other secondary non-driving tasks [27, 28, 29, 30, 31]. The negative consequences of reduced situation awareness when taking over could be further worsened with aging. For instance, a study by Bolstad [32] that investigated the age-related differences in situation awareness found that older adults had lower situation awareness when compared to younger and middle-aged adults in a driving simulator task. Moreover, the findings of a research experiment that examined the time required to achieve situation awareness in situations of transfer of control within a Level 3 autonomous environment showed that younger inexperienced drivers were worse at anticipating latent hazards overall and slower to achieve appropriate situation awareness needed for manual driving than middle-aged drivers [33]. Hence, more research is needed to determine how the situation awareness of younger and older adults is affected by various factors when taking over control in a semi-autonomous vehicle.

There are certain environmental factors that can contribute to crashes on the road. One such factor is road geometry as studies show that the crash rates on curved roads are about 1.5 to 4 times higher than on straight roads [34]. Additionally, the crash severity on curved roads is higher than those that occur on straight roads [35]. Furthermore, the crash risk on curved roads is influenced by the road design which includes the degree of the curve, length of the curve, lane width, surface and side friction, sight distance, and super elevation [36]. In addition, sharp horizontal curves or curved roads with smaller radii can increase the crash risk due to insufficient sight distance [37]. Moreover, the crash risk of an inexperienced driver increases when they drive on a curved road as it requires more skill and experience to handle these complex scenarios [36]. Another environmental factor that might influence driving performance is location. For instance, vehicles are driven at a higher speed on highways which can increase the crash severity. However, on urban non-highway roads, while vehicles are driven at lower speeds, there is a higher presence of other vulnerable road users which might increase the exposure and opportunities for crashes. Therefore, it is important to understand how these environmental factors can impact older and younger drivers' takeover performance and situation awareness in a semi-autonomous vehicle.

1.2 Research Objective

Research on young and elderly drivers indicates a high crash risk amongst these drivers in comparison to other age groups of drivers. Young drivers have a greater propensity to adopt a risky driving style and behaviors associated with poor road safety and higher rates of distracted driving than middle-aged drivers. On the other hand, senior adults aged 65 years and older are susceptible to age-related declines in sensory, cognitive and psychomotor abilities that might negatively impair their driving performance and safety on the road. Moreover, these drivers can experience difficulties in certain driving situations that have particular road geometry such as turning on curved roads, as well as higher levels of traffic density including the presence of vulnerable road users and driving at higher speeds on highways. In addition, younger inexperienced drivers tend to have poor situation awareness, and the age-related decline in mental functions of older adults leads to a deterioration in their situation awareness which is essential in high-risk tasks such as driving. The following research objectives aim to examine the effect of different driving conditions in different age groups and are the focus of this thesis:

1. Differences in situation awareness across young (18-24 years) and middle-aged (35-55 years).
2. Differences in takeover performance across the age groups measured through vehicle kinematics, takeover time and collision rates.
3. The influence of demanding road conditions, in particular road geometry and highway versus urban scenarios, on driving performance.
4. The effect of performing a secondary non-driving distracting task during vehicle autonomous driving on takeover performance.
5. The effect of age, road types, road geometry and distracting task on situation awareness after taking over from semi-autonomous driving.
6. The effect of age, road types, road geometry and distracting task on takeover performance from semi-autonomous driving.

1.3 Impact of COVID-19

Since the older adults aged 65 years and above were considered to be vulnerable to COVID-19, it was not possible to obtain ethics approval to conduct in-person research with this group. Hence, the scope of this thesis is limited to data collected from young and middle-aged drivers. The data from older drivers will be collected when it is deemed safer to do so in the future and is beyond the scope of the current thesis.

1.4 Thesis Overview

The remainder of this thesis is structured as follows:

1. Chapter 2 provides an overview of the literature on younger and older drivers, semi-autonomous vehicles and takeover performance, situation awareness in driving, and the effect of different environmental factors on road safety.
2. In Chapter 3, the hypotheses are defined and the experiment protocol is outlined. The study methodology and experiment used are described.
3. In Chapter 4, the findings of the situation awareness and takeover performance are presented.
4. Chapter 5 discusses and interprets the meaning of the findings
5. Chapter 6 provides a conclusion and summary of the research.

Chapter 2

Background

2.1 Younger drivers

2.1.1 Driving behavior

Motor vehicle crashes continue to be the leading cause of death among young adults, typically between the ages of 18 to 25 years. Among all age groups, young people have the highest rates of traffic death and injury per capita per kilometer driven [38]. Crash statistics on Canadians show an over-representation of young drivers: despite representing only 13% of the licensed driving population, they account for approximately 20% of motor vehicle deaths and injuries [39]. Experimental studies and data from real-world traffic incidents indicate that several factors contribute to young drivers' poor driving performance and safety on the road. Some of the major contributors are lack of driving experience, inadequate driving skills, driver distraction and inattention, low seat belt use, nighttime and weekend driving, impaired driving, speeding, and aggressive driving [40]. Young drivers tend to take risks while driving. A review was conducted by Jonah [41] on the various risk-taking behaviors among young drivers on the road. A correlation was found between age and speed where younger adults were observed to drive at higher speeds on various roads and locations than older drivers. Young drivers were also more likely to speed in light traffic where there is a greater opportunity to drive fast. Moreover, young drivers were found to receive more speeding tickets per distance traveled than older drivers and were most likely to perform reckless offenses by driving too fast for prevailing conditions and/or losing control of the vehicle. Furthermore, photographic evidence from highways showed that younger drivers took greater risks by travelling with shorter headways than older drivers, and accepted narrower gaps in traffic when pulling away from an intersection.

A lack of experience in young drivers can be seen in their visual perception while driving. Novice drivers are likely to search the roadway close in front of the vehicle and toward the roadside which suggests their incapacity to scan the road ahead to detect potential hazards and perform evasive actions in the event of an emergency [42]. In driving simulator studies, younger drivers (under 25 years) and older drivers (over 55 years) were found to take more time to recognize potential hazards than middle-aged drivers. The younger drivers' slower perception of hazards could be attributed to their failure to recognize the situation as being hazardous [43]. Despite a lack of experience, young drivers have an overconfidence and self-enhancement bias in their skills. They report more confidence in their ability to avoid a crash, and drivers with 3 years of experience considered their overall driving ability, reflexes, vehicle handling skills and driving judgment to be better than average [44, 41]. In a study that examined behavioral factors as predictors of motor vehicle crashes in the first 12 months of driving, the findings showed a twofold increase in motor vehicle crashes among young drivers who were considered to be impulsive, sensation seekers and confident-adventurous in comparison to drivers who were not impulsive/sensation seekers and had low to moderate levels of confidence-adventurousness [45]. In line with the concept of optimistic bias, young drivers may overestimate their driving skills which may lead them to take driving risks that older drivers would avoid [46].

One possible explanation for young drivers' overrepresentation as casualties in a crash is their failure to wear a seatbelt which puts them at a greater risk of an injury if they are involved in a crash [8]. Moreover, young drivers have a lowered perception of risk. Findings from surveys have shown that when deciding on which vehicle to buy they rate the importance of safety features lower in comparison to older drivers (as cited in[41]). Furthermore, the presence of peer passengers is often implicated in the risky driving behavior and increased collision rate of young drivers [4]. They are more likely to engage in high-risk behaviours such as speeding, not wearing a seatbelt and nighttime/weekend driving when accompanied by peer passengers. For instance, young drivers who were influenced by their peers to achieve social prestige and through peer intervention in their decisions were found to commit more driving violations [47]. Other studies have also shown that crash rates are especially high for teenagers when there are two or more passengers in the vehicle, especially when they are driving at night, on weekends and without adult supervision [48, 49, 50, 51]. Additionally, young drivers are likely to be distracted by performing risky actions while driving such as talking to passengers, mobile phone use, using the in-vehicle infotainment system, smoking, eating, and drinking [52, 53].

Alcohol and drugs increase the risk of a crash for all drivers including young drivers. A focus group study was conducted by Basch et al. [54] to investigate the decision processes of young drivers to drink and drive. The discussion identified reasons such as lack of knowledge and decision-making skills, perceived norms, a propensity to disregard the increased risk of driving intoxicated, social benefits, and a rationalization of their drinking and driving behaviour. Another risk behavior that young drivers engage in is driving while fatigued with research indicating that fatigue is a contributing factor for fatal crashes of young drivers involving two vehicles [55].

2.1.2 Human factors

Cognitive functioning along with driving attitudes and personality traits have been found to contribute to driving behavior and account for young people's driving performance. In a driving simulator study, the young drivers who performed better on cognitive functioning tasks (attention, processing speed, executive function, visuospatial perception, memory, and psychomotor performance) engaged in less speeding behavior and less lane deviation than those who performed worse on these tasks [56]. Hence, lower visual perception abilities, speed of processing, mental flexibility and executive functioning skills might contribute to the increased crash risk in younger drivers. A review study by Walshe et al. [57] also suggested that a potential contributing risk factor for motor vehicle crashes among young drivers is the development of their executive functioning with the maturation of the frontal lobe through adolescence and into early adulthood. Risky driving and crash outcomes have been associated with atypical development resulting in poor or impaired executive functioning.

Several personality factors are associated with risky behaviors among young drivers. People with a risk-taking tendency, sensation-seeking personality, impulsiveness or who exhibit tendencies of hostility, anger, aggression and normlessness, and low levels of altruism have a higher likelihood of being involved in crashes [58, 59, 60, 61, 62]. Moreover, young drivers who have a higher tolerance of deviance, the acceptance of behaviors that most others would consider to be wrong or immoral, tend to have more traffic crashes [2]. Furthermore, adolescents may be particularly susceptible to peer influence that can be influenced by social identity, modeling, peer pressure or perceived social norms that are considered to be acceptable and expected by their close friends and peer group [63]. The increase in risk-taking is also a result of development in the brain's socio-emotional system that leads to increased reward-seeking, especially in the presence of peers. Hence, this increases the propensity of young adults to engage in risky driving behaviors.

The Problem-Behaviour Theory [64] can be used to explain the psychosocial risk factors for adolescent problem behaviors. It suggests that the various problem behaviors which they tend to engage in co-vary and are interrelated making this syndrome of adolescent problem behavior an aspect of their general lifestyle. Problem-Behaviour Theory includes three systems of psychological influence: the Personality System, the Perceived Environment System, and the Behavior System which reflect the urge to engage in problem behavior or control against it. Hence, this implies that risky driving is an aspect of a wider adolescent lifestyle pervaded by problem behaviors. Møller [5] conducted focus group interviews to explore the psychosocial function of driving and the relationship between lifestyle and driving behavior among young drivers. The four categories of psychosocial function identified were 'visibility', 'status', 'control' and 'mobility' with each including several dimensions. Some of the dimensions such as 'recognition by friends', 'personal rights' and 'risk perception' can explain the risk-taking problem behavior of young drivers. The three lifestyle aspects were 'leisure time', 'friends' and 'driving pattern' with each category including several dimensions. In particular, the dimensions of 'entertainment' and 'self-expression' revealed that younger drivers show-off, compete and entertain with friends through risk-taking behaviour.

2.2 Older drivers

2.2.1 Importance of driving

To many older people aged 65 years and above who have depended on vehicle use for the majority of their adult lives, there is a strong association with retaining their ability to drive safely and continued autonomy and mobility [65]. Despite the availability of alternative public transportation, the ability to travel unaided is a major component of older adults' sense of functional independence [66]. The majority of older adults will want to maintain their independence in the future living at home. A common reason for elderly people to move to an assisted living facility is partly due to age-related changes in cognition which prevent them from successfully carrying out everyday activities such as driving [67]. A report by Transport Canada [68] stated that although drivers aged 65 years and over account for 14% of licensed drivers, they represent 17% of fatalities. In Canada, many older people drive vehicles as their dominant transport mode and older drivers tend to drive more often and over longer distances [69].

It is important for older adults to have accessible and safe transport to maintain their life satisfaction, health, quality of life and well-being [70, 71]. Besides driving, there are fewer options for older road users (i.e. motorists, passengers, pedestrians, cyclists) to remain mobile which can be a problem for themselves, their families and society [72, 73, 74]. For instance, in rural areas where the travel distances are large and there are less prevalent modes of transport beyond driving, older adults need transportation to access healthcare [14]. Moreover, research shows that ceasing to drive is associated with poor health trajectories. A study by Edwards et al. [75] identified declines in physical and social functioning and performance accompanied the transition to driving cessation. Older adults might also experience loneliness, loss of independence and freedom, decreased out-of-home activity levels and higher depression rates [15, 76, 16, 77]. Additionally, older adults who have ceased driving rely on their family and friends for medical and other essential trips which might eventually become an inconvenience for the caregiver [78].

However, older drivers are likely to avoid driving situations they perceive as difficult and drive less in general [79]. They may choose to self-regulate their driving to avoid stressful situations such as heavy traffic, or where their deficiencies are more noticeable (e.g. driving in poor weather conditions, at night and on highways or high-speed roads), and may even cease to drive even though they are still fairly safe drivers [80, 81]. They are also more likely to restrict long-distance travel and drive only on familiar and well-lit roads which can limit their accessibility [82]. For instance, the findings of a longitudinal study on changes in self-regulatory driving among older drivers showed an association with increasing impairments in memory and physical mobility and an increase in avoiding more driving situations over time. The number of miles driven also decreased with reported impairments [83]. Similar findings were obtained in another study where older drivers with a history of at-fault crashes in the prior five years reported more driving avoidance than those who had crash-free records [84]. Hence, it is important to mitigate crash-related injuries and deaths as the population of older adults increases.

2.2.2 Human factors and psychological limitations

Driving is a complex task that necessitates the interaction and coordination of a variety of physical and cognitive functions [85]. There is well-documented evidence that shows aging is accompanied by a decline in perceptual, cognitive and psychomotor capacities [86, 87]. This may impair the performance, ability and safety of older drivers and make driving more demanding resulting in them becoming more vulnerable to certain types of collisions and motoring offences, typically in situations that require complex interaction with other road users, such as at intersections, merging or lane changing in dense traffic [84, 3]. Due to perceptual and attention problems and misjudgments, senior drivers are more likely than younger drivers to be cited for illegal actions or driver errors such as failure to yield the right-of-way, disregarded the traffic signal and are responsible for their collisions more often than middle-aged and young drivers [88]. A meta-analytic review by Anstey and colleagues

[89] identified a relationship between older adults' low scores on cognitive tests and poor driving performance and high crash risk. The age-related impairments and decline in functions that are needed for driving include executive function [90], impaired vision [91], hazard perception [92], reaction time [93], working memory and information processing speed [94]. Hence, a deficit in these abilities can decrease the safety of older drivers on the road.

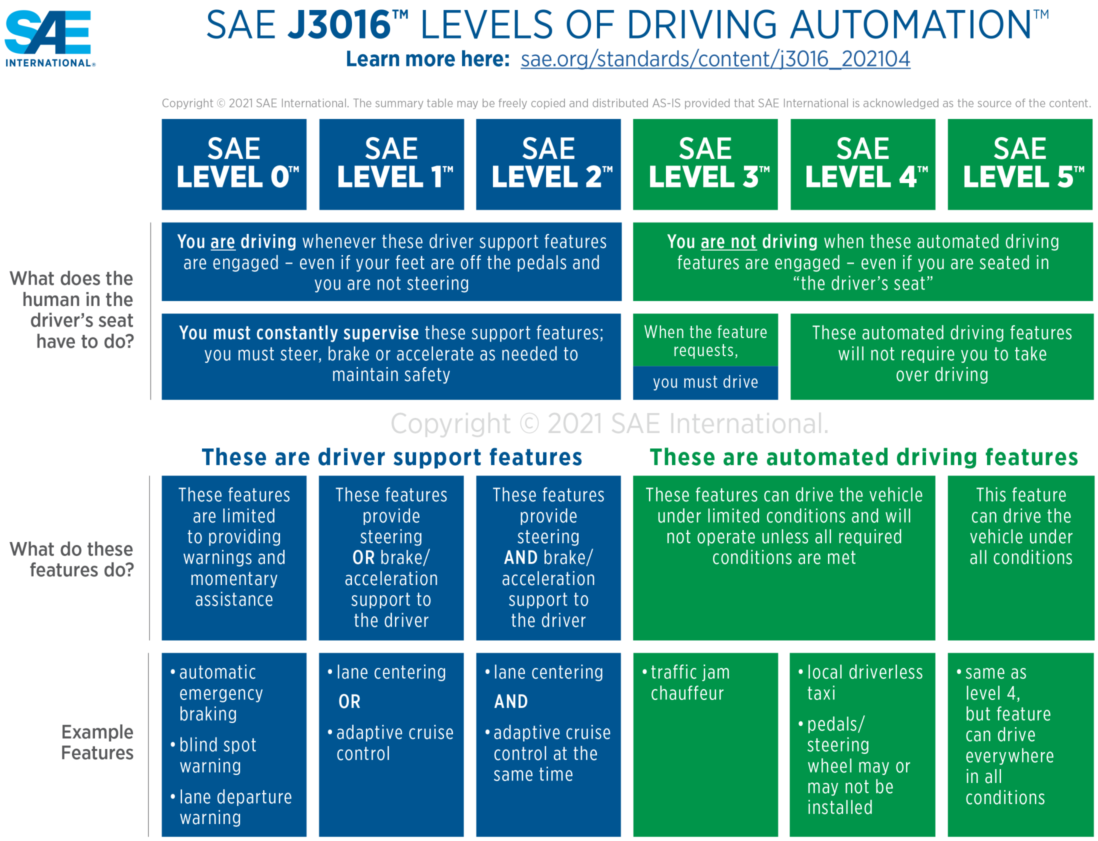
As driving is a highly visual task and most aspects of visual function start to decline with old age, there is some evidence that people with visual impairment are more likely to report difficulty driving and have a higher risk of crash involvement. A prospective study on motor vehicle crashes found that glare sensitivity, visual field loss and poor visual attention were significant predictors of crash involvement among older drivers [95]. Moreover, the visual search of older drivers is inefficient [96], they are more likely to erroneously estimate the speed of other vehicles [97], and take more time to switch tasks [98]. Furthermore, older drivers have reported having increasing difficulty in not having enough time to read, compute and comprehend road signs, maintaining a constant speed at the speed limit, and increased tiredness and fatigue [99]. In addition, a study by Horswill et al. [92] on the hazard perception ability of older drivers showed they were slower at responding to traffic conflicts in a video-based hazard perception test which could be accounted for by declines in cognitive and visual processes.

Hertzog et al. [100] described this decline in abilities as the "zone of possible functioning" that is defined by person-specific endowments and age-related constraints. A person's position in this zone is contingent on their engagement with beneficial intellectual, physical, and social activities. Hence, good cognitive functioning can be sustained even at an older age with the right conditions. Additionally, performance in naturalistic common and cognitive tasks is also influenced by specific knowledge, expertise and relevant information structures besides cognitive abilities [101, 102]. Thus, aging may not necessarily result in a deterioration in driving performance for everyone as it depends on the situation and individual lifestyle such as compensatory adaptations, experience-related changes and acquisition of expertise.

2.3 Autonomous vehicles

The availability of vehicles equipped with Advanced Driving Assistance Systems (ADAS) that are deployed in the market has become increasingly common these days. These systems use sensors and cameras to assist drivers with driving and parking tasks as well as to detect nearby obstacles or driver errors, and respond accordingly [19]. Hence, it can increase vehicle and road safety by providing real-time advice, instruction and warning which will reduce human error [103]. These adaptive features can warn the driver of problems, implement safeguards and take control of the vehicle if necessary to avoid collisions. For instance, ADAS can provide adaptive cruise control (ACC), alert drivers to possible obstacles and blind spots, incorporate satellite navigation and traffic warnings, assist in lane departure and lane centering, automate emergency braking, detect driver drowsiness and warn of possible impending collisions [104].

As the technology of ADAS improves, the level of vehicle automation increases from No Automation (Level 0) to Driver Assistance (Level 1) and Partial Automation (Level 2) where the human driver monitors the driving environment with the system capable of some driving modes, through to Conditional Automation (Level 3), High Automation (Level 4) and Full Automation (Level 5) where the automated driving system monitors the driving environment when its engaged and is capable of performing some to all of the driving modes [1]. This allows the driver to delegate part of their driving task to the vehicle and have their errors corrected to prevent crashes. Figure 2.1 illustrates the different levels of driving automation. From Levels 0 to 2, the user performs the entire dynamic driving task (DDT) (Level 0) or the remainder of the DDT not performed by the driving automation system, and supervises the driving automation system and intervenes as necessary to maintain operation of the vehicle (Levels 1 and 2). When the driving automation is engaged, it performs part of the DTT by executing either the longitudinal or the lateral vehicle motion control (Level 1) or both types of control (Level 2). From Levels 3 to 5, the automation driving system performs the entire DDT while it is engaged. However, at Level 3, the user is expected to be fallback-ready and intervene to resume the DDT when requested by the system. At Level 4, the user travels in an automation engaged vehicle as a passenger and may be required to drive only hen the automation system has reached its operational design domain (ODD) limit. However, such a system is capable of performing a DDT fallback and automatically transitioning to a minimal risk condition when it a DDT failure occurs or it reaches its ODD limit. A Level 5 automation system includes all these capabilities without an ODD limit and needing a fallback-ready user.



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What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/ acceleration support to the driver	These features provide steering **AND** brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Figure 2.1: SAE [1] levels of driving automation

2.3.1 ADAS and young drivers

Since younger drivers often lack the necessary experience and skills and engage in risky driving behaviors, they are another group of drivers that could benefit from ADAS and autonomous vehicles. For instance, in a simulator study with younger drivers, the experimental results indicated that drivers who drove a vehicle with an intersection collision warning system (ICWS) audio signal at an intersection had a faster reaction time, lower speed and decreased crash rate compared to those who drove a vehicle without an ICWS audio signal [105]. Moreover, research by Mueller and Cicchino [106] showed that crash avoidance features and teen-specific vehicle technologies can prevent or mitigate up to 75% of fatal crashes that involve teen drivers. The researchers analyzed passenger-vehicle crashes with teen drivers that occurred on U.S. roads during 2016-19, where three crash avoidance features (front crash prevention, lane departure warning/prevention and blind-spot monitoring) and three technologies designed for teen drivers (speeding prevention features, nighttime curfew notifications and extended reminders or gearshift interlocks to encourage seat belt use) were used. The results showed that altogether the technologies could prevent 78% of teen driver fatalities, 47% of teen driver injuries and 41% of crashes involving teen drivers. These benefits were further seen in another study by the Highway Loss Data Institute (HLDI) that found ADAS also reduced the number of insurance claims more for younger drivers than experienced drivers. The data from the collision avoidance features of Subaru, Honda and Kia vehicles indicated that drivers under 25 years had larger reductions in the frequency of collision and property damage liability (PDL) claims in comparison to those who were 25 years and older [107, 108, 109]. However, since these features can be turned off, there is no way to determine if older drivers might not be using them since they have more road experience. Nevertheless, as these features continue to improve and assist with various driving tasks and evolve the autonomous driving capability of the vehicle, it is expected that self-driving vehicles will reduce the crash risk and improve the safety of younger drivers.

2.3.2 ADAS as an aid for older drivers

Since older drivers tend to self-regulate by avoiding driving situations they perceive as difficult and drive less overall, ADAS such as collision warning systems and intersection assistants can be beneficial for older adults by increasing their confidence in driving [110], and avoiding the negative effects associated with driving cessation [111]. The age-related declines in sensory abilities can impact the information that they receive from other road users, the infrastructure, and their own vehicles. Perceptual and cognitive processes are involved in the selection of appropriate information, interpretation and decisions made on the appropriate driving action [112]. Physical abilities such as joint flexibility, muscular strength and reduced manual dexterity can decline as people get older and influence their ability to operate the vehicle as well as susceptibility and recovery from injuries [113]. Several studies have shown that older adults often have difficulties with judging the movement of fellow road users and the speed they approach the intersection, overlooking other road users while merging and changing lanes, overlooking traffic signs and signals, and slowed reaction time as the complexity of the traffic situation increases which leads to crashes [114]. Hence, autonomous vehicles can act as a cognitive assistance device by performing some of these driving tasks that might reduce the difficulties resulting from older adults' limitations [115]. Although older adults might have physical and cognitive incapacities and less familiarity with new technologies, they have a positive attitude towards technologies that are perceived to be beneficial to their current lifestyle (e.g. [116, 117]. Thus, their driving cessation can be avoided and they can safely extend their driving with autonomous vehicles.

2.3.3 Perceptions of ADAS and AVs

The adoption of autonomous vehicles is contingent upon their perceptions and social acceptability as well as the knowledge and trust in the system. A survey by Hulse et al. [118] found that the perceived risk of different vehicle types and general attitudes towards autonomous vehicles varied according to gender, age and risk-taking, with males and younger adults showing greater acceptance. However, while high sensation seekers are expected to intend to use a fully automated vehicle more than low sensation seekers to experience novelty and adventure, the delegated driving may lower their thrill experience [119]. For example, when using an ACC device high sensation seekers were found to drive faster on average with shorter headways between vehicles and stronger braking force [120]. This implies that high sensation seekers might adapt their behavior to being less careful while being driven by an electronic system in their own vehicle. Despite this implication, drivers with high self-confidence in their manual operation of the vehicle may quickly take back control from the automation if their trust is compromised [121]. Nevertheless, the findings of online surveys have shown that fully autonomous driving was preferred on highways, in traffic congestion and for automatic parking which indicates that they perceive these features to be useful [119]. To investigate the development of trust and acceptance of HAD, Hartwich et al. [122] conducted a driving simulator study where the trust and acceptance of older and younger drivers were assessed before and after the use of the automated system. The results showed a significant increase from the slightly positive a priori trust and acceptance ratings from both age groups after experiencing the HAD system. Similar findings were also observed in other surveys which showed that feelings of safety and knowledge about semi-autonomous vehicles were positively related to the adoption of the technology [123, 124, 18]. Hence, this suggests that both age groups of concern might use autonomous vehicles as they become more prevalent in the near future.

2.4 Level 3 – semi-autonomous vehicles

2.4.1 Situations where drivers still need to takeover

Currently, given the approval of Level 3 semi-autonomous vehicles for use on the road, it is essential to examine the interaction between the autonomous technology that drives the vehicle and the human driver who is still needed to perform some of the driving tasks. This interaction is important as there may be situations wherein the authority of the vehicle is returned to the driver due to threats and hazards that are beyond the regular operative conditions of the vehicle such as a sensor malfunction and external conditions outside the autonomous technology capability [125]. In fact, the human driver serves as a backup whenever the system of a semi-autonomous vehicle disengages following a failure, and some current regulations require the human driver to constantly and carefully monitor the outside environment (even during vehicle automation) and have the ability to immediately resume control if the vehicle requests [126]. During a Level 3 takeover request (TOR) from autonomous to manual driving, the time window for the driver to regain full comprehension of the driving environment can be extremely short (average 6 seconds). The human driver will be needed to quickly and appropriately comprehend the situation to avoid any potential risks during take-over [127]. Therefore, to ensure proper handling of the transition, it is critical to identify a reasonable time frame for TORs that is appropriate for different drivers in various situations.

2.4.2 Autonomous vehicle's behavior after the TOR

The handover process of autonomous vehicles after it sends a takeover request is crucial in order to ensure the safety of the driver and other users on the road while they takeover. With the existing Level 3 vehicles, the autonomous driving systems are capable of continuing to perform the driving task for at least several seconds after providing the driver with a request to intervene. The human driver is then expected to manually operate the vehicle or achieve a minimal risk condition if necessary. A Level 3 automation should also have a failure mitigation strategy such as bringing the vehicle to a controlled stop if the driver fails to take over when prompted [1]. Cadillac's Super Cruise follows this method: if the driver does not take over steering immediately when alerted, the vehicle slows down in the lane of travel and will eventually brake to a stop [128]. Alternatively, some manufacturers consider it to be better for the vehicle to move into a safer mode such as pulling over when the technology detects an upcoming hazard, rather than immersing the driver at short notice [129, 130].

There have been several laboratory studies conducted with semi-autonomous vehicle simulators to investigate the takeover performance. In some simulator setups, the system was deactivated either through the driver intervention or automatically after a certain amount of time elapsed [131]. Typically, participants could override and deactivate the automation in three ways: by pressing a button on the steering wheel that also enables the self-driving mode, turning the steering wheel or pressing the accelerator or brake pedal [132, 133, 134, 135, 136, 31]. To increase the fidelity of the simulator and make it similar to driving the current Level 3 vehicles that are available in the market, some studies required the participants to only press the pedals a certain amount (e.g. 10%) or apply torque on the steering wheel (e.g. a minimum 45° change in the current steering wheel angle) to override the automation and seamlessly transition back to driving the vehicle [137, 138]. The behavior of the vehicle following the TOR differs across the studies. In their experiment to measure the quality of the driver's recovery on curved roads, Favaro et al. [139] set the vehicle to continue heading in a straight line rather than following the road as it disengaged. On the contrary, the vehicle used by Forster et al. [137] would not decelerate but drift slowly in the direction of the current steering wheel direction when automation was deactivated. However, in accordance with the standards set by the Society of Automotive Engineers (SAE [1]), a more realistic option would be to either bring the vehicle to a controlled stop or to pull over if the human driver does not take over in time.

2.5 Takeover performance

There is a significant amount of literature on the takeover performance of semi-autonomous vehicles with various studies investigating the time needed and takeover quality. It is vital to inform the driver of this transition well in advance to prevent potentially unsafe situations and to ensure a comfortable takeover process. Since the available time is limited by the system's sensors and their ability to predict the system boundaries, the take-over time needed to engage the driver who is out of the loop is an important issue for vehicle manufacturers to consider when designing their automation systems [140]. Some of the metrics typically measured are takeover reaction, minimum time to collision (TTC), crash rate, critical events, maximum longitudinal and lateral acceleration, steering response, accelerator and brake pedal input, eyes-on-road reaction time, glancing at the mirrors and speedometer, deviation from lane center [141, 142, 143, 140, 144, 133, 145, 146, 135, 136, 147, 148, 149, 131]. Since autonomous driving does not typically require the driver to monitor the environment, this would allow them to engage in other nondriving tasks such as interacting with other passengers, using mobile devices, eating or drinking. Several studies have examined the impact of these secondary tasks on takeover performance and found an impairment in the takeover quality. Participants were auditorily, visually and manually distracted using standardized and realistic tasks such as the n-back, surrogate reference task (SuRT), critical tracking task (CTT), texting task, 20 Questions Task, video watching, reading, typing and interacting with the in-vehicle information system (IVIS) [150, 133, 151, 134, 145, 146, 135, 136, 148, 149, 131].

2.5.1 Age differences

Since older adults are susceptible to age-related declines, it is likely that some aspects of their takeover performance may be negatively affected when driving a semi-autonomous vehicle. Several studies have attempted to investigate the age differences when interacting with autonomous vehicles. In one such study, Körber et al. [152] examined the takeover performance of older and younger drivers in a driving simulator with or without a non-driving task on a six-lane highway. The participants encountered varying levels of traffic density (no, medium, high) and had to resume control of the vehicle and evade an obstacle on the road. The researchers found that while older drivers had a similar reaction time to younger drivers, they exhibited more frequent and stronger braking and maintained a higher TTC. Engaging in a non-driving task and an increase in traffic density led to a deterioration of takeover time and quality for both age groups. In another driving simulation study on the effects of age and level of driving disengagement on the takeover control performance, older drivers were slower to respond and make decisions than younger drivers. Differences in certain aspects of their takeover quality were also observed with older drivers showing significantly higher acceleration and steering wheel deviation than younger drivers. A complete disengagement from driving the vehicle resulted in longer takeover time and worse takeover quality which had a higher effect on older drivers than younger drivers [22]. Moreover, in an experiment that examined the effect of age on level of activity-engagement and takeover notification interval on takeover performance, although voluntary engagement in non-driving-related activities did not impair takeover performance, older drivers who were more engaged braked harder than those with low activity engagement during the takeover. The longer notification interval also better enabled older drivers to respond to the notifications than younger drivers [153]. Additionally, another study by Clark et al. [154] found that older age and a greater number of distinct non-driving-related activities were associated with an overall lower takeover speed. In contrast, there was a positive relationship between age and average takeover speed for younger drivers which might indicate an overall better vehicular control with more driving experience.

Furthermore, takeover performance has been investigated in adverse weather conditions which reduce the visual clarity of the road ahead. Older drivers had longer takeover times and worse takeover quality which suggests that they could benefit from a more supportive TOR to compensate for their reduced visibility [23]. However, in the study by Favaro et al. [143] that examined the quality of control following disengagements in a semi-autonomous vehicle simulator, contrary to expectations, the drift performance of older participants was better than or equal to the younger and middle-aged groups. Nonetheless, they did have higher response times when the takeover was with a high vehicle speed. The findings are similar to another study that found no differences in the takeover times of younger and older drivers [155]. The authors reasoned that a cautious driving style and compensatory behaviors such as less involvement in nondriving tasks may diminish the effects of aging. A riskier takeover performance has also been identified with younger drivers in comparison to middle-aged and older drivers. For instance, following the transition from automated driving, young drivers showed greater mean and minimum speeds [156], and longer eyes-off-the-road durations than other age groups of drivers [157]. However, when Kaye et al. [158] assessed the extent to which using a hand-held mobile phone affected young drivers' takeover control in a semi-autonomous simulator, the results revealed that there were no significant differences in the takeover when drivers used their hand-held mobile phones compared to completing the working memory n-back task or monitoring the road environment (control condition).

2.6 Importance of situation awareness

According to Endsley [159], situation awareness (SA) is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". There are three levels of situation awareness: perception of the elements in the environment, comprehension of the current situation, and projection of future situations based on current perceptions and background knowledge. One method of measuring SA is the Situation Awareness Global Assessment Technique (SAGAT) that can assess all elements of SA including Level 1 (perception of data), Level 2 (comprehension of meaning) and Level 3 (projection of the near future). This involves freezing and blanking the system at a particular time and then questioning the operators on their perceptions of the situation at that time [160]. Another technique to measure drivers' SA is to use the Situation Present Awareness Method (SPAM [161]). With this method driving scenario in a simulator is paused at random times, but the scenario remains visible. The driver is then asked one or two questions about the scenario with response time as the main variable. The Situation Awareness Rating Technique (SART

[162]) is also administered to participants after they perform a task to determine their SA. Participants rate their experience in the performed task on several items using a seven-point rating scale.

2.6.1 Situation awareness when driving

SA is crucial when performing any dynamic complex task, especially driving. Drivers need to have SA of factors such as the speed, fuel level, and functioning of their vehicle; the relative distance, speed, and trajectories of surrounding traffic; the impact of weather and hazards; their location, projected time and distance to the destination; compliance with posted speeds and laws; and knowledge of abnormal vehicle states and their effect on vehicle safety and performance [163]. SA involves identifying the relevant environmental stimuli, incorporating that information into the operator's knowledge base to form a mental model or representation of the situation, and using this representation to project the occurrence of events in the near future [159]. SA includes the driver attention and perception, the ability to make meaningful assessments of the significance of perceived information to one's goals such as knowing to change lanes in advance of an upcoming exit or collision; and projecting likely future events to make proactive decisions, for example, reacting to brake lights by slowing down or rerouting around heavy traffic [21]. Drivers need to identify the relevant information in the rapidly changing traffic environment such as the distance to other vehicles, and be ready to react to events that may occur, for example, a vehicle backing out of a driveway or a stop sign, to avoid crashes. SA requires perception and pattern recognition abilities, attention, working memory, as well as long-term memory [164]. Hence, distractions that overload a driver's cognition may adversely impact their SA which is needed for attention and hazard detection. In addition, improper lookout, inattention and recognition errors (e.g., looked but did not see or interpret incorrectly) are instances of failures to maintain SA which has often been implicated in vehicle crashes [165].

2.6.2 Effect of distractions

Several studies have shown that distractions can diminish the attention of the driver to the driving task resulting in unsafe conditions and vehicular crashes. In a driving simulator study that was conducted to assess the level of engagement with an in-vehicle secondary task, the performance of young drivers declined if they had many long in-vehicle display glances. The high-risk group that looked away from the road for the longest periods also had shorter minimum TTC during lead vehicle braking events [166]. According to the findings of a systematic review, one of the determinants of the discrepancies in performance between young novice and experienced drivers was the incomplete maturation of cognitive skills crucial to safe driving such as visual scanning, hazard anticipation and handling of in-vehicle distractions [58].

2.6.3 Change with driver's age

Research on the risk exposure of young drivers under different road conditions demonstrates that they have rigid visual search strategies in comparison to experienced drivers who have more flexible search patterns. Due to their inexperience, novice drivers may not have the ability to handle the cognitive load of complex road conditions while simultaneously attending to the demands of the driving task [42]. Wright et al. [33] found that experienced middle-aged drivers were better at anticipating hazards and could quickly achieve appropriate situation awareness than inexperienced younger drivers when a transfer to manual control was required from a Level 3 simulated autonomous system. However, in a driving simulator study, while novice drivers committed more driving infractions and were less situationally aware than their experienced counterparts, both groups suffered similar decrements in their performance when cognitively distracted with a hands-free cell phone conversation [25].

Due to the process of aging, several cognitive and physical abilities that are needed for situation awareness can decline. Using a concurrent memory probe technique, Bolstad [163] found that older adults had lower SA in a driving simulator experiment when compared to younger and middle-aged adults. The findings implied that as the driving complexity increased, their attention was more likely to get narrowed and that they were aware of their own performance, but less aware of their surroundings. On the contrary, research by Scott-Parker et al. [167] showed young, middle-aged and older drivers had similarities in their SA when observing a 16-minute day-time driving scenario and all participants commented on the driving hazards in the immediate environment (e.g., vehicle immediately in front). However, there were differences observed in their verbal commentary. Middle-aged drivers produced the greatest number of words, followed by older and then younger drivers. Learners also focused on the school zone, middle-aged drivers focused on sharing the road and older drivers focused on the hazards associated with the road environment. Moreover, an on-road driving and video-based hazard perception task study found no differences in the SAGAT scores of older and younger drivers. However, the younger drivers did perform better on the hazard perception task than older drivers and were particularly faster to detect a hazard. The older drivers also had less awareness of what was behind their vehicles [168].

2.6.4 Autonomous driving

There is evidence that automation can result in an out-of-the-loop performance problem which handicaps operators of automated systems in their ability to take over manual operations if the automation fails. This is likely due to the loss of skills and SA caused by poor vigilance, complacency, a shift from active to passive information processing, and a change in the feedback provided to the operator [26]. When operators monitor automation, they are slow to identify problems that require intervention, and need time to sufficiently understand the problem and intervene accordingly [21]. Research on human-automation integration shows that a driver's ability to intervene and take over from automation depends on their SA of critical information in the driving environment which is influenced by trust, engagement and mental models. When automation has high reliability, trust is increased and people are more inclined to divert their attention to other competing tasks. Drivers can become less engaged under automation which lowers their SA and response to hazardous situations. Finally, as automation becomes more capable and complex, it becomes difficult for the operator to create an accurate mental model of the system which negatively affects their SA.

Experiments with driving simulators have shown an increase in driver distraction with the implementation of autonomous systems. As trust in the automation increased, visual monitoring frequency and duration were found to decrease, particularly when attending to a visually demanding non-driving-related task [169]. Moreover, with highly automated driving and ACC, drivers were more likely to pick up tasks that are unrelated to driving which deteriorated their SA in comparison to manual driving [27]. This was further seen in other studies that showed engagement in non-driving tasks increased from manual to semi-automated driving and HAD [170, 171]. Additionally, younger and older drivers were found to engage in various non-driving-related activities during the automated drive, with younger drivers mostly using an electronic device while older drivers preferred to converse. This indicates that the tendency to engage in secondary tasks is consistent across age and highly engaged older drivers were also found to brake harder than those with low activity engagement during the takeover [153].

Furthermore, when distracted by secondary tasks, drivers were slow to respond to critical incidents and had worse performance when required to regain vehicle control in the automated driving conditions [172]. Thus, as also shown in the video-based study with highly automated driving, there is an association with low levels of SA and longer takeover times [154]. In addition, there is a possibility that interacting with the automation itself can create a distraction and slow the reaction time of drivers when they have to respond to an emergency event [173]. Another experiment also showed that drivers experiencing automation were more heavily involved with the in-vehicle entertainment tasks than they were in manual driving and had less visual attention to the road ahead. The drivers refrained from overtaking which suggests that drivers preferred to relinquish their supervisory responsibilities with a highly automated drive [174]. However, as the supervisory demand of the vehicle automation increased with heavy traffic, the participants did increase their attention to the roadway which indicates their understanding of their supervisory responsibilities in critical situations.

On the contrary, some studies have found an improvement in SA and collision response time when the drivers were informed about the reliability of the automation [175]. Kaber and Endsley [176] also found that SA improved with ACC which could be a result of an increase in drivers' available mental capacity for attending to traffic. Additionally, in a preliminary naturalistic on-road study with the Tesla Model S, Endsley [21] found an increase in her SA as she was able to look around more at other traffic, signage and information displays rather than being highly focused on maintaining vehicle speed and trajectory. However, she did find several instances of distraction and loss of attention as her attention wandered over time, and she was more likely to daydream, interact with the navigation system or sound system and even text while driving in comparison to manual driving.

2.7 Driving conditions

2.7.1 Road geometry

Road geometry has been identified as a contributing crash factor with curved roads having a higher crash rate than straight roads. The crash rates on curved roads are about 1.5 to 4 times higher than on straight roads [34]. Sharp horizontal curves or curves with a smaller radius increase the likelihood of crashes as they require more steering control due to the difficulty of negotiating the curve and less time to perform corrective maneuvers. These curves are also associated with limited sight distance of the upcoming curve and driving hazards such as other vehicles [37]. Moreover, the crash severity on curved roads is higher than those that occur on straight roads [36]. Crashes on curves result in more severe injuries as the complex roadway conditions place increased demands on the driver and the vehicle that could lead to a wrong choice of speed and trajectory [35]. In Queensland, Australia, the fatality rate of road-curve crashes was more than twice that of straight-road crashes, and 45.2% of persons injured in road-curve crashes required hospitalization, compared to 37.3% of drivers injured on straight-road crashes [177].

Several studies have attempted to develop models to understand the factors that contribute to crashes on rural roadways. For instance, a statistical analysis of crash severity on rural freeways provided evidence for the effect that environmental conditions, highway design, crash type, driver characteristics and vehicle attributes have on crash severity. Specific highway designs such as a high percentage of horizontal curve length and a greater number of horizontal curves both increased the likelihood of property damage only [178]. In a report by the National Highway Traffic Safety Administration [179] that examined the factors that contribute to run-off-road (ROR) crashes, the results showed that rural roadways and roadway alignments with curves were significant factors related to the high risk of fatal single-vehicle ROR crashes. Curved road segments and rural roads were more likely to be the scene of ROR crashes in comparison to straight roadways and urban roads respectively. Similarly, a study on collisions on urban and rural two-lane highways in Virginia by Kassebaum and Garber [180] showed that the main type of collision was ROR crashes with roadway curvatures and traffic volume determined to be the significant causal factors in these collisions. Hence, curved roads can increase the likelihood of a crash occurring.

For driver characteristics, several studies have shown that the risk of collision, as a function of age, conforms to a U-shaped relationship where crash rates are high among teenagers, lower among middle-aged drivers, and increase again among older drivers [88]. Young and older drivers also experience higher fatality involvement rates than the average driver population and both groups were more likely to be considered at-fault [3]. Furthermore, environmental factors such as curved and inclined roads, and areas with a speed limit of 100 km/h or greater were found to be more frequent in the crashes of older rural drivers and additionally associated with increased injury severity in younger drivers [181]. The existence of a curve or grade were determinants of higher young driver crash severity while having a frontal impact point was a severity determinant for older drivers [182]. Clarke et al. [183] analyzed a sample of fatal road traffic crashes to understand the causation and underlying factors. The findings showed that young drivers had a majority of their crashes by losing control on bends or curves, typically at night in rural areas and/or while driving for leisure purposes. These crashes indicated high levels of speeding, alcohol involvement and recklessness. Therefore, it is crucial to understand the takeover performance in situations where younger and older drivers need to regain control of the vehicle before approaching a curve.

2.7.2 Highway and non-highway urban locations

Highways allow drivers to drive at higher speeds which can increase the chances and severity of crashes in unsafe driving behavior and conditions [184]. Several studies have identified speed to be one of the main factors of road crashes where the severity and frequency of collisions vary directly with speed. Loss of vehicle control, overspeeding, misjudgments and improper overtaking are all related to the speeding factor which contributed to 44% of all police-reported crashes in Kenya, and 50% of road crashes in South Africa and Ghana [185, 186]. Excessive speed was also the second major contributing factor in road crashes in the United Arab Emirates accounting for 16% of all casualties and 27% of fatalities in 2000 [187]. Moreover, highway driving behavior can vary according to driver characteristics. Research by Zhao et al. [188] indicated that drivers with high violations scores on the Driver Behavior Questionnaire drove faster, had poorer lateral control, changed lanes more frequently, spent more time in the left lane, and had more sudden unidirectional accelerations when driving on an actual highway. Furthermore, middle-aged drivers with high violation scores had higher velocities than those with low violation scores. Additionally, an analysis by age showed that the violations of young and middle-aged drivers did not have significant effects on the number of hard brake events, but drivers in the older-aged group with high violation scores were likely to brake more than those with low violation scores. Another study that analyzed reports of 2,000 highway crashes involving young drivers for behavioral crash contributors found that the majority of non-fatal crashes resulted from errors in attention, visual search, speed relative to conditions, hazard recognition and emergency maneuvers [189]. These findings imply that certain age groups with dangerous driving styles are more likely to drive aggressively on the highway. In addition, an investigation into urban and highway rural crashes showed that some of the driver-related contributory factors were alcohol involvement, lack of seat belt usage, excessive speed, and driver ejection or being trapped due to the crash that resulted in more severe crashes. Roadway geometry-related parameters such as curved and graded roads also contributed to higher crash severity [190]. The crash rates and severity of crashes are quite high at horizontal curves due to drivers either being unaware or underestimating the approaching horizontal curve or the radius or sharpness of the curve. Thus, it has been recommended to lower the operating speeds on horizontal curves from the design speed of the highways [191].

Traffic collisions are also likely to occur in non-highway urban areas with a different crash severity and collateral damage. Research by Cabrera-Arnau et al. [192] on the patterns of road crashes in the urban areas of England and Wales revealed that minor and serious crashes were more frequent in urban areas. The number of crashes in the urban area was also dependent on the population size superlinearly which became stronger for lower degrees of severity. Moreover, the probability that a crash was fatal or serious decreased with the population size and the probability of minor crashes increased sublinearly. There are several reasons for the observed population scaling behaviors of traffic collisions. As the population size of an urban settlement increases, the road surface sublinearly increases which could contribute to the increase in traffic congestion [193, 194]. However, other studies have shown that traffic congestion has little or no impact on the frequency of road crashes (e.g. [195]). Some studies have also shown that the variations in traffic can influence the crash occurrence and severity with low severity crashes occurring in congested traffic flow conditions, and severe and fatal crashes occurring more often in non-congested traffic and when there are large differences in speed between adjacent lanes [196, 197]. Furthermore, in an experiment that investigated the behavioral factors that predicted motor vehicle crashes, young urban drivers had a higher incidence rate for a motor vehicle crash compared to young rural drivers [45]. Since older adults struggle with complex traffic situations, turning, intersections, yielding and backing up [198], these findings indicate that the driving performance of certain age groups may increase the vulnerability of other road users in urbanized areas. Additionally, urban areas have the highest population-based rates for both injury and property-damage-only crashes, and the death rates for motorcyclists, pedestrians and bicyclists are highest in these areas [199]. Hence, it is important to focus on reducing the number and severity of crashes in non-highway urban environments, especially as autonomous vehicles are being introduced into cities and need to learn to recognize and safely avoid colliding with vulnerable road users.

2.8 Summary

To summarise, there is insufficient research conducted on the driving performance of different age groups in a semi-autonomous vehicle. Since younger and older drivers tend to have higher rates of crashes in comparison to middle-aged drivers, they are likely to benefit from using semi-autonomous vehicles that might help to avoid collisions that occur from younger drivers' poor driving style, and improve the road safety and mobility of older drivers who experience age-related declines in their driving abilities. With semi-autonomous vehicles, young drivers can safely engage in secondary non-driving tasks during vehicle automation and then focus on driving after a TOR. Driving a semi-autonomous vehicle may also reduce the cognitive workload of older drivers and increase their safety. The existing literature on takeover performance has examined the takeover quality of younger and older drivers after performing a non-driving task, and in varying levels of traffic density, weather conditions and vehicle speed. However, there may be other complex conditions such as different road geometries and road types that could also affect takeover performance. Hence, this thesis aims to fill the gap on takeover performance of younger and older drivers on straight versus curved roads and on highway versus non-highway urban roads. Moreover, there are very few studies conducted on SA while driving a semi-autonomous vehicle which is critical when taking over from vehicle automation. Therefore, the current research will indicate how SA varies according to age and different road conditions when taking over from vehicle automation after being distracted by a secondary non-driving task.

Chapter 3

Current study

3.1 Hypotheses and study overview

This study aimed to examine age (young versus middle-aged drivers) differences in the situation awareness (SA) and takeover performance on different road types (highway versus urban), road geometries (straight versus curved) and drive types (manual versus autopilot only versus autopilot with distraction).

For the variables age (1), road type (2), road geometry (3) and drive type (4),

H_0: there will be no main effect

H_A: there will be a main effect

and

H_0: there will be no interaction effect

H_{A12}: there will be an interaction effect between age and road type

H_{A13}: there will be an interaction effect between age and road geometry

H_{A14}: there will be an interaction effect between age and drive type

H_{A23}: there will be an interaction effect between road type and road geometry

H_{A24}: there will be an interaction effect between road type and drive type

H_{A34}: there will be an interaction effect between road geometry and drive type

H_{A123}: there will be an interaction effect between age, road type and road geometry

H_{A124}: there will be an interaction effect between age, road type and drive type

H_{A134}: there will be an interaction effect between age, road geometry and drive type

H_{A234}: there will be an interaction effect between road type, road geometry and drive type

H_{A1234}: there will be an interaction effect between age, road type, road geometry and drive type

on situation awareness.

The same hypotheses and model setup will be used for the takeover performance.

The current study investigated the situation awareness and takeover performance of young and middle-aged drivers in a semi-autonomous vehicle simulator. The participants drove a semi-autonomous vehicle in different conditions such as on straight and curved roads which were on a highway and in non-highway urban locations. For each of the road types, they either manually drove the vehicle, engaged autopilot and then performed a takeover, or engaged autopilot, performed a secondary distracting task and then resumed manual control when requested by the system which resulted in a total of 12 driving scenarios. Their situation awareness (SA) was assessed using SAGAT scores after the takeover and eye-tracking data. The reaction time and takeover quality were obtained from the data saved by the simulator software.

3.2 Materials

The participants were screened using the Trail Making Test (TMT [200]) and the Motion Sickness Susceptibility Questionnaire-Short form (MSSQ-Short [201], see Appendix A). The Trail Making Test is a neuropsychological test that assesses visual attention and task switching. It requires the test-taker to connect a sequence of 25 consecutive targets on a sheet of paper or computer screen and consists of two parts (A and B). In part A, the targets are all numbers from 1 to 25 which need to be connected in sequential order. In part B, the targets include numbers from 1 to 13 and letters from A to L. The test-taker has to connect the targets in order while alternating letters and numbers, in the shortest time possible. If they make an error, the test administrator corrects them before they move on to the next target. The MSSQ-Short measure how susceptible an individual is to motion sickness, and the sorts of motion that are most effective in causing that sickness (feelings of queasiness, nausea or actual vomiting). The participants were also screened for visual acuity using a standard Snellen eye chart [202]. They had to stand 10 feet away from the wall and read the 20/50 line with both eyes open, with or without the aid of corrective lenses (glasses or contact lenses).

SA after the takeover was measured using an Ergoneers Dikablis 3 eye-tracker (see Figure 3.1) and Level 1 SAGAT (see Appendix B for a sample list of questions). The responses to the SAGAT questions were scored as correct or incorrect and since two questions were asked at the end of every trial, the participant could obtain a total score out of 2 per trial. The Ergoneers Dikablis 3 is a wearable wired binocular eye-tracker with 60 Hz eye camera tracking frequency, 0.05° visual angle pupil tracking accuracy and 0.1°–0.3° visual angle glance direction accuracy. The eye camera resolution is up to 648 × 488 pixels and the field (scene) camera resolution is 1920 × 1080 pixels, 30 fps (frames per second). A red circular cross-hair indicates the wearer's current focal point on the field camera view and recording. The eye-tracker must also be calibrated to suit the current wearer before recording by using the calibration assistant to perform automatic calibration. While the person holds the same position they will be in for the trials, the eye camera is adjusted so that the pupil is in the center of the image and the eye mask area is set for pupil detection. To perform calibration, the wearer is required to not move their head and only glance at the markers placed at the four corner points of the screen, one after another (there is one point in each image quadrant), while the experimenter uses the mouse button to click on the corresponding points in the field camera image. The eye tracker can also be calibrated or finely adjusted manually.

Figure 3.1: The Ergoneers Dikablis Glasses 3 Eye Tracker used in the experiment

The driving scenarios and takeover tasks were programmed and run on CARLA [203], a driving simulator software for AV. Figure 3.2 shows a sample of the driving scenario. The driving simulator and eye-tracking software were installed on a CyberPower PC Gaming Desktop (Intel i7-9700K CPU @ 3.60 GHz, 16GB RAM, Nvidia GeForce GTX 2070 Super). The simulator setup included a Logitech G29 steering wheel controller with force feedback and a set of pedals were used to control the vehicle, and a GTR Simulator racing seat with horizontal seat adjustment. The driving scenarios were displayed on a single 27-inch Full HD 1080p LED monitor that provided the participants with a high resolution and wide-angle vision view of the road ahead and view of the rear and side mirrors. The non-driving related distracting tasks were presented on a Dell Precision 5520 laptop with a 15-inch screen and a display resolution of 1920 × 1080 (refresh rate = 60 Hz). The tasks used were the Auditory n-Back Task [204], Surrogate Reference Task (SuRT [205]) or the Critical Tracking Task (CTT [206]). See Figure 3.3 for a sample of the simulator setup. The three questionnaires (demographics, MSSQ and SSQ) were hosted on the Qualtrics online platform.

Figure 3.2: The takeover warning used in the autopilot drives

Location A

steer: -0.00, brake: 0.00, gas: 0.73
1 Gear

Please takeover control of the vehicle

Autopilot: ON
Speed: 88 km/h

Figure 3.3: Simulator setup – includes the Logitech G29 steering wheel and pedal set, and the laptop used for the distracting tasks

3.3 Participants

In order to be eligible for the research, participants should have been between the ages of 18-24 (young) or 35-55 (middle-aged) years. They were required to possess a valid Canadian Driver's License (e.g. Ontario Class G2 or G) with at least one year of driving experience and be active drivers at the time they participate in the experiment. They were screened using the cut-off score of 29 seconds or greater for test A and 273 seconds or more for test B on the TMT [200] and a cut-off score of 23 on the MMSSQ-Short[201]. Those who had a visual acuity poorer than 20/50 with or without the aid of corrective lenses were excluded from the study.

The middle-aged drivers aged 35-55 years were used as the control group to compare with the experimental younger group aged 18-24 years. Since opportunity sampling was used, the participants were recruited from the local Kitchener and Waterloo communities after ethical approval to conduct the study was obtained. The young drivers were mostly students from the University of Waterloo as well as the neighboring universities and colleges. Participants were solicited through advertisements on posters and social media platforms and screened for normal visual acuity and normal contrast sensitivity using the standard Snellen Near and Far Visual Acuity tests [207]. To statistically computer the sample size, G*Power 3.1.9.6 [208] was used to determine the number of participants. The parameters used for the 'ANOVA: Repeated measures, between factors' statistical test were α=.05, power (1–β)=.95, effect size f = .4, 3 groups, 4 measurements and 0.5 correlation among repeated measures. Although a power (1–β) of 0.8 is the recommended minimum, a higher power (1–β) of 0.95 was used as it is more desirable to avoid Type 2 errors [209], and an effect size f of 0.4 was used as it is considered to be a large effect [210]. An a priori power analysis for a $3 \times 2 \times 2 \times 3$ mixed factorial design indicated that a minimum of 66 participants was required. However, to increase the reliability and accuracy of the study and taking into consideration possible dropouts, it was decided that a sample of 72 participants will be recruited comprising of 24 young, 24 middle-aged and 24 old (future study) male and female adults.

For the current study, a sample of 55 participants was recruited but due to simulator sickness in the middle-aged group and incomplete data, 7 data points were excluded from the analysis. A summary of the analyzed sample's descriptive data is provided in Table 3.1. The sample comprised of 24 young (18-24 years; *M*=21.15, *SD*=2.14) and 24 middle-aged (35-52 years; *M*=42.04, *SD*=5.93) adults, and a total of 22 females (11 middle-aged and 11 young) and 26 males (13 middle-aged and 13 young). Of the young participants, 17 possessed a valid G driver's license while 7 had a valid G2 driver's license. All 24 middle-aged participants possessed a valid G driver's license. The young participants had between 1.5 to 8 years of driving since obtaining their first driver's license with an average of 4.5 years, while the middle-aged participants had between 10 to 36 years of driving with a mean of 22.13 years. The middle-aged group drove a lifetime average of 21,189,500 km (*SD*=101,987,464) whereas the young group drove a lifetime average of 41,395 km (*SD*=60,001). Of the 3 middle-aged participants who reported using semi-AVs, they drove their vehicle for an average of 21 months, and the 3 young participants who reported semi-AV usage drove their vehicle for an average of 3 months. The middle-aged participants had a mean MSSQ score of 9.42 (*SD*=9.38) while the young participants had a mean score of 4.42 (*SD*=5.07). The scores of the middle-aged ranged from 0 to 38 whereas for the young group it ranged from 0 to 19. Unfortunately, 3 middle-aged drivers reported symptoms of motion sickness on the SSQ. Two middle-aged participants dropped out after experiencing motion sickness during the practice trials. No young drivers reported feeling motion sickness at the end of the experiment.

Table 3.1: Analyzed sample demographics

Demographic	**Young (*n*=24)**	**Middle-aged (*n*=24)**
Age (years)		
Minimum–Maximum	18–24	35–52
Mean (SD)	21.15 (2.14)	42.04 (5.93)
Gender *n*(%)		
	11 (45.8%) females 13 (54.2%) males	11 (45.8%) females 13 (54.2%) males
Driver's license *n*(%)		
G*	17 (70.8%)	24 (100%)
G2**	7 (29.2%)	
Driving experience (years)		
Minimum–Maximum	1.5–8	10–36
Mean (SD)	4.5 (1.90)	22.13 (6.41)
Total lifetime driving kilometers		
Minimum–Maximum	1000–200,000	45,000–500,000,000
Mean (SD)	41,395 (60,001)	21,189,500 (101,987,464)
Semi-AV use (months)		
Minimum–Maximum	1–7	4–48
Mean (SD)	3 (3.46)	21 (23.64)
MSSQ		
Minimum–Maximum	0–19	0–38
Mean (SD)	4.42 (5.07)	9.42 (9.38)

**G is Ontario's full, unrestricted drivers' license [211].*

***G2 is Level Two of the Ontario graduated licensing. Holders may drive without an accompanying driver but are subject to certain conditions [211].*

3.4 Experimental design

The study used a mixed factorial design ($2 \times 2 \times 2 \times 3$; age × road type × road geometry × drive type). The between-subjects independent variable was the age (young versus middle-aged drivers). The within-subjects independent variables were the road type (highway versus urban non-highway), road geometry (straight versus curved) and drive type (manual versus autopilot only versus autopilot with distraction).

3.4.1 Dependent variables

The dependent variables adopted are summarized in Table 3.2. Drivers' takeover performance is quantified by the reaction time aspects of takeover and takeover quality.

SA composes of hazard detection and hazard perception time which is the time from the onset of the hazard to the time they fixate at it, as well as the SAGAT scores after the takeover.

Takeover time is the time between the takeover request (TOR) and the driver's first active input to the controls of the vehicle which is an input of the steering wheel angle of 2° and/or 10% movement of the accelerator or brake pedal positions.

The resulting acceleration is the force transferred by the vehicle tire to the ground. The greater the value of the parameter, the higher the chance that the takeover was unstable. It is calculated using the maximum longitudinal and lateral acceleration in the following equation [23]:

$$Resulting\ Acc = \sqrt{MaxLongAcc^2 + MaxLatAcc^2}$$

where the maximum longitudinal acceleration is the maximum force applied during acceleration and braking, and maximum lateral acceleration is the maximum force that acts transversely to the direction of travel of a vehicle and occurs during cornering [212].

The number of collisions recorded during the takeover process is an effective measurement to evaluate the success of the takeover. It measures the total number of collisions during the takeover including colliding with the obstacle and driving off the road.

Lane deviation attempts to measure how much the vehicle crosses a lane marking. The lateral deviation from the center line of the lane was recorded since the start of the takeover till the end of the trial and a standard deviation of lane position (SDLP) was calculated for the values recorded after the takeover. A higher value represents a less stable takeover performance.

Table 3.2: Overview of dependent variables

Construct	**Variable**	**Unit**
Situation Awareness	Hazard detection	Count
	Hazard perception time	s
	SA after takeover	Score
Reaction Time aspects of takeover	Takeover time	s
Takeover quality	Resulting acceleration	m/s^2
	Lane deviation	m
	Number of collisions	Count

3.5 Procedure

The participants' consent was obtained before they participated in the study. They completed a short demographics questionnaire (see Appendix A) to indicate their personal information such as age and driving experience, and completed a computerized version of the TM) [200] and the MSSQ-Short [201]. Following completion of the two questionnaires and the TMT, their visual acuity was assessed and they were given verbal instructions regarding the task. They adjusted their seat position as needed and the eye-tracker was fitted and calibrated. Before commencing the experiment, they were briefed about the automated driving system, its limits, the driver's responsibilities in a semi-AV and the procedure for the experiment. They were informed that they do not have to monitor the system but may have to take over control of the vehicle when the system is incapable of autonomously driving and will send a warning signal. Participants were instructed to drive the simulator vehicle onto the road, engage autopilot and perform a non-driving related task such as the Auditory n-Back Task [204], Surrogate Reference Task (SuRT [205]) or the Critical Tracking Task (CTT [206]) in the distracted condition. They were also informed of a potential takeover at some point during their journey. This was followed by a trial that gave them sufficient practice to familiarise themselves with the driving simulation and the vehicle automation before attempting the main experimental task. When the participant felt comfortable and able to handle the driving task and the functions of the vehicle, the main drive was started. They performed 12 driving trials with each scenario lasting about 5 minutes. In each session, the vehicle was driven for 3-4 minutes and after the takeover, 2 situation awareness questions were asked and answered. The total duration of each experiment was 90 minutes. Their SA, reaction time and takeover quality were measured. SA was assessed using Level 1 SAGAT scores after the takeover and eye-tracking data. The reaction time and takeover quality were obtained from the data saved by the simulator software. Lastly, they completed the Simulator Sickness Questionnaire (SSQ [213], see Appendix A) to measure their perceived simulator sickness. Finally, the participants were thanked for their participation, remunerated accordingly and verbally debriefed at the end of the experiment.

3.6 Driving scenarios

A description of the 12 driving scenarios can be found in Table 3.3. Complete counterbalancing with a Latin square design [214] was applied on the locations used for each of the three drive types (manual, autopilot only, autopilot with distraction) resulting in six possible sequences. The scenario order was counterbalanced across subjects. For both age groups, half of the group did the highway scenarios first and then the urban non-highway scenarios. Moreover, half of the group did the straight roads first and then the curved roads. This resulted in the following order of testing conditions:

- Highway-straight, highway-curved, urban non-highway-straight, urban non-highway-curved
- Urban non-highway-straight, urban non-highway-curved, highway-straight, highway-curved
- Highway-curved, highway-straight, urban non-highway-curved, urban non-highway-straight
- Urban non-highway-curved, urban non-highway-straight, highway-curved, highway-straight

Participants drove a Level 3 semi-autonomous vehicle at a speed of 90 km/h on a two-lane highway and on an urban non-highway road at a speed of 30 km/h. There was moderate scripted traffic in all scenarios; the highway had 10 vehicles per kilometer and lane located approximately 100 m away from the ego vehicle, and the urban non-highway road had 6 vehicles per kilometer and lane and 2 pedestrians and 2 cyclists located approximately 100 m away from the ego vehicle. The implemented automation carried out longitudinal and lateral control. Longitudinal control functioned like an ACC system and the automation followed the indicated speed limits, adjusted the speed automatically in case of a slower leading vehicle and kept the vehicle in the center of the current lane. In the takeover scenarios, the participants turned on the Autopilot feature from the start. Due to the system boundaries, six different situations (such as a vehicle collision, a stopped lead vehicle, a vehicle merging from the hard shoulder, road debris, or the appearance of a bicyclist or pedestrian) represented the vehicle takeover scenarios. These occurred twice for each participant, once in the highway and non-highway urban scenarios. Some of the hazards were bottom-up threats such as vehicle merging from the hard shoulder, road debris, or the appearance of a bicyclist or pedestrian while the vehicle collision and stopped lead vehicle were top-down threats. The hazard was spawned from the start of the scenario and appeared on or from the hard shoulder (highway scenarios) or the pavement (urban non-highway scenarios). To avoid the crash, the driver could either slow down or stop on their lane, or change to the left or right lane. To make the lane changing possible, the adjacent left or right lanes were not occupied by any other vehicles. Only one TOR was used in each scenario. Seven seconds before the ego vehicle collided with the hazard, a visual and auditory TOR was given requesting the driver to take over vehicle control. This was in the form of a continuous chime, and a steering wheel icon flashed on the screen along with the message ‘Please takeover control of the vehicle’ (see Figure 3.2). The takeovers occurred at random times for each location to avoid the participant expecting the TOR at fixed times throughout the drive. To examine the effect of road geometry, the TOR was given just before entering a curve in the curved road conditions or on a straight road. The driver had to provide 10% input to the accelerator or brake pedals or turn the steering wheel at least 2° in either direction to switch off the vehicle automation, i.e. transfer longitudinal and lateral control back to the driver. After passing the hazard event, the driver continued to manually drive for a further 50 m and the scenario automatically ended. If the driver was unable to takeover control in time, the vehicle rapidly decelerated to a stop within the current lane to avoid colliding with the hazard.

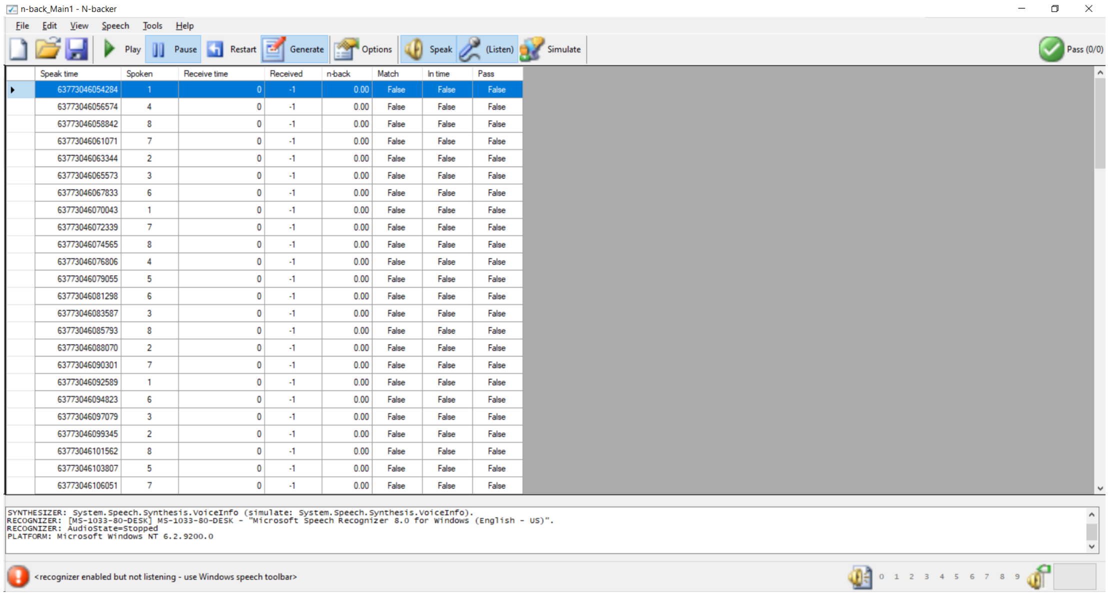
Table 3.3: Driving scenarios

Road type	**Road geometry**	**Drive type**	**Scenario No.**
Highway (90 km/h)	Straight road	Manual	Scenario 1
		Without secondary task	Scenario 2
		With secondary task	Scenario 3
	Curved road	Manual	Scenario 4
		Without secondary task	Scenario 5
		With secondary task	Scenario 6
Urban non-highway (30 km/h)	Straight road	Manual	Scenario 7
		Without secondary task	Scenario 8
		With secondary task	Scenario 9
	Curved road	Manual	Scenario 10
		Without secondary task	Scenario 11
		With secondary task	Scenario 12

3.7 Secondary tasks

In order to mimic a realistic case scenario, where the driver is out of the loop and not monitoring the automated vehicle system by being engaged in a visually demanding non-driving-related task, the drivers completed one of three secondary tasks that are standardized for reproducing attentional demands on drivers in an experimental setting [215]: the n-Back Task [204], Surrogate Reference Task (SuRT [205]) and the Critical Tracking Task (CTT [206]). The participants were given sufficient practice according to the ISO Standard with all three tasks before performing them in the main experimental scenarios. The tasks were presented on the 15-inch laptop notebook to the participants. They were evenly distributed across the distracted trials so that all tasks were used for the same number of times at the end of the data collection. The participants were instructed to complete the n-back, SuRT or CTT during the distracted driving scenarios at their own pace, but encouraged to do so as quickly as possible. The task was stopped (in the case of the n-back) or the participants were instructed to stop performing the task (for SuRT and CTT) and to takeover control of the vehicle simulator as soon as they heard the TOR.

The n-back task is an auditory-vocal task that requires a participant to listen to a continuous sequence of numbers presented at a fixed interval. The participant shall then respond during the intervals with the appropriate number back in the sequence depending on which version of the n-back is being used, typically 0-, 1- or 2-back. Participants are instructed to perform the task as accurately as possible and the experimenter records the response accuracy. For the current experiment, the participants had to perform a 2-back task and the N-backer software [216] was used to present the numbers at a fixed inter-stimulus interval of 2250 ms. The experimenter manually recorded and scored the responses. Figure 3.4 shows the main interface window of the software.



Speak time	Spoken	Receive time	Received	n-back	Match	In time	Pass
63773046054284	1	0	-1	0.00	False	False	False
63773046056574	4	0	-1	0.00	False	False	False
63773046058842	8	0	-1	0.00	False	False	False
63773046061071	7	0	-1	0.00	False	False	False
63773046063344	2	0	-1	0.00	False	False	False
63773046065573	3	0	-1	0.00	False	False	False
63773046067833	6	0	-1	0.00	False	False	False
63773046070043	1	0	-1	0.00	False	False	False
63773046072339	7	0	-1	0.00	False	False	False
63773046074565	8	0	-1	0.00	False	False	False
63773046076806	4	0	-1	0.00	False	False	False
63773046079055	5	0	-1	0.00	False	False	False
63773046081298	6	0	-1	0.00	False	False	False
63773046083587	3	0	-1	0.00	False	False	False
63773046085793	8	0	-1	0.00	False	False	False
63773046088070	2	0	-1	0.00	False	False	False
63773046090301	7	0	-1	0.00	False	False	False
63773046092589	1	0	-1	0.00	False	False	False
63773046094823	6	0	-1	0.00	False	False	False
63773046097079	3	0	-1	0.00	False	False	False
63773046099345	2	0	-1	0.00	False	False	False
63773046101562	8	0	-1	0.00	False	False	False
63773046103807	5	0	-1	0.00	False	False	False
63773046106051	7	0	-1	0.00	False	False	False

```
SYNTHESIZER: System.Speech.Synthesis.VoiceInfo (simulate: System.Speech.Synthesis.VoiceInfo).
RECOGNIZER: [MS-1033-80-DESK] MS-1033-80-DESK - "Microsoft Speech Recognizer 8.0 for Windows (English - US)".
RECOGNIZER: AudioState=Stopped
PLATFORM: Microsoft Windows NT 6.2.9200.0
```

<recognizer enabled but not listening - use Windows speech toolbar>

Figure 3.4: N-backer main interface window

The SuRT is a standardized visual search and manual input task where drivers are asked to identify a larger (target) circle among circles of the same size (distractor). They have to select the target circle using the left and right keypad buttons. The level of demand can be easy or hard depending on the difference in the size of the target circle and surrounding circles. The target and distractors were white circles in front of a black background. Participants responded by tapping on the identified target using the laptop trackpad which indicated if the target had been correctly chosen by flashing either green for correct or red for wrong, and then displaying the next trial. The more difficult version of this task was used where distractors had a radius of 0.6 mm and a line width of 4.0 mm, and the target had a radius of 0.75 mm and a line width of 4.0 mm. Figure 3.5 shows the interface of the DominionSURT software [217] that was used.

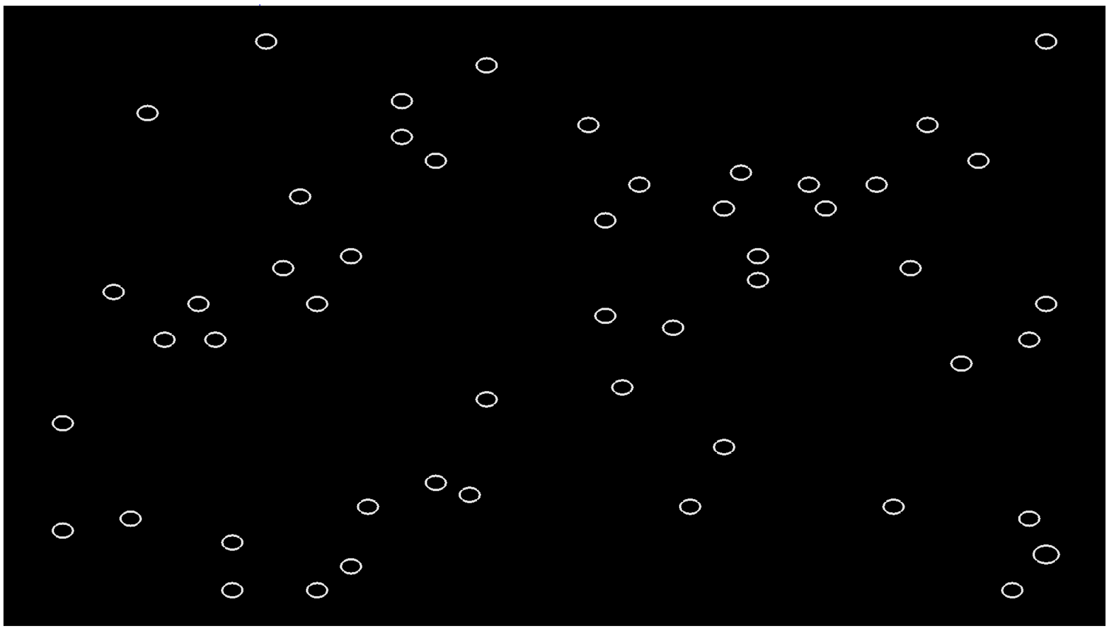


Figure 3.5: SURT interface with distractors and target

The CTT requires an operator to stabilize a bar, which is displayed on a computer screen, such that it does not depart from a predefined target position. Participants use the keys to bring the bar back to the target position; a task that becomes increasingly difficult over time. The level of instability is represented by a λ-value (with $\lambda = \frac{1}{T}$, T being the divergent time constant measured in s), which increases constantly. The value at which control is lost is recorded as a performance measure. The current study used the CTT software [218] with a fairly easy level of $\lambda = 1.0$ and a gain value (keyboard sensitivity) of 50. Figure 3.6 shows the interface of the software.

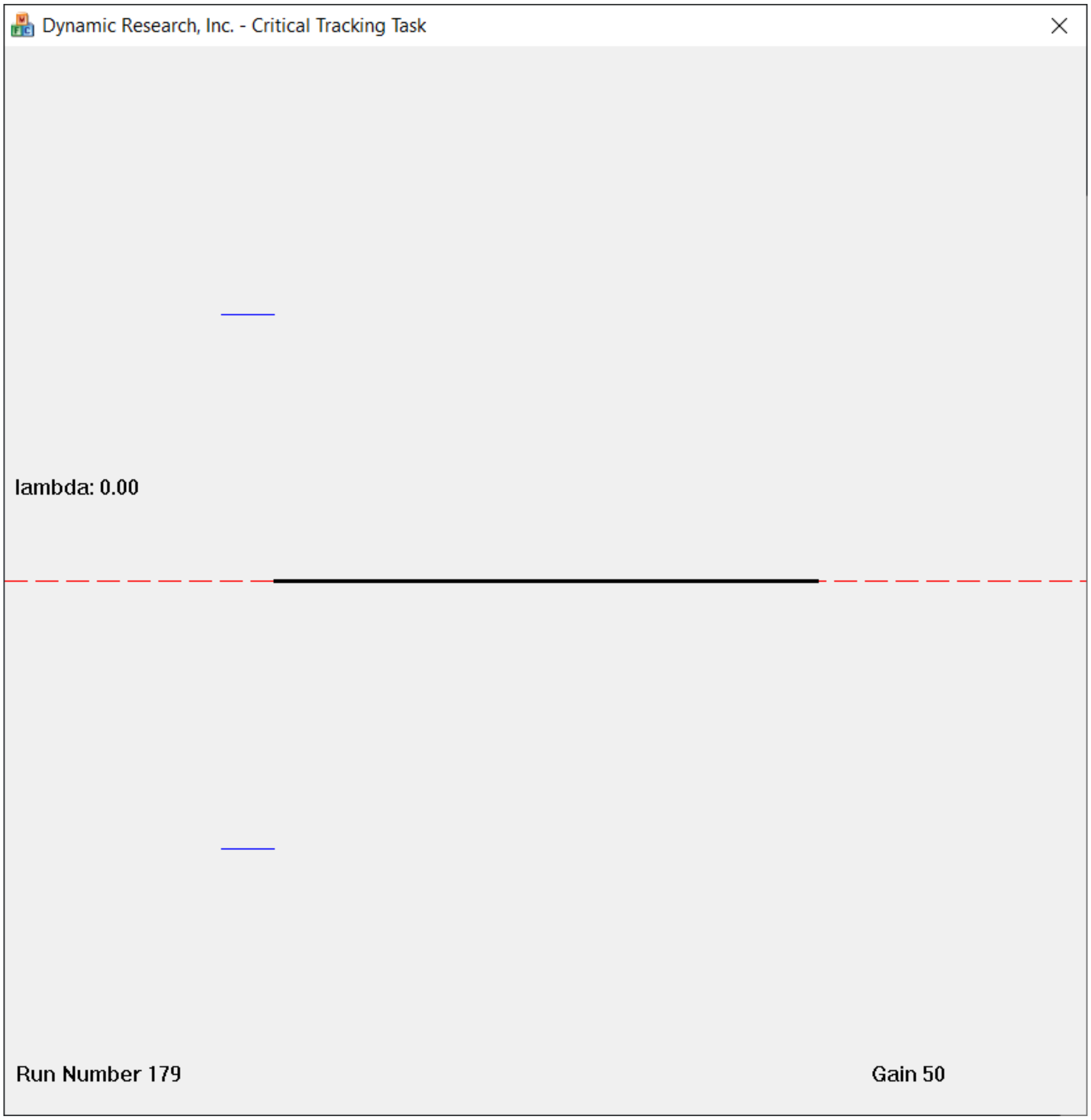


Figure 3.6: CTT interface

Chapter 4

Analysis & Results

A $2 \times 2 \times 2 \times 3$ four-way mixed ANOVA was conducted using the SPSS 26 [219] software with two groups of young and middle-aged drivers, a highway or urban non-highway road type, a takeover before entering a curved lane versus a straight lane, and a distraction, no distraction condition and manual drive, to test for significant effects for each of the dependent variables.

4.1 SA

4.1.1 Hazard detection

Nearly all participants were able to detect the hazard in all 12 scenarios, except 2 participants. The middle-aged participant was unable to detect the hazard in an urban scenario with a takeover on a curved road. The young participant was unable to detect the hazard in an urban scenario with a takeover on a curved road occurring after being distracted with a secondary task.

4.1.2 Hazard perception time

Table 4.1 shows the descriptive statistics for young and middle-aged drivers.

Table 4.1: Descriptive statistics of the hazard perception time

Road type	**Road geometry**	**Drive type**	**Hazard perception time (s)**	
			Young	**Middle-aged**
Highway	**Straight**	**Manual**	6.73 (2.97)	6.63 (3.94)
		AP only	7.18 (2.64)	7.58 (2.34)
		AP with distraction	7.89 (2.24)	8.28 (2.55)
	Curved	**Manual**	5.41 (2.76)	5.71 (2.84)
		AP only	6.11 (2.17)	6.18 (2.58)
		AP with distraction	6.10 (2.13)	6.06 (2.69)
Urban non-highway	**Straight**	**Manual**	2.75 (2.71)	2.53 (2.65)
		AP only	4.42 (1.86)	5.10 (1.95)
		AP with distraction	5.49 (2.03)	5.56 (1.65)
	Curved	**Manual**	7.56 (1.81)	7.88 (1.53)
		AP only	8.85 (2.82)	8.37 (1.72)
		AP with distraction	9.47 (2.33)	8.83 (2.67)

Values shown are Mean (SD)

A mixed-design ANOVA was conducted to test the effect of the driver's age (young, middle-aged) between-subjects factor, and road type (highway, urban non-highway), road geometry (straight, curved), and drive type (manual, autopilot only, autopilot with distraction) within-subjects factors on hazard perception time.

There was a significant interaction effect between road geometry and road type [$F(1, 44) = 341, p \leq .001, \eta_p^2 = 0.89$, observed power = 1.00; see Figure 4.1]. In the highway scenarios, the hazard perception times were longer with a straight road (M = 7.38, SE = 0.16) compared to a curved road (M = 5.93, SE = 0.13), while the urban non-highway scenarios showed shorter hazard perception times for the straight road (M = 4.31, SE = 0.17) in comparison to the curved road (M = 8.49, SE = 0.18).

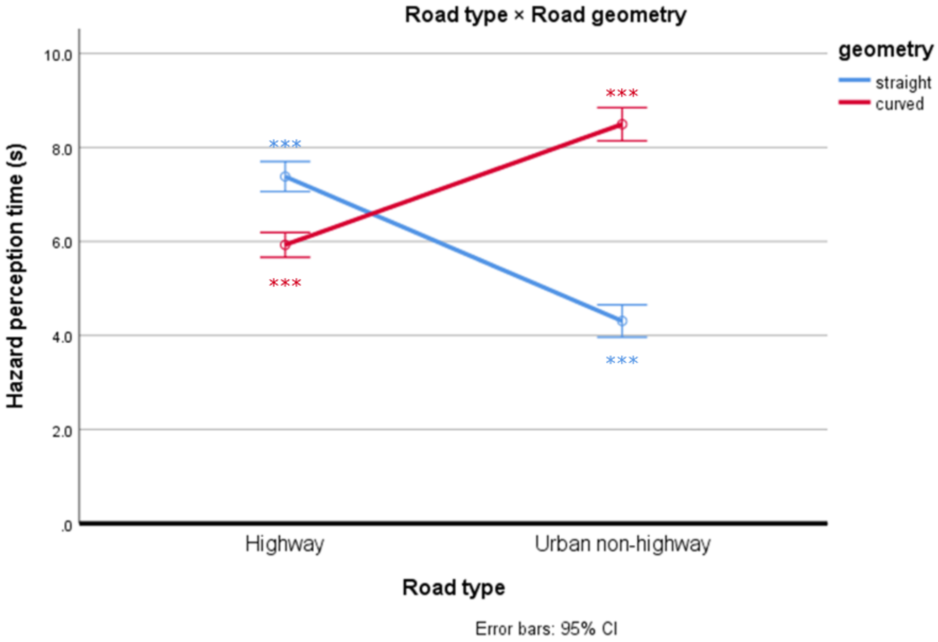


Figure 4.1: The interaction effect between road type and road geometry on hazard perception time (s)

*** indicates $p \leq .001$

The interaction between road type and drive type showed a significant difference only for the manual versus autopilot with distraction drives [$F(1, 44) = 4.24$,$p < .05, \eta_p^2 = 0.088$, observed power $= 1.00$; see Figure 4.2]. In the highway and urban scenarios, the hazard perception times were shorter in the manual drive (highway: $M = 6.12$, $SE = 0.38$; urban: $M = 5.18$, $SE = 0.22$) compared to the autopilot with distraction drive (highway: $M = 7.08$, $SE = 0.29$; urban non-highway: $M = 7.34$, $SE = 0.22$).

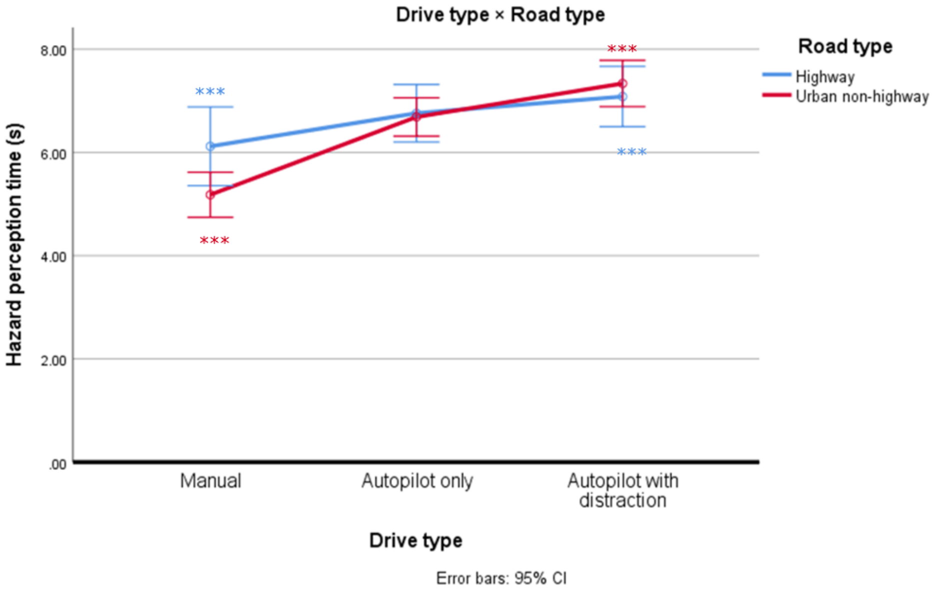


Figure 4.2: The interaction effect between drive type and road type on hazard perception time (s)

*** indicates $p \leq .001$

There was also a significant interaction effect between drive type and road geometry only for the manual versus autopilot with distraction drives [$F(2,88) = 4.9, p < .01, \eta_p^2 = 0.10$, observed power $= 0.80$; see Figure 4.3]. For the straight and curved road scenarios, the hazard perception times were shorter in the manual drive (straight: $M = 4.66$, $SE = 0.30$; curved: $M = 6.64$, $SE = 0.23$) compared to the autopilot with distraction drive (straight: $M = 6.80$, $SE = 0.22$; curved: $M = 7.61$, $SE = 0.26$).

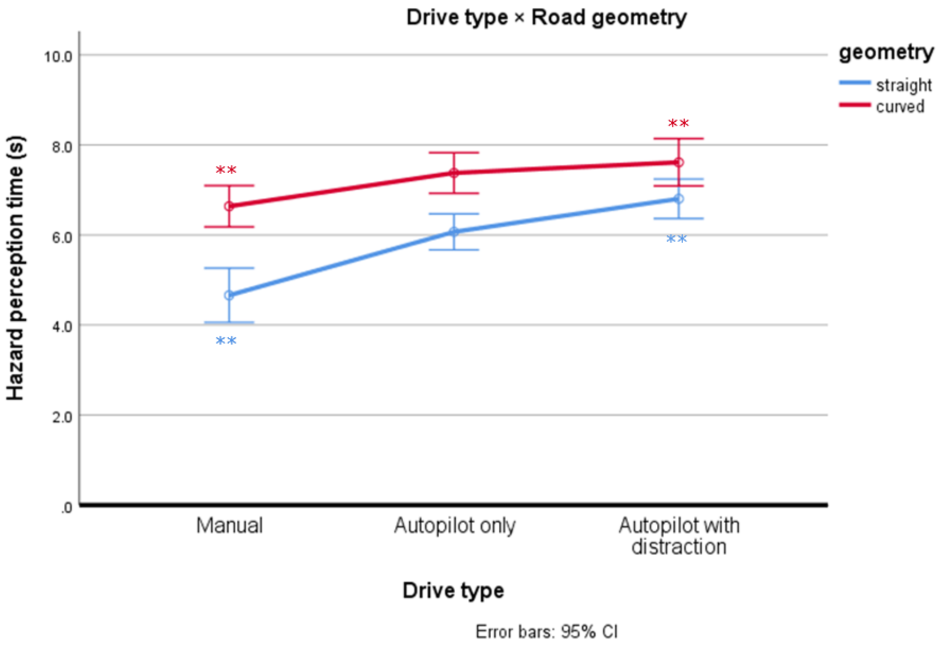


Figure 4.3: The interaction effect between drive type and road geometry on hazard perception time (s)

** indicates p <.01

Table 4.2 shows the ANOVA values of the main effects. There was a significant main effect of road geometry and further analysis, using Bonferroni t, showed significantly shorter hazard perception times for the straight road (M = 5.84, SE = 0.13) compared to the curved road (M = 7.21, SE = 0.11, $p \leq .001$; see table 4.3). There was also a significant main effect of drive type. The hazard perception time for the manual drive was significantly shorter (M = 5.65, SE = 0.23) than the autopilot only drive (M = 6.72, SE = 0.17, p <.01) and the autopilot with distraction drive (M = 7.21, SE = 0.20, $p \leq .001$; see table 4.3). There was no significant difference between the autopilot only and autopilot with distraction drives (p = 0.29). There was no significant main effect of driver age and road type.

Table 4.2: ANOVA table for hazard perception time

Variable	$df_{hypothesis}$	df_{error}	F	p	η_p^2	**Observed Power**
Age	1	44	0.11	0.74	0.003	0.06
Road type	1	44	2.92	0.094	0.06	0.39
Road geometry	1	44	95.1	<0.001*	0.68	1.00
Drive type	2	88	13.4	<0.001*	0.23	0.99

*** indicates $p \leq .001$

Table 4.3: Descriptives of road geometry and drive type for hazard perception time

		Hazard perception time (s)
Road geometry	**Straight**	5.84 (0.13)
	Curved	7.21 (0.11)
Drive type	**Manual**	5.65 (0.23)
	AP only	6.72 (0.17)
	AP with distraction	7.21 (0.20)

Values shown are Mean (SD)

4.1.3 SAGAT

Table 4.4 shows the descriptive statistics for young and middle-aged drivers.

Table 4.4: Descriptive statistics of the SAGAT scores

	Age group	**Young**	**Middle-aged**
Road type	**Highway**	9.08 (1.08)	8.77 (1.29)
	Urban non-highway	8.60 (1.58)	7.73 (1.36)
Road geometry	**Straight**	9.21 (1.34)	9.07 (1.42)
	Curved	8.48 (1.21)	7.44 (1.35)
Drive type	**Manual**	6.37 (0.95)	5.85 (.15)
	AP only	5.79 (1.12)	5.60 (1.11)
	AP with distraction	5.52 (0.96)	5.04 (1.27)
Total		1.50 (0.56)	1.35 (0.61)

Values shown are Mean (SD)

A two-way mixed-design ANOVA was conducted to test the effect of the driver's age (young, middle-aged) between-subjects factor with each of the within-subjects factors on SAGAT scores.

There was a significant main effect of road type [$F(1,46) = 8.44, p < .01, \eta_p^2 = 0.16$, observed power = 0.81; see Figure 4.4]. Further analysis, using Bonferroni t, showed that for the road type, the SAGAT score was significantly higher in the highway scenarios (M = 8.93, SE = 0.17) compared to the urban non-highway scenarios (M = 8.17, SE = 0.21, $p < .01$).

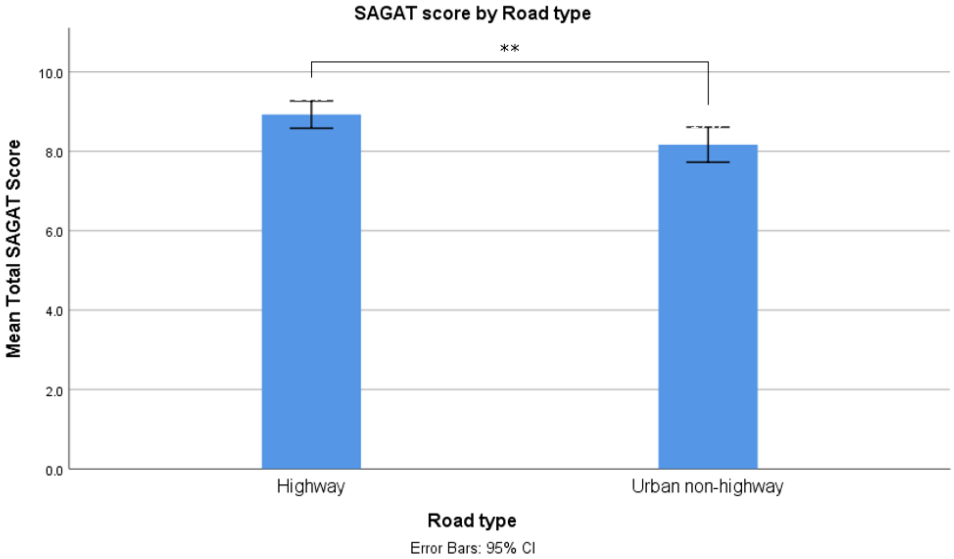


Figure 4.4: SAGAT scores on highways and urban non-highway scenarios
** indicates p <.01

There was a significant main effect of road geometry [$F(1, 46) = 20.7, p \leq .001, \eta_p^2 = 0.31$, observed power $= 0.99$; see Figure 4.5]. The SAGAT score was significantly higher with the straight roads ($M = 9.14$, $SE = 0.20$) than the curved roads ($M = 7.96$, $SE = 0.19$, $p \leq .001$).

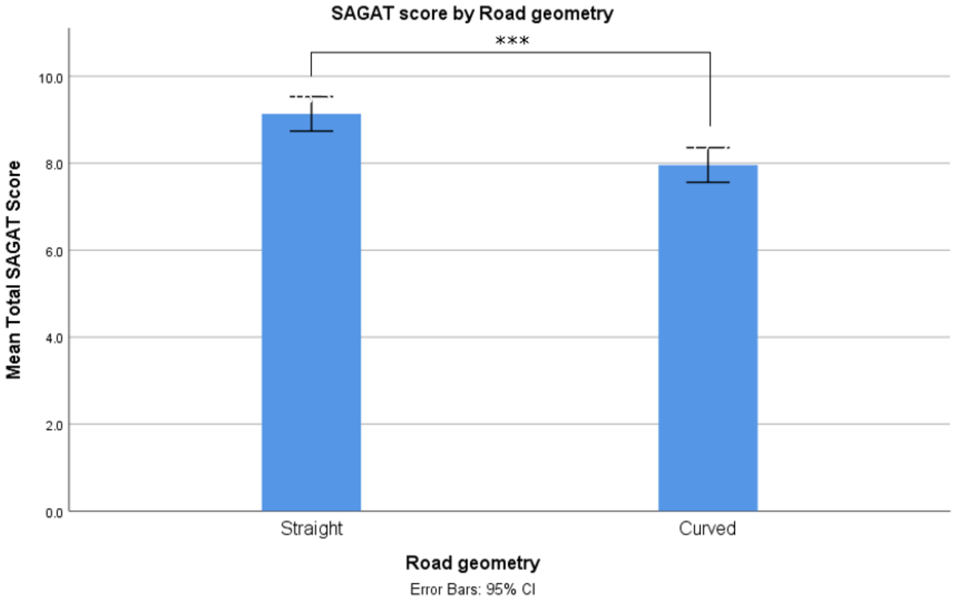


Figure 4.5: SAGAT scores on straight and curved roads
** indicates $p \leq .001$

There was a significant main effect of drive type [$F(2,92) = 7.16$, $p < .01$, $\eta_p^2 = 0.14$, observed power = 0.97; see Figure 4.6]. The SAGAT scores were significantly higher in the manual drive ($M = 6.12$, $SE = 0.15$) compared to the autopilot with distraction drives ($M = 5.28$, $SE = 0.16$, $p \leq .001$). There was no significant difference between the manual and autopilot only drives ($p = 0.17$) and the autopilot only and autopilot with distraction drives ($p = 0.30$).

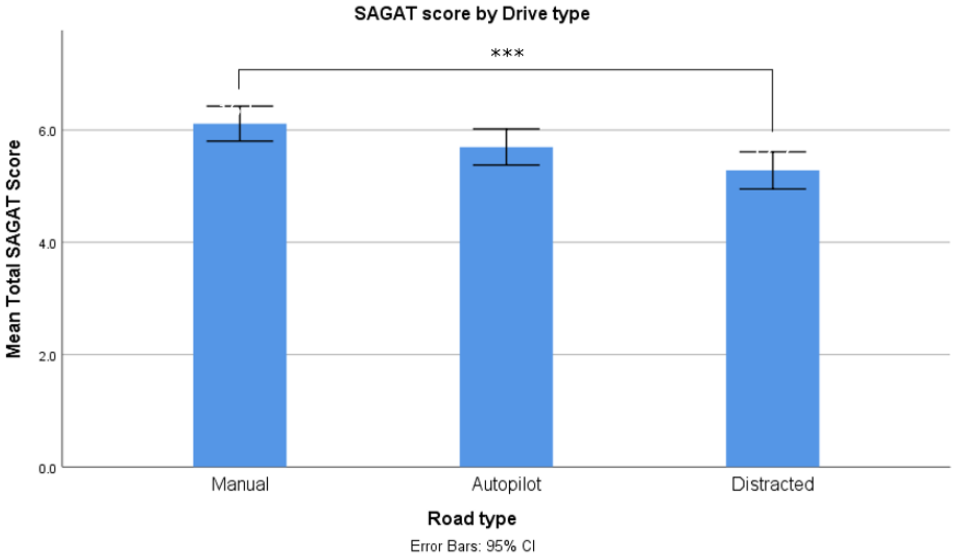


Figure 4.6: SAGAT scores with manual, autopilot only and autopilot with distraction drives

** indicates p <.01

An independent samples t-test with age groups indicated that the young drivers had significantly higher SAGAT scores ($M = 1.50$, $SD = 0.56$) than the middle-aged drivers ($M = 1.35$, $SD = 0.61$), $t(574) = 3.17$, p <.01, $d = 0.60$ (see Figure 4.7).

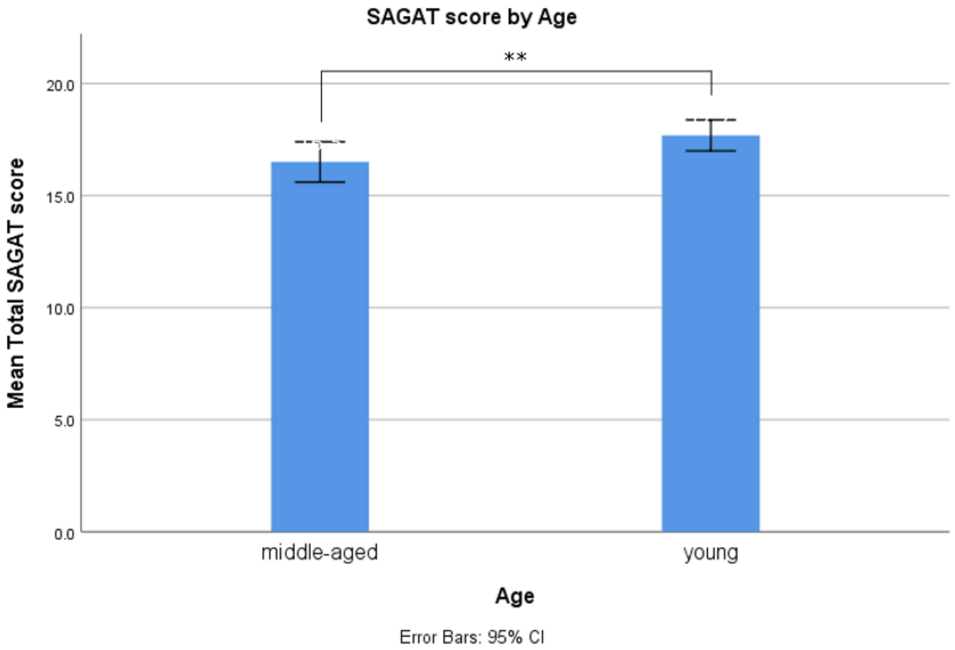


Figure 4.7: SAGAT scores of middle-aged and younger drivers
** indicates $p < .01$

There were no statistically significant interaction effects between age and road type, road geometry or drive type on SAGAT scores.

4.2 Takeover time

Table 4.5 show the descriptive statistics for young and middle-aged drivers.

Table 4.5: Descriptive statistics of takeover time

Road type	**Road geometry**	**Drive type**	**Takeover time (s)**	
			Young	**Middle-aged**
Highway	**Straight**	**AP only**	3.93 (2.35)	4.90 (3.66)
		AP with distraction	4.42 (2.30)	4.42 (2.17)
	Curved	**AP only**	3.85 (2.74)	4.27 (2.49)
		AP with distraction	4.17 (2.26)	5.01 (3.46)
Urban non-highway	**Straight**	**AP only**	4.01 (2.12)	4.66 (2.11)
		AP with distraction	4.16 (1.84)	5.86 (4.83)
	Curved	**AP only**	4.76 (3.97)	5.31 (4.34)
		AP with distraction	5.39 (4.29)	5.33 (4.00)

Values shown are Mean (SD)

A mixed-design ANOVA was conducted to test the effect of the driver's age (young, middle-aged) between-subjects factor, and road type (highway, urban non-highway), road geometry (straight, curved), and drive type (autopilot only, autopilot with distraction) within-subjects factor on takeover time.

There was a significant interaction effect between road type and road geometry [F (1, 46) = 4.53, $p < .05$, $\eta_p^2 = 0.090$, observed power = 0.55; see Figure 4.8]. In the highway scenarios, the takeover time was slightly slower with a straight road ($M = 4.42$, $SE = 0.26$) compared to a curved road ($M = 4.32$, $SE = 0.24$), while the urban non-highway scenarios showed faster takeover times for the straight road ($M = 4.67$, $SE = 0.28$) in comparison to the curved road ($M = 5.20$, $SE = 0.34$).

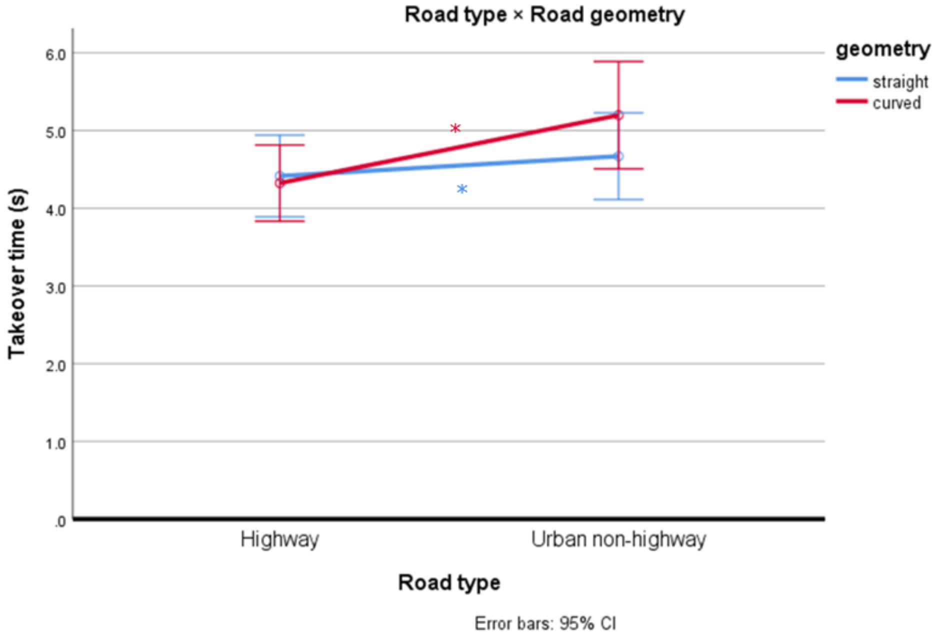


Figure 4.8: The interaction effect between drive type and road geometry on takeover time
* indicates $p < .05$

There was a significant main effect of road type [F (1, 46) = 7.67, $p < .01$, $\eta_p^2 = 0.14$, observed power = 0.77]. Further analysis, using Bonferroni t, showed that the takeover times were significantly faster in the highway scenarios (M = 4.37, SE = 0.17) compared to the urban non-highway scenarios (M = 4.93, SE = 0.21, $p < .01$).

There was no significant main effect of road geometry [F (1, 46) = 0.31, p = 0.58, $\eta_p^2 = 0.007$, observed power = 0.09], drive type [$F(1, 46) = 1.11, p = 0.30, \eta_p^2 = 0.024$, observed power = 0.18], and driver age [F (1, 46) = 3.75, p = .059, $\eta_p^2 = 0.075$, observed power = 0.47].

4.3 Takeover quality

4.3.1 Resulting acceleration

Table 4.6 shows the descriptive statistics for young and middle-aged drivers.

Table 4.6: Descriptive statistics of the resulting acceleration

Road type	**Road geometry**	**Drive type**	**Resulting Acceleration (m/s2)**	
			Young	**Middle-aged**
Highway	**Straight**	**Manual**	5.15 (2.67)	6.61 (5.15)
		AP only	7.63 (6.81)	8.89 (6.40)
		AP with distraction	10.01 (12.05)	10.24 (8.02)
	Curved	**Manual**	4.63 (2.56)	6.77 (3.25)
		AP only	6.03 (1.76)	6.15 (2.76)
		AP with distraction	5.62 (1.76)	6.59 (2.18)
Urban non-highway	**Straight**	**Manual**	5.50 (6.72)	5.40 (6.65)
		AP only	9.05 (10.07)	11.03 (11.04)
		AP with distraction	8.90 (9.95)	10.70 (16.16)
	Curved	**Manual**	6.69 (7.28)	4.15 (1.17)
		AP only	5.87 (6.11)	8.66 (9.16)
		AP with distraction	5.65 (5.15)	7.07 (7.37)

Values shown are Mean (SD)

A mixed-design ANOVA was conducted to test the effect of the driver's age (young, middle-aged) between-subjects factor, and road type (highway, urban non-highway), road geometry (straight, curved), and drive type (manual, autopilot only, autopilot with distraction) within-subjects factors on the resulting acceleration.

There was a significant interaction effect between road geometry and drive type only for the manual versus autopilot with distraction drives $[F(2, 92) = 2.72, p < .05, \eta_p^2 = 0.06$, observed power $= 0.53]$. For the straight and curved road scenarios, the acceleration was lower in the manual drive (straight: $M = 5.66$, $SE = 0.56$; curved: $M = 5.56$, $SE = 0.41$) compared to the autopilot with distraction drive (straight: $M = 9.96$, $SE = 1.22$; curved: $M = 6.23$, $SE = 0.50$).

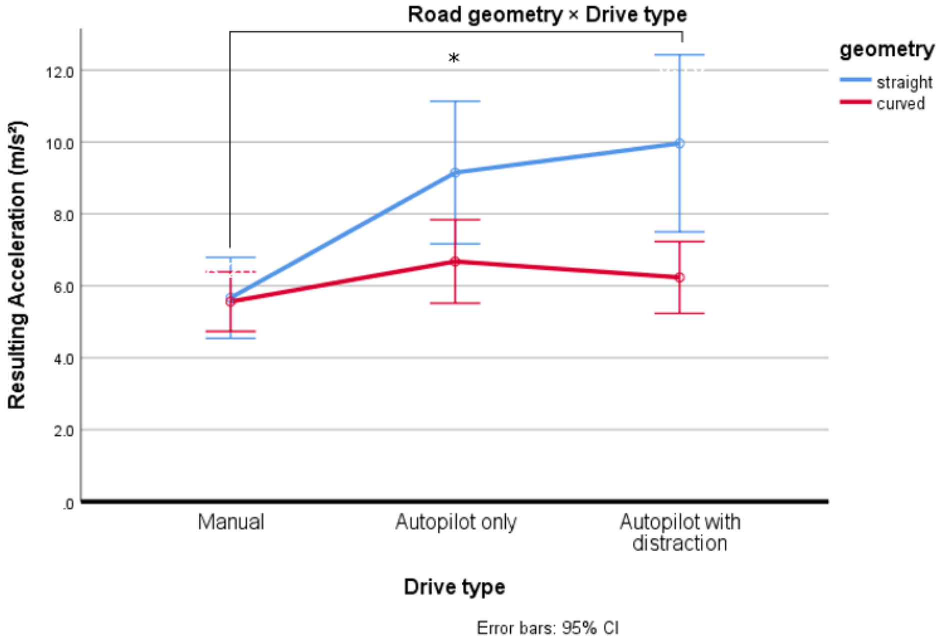


Figure 4.9: The interaction effect between road geometry and drive type on resulting acceleration

Table 4.7 shows the ANOVA values of the main effects. There was a significant main effect of road geometry. Further analysis, using Bonferroni t, showed significantly higher acceleration for the straight road (M = 8.26, SE = 0.53) compared to the curved road (M = 6.16, SE = 0.31, $p \leq .001$; see table 4.8). There was also a significant main effect of drive type. The acceleration for the manual drive was significantly lower (M = 5.61, SE = 0.32) than the autopilot only drive (M = 7.91, SE = 0.62) and the autopilot with distraction drive (M = 8.10, SE = 0.69, $p < .01$; see table 4.8). There was no significant difference between the autopilot only and autopilot with distraction drives (p = 1.00). There was no significant main effect of road type and driver's age.

Table 4.7: ANOVA table for resulting acceleration

Variable	$df_{hypothesis}$	df_{error}	F	p	η_p^2	**Observed Power**
Age	1	46	1.87	0.18	0.039	0.23
Road type	1	46	0.49	0.49	0.011	0.11
Road geometry	1	46	17.71	$\leq .001^{***}$	0.28	0.99
Drive type	2	92	6.56	$< .01^{**}$	0.13	0.98

*** indicates $p \leq .001$

** indicates $< .01$

Table 4.8: Descriptives of road geometry and drive type for resulting acceleration

		Resulting acceleration (m/s^2)
Road geometry	**Straight**	8.26 (0.53)
	Curved	6.16 (0.31)
Drive type	**Manual**	5.61 (0.32)
	AP only	7.91 (0.62)
	AP with distraction	8.10 (0.69)

Values shown are Mean (SD)

4.3.2 Lane deviation

Table 4.9 show the descriptive statistics for young and middle-aged drivers.

Table 4.9: Descriptive statistics of lane deviation

Road type	**Road geometry**	**Drive type**	**Lane deviation (m)**	
			Young	**Middle-aged**
Highway	**Straight**	**Manual**	0.55 (0.24)	0.73 (0.58)
		AP only	0.68 (0.65)	0.81 (0.56)
		AP with distraction	0.55 (0.45)	0.63 (0.44)
	Curved	**Manual**	0.80 (0.16)	0.88 (0.20)
		AP only	0.87 (0.35)	0.94 (0.24)
		AP with distraction	0.83 (0.35)	0.78 (0.15)
Urban non-highway	**Straight**	**Manual**	0.69 (0.38)	0.71 (0.34)
		AP only	0.63 (0.40)	0.70 (0.46)
		AP with distraction	0.62 (0.39)	0.64 (0.42)
	Curved	**Manual**	0.75 (0.29)	0.89 (0.25)
		AP only	0.75 (0.33)	0.78 (0.28)
		AP with distraction	0.766 (0.31)	0.75 (0.25)

Values shown are Mean (SD)

A mixed-design ANOVA was conducted to test the effect of the driver's age (young, middle-aged) between-subjects factor, and road type (highway, urban), road geometry (straight, curved), and drive type (manual, autopilot only, autopilot with distraction) within-subjects factor on lane deviation. Table 4.12 shows the ANOVA values of the main effects. There was a significant main effect of road geometry. Further analysis, using Bonferroni t, showed significantly lower lane deviation for the straight road (M = 0.66, SE = 0.03) compared to the curved road (M = 0.82, SE = 0.02, $p \leq .001$; see table 4.11). There was also a significant main effect of drive type. The lane deviation for the autopilot only drive was significantly higher (M = 0.77, SE = 0.03) than the autopilot with distraction drive (M = 0.69, SE = 0.02, $p < .05$; see table 4.11). There was no significant difference between the manual and autopilot only drives (p = 1.00) and manual and autopilot with distraction drives (p = 0.13). There was no significant main effect of road type and driver's age.

Table 4.10: ANOVA table for lane deviation

Variable	$df_{hypothesis}$	df_{error}	F	p	η_p^2	**Observed Power**
Age	1	46	3.34	0.074	0.068	0.43
Road type	1	46	2.00	0.16	0.042	0.28
Road geometry	1	46	26.47	$\leq .001^{***}$	0.37	0.99
Drive type	2	45	3.73	$< .05^{*}$	0.075	0.72

*** indicates $p \leq .001$

* indicates $p < .05^{*}$

Table 4.11: Descriptives of road geometry and drive type for lane deviation

		Lane deviation (m)
Road geometry	**Straight**	0.66 (0.03)
	Curved	0.82 (0.02)
Drive type	**Manual**	0.75 (0.02)
	AP only	0.77 (0.03)
	AP with distraction	0.69 (0.02)

Values shown are Mean (SD)

4.3.3 Number of collisions

There was a total of 6 collisions that occurred in the driving scenarios (see Table 4.12). Two young drivers and 4 middle-aged drivers collided with the hazard. Of the 5 collisions that occurred in the highway straight road scenarios, 2 were during the autopilot only takeover, and 3 were during the autopilot with distracted takeover. One collision occurred in the autopilot only takeover over a straight urban road. Since the descriptives indicated that there were no major differences in the number of collisions across the two age groups, road types, road geometries and drive type, there was no statistical test performed to identify significant differences.

Table 4.12: Descriptive statistics of the number of collisions

Road type	**Road geometry**	**Drive type**	**Number of Collisions** **Young**	 **Middle-aged**
Highway	**Straight**	**AP only**	1	1
		AP with distraction	1	2
	Curved	**AP only**	0	0
		AP with distraction	0	0
Urban	**Straight**	**AP only**	0	1
		AP with distraction	0	0
	Curved	**AP only**	0	0
		AP with distraction	0	0

4.4 Secondary non-driving tasks performance

4.4.1 n-back

An independent-samples *t*-test was carried out to determine whether young drivers had better performance on the n-back task than middle-aged drivers. There was no significant difference in the response accuracy of young (M = 78.95, SD = 15.98) and middle-aged drivers (M = 77.77, SD = 13.80), t (62) = 0.32, p = 0.75.

4.4.2 SuRT

An independent-samples *t*-test was carried out to determine whether young drivers had better performance on the SuRT than middle-aged drivers. There was no significant difference in the percentage of correctly solved screens by young (M = 99.04, SD = 2.52) and middle-aged drivers (M = 98.88, SD = 1.93), t (62) = 0.23, p = 0.78. There was no significant difference in the mean response time (ms) per SuRT screen of young (M = 3320.82, SD = 721.33) and middle-aged drivers (M = 3343.31, SD = 670.83), t (62) = -0.13, p = 0.90.

4.4.3 CTT

An independent-samples *t*-test was carried out to determine whether young drivers had better performance on the CTT than middle-aged drivers. There was no significant difference in the root mean square deviation (RMSD) of the target bar between young (M = 3.11, SD = 1.43) and middle-aged drivers (M = 3.09, SD = 2.39), t (62) = 0.043, p = 0.97.

For all the participants, the percentage of time with the target bar at the upper or lower limit was 0%.

4.5 Summary of results

The following tables summarize the hypotheses and their results:

Table 4.13: Summary of situation awareness analysis

Hypotheses	**Result**	$\boldsymbol{p}$	**Effect size**	**Statistical Conclusion**
H_0: there will be no main effect of age	No effect of age on hazard perception times	$p = .74$	$\eta_p^2 = 0.003$	Fail to reject H_0
H_{A1}: there will be a main effect of age	Young drivers had significantly higher SAGAT scores than the middle-aged drivers	$p < .01$	$d = 0.60$	Reject H_0
H_0: there will be no main effect of road type	No effect of road type on hazard perception times	$p = .094$	$\eta_p^2 = 0.06$	Fail to reject H_0
H_{A2}: there will be a main effect of road type	The SAGAT score was significantly higher in the highway scenarios compared to the urban scenarios	$p < .01$	$\eta_p^2 = 0.16$	Reject H_0
H_0: there will be no main effect of road geometry	Shorter hazard perception times for the straight road compared to the curved road	$p \leq .001$	$\eta_p^2 = 0.68$	Reject H_0

Table 4.13 continued from previous page

Hypotheses	**Result**	p	**Effect size**	**Statistical Conclusion**
H_{A3}: there will be a main effect of road geometry	The SAGAT score was significantly higher with the straight roads than the curved roads	$p < .01$	$\eta_p^2 = 0.31$	Reject H_0
H_0: there will be no main effect of drive type	The hazard perception time for the manual drive was significantly shorter than the autopilot only drive and the autopilot with distraction drive	$p \leq .001$	$\eta_p^2 = 0.23$	Reject H_0
H_{A4}: there will be a main effect of drive type	The SAGAT scores were significantly higher in the manual drive compared to the autopilot with distraction drives	$p \leq .001$	$\eta_p^2 = 0.14$	Reject H_0
H_0: there will be no interaction effect between age and road type	No interaction effect between age and road type on hazard perception time	$p = .47$	$\eta_p^2 = 0.012$	Fail to reject H_0
H_{A12}: there will be an interaction effect between age and road type	No interaction effect between age and road type on SAGAT scores	$p = .28$	$\eta_p^2 = 0.024$	Fail to reject H_0
H_0: there will be no interaction effect between age and road geometry	No interaction effect between age and road geometry on hazard perception time	$p = .31$	$\eta_p^2 = 0.023$	Fail to reject H_0
H_{A13}: there will be an interaction effect between age and road geometry	No interaction effect between age and road geometry on SAGAT scores	$p = .09$	$\eta_p^2 = 0.061$	Fail to reject H_0
H_0: there will be no interaction effect between age and drive type	No interaction effect between age and secondary task on hazard perception time	$p = .94$	$\eta_p^2 = 0.001$	Fail to reject H_0

Table 4.13 continued from previous page

Hypotheses	**Result**	***p***	**Effect size**	**Statistical Conclusion**
H_{A14}: there will be an interaction effect between age and drive type	No interaction effect between age and secondary task on SAGAT scores	$p = .71$	$\eta_p^2 = 0.007$	Fail to reject H_0
H_0: there will be no interaction effect between road type and road geometry H_{A23}: there will be an interaction effect between road type and road geometry	In the highway scenarios, the hazard perception times were longer with a straight road compared to a curved road, while the urban scenarios showed shorter hazard perception times for the straight road in comparison to the curved road	$p \leq .001$	$\eta_p^2 = 0.89$	Reject H_0
H_0: there will be no interaction effect between road type and drive type H_{A24}: there will be an interaction effect between road type and drive type	In the highway and urban scenarios, the hazard perception times were shorter in the manual drive compared to the autopilot with distraction drive	$p <.05$	$\eta_p^2 = 0.088$	Reject H_0
H_0: there will be no interaction effect between road geometry and drive type H_{A34}: there will be an interaction effect between road geometry and drive type	For the straight and curved road scenarios, the hazard perception times were shorter in the manual drive compared to the autopilot with distraction drive	$p <.01$	$\eta_p^2 = 0.10$	Reject H_0
H_0: there will be no interaction effect between age, road type and road geometry	No interaction effect between age, road type and road geometry on hazard perception time	$p = .59$	$\eta_p^2 = 0.007$	Fail to reject H_0

Table 4.13 continued from previous page

Hypotheses	**Result**	***p***	**Effect size**	**Statistical Conclusion**
H_{A123} there will be an interaction effect between age, road type and road geometry				
H_0: there will be no interaction effect between age, road type and drive type H_{A124}: there will be an interaction effect between age, road type and drive type	No interaction effect between age, road type and secondary task on hazard perception time	$p = .93$	$\eta_p^2 = 0.002$	Fail to reject H_0
H_0: there will be no interaction effect between age, road geometry and drive type H_{A134}: there will be an interaction effect between age, road geometry and drive type	No interaction effect between age, road geometry and secondary task on hazard perception time	$p = .22$	$\eta_p^2 = 0.034$	Fail to reject H_0
H_0: there will be no interaction effect between road type, road geometry and drive type H_{A234}: there will be an interaction effect between road type, road geometry and drive type	No interaction effect between road type, road geometry and secondary task on hazard perception time	$p = .70$	$\eta_p^2 = 0.008$	Fail to reject H_0

Table 4.13 continued from previous page

Hypotheses	**Result**	***p***	**Effect size**	**Statistical Conclusion**
H_0: there will be no interaction effect between age, road type, road geometry and drive type H_{A1234}: there will be an interaction effect between age, road type, road geometry and drive type	No interaction effect between age, road type, road geometry and secondary task on hazard perception time	$p = .93$	$\eta_p^2 = 0.002$	Fail to reject H_0

Table 4.14: Summary of takeover performance analysis

Hypotheses	**Result**	***p***	**Effect size**	**Statistical Conclusion**
H_0: there will be no main effect of age	No effect of age on takeover time	$p = .059$	$\eta_p^2 = 0.075$	Fail to reject H_0
H_{A1}: there will be a main effect of age	No effect of age on resulting acceleration	$p = .18$	$\eta_p^2 = 0.039$	Fail to reject H_0
	No effect of age on lane deviation	$p = .74$	$\eta_p^2 = 0.068$	Fail to reject H_0
H_0: there will be no main effect of road type	Takeover times were significantly faster in the highway scenarios compared to the urban scenarios	$p <.01$	$\eta_p^2 = 0.14$	Reject H_0
H_{A2}: there will be a main effect of road type	No effect of road type on resulting acceleration	$p = .49$	$\eta_p^2 = 0.011$	Fail to reject H_0
	No effect of road type on lane deviation	$p = .16$	$\eta_p^2 = 0.042$	Fail to reject H_0

Table 4.14 continued from previous page

Hypotheses	**Result**	***p***	**Effect size**	**Statistical Conclusion**
H_0: there will be no main effect of road geometry	No effect of road geometry on takeover time	$p = .58$	$\eta_p^2 = 0.007$	Fail to reject H_0
H_{A3}: there will be a main effect of road geometry	Higher acceleration for the straight road compared to the curved road	$p \leq .001$	$\eta_p^2 = 0.28$	Reject H_0
	Lower lane deviation for the straight road compared to the curved road	$p < .01$	$\eta_p^2 = 0.14$	Reject H_0
H_0: there will be no main effect of drive type	No effect of drive type on takeover time	$p = .30$	$\eta_p^2 = 0.024$	Fail to reject H_0
H_{A4}: there will be a main effect of drive type	The acceleration for the manual drive was significantly lower than the autopilot only drive and the autopilot with distraction drive	$p < .01$	$\eta_p^2 = 0.30$	Reject H_0
	The lane deviation for the autopilot only drive was significantly higher than the autopilot with distraction drive	$p < .05$	$\eta_p^2 = 0.075$	Reject H_0
H_0: there will be no interaction effect between age and road type	No interaction effect between age and road type on takeover time	$p = .71$	$\eta_p^2 = 0.003$	Fail to reject H_0
H_{A12}: there will be an interaction effect between age and road type	No interaction effect between age and road type on resulting acceleration	$p = .89$	$\eta_p^2 = 0.000$	Fail to reject H_0

Table 4.14 continued from previous page

Hypotheses	**Result**	$\boldsymbol{p}$	**Effect size**	**Statistical Conclusion**
	No interaction effect between age and road type on lane deviation	$p = .45$	$\eta_p^2 = 0.010$	Fail to reject H_0
H_0: there will be no interaction effect between age and road geometry	No interaction effect between age and road geometry on takeover time	$p = .62$	$\eta_p^2 = 0.005$	Fail to reject H_0
H_{A13}: there will be an interaction effect between age and road geometry	No interaction effect between age and road geometry on resulting acceleration	$p = .77$	$\eta_p^2 = 0.002$	Fail to reject H_0
	No interaction effect between age and road geometry on lane deviation	$p = .46$	$\eta_p^2 = 0.012$	Fail to reject H_0
H_0: there will be no interaction effect between age and drive type	No interaction effect between age and drive type on takeover time	$p = .97$	$\eta_p^2 = 0.000$	Fail to reject H_0
H_{A14}: there will be an interaction effect between age and drive type	No interaction effect between age and drive type on resulting acceleration	$p = .59$	$\eta_p^2 = 0.008$	Fail to reject H_0
	No interaction effect between age and drive type on lane deviation	$p = .24$	$\eta_p^2 = 0.030$	Fail to reject H_0
H_0: there will be no interaction effect between road type and road geometry	In the highway scenarios, the takeover time was slightly slower with a straight road compared to a curved road, while the urban scenarios showed faster takeover times for the straight road in comparison to the curved road	$p < .05$	$\eta_p^2 = 0.090$	Reject H_0

Table 4.14 continued from previous page

Hypotheses	**Result**	$\boldsymbol{p}$	**Effect size**	**Statistical Conclusion**
H_{A23}: there will be an interaction effect between road type and road geometry	No interaction effect between road type and road geometry on resulting acceleration	$p = .97$	$\eta_p^2 = 0.000$	Fail to reject H_0
	No interaction effect between road type and road geometry on lane deviation	$p = .18$	$\eta_p^2 = 0.040$	Fail to reject H_0
H_0: there will be no interaction effect between road type and drive type	No interaction effect between road type and drive type on takeover time	$p = .47$	$\eta_p^2 = 0.011$	Fail to reject H_0
H_{A24}: there will be an interaction effect between road type and drive type	No interaction effect between road type and drive type on resulting acceleration	$p = .48$	$\eta_p^2 = 0.016$	Fail to reject H_0
	No interaction effect between road type and drive type on lane deviation	$p = .34$	$\eta_p^2 = 0.023$	Fail to reject H_0
H_0: there will be no interaction effect between road geometry and drive type	No interaction effect between road geometry and drive type on takeover time	$p = .94$	$\eta_p^2 = 0.000$	Fail to reject H_0
H_{A34}: there will be an interaction effect between road geometry and drive type	For the straight and curved road scenarios, the acceleration was lower in the manual drive compared to the autopilot with distraction drive	$p < .05$	$\eta_p^2 = 0.10$	Reject H_0
	No interaction effect between road geometry and drive type on lane deviation	$p = .81$	$\eta_p^2 = 0.005$	Fail to reject H_0

Table 4.14 continued from previous page

Hypotheses	**Result**	$\boldsymbol{p}$	**Effect size**	**Statistical Conclusion**
H_0: there will be no interaction effect between age, road type and road geometry	No interaction effect between age, road type and road geometry on takeover time	$p = .072$	$\eta_p^2 = 0.069$	Fail to reject H_0
H_{A123}: there will be an interaction effect between age, road type and road geometry	No interaction effect between age, road type and road geometry on resulting acceleration	$p = .73$	$\eta_p^2 = 0.003$	Fail to reject H_0
	No interaction effect between age, road type and road geometry on lane deviation	$p = .75$	$\eta_p^2 = 0.006$	Fail to reject H_0
H_0: there will be no interaction effect between age, road type and drive type	No interaction effect between age, road type and drive type on takeover time	$p = .45$	$\eta_p^2 = 0.013$	Fail to reject H_0
H_{A124}: there will be an interaction effect between age, road type and drive type	No interaction effect between age, road type and drive type on resulting acceleration	$p = .27$	$\eta_p^2 = 0.028$	Fail to reject H_0
	No interaction effect between age, road type and drive type on lane deviation	$p = .97$	$\eta_p^2 = 0.001$	Fail to reject H_0
H_0: there will be no interaction effect between age, road geometry and drive type	No interaction effect between age, road geometry and drive type on takeover time	$p = .95$	$\eta_p^2 = 0.000$	Fail to reject H_0

Table 4.14 continued from previous page

Hypotheses	**Result**	***p***	**Effect size**	**Statistical Conclusion**
H_{A134}: there will be an interaction effect between age, road geometry and drive type	No interaction effect between age, road geometry and drive type on resulting acceleration	$p = .94$	$\eta_p^2 = 0.001$	Fail to reject H_0
	No interaction effect between age, road geometry and drive type on lane deviation	$p = .75$	$\eta_p^2 = 0.006$	Fail to reject H_0
H_0: there will be no interaction effect between road type, road geometry and drive type	No interaction effect between road type, road geometry and drive type on takeover time	$p = .26$	$\eta_p^2 = 0.027$	Fail to reject H_0
H_{A234}: there will be an interaction effect between road type, road geometry and drive type	No interaction effect between road type, road geometry and drive type on resulting acceleration	$p = .92$	$\eta_p^2 = 0.002$	Fail to reject H_0
	No interaction effect between road type, road geometry and drive type on lane deviation	$p = .99$	$\eta_p^2 = 0.001$	Fail to reject H_0
H_0: there will be no interaction effect between age, road type, road geometry and drive type	No interaction effect between age, road type, road geometry and drive type on takeover time	$p = .92$	$\eta_p^2 = 0.028$	Fail to reject H_0
H_{A1234}: there will be an interaction effect between age, road type, road geometry and drive type	No interaction effect between age, road type, road geometry and drive type on resulting acceleration	$p = .69$	$\eta_p^2 = 0.008$	Fail to reject H_0

Table 4.14 continued from previous page

Hypotheses	**Result**	$\boldsymbol{p}$	**Effect size**	**Statistical Conclusion**
	No interaction effect between age, road type, road geometry and drive type on lane deviation	$p = .88$	$\eta_p^2 = 0.003$	Fail to reject H_0

Chapter 5

Discussion

The current study assessed the SA and takeover performance of young and middle-aged drivers in a semi-AV simulator by using various metrics of SA and takeover performance that will be explained below.

5.1 SA

5.1.1 Hazard detection

The findings of this study showed that almost all participants were able to detect the hazard that the driver could have potentially collided with in the different road types, road geometries and driving tasks. This indicates that there is no difference in the hazard detection abilities of young and middle-aged drivers. It fails to reject the null hypothesis that there would be no difference between the SA of young and middle- aged drivers (H_0). Both age groups are able to identify potential hazards in the forward roadway as shown by their fixation on the hazard in the eye-tracking recordings. The similarity in findings between young and middle-aged drivers could be due to the position of the hazard which was placed close to the roadway. Since the hazard was near their main focal view and area of interest, it was highly likely to be detected after the takeover. The finding contradicts the studies which showed that hazard perception ability increases with driving experience [220, 33], accuracy in anticipating potential hazards decreases when distracted [221], and drivers are likely to experience vigilance decrements in hazard detection performance [222].However, the current study only used overt (visible) hazards which might explain the absence of a difference in the hazard detection abilities of both age groups. Since other studies have shown experienced drivers are more sensitive to covert (hidden) hazards than young-novice drivers [223], differences in the hazard detection of younger and middle-aged drivers might have been observed if covert hazards were used.

This result is similar to the SA during driving experiment by Gugerty [164] where participants were found to be very good at detecting hazards with a mean level of 0.97 out of a perfect performance of 1.0. It also supports the study by Crundall and Underwood [42] which showed that novice drivers are likely to search the roadway close in front of the vehicle and toward the roadside. Hence, a hazard in this field of view would likely be detected by young drivers. Moreover, it is plausible that the working memory load was not too high to prevent the participants from detecting the hazard. The scenarios were not crowded with too many objects that could have occluded the hazard and the secondary-tasks in the distracted condition might have not deteriorated the drivers' visual scanning of the traffic environment when they took over control which allowed them to detect the road hazards.

In the two instances where the middle-aged and young drivers were unable to detect the hazard, their inability could be attributed to the urban non-highway environment and curved road conditions. Drivers generally have a poor line of sight on curved road segments which increases with higher gradients in the curvature as was the case with the urban non-highway scenario locations. Moreover, the urban non-highway scenarios also had more elements in the location such as the presence of pedestrians, cyclists and houses which could have increased the information that had to be processed when taking over. Nevertheless, this was a fairly insignificant proportion of hazard misses (2) out of the total number of driving trials (576).

5.1.2 Hazard perception time

There was an interaction effect found between road type and road geometry which rejects the null hypothesis that there would be no interaction effect of road type and road geometry on situation awareness (H_0). This was an unexpected interaction as the hazard perception time was predicted to be longer on the straight and curved roads on the highway due to driving at a higher speed in comparison to the urban non-highway roads. Nevertheless, since this result had a large effect size of 0.89, there is a large meaningful difference in the hazard perception time as a result of the interaction between road type and road geometry. The longer hazard perception times in the highway scenario compared to the urban non-highway scenario could be due to the speed difference in the road environments. Driving at a higher speed on a straight road on the highway might have slowed down the reaction time of the driver to perceive the hazard since at higher speeds more time may be needed to react appropriately [224]. In contrast, the participants drove the vehicle at a much lower speed in the urban non-highway scenarios which could have given them sufficient time to quickly react and perceive the hazard on the straight road. With the curved road segments, the participants were likely to detect the hazard faster in the highway scenario since it appeared on the apex of the curve where they would most likely be looking at as they navigated the curve. The urban non-highway scenario had a sharp horizontal curve with a smaller radius and the hazard appeared at the end of the curve. Hence, navigating the curve with less sight distance and at a slower speed might have resulted in a longer hazard perception time.

The road type and drive type variables had an interaction effect for the manual versus autopilot with distraction drives. This result rejects the null hypothesis that there would be no interaction effect of road type and drive type on situation awareness (H_0). In the highway and urban non-highway scenarios, the hazard perception times were shorter in the manual drive compared to the autopilot with distraction drive. This could be a result of sustained SA due to manually driving the vehicle versus taking over after not monitoring the driving environment. As stated by Endsley [28], autonomous driving can worsen SA when other tasks are present as drivers tune out and lose vigilance and awareness of critical information. Furthermore, in the autopilot with distraction drive, the hazard perception time in the highway scenario was slightly faster than in the urban non-highway scenario. One possible explanation for this might be that the participants might have tried to quickly regain awareness of their environment since they had to takeover control at a higher speed. However, since the result had a small effect size of 0.09, it is likely that there a small meaningful difference in the hazard perception time as a result of the interaction between road type and drive type. Nevertheless, given the criticality of hazard detection, a 1 to 2 seconds difference between the reaction time when manually driving versus taking over after being distracted might still have relevance for avoiding collisions with potential hazards on highway and urban non-highway roads.

An interaction effect was also found between road geometry and drive type for the manual versus autopilot with distraction drives. This finding rejects the null hypothesis that there would be no interaction effect of road geometry and drive type on situation awareness (H_0). The shorter hazard perception time in the manual drive compared to the autopilot with distraction drive in both road geometries could be attributed to the maintenance of SA when manually driving the vehicle in comparison to taking over control after an absence of monitoring the forward roadway. However, since the result had a small meaningful difference in the hazard perception time as a result of the interaction between road geometry and drive type. Nonetheless, the 1 to 2 seconds slower reaction time when taking over after a distraction might still indicate a driving safety issue in the reaction time to perceive hazards on straight and curved roads.

The road geometry had an effect on hazard perception time as the drivers needed less time to fixate on the hazard when it was located on a straight road in comparison to a more demanding curved road. This result rejects the null hypothesis that there would be no main effect of road geometry on situation awareness (H_0). As this result had a large effect size of 0.68, there is a large meaningful difference in the hazard perception time that is accounted for by the road geometry. Since horizontally curved road segments are often associated with limited sight distance of the upcoming curve and driving hazards such as other vehicles [37], this might have caused the participants to take more time to perceive the hazard.

Moreover, drive type was found to have an effect on hazard perception time which rejects the null hypothesis that there would be no main effect of drive type on situation awareness (H_0). The drivers took less time to perceive the hazard when they were manually driving the vehicle in comparison to taking over control of the vehicle after it was driven by autopilot. The faster perception time in the manual drive could be due to the driver already seeing the road ahead which maintained their SA of the elements in their environment. In contrast, when the drivers had to takeover control from autopilot, they might have needed some more time to re-orient themselves and gain awareness of the road environment since they were not actively monitoring the roadway due to the system handling the driving [21]. The lack of a difference between the autopilot only and autopilot with distraction drives could indicate that the distracting task did not increase the drivers' cognitive workload and negatively affect the time it took them to fixate on the hazard. This further implies that a driver's hazard perception time is unlikely to be worsened by the secondary task they engage in, and is rather due to taking over control from autonomous driving. However, since the result had a small effect size of 0.23, it is likely that there is a small meaningful difference in the hazard perception time as a result of the drive type.

Furthermore, there was no difference in the hazard perception times of young and middle-aged drivers which fails to reject the null hypothesis that there would be no main effect of age on situation awareness (H_0). The result also had a small observed power of 0.06 which could be due to a small sample size. Nevertheless, this implies that younger and middle-aged drivers are not very different in their reaction time to perceive the hazard in the different road types, road geometries and driving tasks that were used in this experiment. The finding contradicts the study by Wright et al. [33] where experienced middle-aged drivers were faster at achieving SA than inexperienced younger drivers when resuming manual control from a Level 3 simulated autonomous system. This supports the research by Scott-Parker et al. [167] which showed no differences in the SA of young, middle-aged and older drivers when observing a driving scenario with hazards in the immediate environment.

The road type did not have an effect on hazard perception time which fails to reject the null hypothesis that there would be no main effect of road type on situation awareness (H_0).The result also had a small observed power of 0.39 which could possibly imply that perhaps increasing the sample size may find meaningful effects. Nonetheless, this implies that overall, driving on a highway or in an urban non-highway area does not affect the time to perceive a hazard. Driving at a high speed on a highway might have increased the participants' perception time, and the urban non-highway scenario might have also had more elements in the environment which could have increased the time to identify the hazard. Hence, the hazard perception time in both road environments was similar. This result is contrary to the video-based hazard perception study by Plummer et al. [225] that showed participants responded earlier to the hazards in the highway environment than in the city environment, but also had a larger response lag in the highway scenes. However, the researchers reported variation in the speeds and density of traffic in both environments which could have had an impact.

5.1.3 SAGAT

The road type had an effect on the SAGAT scores with participants performing better in the highway scenarios compared to the urban non-highway scenarios. This result rejects the null hypothesis that there would be no main effect of road type on situation awareness (H_0). This supports the experiment by Walker et al. [226] that showed road design is crucial to influencing drivers' SA in terms of how they perceive and behave in different road situations. The higher SAGAT score in the highway scenarios could be due to this road type being highly cognitively compatible with what a driver would expect to see in comparison to the urban non-highway scenarios that are less covertly designed and have features that vary from one location to another. However, since the result had a small effect size of 0.16, it is likely that there is a small meaningful difference in the SAGAT scores as a result of the road type.

Road geometry was also found to have an effect as the SAGAT score was higher when driving on the straight roads than the curved roads which rejects the null hypothesis that there would be no main effect of road geometry on situation awareness (H_0). This finding could be explained by the limited sight distance on a curved versus a straight road. When driving on a straight road, the elements in the environment are available to be perceived and can be seen more clearly as the driver approaches them whereas when navigating a curve, the elements are likely to be hidden behind the curve and since the driver's view is typically focussed on the curve, they are likely to miss objects in their peripheral view. This result is similar to the finding by Alyamani and Kavakli [227] where participants had low SA on curved roads and a high SA on straight roads. The result also had a medium effect size of 0.31 which indicates a moderate likelihood of a meaningful difference in the SAGAT scores that can be accounted for by the road geometry.

Drive type had an effect on the SAGAT scores resulting in better performance in the manual drive compared to the autopilot with distraction drives. This result rejects the null hypothesis that there would be no main effect of drive type on situation awareness (H_0). Manually driving the vehicle kept the drivers in the loop as they constantly monitored and perceived elements in the forward roadway. On the contrary, taking over from autopilot after doing a secondary task led to worse SAGAT scores as the drivers were out of the loop and lost vigilance of their environment. This supports the study by De Winter et al. [27] where drivers engaged in non-driving tasks had deteriorated situation awareness for HAD compared to manual driving. The lack of a difference between the manual and autopilot only drives, and the autopilot only and autopilot with distraction drives further indicates that performing a secondary task increases the disengagement from the driving task which leads to poor levels of SA. However, since the result had a small effect size of 0.14, it is likely that there is a small meaningful difference in the SAGAT scores as a result of the road type.

There were age differences found in the SAGAT scores with younger drivers showing a better performance than middle-aged drivers which rejects the null hypothesis that there would be no main effect of age on situation awareness (H_0). This result contradicts the studies by Crundall and Underwood [42] and Wright et al. that showed younger inexperienced drivers had worse SA than experienced middle-age drivers. An explanation for this finding could be that the experienced middle-aged drivers tend to focus on elements of the roadway that could evolve into hazards such as other road users whereas younger drivers might scan all elements of the roadway due to their lack of experience. The driving hazards study by Scott-Parker et al. [167] did find that learners focused more on the school zone while middle-aged and older drivers focused on sharing the road and the hazards associated with the road environment. The result of the current study also had a medium effect size of 0.6 which indicates the likelihood of a meaningful difference in the SAGAT scores that can be accounted for by the drivers' age.

The lack of interaction effects between age and road type, road geometry or drive type fails to reject the null hypothesis that there would be no interaction effects of age, road type, road geometry and drive type on situation awareness (H_0). The results of all three two-way ANOVAs had small observed power values which could possibly imply that a larger sample size might be needed to find meaningful interaction effects between age and road type, road geometry or drive type. This implies that the situation awareness of young and middle-aged drivers does not differ with different road types, road geometries or when having to takeover control from autopilot. The finding does align with the results by Kass et al. [25] that showed novice and experienced drivers had similar decrements in situation awareness when they were cognitively distracted while driving a simulator vehicle. As the study by Bolstad [163]showed, conducting this experiment with older adults might result in them having lower SA when compared to younger and middle-aged adults as the driving complexity increases.

5.2 Takeover time

There was an interaction effect of road type and road geometry on the takeover time which rejects the null hypothesis that there would be no interaction effect of road type and road geometry on takeover performance (H_0). The slightly slower takeover time on the straight road versus the curved road on the highway could be due to chance. However, in the urban non-highway scenarios, the takeover was faster on the straight road compared to the curved road. The slower takeover time on the curved road could be due to needing more time to gain SA in order to appropriately navigate the sharper curve. However, since the result had a small effect size of 0.09, it is likely that there is no meaningful difference in the takeover time as a result of the interaction between road type and road geometry. Nevertheless, since reaction time to road stimuli is important for driving safety [228], a difference of 0.53 seconds between the takeover time on the straight and curved road might still have relevance for designing takeover situations that occur in different road geometries on an urban non-highway road.

The road type had an effect on takeover time with participants showing faster takeovers on highways compared to urban non-highway scenarios. This finding rejected the null hypothesis that there would be no main effect of road type on takeover performance (H_0). The faster takeover time on the highway could be due to the participants being aware that they were driving at a higher speed which created an urgency to quickly takeover in order to avoid a potential loss of control and crash. The vehicle speed in the urban non-highway area was relatively lower and so the participants had a lower risk of loss of vehicle control. The longer takeover time in the urban non-highway scenario could also be due to the unfamiliarity of the environment whereas a highway is compatible with a driver's mental model of that environment. However, since the result had a small effect size of 0.14, it is likely that there is a small meaningful difference in the takeover time as a result of the road type.

There was no difference in the takeover times of both age groups which indicates that younger drivers are equally fast to respond to a takeover request. The result also had a small observed power of 0.47 which could possibly imply that perhaps increasing the sample size may result in meaningful effects that can be accounted for by the age groups. Nonetheless, this contradicts the study by Clark et al. [154] that showed a positive relationship between age and average takeover speed as an indicator of better vehicular control with more driving experience. Despite evidence of younger drivers having risky behaviours, it is possible that risk-taking is not a major factor in the time to takeover as they may understand the importance of quickly taking over to avoid a crash.

Road geometry also did not have an effect on the takeover time which fails to reject the null hypothesis that there would be no main effect of road geometry on takeover performance (H0). The result also had a small observed power of 0.09 which could possibly imply that a larger sample size may be needed to obtain meaningful effects in the road geometry. The finding contradicts previous research which showed longer takeover times prior to a curved than on a straight road [229].Nevertheless, the participants might have reacted equally fast on the straight and curved roads to ensure they immediately gained control of the vehicle as soon as possible to avoid potential collisions. This indicates that the road geometry does not affect a driver's reaction time to take over from vehicle automation when requested.

Drive type did not have an effect on takeover times which implies that engaging in a secondary non-driving task does not impact the time to takeover in comparison to taking over without performing a non-driving task. This finding fails to reject the null hypothesis that there would be no main effect of drive type on takeover performance (H_0). The result also had a small observed power of 0.18 which could possibly imply that perhaps increasing the sample size may result in meaningful effects that can be accounted for by the drive type. Perhaps the secondary task did not have a huge impact on the drivers' cognitive load and impair their reaction time to takeover. This result contradicts the findings of several studies that showed an impairment in the takeover time, and is in line with the studies by Gold et al. [150], Petermeijer et al. [135] and Zeeb et al. [131] that showed the secondary task did not influence takeover time. However, the effect size of drive type in the current study was 0.02 which is much smaller than the effect size of 0.31 in the study by Wandtner et al. [230] that found a slower takeover reaction time when drivers were engaged in a secondary task. Hence, this indicates that the drive type in the current study had a much smaller impact in comparison to the effect of the secondary task in Wandtner et al.'s study.

Since there were no interaction effects between age and road type, road geometry or drive type, this finding fails to reject the null hypothesis that there would be no interaction effects between age and road type, road geometry or drive type on takeover performance (H_0). The results of all interaction effects also had small observed power values which might be due to a small sample size. Hence, a larger sample size may be needed to obtain interaction effects between age and road type, road geometry or drive type. This finding does align with the results by Kaye et al. [158] which showed no significant difference in the takeover when younger drivers used a hand-held mobile phone.

5.3 Takeover quality

5.3.1 Resulting acceleration

The impact of road geometry and drive type was seen in an interaction effect between these two variables but only for the manual versus autopilot with distraction drives. The finding rejects the null hypothesis that there would be no interaction effect of road geometry and drive type on takeover performance (H_0). The resulting acceleration was lower in the manual drive compared to the autopilot with distraction drive, and lower on the curved roads in comparison to the straight roads. While the values were similar for the manual drive on both road geometries, the differences in the autopilot with distraction drive were more pronounced with lower resulting acceleration occurring on the curved roads in comparison to the straight roads. This interaction effect further indicates the influence of road geometry and drive type with better resulting acceleration occurring on curved roads for autopilot with distraction drives than on straight roads. However, since the result had a small effect size of 0.10, it is likely that there is a small meaningful difference in the resulting acceleration as a result of the interaction between road geometry and drive type. Nevertheless, since there was a difference of 4.3 m/s^2 between the manual drive versus taking over after a distraction on a straight road, it might indicate the likelihood of poor takeover quality which can impact road safety.

Road geometry was found to have an effect on the resulting acceleration with higher values for the straight road compared to the curved road which indicates that the participants had a riskier performance on the straight than the curved road. The finding rejects the null hypothesis that there would be no main effect of road geometry on takeover performance (H_0). This contradicts a previous study by Bradenburg and Chuang [231] that showed a small effect of road geometry whereby there was stronger maximum deceleration in response to takeover requests prior to a curve compared to a straight road. An explanation for this finding might be due to the participants driving at higher speeds on the straight road and then having to quickly decelerate or brake in order to avoid colliding with the hazard. On curved roads, the participants might have exercised more caution when navigating the curve by maintaining their speed in order to avoid crossing their lane which could have led to a lower resulting acceleration. The result also had a medium effect size of 0.28 which indicates the likelihood of a moderate meaningful difference in the resulting acceleration that can be accounted for by the road geometry.

Drive type also had an effect where the resulting acceleration was lower in the manual drive in comparison to the autopilot only and the autopilot with distraction drives. The finding rejects the null hypothesis that there would be no main effect of drive type on takeover performance (H_0). This indicates that the participants had the greatest vehicle control when they manually drove the vehicle which decreased when they had to take over control from autopilot and was worst when they had to takeover after being distracted with a secondary task. An explanation for this could be that manually driving the vehicle gives the participants greater control over their acceleration and braking whereas when taking over they have to place their foot on the pedals appropriately to match the speed of the vehicle which may result in higher levels of acceleration and braking. However, the absence of a difference between the autopilot only and autopilot with distraction drives implies that performing a secondary task during autonomous driving does not negatively impact the takeover quality. Nevertheless, the result had a medium effect size of 0.30 which indicates the likelihood of a meaningful difference in the resulting acceleration that can be accounted for by the drive type. This result is also similar to the study by Wandtner et al. [230] that had a large effect size of 0.63 for the effect of a secondary task which showed a higher maximum acceleration in comparison to the baseline without the secondary task.

There was no main effect of road type which indicates that driving on a highway versus in an urban non-highway scenario does not influence the resulting acceleration aspect of takeover quality. The result fails to reject the null hypothesis that there would be no main effect of road type on takeover performance (H_0). The result also had a small observed power of 0.11 which could imply that a larger sample size may be needed to obtain meaningful effects that can be accounted for by the road type. Nonetheless, this could indicate that drivers are able to appropriately accelerate and brake in different road environments even when they have to takeover control from autonomous driving. This finding is similar to the results from Li et al. [23, 22] where there was no significant difference found between the resulting acceleration on a city road versus a motorway after taking over from HAD.

Moreover, age did not have a main effect on the resulting acceleration which fails to reject the null hypothesis that there would be no main effect of age on takeover performance (H_0). The result also had a small observed power of 0.27 which could imply that the sample size was small to acquire meaningful effects that can be accounted for by the age groups. Nevertheless, the finding might indicate that in the absence of a statistical difference, the performance of younger and middle-aged drivers seems comparable under the conditions of this study in manual drive as well as when taking over control from vehicle automation. The finding implies that young drivers are unlikely to be less skilled and experienced than middle-aged drivers when having to resume control of a semi-autonomous vehicle. Since there were no interaction effects between age and road type, road geometry or drive type on resulting acceleration, this fails to reject the null hypothesis that there would be no interaction effect of age, road type, road geometry and drive type on takeover performance (H0). This result indicates that regardless of the driving conditions, younger and middle-aged drivers seem to demonstrate similarities in their longitudinal control of their vehicle.

5.3.2 Lane deviation

The road geometry had an effect on lane deviation with lower lane deviation for the straight road compared to the curved road. The finding rejects the null hypothesis that there would be no main effect of road geometry on takeover performance (H_0). This finding is consistent with the study by Brandenburg and Chuang [231] that showed higher lane deviation when taking over on a curved compared to a straight road. It implies that the straight roads were fairly easier to navigate than the curved roads where participants seemed to have more deviation from the centre of their lane. Higher lane deviations are a common issue with horizontal curves where a vehicle has a higher likelihood of leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve which can have adverse consequences [37]. This might explain why the participants had better stability and vehicle control when driving on the straight road in comparison to the curved road. However, since the result had a small effect size of 0.14, it is likely that there is a small impact of the road geometry on lane deviation.

Drive type also had an effect with higher lane deviation for the autopilot only drive than the autopilot with distraction drive which indicates that they had lower vehicle control when they were not distracted by performing a secondary task. This finding rejects the null hypothesis that there would be no main effect of drive type on takeover performance (H_0). However, this could simply be due to the participants exercising extra caution when taking over as they might have been aware that they were not monitoring the roadway but would have to takeover at some point. The result is contrary to the studies which showed that engaging in a secondary task impacts the lateral takeover control through an increase in maximum average and standard deviation of lane position [230, 131]. However, a study by Wandtner et al. [230] that had a large effect size of 0.65 for the effect of a secondary task did find a higher lane deviation in comparison to the baseline without the secondary task. Hence, since the result of the current study had a small effect size of 0.08, it is likely that drive type had a small impact on lane deviation than the effect of the secondary task used in Wandtner et al.'s research.

Road type did not have a main effect which indicates that driving on a highway versus in an urban non-highway area does not influence the lane deviation aspect of takeover quality. The result fails to reject the null hypothesis that there would be no main effect of road type on takeover performance (H_0). The result also had a moderate observed power of 0.28 which could imply that a larger sample size may be needed to find meaningful effects that can be accounted for by the road type. Nonetheless, this might suggest that drivers are able to appropriately gain vehicle control and stability in different road environments even when they have to takeover control from autonomous driving. One explanation might be that the participants may be familiar with driving on the highway and urban non-highway road areas; hence, their lane deviation was not impacted by these environments.

Moreover, age did not have a main effect which fails to reject the null hypothesis that there would be no main effect of age on takeover performance (H_0). The result also had a moderate observed power of 0.43 which could imply that a larger sample size might show meaningful effects that is due to the age groups. Nevertheless, the current finding shows that younger drivers have the same performance as middle-aged drivers in manual drive as well as when taking over control from vehicle automation. The finding implies that both age groups are cautious of maintaining their lane when manually driving and when resuming vehicle control from automation perhaps in order to avoid collisions with the surrounding traffic and drive safely. As there were no interaction effects between age and road type, road geometry or drive type on lane deviation, the finding fails to reject the null hypothesis that there would be no interaction effects between age, road type, road geometry and drive type on takeover performance (H_0). The results of all interaction effects also had small observed power values which might be due to a small sample size. Hence, a larger sample size may be needed to obtain interaction effects between age and road type, road geometry or drive type. This result is similar to the findings by Favarò et al. [143] who found no significant difference between the lane offset of young, middle-aged and older drivers when manually driving versus taking over from automated driving on an S-curve turn with different speeds and times of disengagement.

5.3.3 Number of collisions

The younger drivers seemed to have better safety and were more careful to not collide with the hazard as only two younger drivers had collisions in comparison to four middle-aged drivers. This is in contrast to studies that showed that younger drivers have higher rates of crashes than middle-aged drivers [25, 2]. Moreover, all six collisions occurred on a straight road which is a surprising result as curved roads are typically considered to be more dangerous than straight roads and have higher rates of crashes [34]. However, the results of this experiment could be due to the study design where the participants were driving at a high speed on the highway and in the urban non-highway scenario and did not have enough time to avoid colliding with the hazard that quickly moved across their lane. Furthermore, since two of the crashes occurred after taking over from autopilot only and three of the crashes occurred during the autopilot with distracted takeover, it indicates that taking over from autopilot can be risky and result in possible collisions if the driver is unable to react in time. Research by Miller et al. [156] and Strand et al. [232] did find that the collisions with a pedestrian occurred shortly after the transition from automation to manual driving. Additionally, experiments by Strayer and Drews [229] and Kass et al. [25] found a two-fold increase in the collisions that occurred when the drivers were engaged in dual-task conditions which involved driving and having a hands-free cell phone conversation. However, they found no significant difference in the collisions across the young, middle-aged and senior driver groups. Nevertheless, due to a fairly low incident rate in this study, the findings are not highly significant to imply that an increased likelihood of collisions occur during these conditions.

5.4 Secondary non-driving tasks performance

There was no significant difference found between the performance of young and middle-aged participants on all three types of secondary tasks. This indicates that both age groups were equally engaged in performing the distracting task during vehicle automation. The result of the n-back task is in line with the study by Gajewski et al. [233] that found no difference between young the middle-aged participants on the 0-back and 2-back conditions. The researchers did find differences between the young and old, and middle-aged and old participants. Moreover, since the participants had a high performance output on the secondary tasks and minimal impact on their SA and takeover performance, it is likely that they were not cognitively loaded when performing these tasks. This explanation could be supported by an experiment that showed the reaction times to takeover control of an automated vehicle by younger and middle-aged drivers did not differ between the control condition (without distractors) and SuRT condition [234]. However, the older drivers did have significantly longer reaction times in the SuRT condition compared to the condition without a distractor.

5.5 Summary

The following tables summarize the results in relation to previous findings:

Table 5.1: Summary of the situation awareness variables

Variable	**Result**	**Comparison to literature**
Hazard detection	Almost all participants were able to detect the hazard.	Similar to the SA during driving experiment where participants were found to be very good at detecting hazards [164].
Hazard perception time	Interaction effect between road type and road geometry.	N/A
	Interaction effect between road type and drive type for the manual versus autopilot with distraction drives.	N/A
	Interaction effect between road geometry and drive type for the manual versus autopilot with distraction drives.	N/A
	Road geometry had an effect. The drivers needed less time to fixate on the hazard when it was located on a straight road in comparison to a curved road.	N/A

Table 5.1 continued from previous page

Variable	**Result**	**Comparison to literature**
	Drive type had an effect. The drivers took less time to perceive the hazard when they were manually driving the vehicle in comparison to taking over control of the vehicle after it was driven by autopilot.	Similar to the study which showed when distracted by secondary tasks, drivers were slow to respond to critical incidents in the automated driving conditions [172].
	Age did not have an effect.	This supports the research which showed no differences in the SA of young, middle-aged and older drivers when observing a driving scenario with hazards in the immediate environment [167].
	Road type did not have an effect.	This result is contrary to the video-based hazard perception study that showed participants responded earlier to the hazards in the highway environment than in the city environment [225].
SAGAT	The road type had an effect. Participants performed better in the highway scenarios compared to the urban non-highway scenarios.	This supports the experiment that showed road design is crucial to influencing drivers' SA in terms of how they perceive and behave in different road situations [226].
	Road geometry had an effect as. The SAGAT score was higher when driving on the straight roads than the curved roads.	This result is similar to the study where participants had low SA on curved roads and a high SA on straight roads [227].

Table 5.1 continued from previous page

Variable	Result	Comparison to literature
	Drive type had an effect. Performance was better in the manual drive compared to the autopilot with distraction drives.	This supports the study where drivers engaged in non-driving tasks had deteriorated situation awareness for HAD compared to manual driving [27].
	Age had an effect. Younger drivers showed a better performance than middle-aged drivers.	This result contradicts the studies that showed younger inexperienced drivers had worse SA than experienced middle-aged drivers [42] [33].
	No interaction effects between age and road type, road geometry or drive type.	The finding does align with the study that showed novice and experienced drivers had similar decrements in situation awareness when they were cognitively distracted while driving a simulator vehicle [25].

Table 5.2: Summary of the takeover performance variables

Variable	Result	Comparison to literature
Takeover time	Interaction effect between road type and road geometry.	N/A
	Road type had an effect. The participants had faster takeovers on highways compared to urban non-highway scenarios.	N/A

Table 5.2 continued from previous page

Variable	**Result**	**Comparison to literature**
	Age did not have an effect.	This contradicts the study that showed a positive relationship between age and average takeover speed as an indicator of better vehicular control with more driving experience [154].
	Road geometry did not have an effect.	Contradicts previous research which showed longer takeover times prior to a curved than on a straight road [230].
	Drive type did not have an effect.	This result is in line with the studies that showed the secondary task did not influence takeover time [150] [135] [131].
	No interaction effects between age and road type, road geometry or drive type.	This finding aligns with research that showed no significant difference in the takeover when younger drivers used a hand-held mobile phone [158].
Resulting acceleration	Interaction effect between road geometry and drive type but only for the manual versus autopilot with distraction drives.	N/A
	Road geometry had an effect. There were higher values for the straight road compared to the curved road.	This contradicts a previous study that showed a higher deceleration when taking on a curved versus a straight road [230].

Table 5.2 continued from previous page

Variable	**Result**	**Comparison to literature**
	Drive type had an effect. The resulting acceleration was lower in the manual drive.	This result is similar to the study that showed a higher maximum acceleration when engaged in a secondary task in comparison to the baseline without the secondary task [230].
	Road type did not have an effect.	N/A
Lane deviation	Road geometry had an effect. There was lower lane deviation for the straight road compared to the curved road.	This is consistent with the study that showed higher lane deviation on a curved compared to a straight road [230].
	Drive type had an effect. There was higher lane deviation for the autopilot only drive than the autopilot with distraction drive.	The result is contrary to the studies which showed that engaging in a secondary task impacts the lateral takeover control through an increase in maximum average and standard deviation of lane position [230, 131].
	Road type did not have an effect.	N/A
	Age did not have an effect.	N/A
Number of collisions	Only two younger drivers had collisions in comparison to four middle-aged drivers.	This is in contrast to studies that showed that younger drivers have higher rates of crashes than middle-aged drivers [25, 2].

Chapter 6

Conclusion

The present study examined the SA and takeover performance of young and middle-aged drivers in a Level 3 semi-AV simulator under various driving conditions such as different road types, road geometries and while performing a secondary task during vehicle automation. The participants drove the vehicle on highway and urban scenarios that had takeovers initiated just before a straight or a curved road. In each road condition, they manually drove the vehicle, took over from autopilot when requested and took over after performing a secondary task during vehicle automation, resulting in a total of 12 drives per participant. Their SA was measured with the eye-tracker data as well as the SAGAT scores, and their takeover performance quality was measured through the vehicle kinematic data obtained from the CARLA simulator software. For the SA measurements, the participants had high hazard detection in all scenarios but their hazard perception time and SAGAT scores varied according to the road type, road geometry and drivers' age. For the takeover quality aspect, the resulting acceleration and lane deviation varied according to the road geometry and drive type. The participants also had a very low number of collisions which occurred only after taking over from vehicle automation.

6.1 Limitations

Given the small effect sizes and post-hoc power values that were obtained from some of the analyses, it is likely that the sample size was not large enough to obtain meaningful interactions between the different variables. Additionally, some middle-aged participants experienced motion sickness and fatigue from using the simulator. Whenever this occurred, the driving trials were immediately stopped, the participants relaxed until their symptoms subsided and they were reminded that they could withdraw from the study. Moreover, there were a few issues with using the Ergoneers eye-tracker due to hardware failure which caused the cross-hair to become misaligned a few times. To ensure that accurate data was obtained for analysis, the experimenter closely monitored the eye-tracker video recording to identify any misalignments and replaced the participants whose data could not be used for analysis. Unfortunately, due to software compatibility issues, the Microsoft Speech Recognition feature of the n-backer software did not work which resulted in the experimenter having to manually record and score the participants' responses. Despite the experimenter doing this to the best of their capability, there might have been a very small probability of human errors when recording the responses. The CTT software also had software compatibility issues which resulted in a slight flickering of the window that could have impacted the participants' perception when performing the visual-manual task.

Since the study was conducted in a laboratory with a low-fidelity driving simulator, it is likely that the simulation is not comparable to the real-world environment. For instance, during the practice trials, the participants initially reported that the Logitech G29 steering wheel and pedals had a different feel from the vehicles they were used to driving. Moreover, the acceleration in the CARLA software did not mimic an actual vehicle's acceleration as the speed would rapidly drop to zero if the foot was taken off the accelerator pedal which meant the participants had to exert extra effort to maintain their speed. Hence, it is possible that these software and hardware limitations might have influenced some of the takeover quality aspects of their driving performance. However, driving simulators in general offer advantages such as controllability, reproducibility and standardization in comparison to using real vehicles which would enable this research to be extended in future if the same conditions are to be used. Using the simulator software also made it possible to create dangerous conditions by enabling a hazard pedestrian, cyclist or vehicle to cross paths with the driver which would have been impossible to re-create without physical risk in the real world [235]. Additionally, due to using only one monitor, the participants' perception might have been limited to what could be displayed on the 27-inch screen at every time frame. Furthermore, driving the vehicle in an experimental context where their performance is being recorded and observed, along with using a driving simulator and wearing an eye-tracker might have affected the participants' performance in comparison to more naturalistic driving conditions. In addition, the secondary tasks might have not sufficiently distracted the participants and increased their cognitive load to have a significant impact on their performance. Perhaps, the results might have been different if typical everyday tasks that people might do during vehicle automation were used such as having a conversation or replying to work emails. Nonetheless, using a real-world task such as a conversation might have resulted in an ability to control the level of distraction for all participants whereas the secondary tasks used in this study were standardised and recommended as non-driving tasks by the ISO [215].

6.2 Implications

The study implies that in terms of their SA, since younger drivers do not differ from middle-aged drivers in their perceptual ability to detect hazards, crashes that may occur during or after takeover might be due to other driver or environmental characteristics. As indicated by the hazard perception time, road geometry and drive type could increase the time to fixate on the hazard with more time being needed on curved roads and after taking over control from autopilot. Given that the drivers needed between 4.4 to 9.5 seconds to identify the hazard, autopilot fallback systems could be designed to give the driver a similar amount of warning time when requesting a takeover before approaching a curved road segment. The drivers also took between 6.4 to 7.6 seconds to fixate on the hazard when they were taking over from autopilot which could be used as the TOR time when the vehicle is on autopilot. Moreover, the interaction effect between road type and road geometry indicated that a warning of between 8.1 to 8.8 seconds may be needed before approaching a curved road in an urban scenario in order to keep most semi-AV drivers safe. In addition, since there was no difference found between younger and middle-aged drivers' hazard perception time in the different road types, road geometries and driving tasks that were used in this experiment, it might suggest that age does not negatively impact the reaction time to perceive the hazard in such situations. Furthermore, since participants had lower SAGAT scores in the urban scenarios, curved roads and autopilot with distraction drives, the vehicle could include features such as providing information of the outside environment to aid the driver's SA. The younger drivers also had higher SAGAT scores than middle-aged drivers which suggests that any errors made by younger drivers might be due to other factors besides their perceptual ability to attend to elements in their environment.

For the takeover aspects of this study, the participants were slower to resume control of the vehicle in the urban scenarios which implies that between 4.5 to 5.4 seconds are needed to take over in these environments. Takeovers on a curved road in an urban scenario were also the slowest and drivers needed between 4.5 to 5.9 seconds. A review by Eriksson and Stanton [236] indicated that takeover times can vary from 1.14 to 15 seconds. Since this study provided different takeover times under various conditions, more experiments are required to obtain more accurate takeover times that could be used by semi-AV designers. Given the high number of vulnerable road users in these environments such as pedestrians and cyclists, it is critical to signal the TOR at an appropriate time to avoid potential collisions. In addition, the lack of a difference in the takeover times of both age groups might indicate that younger drivers are equally fast to respond to a takeover request. Hence, it is likely that their risk-taking behaviour does not impact their reaction time to quickly takeover control and avoid crashes. Moreover, the drivers had a higher resulting acceleration on the straight roads and when taking over after being engaged with a secondary task during vehicle automation. The interaction effect between road geometry and drive type also showed that takeovers were worse on straight roads after an autopilot with distraction drive. Furthermore, the drivers were found to have a higher lane deviation on the curved road and when taking over from autopilot. There were also no age differences found in the resulting acceleration and lane deviation of young and middle-aged drivers which might imply that age does not have an impact on takeover quality. Thus, both age groups could benefit from ADAS technologies that might help with a safer takeover when the automation fails, but certain features may still be available. Hence, the system could be designed to provide a step-wise takeover where it decreases from a Level 3 to a Level 2 or 1 that provides ACC, Emergency Steering or Lane Keeping Assist that can aid the driver and mitigate the likelihood of an unsafe or risky takeover from occurring. Additionally, since there were a few collisions that occurred on a straight road on a highway, the system could continue to provide ADAS features such as a collision avoidance system (CAS) if the radars and sensors are available during the takeover. In addition, drivers could be trained to improve their SA and takeover control in such situations when the vehicle is unable to provide any assistance during the takeover.

6.3 Future work

Since the main objective of this thesis was to examine age differences across young, middle-aged and older drivers, but was impacted by COVID-19, the future experiments will be conducted with the older adult population of 65+ years to identify how their SA and takeover performance differs from the other age groups. The findings from the older population are likely to have value as other studies have shown differences between young or middle-aged drivers and older drivers when driving semi-AV simulators (e.g. [23, 22, 234]). Additionally, due to the unavailability of effect sizes from previous research, a large effect size of 0.4 was used to determine the sample size. However, the actual effect size of some of the results were much smaller than the value that was assumed for the sample size calculation. Hence, a different estimation of the effect size will be used to ensure a larger sample size for future experiments which will aid to identify meaningful differences in the results. Given the difficulty in obtaining effect sizes from previous studies, it is also recommended that all researchers should report the effect sizes in their publications as it will aid in understanding the impact of significant results and calculating better estimates of sample size for future studies. In addition, a future study could examine the impact of top-down versus bottom-up cued hazards on the hazard perception and takeover times. It is likely that bottom-up hazards might be perceived and reacted to faster than top-down hazards. Moreover, future research could measure Levels 2 and 3 SA as it would demonstrate how drivers understand the information they perceive which serves as the basis for their subsequent decision-making and performance as well as project what may happen in the near future based on their analysis of the information and results of their actions. Furthermore, the experiment could be conducted with using realistic non-driving related tasks such as writing an email, reading, watching a video and having a conversation with another passenger or secondary driving related tasks such as using route guidance systems, entertainment systems or IVIS that are likely to occur in the real-world context and have significance for the driver thus impacting their cognitive workload before a TOR.

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APPENDICES

Appendix A

Questionnaires

The questionnaires used in the study are provided below:

Demographics Questionnaire

This is a strictly confidential questionnaire. Only a randomly generated participant ID number, assigned by the research administrator, will be on this questionnaire. No information reported by you here will be traced back to you personally in any way. You can skip any questions you do not feel comfortable answering.

Please enter the 2-digit participant ID that was assigned to you.

____

Gender
Please select only one.

○ Male

○ Female

○ Prefer not to say

○ Prefer to self identify ____

Age
(years)

____

Current Driver's License
Please select only one.

○ G

○ G2

Total number of years of driving since obtaining your first driver’s license

____

What is your estimated total driving kilometers?

____

Have you used a semi-autonomous vehicle?

This is a vehicle that is capable of driving itself safely with little or no human input under certain conditions. The driver has the opportunity to engage in non-driving related tasks during vehicle automation but must be available to take over when the system reaches its limit. For example, Tesla Autopilot or the Traffic Jam Pilot feature in Audi A8 that autonomously steers, accelerates, and brakes the car when enabled.

○ Yes

○ No

If answered ‘Yes’ to the previous question, please specify for how long you have used a semi-autonomous vehicle.

in months

____

Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-Short)

1. Please State Your **Age** .... Years. *2.* Please State Your Sex (tick box) **Male** [ ] 1 **Female** [ ] 2

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

3. **As a CHILD (before age 12),** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

4. **Over the LAST 10 YEARS,** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Scoring the MSSQ- Short

<u>Section A (Child)</u> (Question 3)

Score the number of types of transportation <u>not</u> experienced (i.e., total the number of ticks in the ‘t’ column, maximum is 9).

Total the sickness scores for each mode of transportation, i.e. the nine types from ‘cars’ to ‘big dippers’ (use the 0-3 number score key at bottom, those scores in the ‘t’ column count as zeroes).

MSA = (total sickness score child) x (9) / (9 - number of types not experienced as a child)

Note 1. Where a subject has not experienced any forms of transport a division by zero error occurs. It is not possible to estimate this subject’s motion sickness susceptibility in the absence of any relevant motion exposure.
Note 2. The Section A (Child) score can be used as a pre-morbid indicator of motion sickness susceptibility in patients with vestibular disease.

<u>Section B (Adult)</u> (Question 4)

Repeat as for section A but using the data from section B.

MSB = (total sickness score adult) x (9) / (9 - number of types not experienced as an adult)

Raw Score MSSQ-Short

Total the section A (Child) MSA score and the section B (Adult) MSB score to give the MSSQ-Short raw score (possible range from minimum 0 to maximum 54, the maximum being unlikely)

MSSQ raw score = MSA + MSB

Percentile Score MSSQ-Short

The raw to percentile conversions are given below in the Table of Statistics & Figure, use interpolation where necessary.

Alternatively a close approximation is given by the fitted polynomial where y is percentile; x is raw score
$y = a.x + b.x^{2} + c.x^{3} + d.x^{4}$
a = 5.1160923 b = -0.055169904
c = -0.00067784495 d = 1.0714752e-005

Table of Means and Percentile Conversion Statistics for the MSSQ-Short (n=257)

Percentiles Conversion	Raw Scores MSSQ-Short		
	Child Section A	Adult Section B	Total A+B
0	0	0	0
10	.0	.0	.8
20	2.0	1.0	3.0
30	4.0	1.3	7.0
40	5.6	2.6	9.0
50	7.0	3.7	11.3
60	9.0	6.0	14.1
70	11.0	7.0	17.9
80	13.0	9.0	21.6
90	16.0	12.0	25.9
95	20.0	15.0	30.4
100	23.6	21.0	44.6
Mean	7.75	5.11	12.90
Std. Deviation	5.94	4.84	9.90

Table note: numbers are rounded

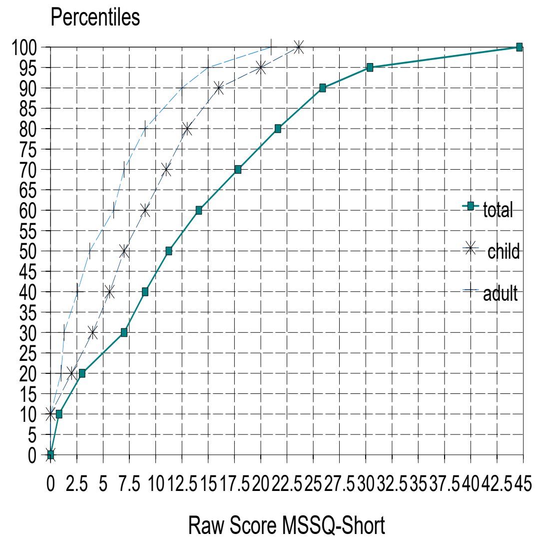

Figure: Cumulative distribution Percentiles of the Raw Scores of the MSSQ-Short (n=257 subjects).

<u>Reference Note</u>

For more background information and references to the original Reason & Brand MSSQ and to its revised version the ‘MSSQ-Long’, see:
Golding JF. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. **Brain Research Bulletin**, 1998; 47: 507-516.
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The Simulator Sickness Questionnaire

Subject _______

SSQ- X

Are you motion sick now? Circle YES or NO

If you are sick, when did you first notice the symptoms? Time: _________ Date:______

Circle how much each symptom below is affecting you now.

0 = "not at all" 1 = "mild" 2 = "moderate" 3 = "severe"

1. General discomfort	0	1	2	3
2. Fatigue	0	1	2	3
3. Headache	0	1	2	3
4. Eyestrain	0	1	2	3
5. Difficulty focusing	0	1	2	3
6. Increased salivation	0	1	2	3
7. Sweating	0	1	2	3
8. Nausea	0	1	2	3
9. Difficulty concentrating	0	1	2	3
10. Fullness of head	0	1	2	3
11. Blurred vision	0	1	2	3
12. Dizziness (eyes open)	0	1	2	3
13. Dizziness (eyes closed)	0	1	2	3
14. Vertigo*	0	1	2	3
15. Stomach awareness**	0	1	2	3
16. Burping	0	1	2	3

*Vertigo is experienced as loss of orientation with respect to vertical upright

**Stomach awareness is usually used to indicate a feeling of discomfort that is just short of nausea.

Walter, Hannah; Li, Ruixuan; Munafo, Justin; Curry, Christopher; Peterson, Nicolette; Stoffregen, Thomas. (2019). APAL Coupling Study 2019. Retrieved from the Data Repository for the University of Minnesota, https://doi.org/10.13020/XAMG-CS69.

A brief explanation of the Simulator Sickness Questionnaire (SSQ)

Each item is rated with the scale from none, slight, moderate to severe. Through some calculations, four representative scores can be found. Nausea-related subscore (N), Oculomotor-related subscore (O), Disorientation-related subscore (D) are the scores for the symptoms for the specific aspects. Total Score (TS) is the score representing the overall severity of cybersickness experienced by the users of virtual reality systems.

The calculations in the Simulator Sickness Questionnaire

None = 0
Slight = 1
Moderate = 2
Severe = 3

	Weights for Symptoms		
Symptoms	Nausea	Oculomotor	Disorientation
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eye strain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total*	[1]	[2]	[3]

Score
Nausea = [1] × 9.54
Oculomotor = [2] × 7.58
Disorientation = [3] × 13.92
Total Score = ([1] + [2] + [3]) *3.74

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* Total is the sum obtained by adding the symptoms scores. Omitted scores are zero

Appendix B

SAGAT questions

The following is a sample list of SAGAT questions used in the study:

Highway scenario

- Did you see any cars in your mirror?
- What speed was your car going at before the session ended?
- What speed was your car going at when you took over?
- Did you notice the pedestrian trying to cross the road?
- Were there any cars around you?
- How many lanes were present?
- Was there a speed limit sign?
- What was the speed limit posted on the sign before the scenario ended?
- Could you briefly describe the billboard sign overhead?
- What input did you first provide when disabling Autopilot?

Urban scenario

- What speed was your car going at when the session ended?
- Did you see a stand on the left?
- Did you notice any traffic signals?
- Did you see any cars in your left mirror?
- What cars were in the opposite lane?
- Was there a bus stop?
- What was the speed limit posted on the sign before the scenario ended?
- Were there any cars ahead?
- What was the road speed limit?
- Was there a vehicle behind you in your rear-view mirror?
- What input did you first provide when disabling Autopilot?