Investigating Older Drivers' Takeover Performance and Requirements to Facilitate Safe and Comfortable Human-Machine Interactions in Highly Automated Vehicles

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Abstract

The forthcoming highly automated vehicles (HAVs) may potentially benefit older drivers. However, limited research have investigated the their performance and requirements when interacting with HAVs in order to provide an understanding of what would facilitate a safe and comfortable human-machine interaction with HAVs for them. This thesis fills the research gap using a range of quantitative and qualitative methodologies through four investigations.

Firstly, a driving simulator investigation was conducted with 76 participants (39 older and 37 younger drivers) to investigate the effects of age and the state of complete disengagement from driving on the takeover performance. This investigation found that age and complete disengagement from driving negatively affect takeover performance. Then, a second driving simulator investigation was conducted to investigate the effect of age and adverse weather conditions on takeover performance. It was found that age affects takeover performance. And adverse weather conditions, especially snow and fog, lead to a deteriorated takeover performance. Next, a qualitative interview investigation was implemented with 24 older drivers who participated the two driving simulator investigations. This study yielded a wide range of older drivers' requirements towards the human-machine interactions in HAVs, especially towards the periods of automated driving and taking over control. Lastly, in the third driving simulator investigation, three human-machine interfaces (HMIs) of HAVs were designed based on older drivers' requirements, their effectiveness on enhancing drivers' takeover performance were evaluated. It has found that the HMI informing drivers of vehicle status together with the reasons for takeover is the most beneficial HMI to the drivers of HAV.

Based on the findings above, the thesis proposed recommendations for facilitating safe and comfortable human-machine interactions in HAVs for older drivers. The thesis concluded the importance of fully considering older adults' performance, capabilities and requirements during the design of human-machine interactions in HAVs.

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Abbreviations

ACC	Adaptive Cruise Control Systems
ADAS	Advanced Driver Assistance Systems
ANOVA	Analysis of Variance
ASCII	American Standard Code for Information Interchange
BASt	German Federal Highway Research Institute
BSW	Blind Spot Warning Systems
CAS	Collision Avoidance System
CC	Cruise Control Systems
CCE	Collisions and Critical Encounters
DDL	Driving Disengagement Level
DfT	Department for Transport
FAV	Fully Automated Vehicle
FCW	Forward Collision Warning Systems
HAV	Highly Automated Vehicle
HMI	Human Machine Interface
HUD	Head-up Display
ISA	Intelligent Speed Adaption System
ITS	Intelligent Transportation System
LDW	Lane Departure Warning Systems
LKA	Lane keeping Assistance Systems
NASA-TLX	The National Aeronautics and Space Administration Task Load Index
NHTSA	National Highway Traffic Safety Administration
OEMs	Original Equipment Manufacturers
ONS	Office for National Statistics
SAE	Society of Automotive Engineering
SAS	Steering Assistance System
TOR	Takeover Request
TTC	Time-to-Collision

Chapter 1 Introduction

1.1 Introduction

The numbers of older people in the UK and across the world are increasing as is their percentage of the overall population. In 2016, 18% of the population of the UK was aged 65 and older, and the figure is predicted to increase to 24.7% by 2046 (ONS, 2017). To many older adults, access to a car is equivalent to maintaining mobility, their social and family networks, continuing to live independently. Thus, it has been generally recognised that continuing mobility is strongly linked to quality of life and wellbeing (Charlton et al., 2006; Guo et al., 2010a; Musselwhite and Haddad, 2010; Bellet et al., 2018). In the UK, travelling by car has become an important transport mode for older people, and most of their trips in cars are as drivers. Moreover, they are tending to drive more frequently and over longer distances (DfT, 2015b). However, driving is a complex activity that requires a variety of physical, mental and cognitive functions and their interaction and coordination (Karthaus and Falkenstein, 2016). However, age-related functional impairments could have a negative effect on older drivers' safe driving ability and this makes them a vulnerable group in terms of the increased frequency of motoring offences, traffic accidents and collisions (Brouwer et al., 1991; Houx and Jolles, 1993; Ball et al., 1998; Owsley et al., 1999; Shanmugaratnam et al., 2010; Karthaus and Falkenstein, 2016; Bellet et al., 2018). In order to compensate for age-related functional decline, some older drivers have to modify and regulate their driving behaviour by changing when, where and how they drive. The ultimate self-regulatory driving behaviour among older drivers is to cease driving altogether (Marottoli et al., 1997; Ball et al., 1998; Kostyniuk and Shope, 1998; Musselwhite, 2011). Nevertheless, this self-regulatory behaviour could result in significant reductions in older people's mobility, independence, and freedom, and could be closely associated with increased social isolation, depressive symptoms and reduced self-confidence (Ball et al., 1998; Siren et al., 2004; Charlton et al., 2006; Donorfio et al., 2008; Kostyniuk and Molnar, 2008; Musselwhite and Haddad, 2010; Musselwhite, 2011).

Meanwhile, technologies for road transport are evolving and the emergence of vehicle automation for operation on public roads may offer the potential to reduce traffic emissions, congestion, and accident rates (DfT, 2015e). It may also have the potential to enhance older drivers' mobility, independence and wellbeing by offering new functionalities to compensate for their functional decline (Young et al., 2017). Governments and original equipment manufacturers (OEMs) have realised the potential benefits that automated vehicles could deliver, and they have been actively promoting and facilitating the development of vehicle automation. In 2014, several vehicle automation projects were launched in cities in the UK, including Greenwich, Milton Keynes, Coventry and Bristol, which in general aimed to explore the requirements for safe and practical implementation of automated vehicles on public roads in the UK (DfT, 2014; UKAutodrive, 2016b; GATEway, 2017b; TRL, 2017; VENTURER, 2018). In addition, a series of tests of automated vehicles based on the Framework 7 programme (FP7) have been implemented in Europe, including SARTRE, HAVE-it, Citymobil, Citymobil 2, V-CHARGE and AdaptiVe, and these projects have made contributions to the development of strategies, technologies and modes of integration of automated vehicles (EuropeanCommission, 2016). In the USA, Nevada, Florida, California and Michigan are the first four states to have passed the legislation to allow the testing of automated vehicles on public roads. The US National Highway Traffic Safety Administration (NHTSA) has published a preliminary statement of policy concerning automated vehicles to ensure the safe implementation of automated vehicle tests and to provide definitions of the levels of vehicle automation (NHTSA, 2013). In Asia, Japan implemented its first public road trail of an AV on a Japanese highway in 2013. China has also realised the potential benefits of AV, and a number of companies are running tests of automated vehicles including Changan, Baidu & BMW, Geely & Volvo and LeSee (Quigley, 2013; Illmer, 2016).

1.2 Highly Automated Vehicles (HAVs)

The currently available advanced driver-assistance systems (ADAS) are able to assist drivers in a variety of ways, including enhancing their sensory abilities, such as with advanced forward lighting systems and night vision systems; providing drivers with information and feedback, such as using in-vehicle navigation systems and lane departure warnings, or intervening in longitudinal and lateral controls of the vehicle, such as via adaptive cruise control, intelligent speed adaptation and lane-keeping assistance (Davidse, 2006; Guo *et al.*, 2010a; Emmerson *et al.*, 2013; Guo *et al.*, 2013a; Edwards *et al.*, 2016; Gish *et al.*, 2017). Notwithstanding the multiple levels of support and assistance that these systems could provide to drivers, the drivers must always be engaged in driving tasks and are fully responsible for the safety of the driving at all times (DfT, 2015c).

The forthcoming highly automated vehicles (HAV), also known as at Level 3 automation (NHTSA, 2013; SAE, 2014; DfT, 2015c), could herald a revolutionary automated driving experience which would allow drivers being conveyed in an automated mode by a HAV to be completely disengaged from driving and may safely perform other non-driving related tasks such as reading, watching films, and using mobile phones, while the drivers' takeover of control of the vehicle is still expected to be necessary occasionally (NHTSA, 2013; SAE, 2014; DfT, 2015c). Takeover is a key feature of the HAV, occurring when drivers' manual control of the vehicle replaces automated driving, either in situations when drivers wish to operate the vehicle manually, or in situations when the automation systems encounter system limitations (such as missing road signs and markings, or in construction areas) and the driver is required to take over control of the vehicle (Flemisch *et al.*, 2008; DfT, 2015c; Melcher *et al.*, 2015; Lu *et al.*, 2016). In these situations, when the HAV system encounters a situation that requires the driver to intervene, it informs the driver by issuing a takeover control request and providing a sufficient lead time for them to take over control of the vehicle before safety is compromised (Gold and Bengler, 2014). Following the takeover request, the driver switches their attention from non-driving related tasks to the road and starts to conduct cognitive processing of the takeover situation, which includes perceiving and understanding the current environment as well as making predictions of its future status, so that a decision can then be made and appropriate action executed (Endsley, 1995b).

1.3 HAV and Older Drivers

Previous studies have identified the potential benefits of current ADAS in improving older driver's driving safety and maintaining their mobility and independence, and significant age differences have also been found in terms of interacting with these systems (Musselwhite and Haddad, 2007; Guo *et al.*, 2010a; Emmerson *et al.*, 2013; Guo *et al.*, 2013a; Edwards *et al.*, 2016; Gish *et al.*, 2017). The potential of vehicle automation for supporting older driver's mobility and improving social inclusion has also been identified (DfT, 2015d; DfT, 2015c; Chan, 2017; GATEway, 2017a; Young *et al.*, 2017; Bellet *et al.*, 2018). The likely forthcoming rollout of HAVs will require a new type of human-machine interaction that allows the driver to be completely disengaged from driving while still expecting drivers' to take over control in some situations. This has created a need to investigate what HAVs may mean for the older driver cohort coherent in terms of their performance when interacting with the systems, any age related preferences, needs and requirements that are specific to their group and what types of interactions will be needed. Only limited research have considered older drivers when studying HAVs (Körber *et al.*, 2016; Miller *et al.*, 2016; Clark and Feng, 2017; Molnar *et al.*, 2017).

1.4 Statement of Problem

Although a small number of studies have considered age when researching HAVs, knowledge is lacking on whether or not older drivers are able to interact with HAVs safely and comfortably due to the potential effects of age on the taking over control ability. Furthermore, it is not yet understood well what additional assistance and support that older drivers may prefer or require in order to guarantee safe and comfortable interaction with HAVs. Such knowledge underpinned by appropriate evidence is essential to ensure a safe design for such systems are made. To date the literature suggests that this has not been fully considered. Given that vehicle and device manufacturers are conducting their own tests and are soon likely to release HAVs (UKAutodrive, 2016a), it is important and indeed imperative for the design of HAVs to fully take into account older drivers' performance, capabilities, and requirements (Musselwhite and Haddad, 2007; Guo et al., 2010a; Emmerson et al., 2013). The potential consequences of ignoring older people's needs and requirements in the design of human-machine interaction for in-vehicle systems could be that these systems may cause more difficulties for older people than they resolve (Young et al., 2017), moreover what is good design for older drivers should also be good design for all drivers and enhance safety for all. Nevertheless, the lack of a knowledge-base of older drivers' interaction with HAVs could potentially become a barrier that prevents older adults from fully benefitting from HAVs, and this then poses the risk that the expected benefits that HAVs could deliver to society could be reduced. This is particularly curious when considering that in much of the early literature on automated vehicles, the potential benefits to the older community was often cited, but much without clear evidence to back the assertion up (Musselwhite and Haddad, 2007; Guo et al., 2010a; Young et al., 2017). However it seems that in reality, research into and the demonstrations of HAVs to date have largely focused on general drivers and not the specific older driver cohort (Gold et al., 2013a; van den Beukel and van der Voort, 2013; Gold and Bengler, 2014; Radlmayr et al., 2014; Louw et al., 2015; Zeeb et al., 2016; Eriksson and Stanton, 2017; Zeeb et al., 2017).

1.5 Research Questions

This thesis aims to carry out novel research and to create new knowledge by addressing the following research questions:

- What are the effects of age in influencing the performance of drivers when interacting with HAVs during the process of taking over control?
- What are the effects of the state of complete disengagement from driving in HAVs on drivers’ performance during the process of taking over control?
- What are the effects of adverse weather conditions (impacting on visibility on the road environment) on drivers’ takeover performance in HAVs?
- What are older drivers’ needs and requirements towards human-machine interaction in HAVs?
- How should age-friendly human-machine interfaces (HMI) in HAVs be designed based on older drivers’ requirements and what are the effects of these HMIs on drivers’ performance of interacting with HAVs?

1.6 Aim and Objectives

The global aim of this study is to investigate older drivers’ takeover performance in HAVs as well as to explore and test their needs and requirements of HAVs in order to develop knowledge to facilitate safe and comfortable human-machine interactions in HAVs.
In order to achieve the aim, the following objectives should be met:

- To understand older drivers’ mobility issues in the context of forthcoming HAVs;
- To design and develop HAV scenarios that incorporate situations where a driver is requested to take over manually driving control from a position where the HAV is initially performing automated driving and to implement them on the driving simulator;
- To investigate the effect of age and complete disengagement from driving in HAVs on the takeover performance of drivers;
- To investigate the effect of adverse weather conditions (affecting visibility on the road environment) on takeover performance of older drivers;
- To explore older driver’s needs and requirements concerning human-machine interaction in HAVs;

- To test the effectiveness of several age-friendly HMI concepts based on older drivers' requirements in enhancing their takeover performance in HAV; and
- To provide recommendations to policy makers and OEMs about facilitating older drivers' safety and comfort when interacting with HAVs.

1.7 Potential Benefits and Contributions

To ensure that older drivers could be among the prime beneficiaries of HAVs, it is very important to develop knowledge concerning older drivers' performance and what measures and actions should be taken to prevent dangerous and unpleasant interactions with HAVs and what assistance and support should be implemented to enhance safe and comfortable interaction with HAVs. Such guidance could be a valuable interface that connects vehicle automation technologies and ageing population.

For older drivers, the knowledge yielded by this thesis could not only improve the safety and comfort of their interaction with HAVs but also increase their trust and confident in using the vehicles, thereby facilitating their adoption of HAVs and ultimately to enhance their mobility, independence and wellbeing. For transport academics, this study emphasises the importance of considering older drivers' performance, capabilities, and requirements when researching future mobility issues. For policymakers and vehicle manufacturers (OEMs), the knowledge and guidance yielded from this study could be crucial in developing relevant policies for HAVs and their end-users and enable them to develop a more comprehensive understanding of one of the potentially very important user groups of HAVs which is older drivers. Finally, the knowledge and guidance concerning older drivers' interaction with HAVs could potentially benefits all drivers by informing them about how to interact with HAVs safely and comfortably.

1.8 Thesis Structure

This thesis consists of nine chapters which detail the steps and processes undertaken in order to achieve the aim and objectives of the study described in section 1.6. The structure of the thesis is presented below in Figure 1.1.

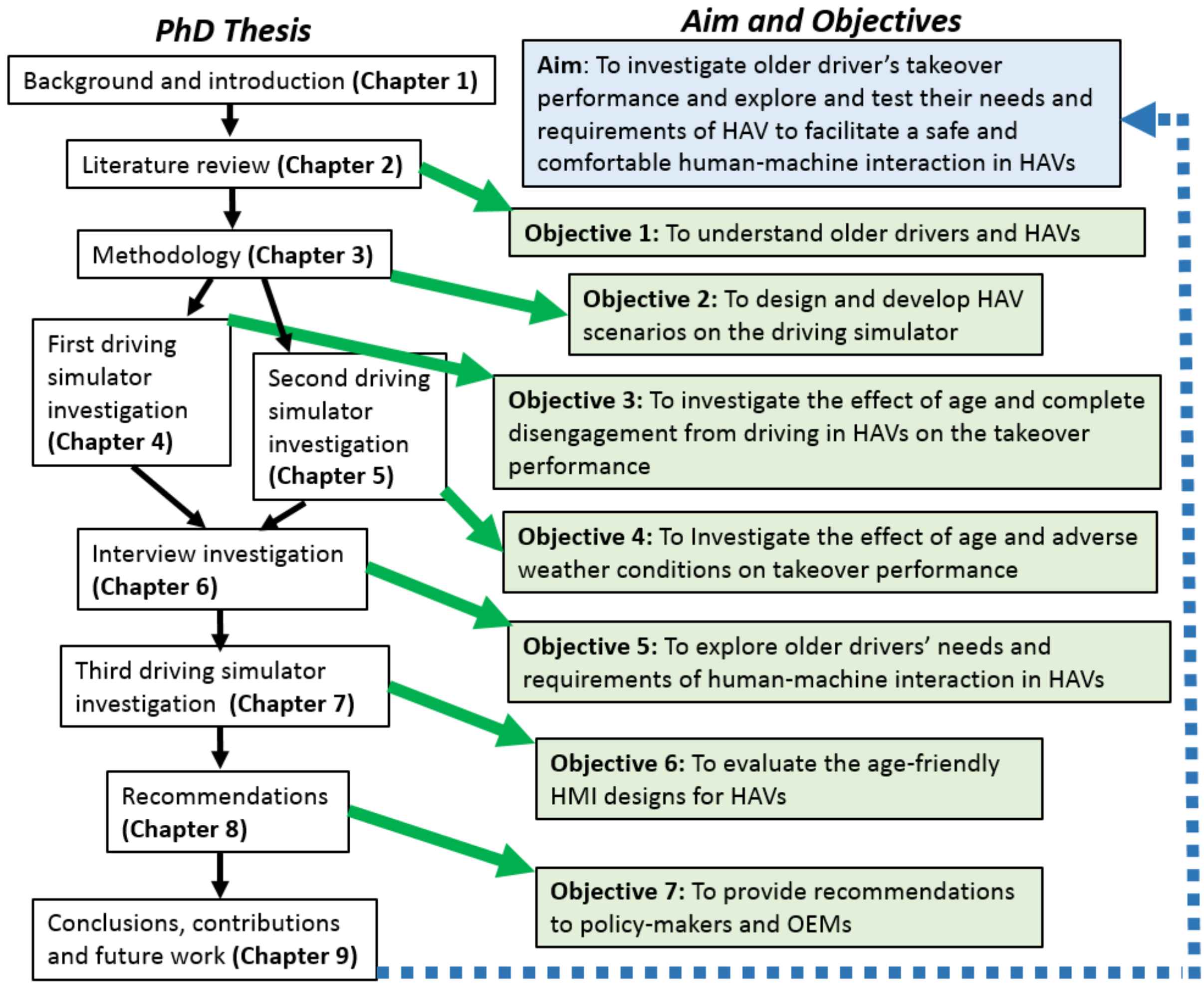


Figure 1.1 Thesis structure

Chapter 2. Literature Review

2.1 Introduction

The purpose of this chapter is to critically review the existing knowledge regarding older drivers' mobility as well as the human-machine interaction in HAVs. By reviewing the features and limitations of existing research, this chapter identifies the research gaps in the literature and also provides a platform to take into consideration for the choice of methodology for the original research carried out in this PhD thesis. As Figure 2.1 illustrates, this literature review consists of four main sections. Section 2.2 focuses on older drivers' mobility issues, and Section 2.3 covers vehicle automation as well as the issue of drivers' takeover of control in HAV. Section 2.4 reviews the existing knowledge regarding older drivers and HAVs, and then the key knowledge gaps in research on older drivers and HAVs are identified in Section 2.5. Finally, the conclusions are highlighted in Section 2.6.

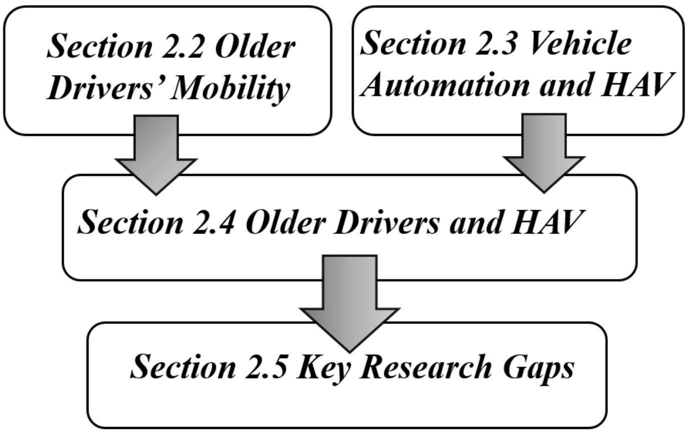


Figure 2.1 Structure of the literature review

2.2 Older Drivers' Mobility

2.2.1 Ageing population

The population of the world and the UK is ageing and is predicted to continue to grow older at a rapid pace over the next few decades. People aged 60 years and over are generally referred as old people (WHO, 2016). In 2015, there were around 901 million older people across the world, which accounted for 12.3% of the global population (UN, 2015). And it is predicted that this figure will grow to 1.4 billion in 2030, and then to 2.1 billion in 2050 and 3.2 billion in 2100 (UN, 2015). In the UK, the percentage of older people also exhibits an increasing trend and is predicted to continue to grow in the future. As Figure 2.2 indicates, 16.25% of the UK population was aged 60 and over in 1955, increasing to 20.47% in 1985 and further growing to 23.21% in 2015 (ONS, 2014).

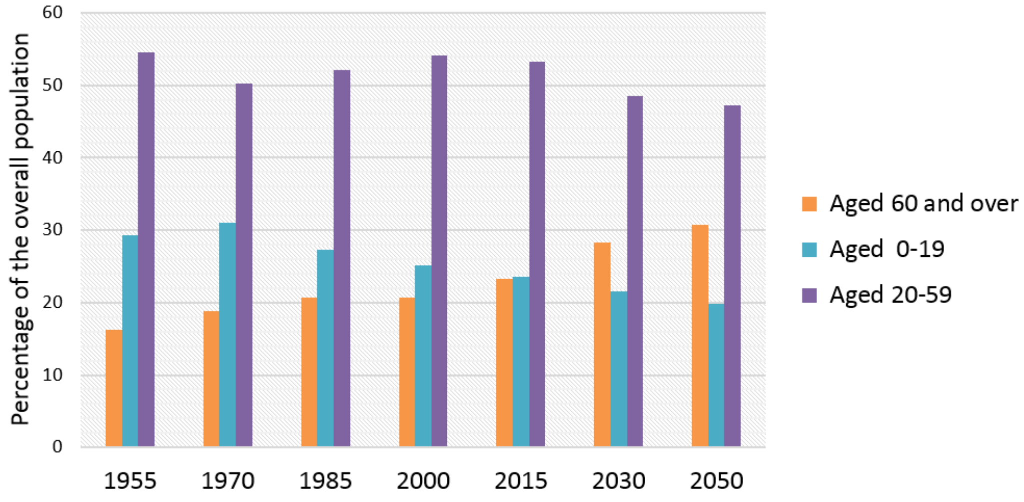


Figure 2.2 Age structure of the population in the UK from 1955 to 2050 (Office for National Statistics, 2014)

In addition, among the ageing population in the UK, the percentage of people aged 85 and over has been increasing at the fastest pace (Figure 2.3). From 1985 to 2010 the percentage of this age group has doubled from 1% to 2%. From 2010 to 2035, the proportion of this age group in 2035 will reach 3.5 million, making up of 5% of the overall population in the UK(ONS, 2012; ONS, 2014).

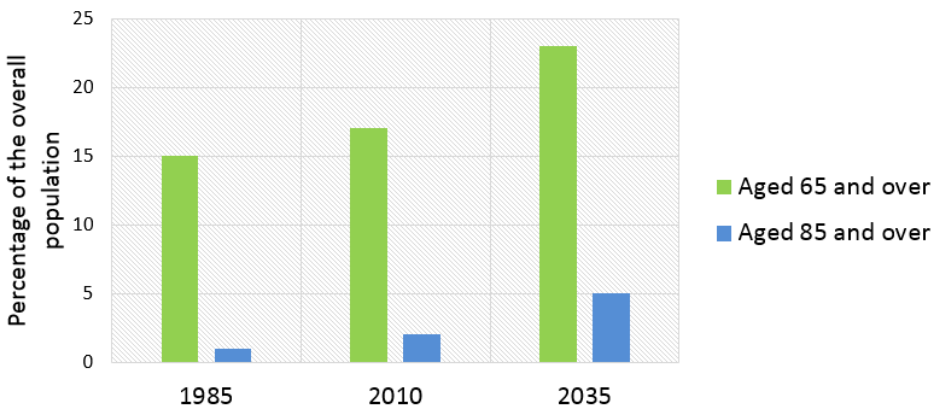


Figure 2.3 Percentage of older people in the UK in 1985, 2010 and 2035 (Office for National Statistics, 2012)

2.2.2 Older people and driving

For many older adults, driving is equivalent to maintaining mobility and being independent, which is strongly linked with quality of life and wellbeing (Musselwhite and Haddad, 2007; Guo *et al.*, 2010a; Musselwhite and Haddad, 2010; Musselwhite, 2011; Emmerson *et al.*, 2013; Guo *et al.*, 2013a). Musselwhite (2011) argued that driving is important for older people to fulfil their daily needs, such as in going to hospital and doing the shopping; to fulfil social needs, such as in participating in activities in their communities, and visiting family and friends; Also, driving makes older people feel independent and allows them to feel valued and to maintain identity. For example, driving can not only enable them to take care of themselves but also provide assistance to people around them.

In the UK, traveling by car has been a dominated mode of transport for older people, and the majority of trips in a car by older people were as drivers. As Figure 2.4 indicates, the percentage of trips by car among older people in the UK has increased from 58% in 1998 to 69% in 2012, whereby the percentage of the trips as a driver by older people has grown from 38% in 1998 to 49% in 2012. In addition, the number of older adults who has a valid driving licence has shown the greatest increase among all the age groups (DfT, 2015b). The percentage of driving licence holders aged 60-69 in the UK has significantly increased from 35% in 1975 to 79% in 2012, in the meantime, the figure driving licence holders aged 70 and over has increased from 15% to 58%. In England from 1975 to 2015 this figure for older drivers aged 60-69 years has grown from 35% to 81%, while for the 70 and over years old age group it has increased from 15% to 64% (DfT, 2015b).

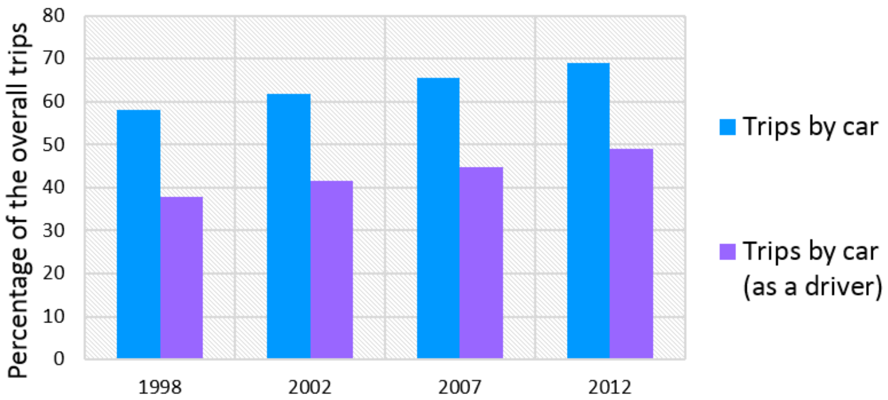


Figure 2.4 Percentage of trips by car of older people in the UK (National Travel Survey, 2016)

2.2.3 Age-related functional impairments in older drivers

Driving is a complex activity that requires a variety of physical, mental and cognitive functions and their interaction and coordination (Eby and Molnar, 2012; Karthaus and Falkenstein, 2016). As people age, a range of age-related functional impairments could negatively affect their safe driving ability, including decline in the sensory, cognitive and psychomotor functions (Attebo et al., 1996; Ball et al., 1998; Haegerstrom-Portnoy et al., 1999; Karthaus and Falkenstein, 2016).

2.2.3.1 Age-related impartments in sensory function

Age-related sensory function impairments generally refer to visual and hearing problems. Among these, visual impairments are most closely linked to driving safety, as visual information accounts for a high proportion of the information required by the driver during driving (Attebo et al., 1996; Karthaus and Falkenstein, 2016). A variety of visual abilities could decline due to the ageing process. Haegerstrom-Portnoy et al. (1999) indicated that the ageing process decreases static and dynamic visual acuity and contrast sensitivity. Also, a study by Schieber (1994) showed that the time that older participants took to recover from the deleterious effects of glare is about three times longer compared to younger counterparts. In addition, the useful field of view (UFOV) is positively associated with driving performance (Ball et al., 2005), and it is negatively affected by the ageing process (Sekuler et al., 2000). Older drivers who have seriously impaired UFOV are more likely to have been involved in car collisions (Huisingh et al., 2015; Karthaus and Falkenstein, 2016). In addition, motion sensitivity also increases with age, for example, Trick and Silverman (1991) found that participants aged over 70 years old exhibited levels of motion sensitivity about twice those of participants aged 30 years old and under. These impaired visual abilities can negatively affect drivers' safe driving ability (Eby and Molnar, 2012). For example, they could increase the risk of crashes among older drivers when driving at night and in environments with low light levels; they could also result in difficulties for older drivers in clearly reading warning, direction, information, road work signs, as well as traffic lights and road markings and lines (Eby and Molnar, 2012). Apart from the visual decline due to normal ageing processes, eye diseases among older drivers also seriously affect their vision and thus reduce safe driving performance. For example, eye cataracts are a common condition that influence a higher proportion of people aged 65 and over, significantly increasing their probability of being involved in a car crash (Owsley et al., 1999; Karthaus and Falkenstein, 2016). The hearing function also seriously declines due to the ageing process, which could result in missing important auditory information such as warning signals, potentially endangering older drivers (Karthaus and Falkenstein, 2016).

2.2.3.2 Age-related impairments in cognitive functions

Apart from sensory abilities, a range of cognitive abilities and the seamless interaction of these abilities are also crucially important for driving safety, including attention, perceptual motor skills, memory, and decision-making (Anderson et al., 2005). The attention abilities that are relevant to driving include selective attention, divided attention and sustained attention (McDowd and Birren, 1990). Selective attention refers to the ability of the driver to effectively select suitable and useful stimuli and to disregard distracting and useless stimuli during driving (McDowd and Birren, 1990). Pollatsek et al. (2012) conducted experiments both on a driving simulator and in real road environments to examine the influence of age on selective attention, and they revealed that older participants exhibited reduced selective attention compared to younger participants. Divided attention refers to the ability when people have to concentrate on multiple sources of information or perform several tasks at a same time (McDowd and Birren, 1990; Brouwer et al., 1991). Brouwer et al. (1991) administered a driving simulator investigation to examine the effect of age on divided attention and found that compared to younger participants, older participants had a significantly declining ability of divided attention. Sustained attention refers to the ability to concentrate on an activity for a long duration, which is closely related to the vigilance and alertness of driving (McDowd and Birren, 1990). It was found to decline with age (Davies and Davies, 1975; Mani et al., 2005).

Apart from attention abilities, the speed of processing various information also plays an essential part in driving, especially when driving in difficult and complex situations, such as heavy traffic and adverse weather situations, and it has been found the speed of information processing slows down with age (Panek et al., 1977; Pichora-Fuller, 2003). After the information gained while driving has been successfully processed, executive functions enable drivers to effectively plan an effective strategy and execute corresponding responses, and the executive functions can also deteriorate during ageing (Daigneault et al., 2002; Insel et al., 2006).

2.2.3.3 Age-related impairments of psychomotor abilities

Psychomotor abilities refer to a person's capabilities to control and coordinate his or her body (Kelso, 1982; Houx and Jolles, 1993; Shanmugaratnam et al., 2010). Those are strongly related to driving safety are the speed of reaction, mobility and flexibility of limbs and neck, and movement coordination. It has been well recognised that these psychomotor abilities deteriorate due to the normal ageing process and some age-linked illnesses and diseases, such as osteoarthritis, Parkinson's disease, Huntington's chorea, deconditioning and cerebrovascular accidents (Houx and Jolles, 1993; Rodríguez-Aranda et al., 2006; Shanmugaratnam et al., 2010).

One well-established age-linked psychomotor changes concerns increases in older drivers' reaction time. Ferreira et al. (2013b) argued that the effect of age on reaction time was significant in terms of both psychological assessments and driving performance. Age-linked reduced muscle strength could also make it difficult for older drivers to operate the control of the vehicle accurately and effectively, which would potentially increase the probability of being involved in a vehicle collision (Kallman et al., 1990). In addition, the age-linked impaired limb mobility and flexibility will affect drivers' ability to effectively operate steering wheel or shift their foot between the accelerator and brake pedals to execute a safe manoeuvre of a vehicle to effective evade a potential collision; and also the declining neck mobility and flexibility would make it difficult for the older adults to effectively check the side mirrors and to make shoulder checks when merging, changing lanes and reversing (Staplin et al., 1999; Marmeleira et al., 2009).

2.2.3.4 Age-related fragility and frailty

Moreover, another significant area of functional decline with increasing age is fragility and frailty. Fragility refers to the possibility of being injured easily or more seriously for a fixed level of severity, and frailty reflects the ability to returning to a healthy condition from an injury (Braver and Trempel, 2004; Kent et al., 2009). Older drivers are more likely to be seriously injured or killed if involved in vehicle collisions, for example, Li et al. (2003) reported that, compared to drivers aged under 60, older drivers aged 70-74 had death rates twice as high and those aged 80 and over five times as high when involved in vehicle collisions of same severity.

2.2.4 Self-regulatory behaviour and the cessation of driving among older drivers

In order to compensate for the negative effects of these age-related functional impairments on driving, many older adults are very cautious when driving (Eberhard, 1996; Charlton et al., 2006) and a great number of them modify and regulate their driving behaviour to reduce or avoid their exposure to certain situations that they believe are difficult or potentially dangerous for them, for example avoiding or reducing making left turns (U.S research), driving in adverse weather conditions, driving around sunrise or sunset, or at night, driving in heavy traffic or peak hours, driving long-distance, and driving alone (Eberhard, 1996; Ball et al., 1998; Charlton et al., 2006; Kostyniuk and Molnar, 2008).

2.2.4.1 Older drivers' self-regulatory behaviour in adverse weather conditions

Among these self-regulatory behaviours, reducing or completely avoiding driving in adverse weather conditions is one of the most common behaviours adopted by older drivers, mainly due to the deteriorating visibility in these conditions (Kline et al., 1992; Marottoli et al., 1993; Persson, 1993; Hennessy, 1995; Ball et al., 1998; Kostyniuk and Shope, 1998; Lyman et al., 2001; Charlton et al., 2006; Bellet et al., 2018).

Hennessy (1995) found that reduced visual ability is the major reason for older drivers to limit their driving in adverse weather conditions such as in rain or fog. This finding was supported by Ball et al. (1998), who studied the self-regulatory behaviour of 257 older drivers and found that the most common self-regulatory behaviours that older drivers adopted was to limit their driving in adverse weather, at night, in heavy traffic and at peak times. In addition, Kostyniuk and Shope (1998) conducted a study using a series of focus groups with 39 older drivers. They found that impaired visual ability was the most commonly reported age-related impairment experienced by older drivers, and in order to deal with this, most of them reduced or completely avoided driving in adverse weather conditions such as at night, or in rain, ice or snow. Moreover, Myers et al. (2008) examined driving confidence among 143 older drivers and found that older drivers evaluated driving in foggy weather as the most uncomfortable driving situation. Of course, one positive side of limiting driving in bad weather conditions is that older people are less likely to be involved in collisions and accidents in adverse weather conditions (McGwin Jr and Brown, 1999), however, this has resulted in significant reductions in mobility and independence among older drivers (Ball et al., 1998; Lyman et al., 2001; Bellet et al., 2018).

2.2.4.2 Different responses to self-regulatory behaviour among older drivers

Older drivers have different opinions towards the concept of adopting self-regulatory driving behaviours. Some older drivers were found to be more likely to adopt self-regulatory driving behaviour comparing to others, such as female older drivers, drivers aged 75 and over and older adults who were not the main driver in their home, as well as older drivers who had been involved in car collisions, those with objectively determined visual and/or cognitive impairments, kidney disease, cataracts and high blood pressure (Ball et al., 1998; Lyman et al., 2001; Charlton et al., 2006).

However, some older drivers do not support the idea of self-regulatory driving behaviour. Jette and Branch (1992) reported that some older adults insisted on carrying on driving as long as they could and would not self-regulate their driving or choose to use other alternative transportation modes, and they pointed out that reducing driving by adopting self-regulatory behaviour may not be a perfect and practical method to ensure driving safety for all older adults.

2.2.4.3 Driving cessation among older drivers

The ultimate level of self-regulatory behaviour that older drivers may have to face is completely give up driving. Decisions of driving cessation is not only due to health factors or age-related functional impairments, but may also be triggered by socioeconomic factors such as lower income, retiring from work, living close to the city centre and the availability of other alternative transport modes (Marottoli et al., 1993; Persson, 1993; Marottoli et al., 1997; Kostyniuk and Shope, 1998). In general, the most common reasons for driving cessation among older drivers are medical issues as well as lack of confidence and increased nervousness while driving (Persson, 1993; Brayne et al., 2000).

Considering the shortage of the effective transport modes that could completely replace the functions of driving cars among older drivers, driving cessation could lead to a substantial decline in older drivers' ability to travel anywhere at any time when they want and need to (Kostyniuk and Molnar, 2008; Eby and Molnar, 2012). It has been widely recognised in previous studies that reducing driving and driving cessation could have negative impacts on older drivers' mobility, independence and freedom, and are highly associated with increased social isolation, depressive symptoms and reduced self-worth and identity (Marottoli et al., 1993; Persson, 1993; Marottoli et al., 1997; Ball et al., 1998; Lyman et al., 2001; Musselwhite and Haddad, 2007; Musselwhite and Haddad, 2010; Musselwhite, 2011; Eby and Molnar, 2012).

The significant difficulties that older drivers have to deal with are not only the behaviour of stopping driving physically, but also accepting it mentally. Musselwhite (2011) pointed out that the concept of driving cessation should be given attention by the whole society as early as possible in order to support older drivers to effectively and smoothly adapt to alternative transport modes to replace driving. Therefore, a detailed and through plan for older people after driving cessation could be useful in helping them to better adapt to the life without driving, such as adjusting lifestyles or finding alternative transportation. Musselwhite and Shergold (2013) found that older drivers who had well planned a strategy to adapt to driving cessation were happier and had a higher quality of life after giving up driving compared to those did not. In addition, the negative effect of driving cessation on older people's wellbeing, such as in mood or attitudes, should be considered when suggesting them about stopping driving as well as when exploring alternative travel strategies for them (Marottoli et al., 1997; Musselwhite and Shergold, 2013).

In summary, it is essential for the family and friends of older drivers, as well as policymakers, OEMs and academics as well as the entire society to closely work together to explore methods and strategies to ensure that the mobility and travel needs can be met for the older drivers who adopt self-regulatory driving behaviour or have already stopped driving.

2.3 Vehicle Automation and HAVs

Along with global ageing trends, technologies for road transport are developing and the forthcoming arrival of automated vehicles for public roads may have the potential to reduce traffic emissions, congestion, and accident rates. Additionally, they may potentially benefit older drivers by offering new functionalities that will enable older people to drive safely for a longer time.

2.3.1 Levels of vehicle automation

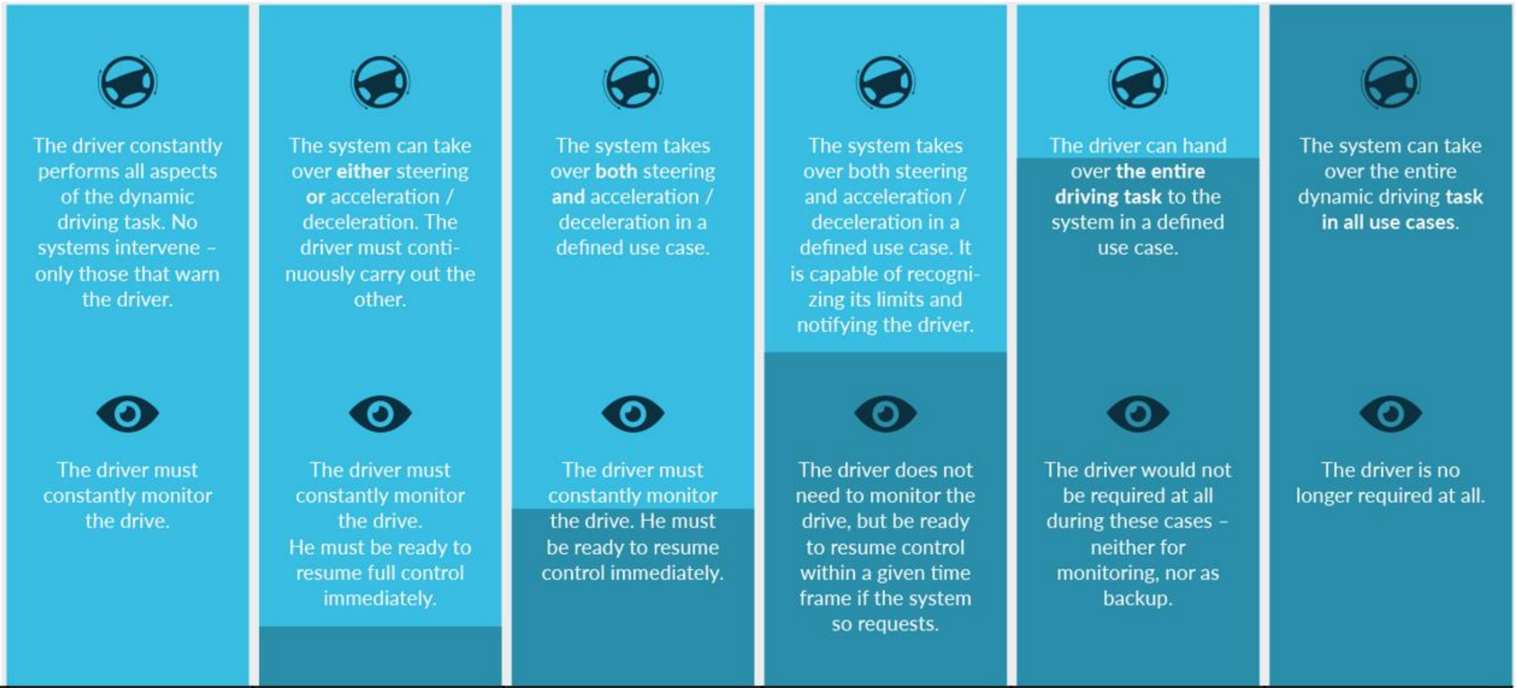
Vehicle automation could be classified into several levels. In order to provide a clear and systematic classification based on different functionalities and capabilities, several government and research organizations have proposed definitions of levels of vehicle automaton, including the German Federal Highway Research Institute (BASt), the US National Highway Traffic Safety Administration (NHTSA), the UK Department for Transport (DfT) and the Society of Automotive Engineering (SAE). A summary of these definitions is given in Figure 2.5. Although different names are used by different organizations, they generally follow a similar hierarchical structure, where each level has different features and potentially offers different functionalities to the vehicle and support the driver in different ways. These are reviewed in the following sections.

- The basic level of vehilce automation is named "Level 0 No Automation" by the SAE (2014), "Driver Only" by the BASt (Gasser and Westhoff, 2012), and "Level 0 No Automation" by the NHTSA (2013), and it is covered in the "Driver Assistance" category proposed by the DfT (2015c).

Cars of level 0 vehicle automation are not able to perform any automated longitudinal or lateral control of the vehicle, although they may be able to provide warnings or assistance to support the safe driving of human drivers through a range of in-vehicle driver assistance systems, for example, forward collision warning (FCW) systems, blind spot warning (BSW) systems, lane departure warning (LDW) systems, satellite navigation systems, night vision enhancement systems. In level 0 vehicle automation, the human driver is fully responsible for operating the longitudinal and lateral control of the vehicle as well as monitoring driving the environment throughout the complete journey.

- The first level of vehicle automation is defined as "Level 1 Driver Assistance" by the SAE (2014), "Assisted" by the BASt (Gasser and Westhoff, 2012), and "Level 1 Functional Specific Automation" by the NHTSA (2013). And it is also covered in the "Driver Assistance" category proposed by the DfT (2015c).

Compared to level 0 automation in which the automation systems are not supposed to perform any parts of the driving control of the vehicle on a sustained basis, systems at the first level of vehicle automation are able to execute either longitudinal or lateral control of the vehicle. There are cases in the first level of automation in which both longitudinal and lateral can be automated, but they operate separately from each other and cannot operate concurrently (Gasser and Westhoff, 2012; NHTSA, 2013; SAE, 2014), such as in cruise control (CC) systems, adaptive cruise control (ACC) systems and lane keeping assistance (LKA) systems.



SAE (J3016)	**Level 0 NO Automation**	**Level 1 Driver Assistance**	**Level 2 Partial Automation**	**Level 3 Conditional Automation**	**Level 4 High Automation**	**Level 5 Full Automation**
BASt	**Driver Only**	**Assisted**	**Partially Automated**	**Highly Automated**	**Fully Automated**	**-**
NHTSA	**Level 0 No Automation**	**Level 1 Function Specific Automation**	**Level 2 Combined Function Automation**	**Level 3 Limited Self-Driving Automation**	**Level 4 Full Self-Driving Automation**	
DfT	**Driver Assistance**			**High Automation**	**Full Automation**	

Figure 2.5 Summary of definitions of levels of vehicle automation by SAE, BASt, NHTSA and DfT (Gasser and Westhoff, 2012; NHTSA, 2013; 2025AD, 2015; DfT, 2015c).

At this level of automation, the driver should constantly monitor driving and is fully responsible for the control and safety operations of the vehicle.

- The second level of vehicle automation is defined as “Level 2 Partial Automation” by the SAE (2014), “Partially Automated” by the BASt (Gasser and Westhoff, 2012), and “Level 2 Combined Function Automation” by the NHTSA (2013), and is included in the “Driver Assistance” category proposed by the DfT (2015c).

Level 2 automation systems are able to perform the lateral and longitudinal control of the vehicle, allowing the human driver to take his/her hands and feet off the vehicle controls, but the drivers are not allowed to remove their eyes off roads and be mentally disengaged from driving or perform any other non-driving related tasks. And they are fully responsible for the safety of the driving and are required to constant monitor driving and be available to take over vehicle control at any time of the journey without prior warning (Gasser and Westhoff, 2012; NHTSA, 2013; SAE, 2014; DfT, 2015c).

- The third level of automation would enable drivers to be completely disengaged from driving. It is defined as “Level 3 Conditional Automation” by the SAE (2014), “Highly Automated” by the BASt (Gasser and Westhoff, 2012), “Level 3 Limited Self-driving Automation” by the NHTSA (2013) and “High Automation” by the DfT (2015c).

While at levels 0 to 2 automation discussed above the driver is required to be engaged in driving and be constantly monitoring the driving environment, vehicles equipped with level 3 high automation systems are able to perform full dynamic driving control (steering, accelerating and braking) as well as monitoring the driving environment. The driver must be present but is allowed to be completely disengaged from driving and can safely engage in other non-driving related tasks. However, there are situations which the Level 3 automation systems will not be able to cope with, such as entering a construction area, or a rural road without lane markings and network connections. In such situations the highly automated driving system will send a takeover request to the driver and provide a sufficient lead time for them to take over control of the vehicle and, in order to ensure safety, the driver must successfully take over control of the vehicle within the lead time provided (Gasser and Westhoff, 2012; NHTSA, 2013; SAE, 2014; DfT, 2015c). In addition, the SAE (2014) has specified a “Level 4 High Automation” in which the automated vehicle can automatically initiate a safe mode to ensure safety even if the drivers do not take over control of the vehicle in the time requested.

- The ultimate level of vehicle automation is defined as “Level 5 Full Automation” by the SAE (2014), “Fully Automated” by the BASt (Gasser and Westhoff, 2012), “Level 4 Full Self-Driving Automation” by the NHTSA (2013) and “Full Automation” by the DfT (2015c).

Such systems are designed to perform all safety-critical driving control and to monitor driving for an entire journey under all conditions, and they may require drivers to provide destination or navigation information but they are not expected to take over control of the vehicle at any time during a journey (Gasser and Westhoff, 2012; NHTSA, 2013; SAE, 2014; DfT, 2015c).

2.3.2 Issues of takeover in HAVs

In automation systems, control of the system could be transferred between the human and the automation systems, as Figure 2.6 illustrates. Such transitions of control include when the human gives the control to the automation systems and when the human takes over control from the automation system (Flemisch et al., 2008).

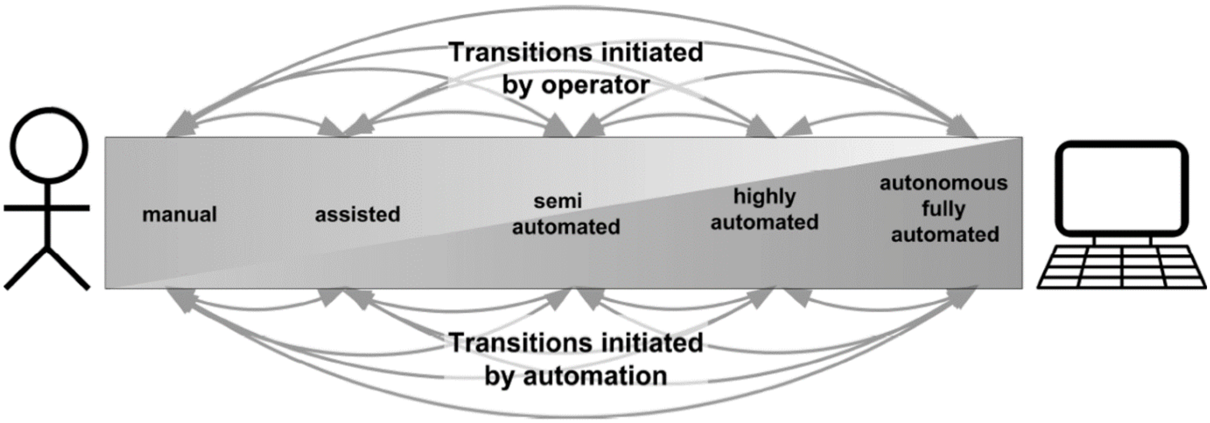


Figure 2.6 Transitions of control between human operators and automation systems (Flemisch et al., 2008)

In the context of driving, human error is the main reason for more than 90% of road collisions (Reason et al., 1990), and the introduction of automated vehicles may have the potential to reduce collisions and accidents (DfT, 2015c). However, until the ultimate level of vehicle automation becomes widespread, there are still situations where input from human drivers is necessary. The issue of takeover refers to situations where a human driver takes over control of the vehicle from the automated driving system (Gold et al., 2013a; Radlmayr et al., 2014; Gold et al., 2016; Clark and Feng, 2017; Eriksson and Stanton, 2017). The complexity and criticality of the takeover situation vary between different levels of vehicle automation. At lower levels of automation, such as SAE Levels 0, 1 and 2 automation systems (SAE, 2014), drivers are required to be constantly monitoring driving and are fully responsible for the safe driving of the vehicle at all times (SAE, 2014), and therefore takeovers would be relatively less complex as they are always to be undertaken while the human drivers are fully engaged in the driving of the vehicle. Likewise, takeover at the ultimate level of automation systems, such as SAE Level 5 systems, would not be needed, as they are capable of safely performing all driving tasks for the whole journey in all use cases (Gasser and Westhoff, 2012; SAE, 2014).

However, in a highly automated vehicle (HAV), which refers to SAE Level 3 systems in this study, takeover is more complex and represents an important human-machine interaction (Gold et al., 2013a; Radlmayr et al., 2014; Gold et al., 2016). In HAVs, human drivers are permitted to be completely disengaged from driving and also have the freedom to perform various types of non-driving tasks during automated driving. However, in takeover situations, drivers need to promptly switch their attention from the non-driving tasks they were performing to the driving task, regain situation awareness of the driving environment and effectively take over the control of the vehicle within a lead time provided by the HAV system (Gasser and Westhoff, 2012; Gold et al., 2013a; NHTSA, 2013; SAE, 2014). The state of complete disengagement from the operation of a system could lead to out-of-the-loop performance problems, which could lead to deteriorations in the human performance in retaking manual control of the system (Endsley and Kiris, 1995; Kaber and Endsley, 1997). Therefore, the process of takeover in HAVs could be potentially complicated and demanding for drivers and it is crucial for the safety of HAVs.

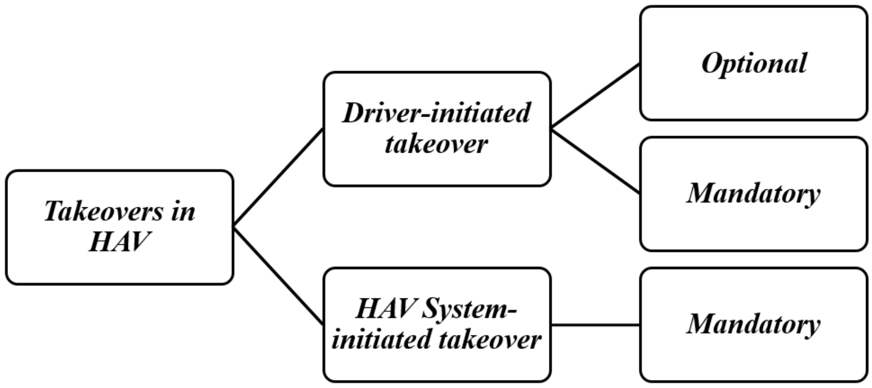


Figure 2.7 Types of takeover in HAVs (Flemisch et al., 2008; Melcher et al., 2015; Lu et al., 2016).

Generally, as Figure 2.7 illustrates, takeovers in HAVs could be broadly grouped into two main categories: driver-initiated and HAV system-initiated takeovers (Flemisch et al., 2008; Melcher et al., 2015; Lu et al., 2016). A driver-initiated takeover refers to situations when the human driver makes the decision to deactivate automated driving and to manually drive the vehicle by themselves. This is generally in ordinary situations of low urgency (Lu et al., 2016). There are two types of driver-initiated takeover: optional and mandatory cases (Lu et al., 2016). The optional driver-initiated takeover happens when a driver decides to manually drive in non-critical situations (Lu et al., 2016). For example, a driver ascertains that the driving conditions such as weather and traffic conditions are suitable so that they would like to manually drive the car. Although driver-initiated takeovers are generally low in urgency and criticality, they could sometimes pose a safety threat if the driver initiates a takeover request to the HAV in unsuitable situations in which HAVs could be more suitable compared to the human drivers, for example, in the task of constantly maintaining low distance between vehicles when driving in heavy traffic on a motorway for a prolonged period of time (Lu et al., 2016). Compared to the optional driver-initiated takeover, a mandatory driver-initiated takeover has a relatively low probability of occurrence. It happens when the drivers detect an abnormal situation so that they must take over control of the vehicle, such as when, during automated driving, drivers detect an error in the HAV system but the HAV system does not notice it and fails to alert the driver (Lu et al., 2016).

The second category is the HAV system-initiated takeover. It could be more critical and demanding for the drivers compared to a driver-initiated takeover. It happens when the HAV system detects a system limitation, such as driving in places without full road signs and markings, construction sites, or rural areas with no signal or network connections. The human driver is then required to take over control of the vehicle within a lead time period (Gold et al., 2013a; Gold and Bengler, 2014; Melcher et al., 2015; Gold et al., 2016; Lu et al., 2016). Gold and Bengler (2014) have explained the whole process of a generic HAV system-initiated takeover situation. As Figure 2.8 indicates, the HAV is automatically driving and the driver is disengaged from driving and performing non-driving related tasks. Suddenly the HAV detects a system limitation. It then informs the driver with a takeover request and provides a sufficient lead time to reassume control of the vehicle. Within the lead time, the HAV continues to drive until it reaches the system limitation. Following the takeover request, the driver switches their attention from non-driving tasks to the road and starts to conduct the cognitive processing needed for takeover. After perceiving and comprehending information concerning the takeover situation, the driver executes active input to the vehicle controls such as steering wheel, accelerator or brake pedal. As soon as the HAV receives the active input from the driver, it transfers control to the driver. Then drivers initiates their manoeuvres to deal with the system limitation.

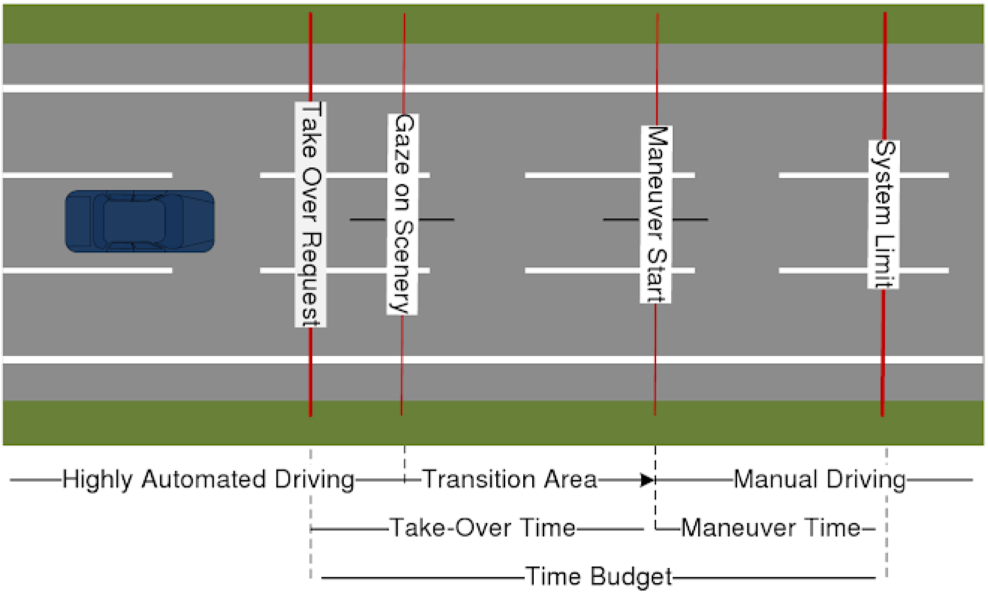


Figure 2.8 Illustration of a generic HAV system-initiated takeover situation (Gold and Bengler, 2014).

2.3.3 Data requirements to quantify takeover performance in HAV

Considering the significance of the takeover control to the safety of HAVs, it is important to quantify takeover performance. Data required for that can be broadly divided into two categories concerning the time and quality aspects of takeover (Gold *et al.*, 2013a; Gold and Bengler, 2014; Gold *et al.*, 2016). In terms of the time aspects, the takeover time describes how soon the driver generates the first active input to the vehicle after being requested to take over by HAVs (Gold and Bengler, 2014). In addition, the hands-on time is the time from the takeover request to the point that the driver has put their hands on the steering wheel (Gold et al., 2013a; Gold and Bengler, 2014). Similarly, gaze time is the time between the takeover request and the point that the driver moves their sight line away from the non-driving-related task (Gold et al., 2013a; Gold and Bengler, 2014). Regarding the quality aspects, the resulting acceleration represents the maximum force that the driver generates on to the road, and the larger its value the closer it is to the physical limit of the force the car tyre can transfer to the ground, reflecting an unstable and dangerous takeover (Gold et al., 2013a; Gold and Bengler, 2014; Radlmayr et al., 2014). Also, drivers' braking and steering behaviour is useful to quantify how drivers responses to the system limitations of the HAV (Gold et al., 2013a; Gold and Bengler, 2014). Also, previous research has used the stability of the vehicle as a measurement of takeover quality, such as by calculating the standard deviation of the steering wheel input (Mok et al., 2015a; Körber et al., 2016). Higher values represent less stable takeover. Moreover, minimum time-to-collision (TTC) is a parameter used to measure the urgency of takeover, defined as the time required for the vehicle to collide with the system limitation if it continues driving at the present speed (van der Horst and Hogema, 1993). Smaller values of TTC represent more critical takeover (Gold and Bengler, 2014; Radlmayr et al., 2014). Finally, the total number of collisions during the takeover process could be used to quantify takeover quality, where the greater the number of collisions, the worse the takeover quality (Gold and Bengler, 2014; Radlmayr et al., 2014).

2.3.4 Situation awareness in HAVs

Situation awareness plays a crucial role in the driver's driving performance (Endsley, 1995b; Endsley, 1995a). Endsley (1995b) defined situation awareness as:

"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."

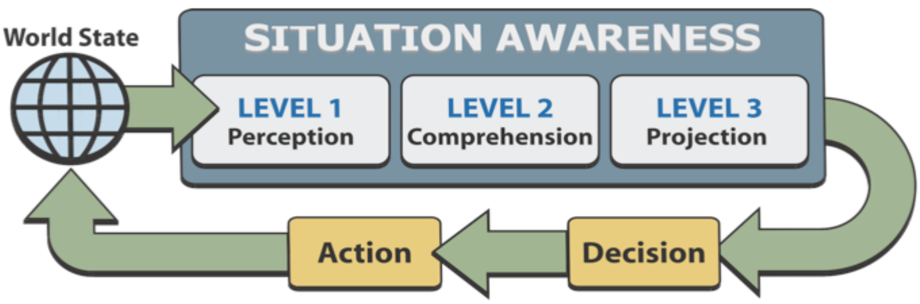


Figure 2.9 The three levels of situation awareness (Endsley, 1995b; Jones et al., 2011).

As Figure 2.9 illustrates, situation awareness can be classified into three levels (Endsley, 1995b; Endsley, 1995a; Jones et al., 2011). Level 1 refers to the perception of the important information in the environment relevant to task performance. Level 2 refers to the ability to be able to understand the meaning of the perceived information of the environment. Finally Level 3 relates to the ability to be able to predict what will happen in the future.

There are several methods available to measure situation awareness (Salmon et al., 2006). Freeze probe techniques are commonly used methods, where ongoing tasks are suddenly paused, and then several situation awareness questions are asked of participants and they need to answer the questions according to the information may have about the situation at the moment the task was paused (Salmon et al., 2006). The SAGAT (situation awareness global assess technique) is the most popular freeze probe technique (Endsley, 1995a; Salmon et al., 2006). The limitation of this method is that they rely on the pausing of the tasks which could potentially affect the sequence and coherence of experiments. Another common method used to measure situation awareness involves self-rating methods such as the situation awareness rating technique (SART) which is typically carried out after the trial (Salmon et al., 2006). The advantage of this method is that it is flexible and cost-effective; however, a limitation is that participants may find it difficult to recall the necessary information after the experiment (Salmon et al., 2006). Apart from the above methods, performance measures are also commonly used to measure situation awareness indirectly; for example, where the driver's situation awareness in driving could be measured by performance in detecting danger and collision avoidance (Gugerty, 1997; Salmon et al., 2006).

Researchers have realised the potential impact on drivers' situation awareness due to the change in the roles of drivers in HAVs. Merat and Jamson (2009) conducted a driving simulator investigation with 39 participants aged 23 to 63 years to assess the effect of experiencing the HAV on situation awareness. The drivers' time to react to critical events was used to measure situation awareness and it was found that compared to manual driving, HAVs significantly reduced situation awareness. In addition, van den Beukel and van der Voort (2013) examined drivers' situation awareness in HAVs, and found that it positively correlated with the length of the lead time available to take over control in the HAV. Meanwhile drivers' situation awareness as measured by SART was found to be positively correlated with the success of the takeover of control of the vehicle in HAVs.

2.3.5 Effect of complete disengagement from driving on takeover performance

A key revolutionary feature of HAV is to allow drivers to not constantly have to monitor driving and to be completely disengaged from driving (SAE, 2014; DfT, 2015c). Previous studies have investigated the potential impact of this key feature of HAVs on drivers' takeover performance. In order to achieve a state of complete disengagement from driving, a common strategy adopted in previous studies was to apply mandatory non-driving related tasks which the participants had no other choice but to perform. Various types of tasks were adopted, which could be broadly grouped into two categories: standardized and naturalistic tasks (Zeeb et al., 2016).

Some studies adopted standardized tasks to study the complete disengagement in driving in HAVs, and found that it leads to deteriorations in performance. Merat et al. (2012) carried out a driving simulator study with 50 drivers aged between 28 and 68 years to examine the effect of complete disengagement from driving on performance. The drivers were disengaged from driving by performing twenty-question tasks in the HAV. It was found that, when not distracted by the twenty-question tasks, participants exhibited similar responses when manually driving the vehicle and using the HAV. However, when they were performing the non-driving-related tasks, their performance was worse. In addition, Gold et al. (2013a) conducted a driving simulator investigation with 45 participants aged between 19 and 57 years. The participants were asked to perform a standard task of surrogate reference task (SuRT) delivered by a tablet before being requested to take over the control from the HAV. They found that compared to when manually driving the vehicle, complete disengagement from driving in the HAV resulted in more critical and sudden acceleration and braking manoeuvres, and thus worse takeover quality. Radlmayr et al. (2014) implemented a driving simulator investigation with 48 participants (mean age= 33.5 years, SD=9 years) to examine the effects of complete disengagement from driving on takeover performance achieved by performing two standard tasks; a cognitively distracting n-back Task and a visually distracting surrogate reference task (SuRT). The results showed that, compared to performance while manually driving, complete disengagement from driving achieved by performing these two tasks led to slower takeover time and poorer takeover quality among the participants.

Apart from standardized tasks, many studies have used naturalistic tasks to enable a state of complete disengagement from driving among participants, and they also found the negative effect of a state of complete disengagement from driving on takeover performance in HAVs.

Louw et al. (2015) conducted a driving simulator study with 16 younger drivers aged between 19 to 26 years. A reading task displayed on a tablet was used to enable the drivers to be completely disengaged from driving. It was found that, compared to manual driving, complete disengagement from driving resulted in significantly slower reactions and decision making and worse takeover quality. Comparing to monitoring driving, complete disengagement also resulted in greater resulting acceleration and slower decisions in changing lane, although the results were not statistically significant. Eriksson and Stanton (2017) studied the effect of complete disengagement from driving caused by a task which involved reading a newspaper on takeover performance with 26 participants aged between 20 to 52 years. They found that, compared to when monitoring driving, participants exhibited greater variance and significantly slower takeover behaviour when they were completely disengaged from driving. Zeeb et al. (2016) investigated the impact of complete disengagement from driving on takeover performance caused by three naturalistic tasks of writing an email, reading the news and watching video with 79 participants (mean age=39.5 years, SD=10.3 years). Interacting with the HAV without performing non-driving related tasks was selected as the control group. It was found that, complete disengagement from driving had little effect on takeover time; however, it negatively affected takeover quality. Research by VENTURER (2017) conducted a driving simulator experiment to examine drivers' takeover behaviour in HAVs with 31 participants (18-69 years, mean age=41.0 years, SD=13.9 years). A proof reading task was adopted to disengage the participants and they found that drivers took around 2.5s to initiate their first contact to the vehicle controls. Furthermore, Zeeb et al. (2017) has investigated the effects of performing non-driving related tasks with different degrees of manual task load on takeover performance in the HAVs. They found that engaging in a non-driving-related tasks with higher manual task load (reading from a handheld tablet) lead to worse takeover performance compared to a task with lower manual task load (reading from a mounted tablet).

The above studies have used both standardized and naturalistic tasks to achieve the stage of complete disengagement from driving. Both methods have their own strengths. Using standardized tasks allows the study to precisely control the amount of task load, whereas using naturalistic tasks could reflect authentic use cases of HAVs and thus increase the ecological validity of the study (Zeeb et al., 2016). Despite the different types of non-driving related-tasks used, these studies have yielded consistent findings which indicate that the state of complete disengagement from driving in the HAV could have a negative impact on drivers' takeover performance compared to when they were monitoring driving in the HAV or manually driving the vehicle. An important explanation for these findings concerns the 'out-of-the-loop' (OoTL) performance problem (Endsley and Kiris, 1995; Kaber and Endsley, 1997). OoTL refers to a state when the human operator of a system no longer has an awareness of the status of the system and the outside environment due to the lack of interaction with the system (Kaber and Endsley, 1997). This affects operators' ability to resume control of the system (Endsley and Kiris, 1995; Kaber and Endsley, 1997).

However, the above studies have only tested participants of relatively young ages, and the findings may not be able to clearly explain how the state of complete disengagement from driving affect older drivers' performance of interacting with HAVs.

2.3.6 Effect of lead time on takeover performance

Despite the fact that the drivers can be completely disengaged from driving in HAVs, sometimes their takeover of the vehicle control is still needed, and the HAV will provide them with a sufficient lead time to do that (SAE, 2014; DfT, 2015c). Previous studies have attempted to explore how long a time is sufficient for drivers to take over control back from the automated vehicle.

van den Beukel and van der Voort (2013) implemented a driving simulator study with 34 university students (mean age of 21.3 years) to study the effect of three relatively short lead time (1.5s, 2.2s and 2.8s) on drivers' situation awareness and takeover performance. They found that, although the participants were able to take over control from a HAV, all three lead times were deemed insufficient as they all resulted in varying proportion of collisions among participants (1.5s: 47.5%, 2.2s: 20.8%. 2.8s: 12.5%). Furthermore, as the length of lead time increased, the participants exhibited slightly more comfortable takeover performance and higher situation awareness, which suggested the need for future research to test longer lead times. The effects of two longer lead times of 5s and 7s on takeover performance were tested by Gold et al. (2013a). They found that the average response times for braking input were 2.06s (5s lead time) and 3.10s (7s lead time), and average response times for steering input were 2.27s (5s lead time) and 3.65s (7s lead time). They also found that with the shorter lead time, the drivers made faster decisions and responses but exhibited worse takeover quality, and it was suggested that 7s could not be treated as a sufficient lead time due to the poor takeover performance it resulted in among participants.

In addition, Mok et al. (2015b) conducted a driving simulator study with 27 participants aged between 19 to 81 years to investigate their takeover performance in an HAV when three lead times of 2s, 5s and 8s were provided. The participants did not perform any non-driving related-tasks and were required to monitoring driving during automated driving in the HAV. It was found that a lead time of 2s is not sufficient for drivers to reassume control from the HAV. When providing 2s to take over, the drivers exhibited significantly worse takeover performance, and they evaluated it as less enjoyable and more uncomfortable. However, 5s was found to be a sufficient lead time for drivers to successfully take over control from the HAV, and there was no difference in driver's takeover performance between lead times of 5s and 8s. Therefore they suggested that a sufficient lead time would be between 2s and 5s. However, in this study, the participants were not asked to perform any non-driving-related task but were monitoring driving before being required to take over vehicle control. So a lead time between 2s and 5s may only be sufficient for drivers who are engaged in monitoring driving to take over, but it may not be enough for drivers who are completely disengaged from driving to safely and effectively reassume control in HAVs. Having realised the limitation of the study in terms of lead times with drivers who were purely monitoring driving before taking over in the HAV, they conducted another driving simulator test which had the same conditions except that the drivers were distracted on a video presented by a tablet for the whole time during automated driving in the HAV (Mok et al., 2015a). Surprisingly, they found that there was no difference in takeover performance between the drivers who were distracted by the video during automated driving and those who were monitoring driving. The reason for this finding could possibly be because, although in the latter study the participants were distracted by a video presented on a mounted tablet in the HAV, there was no measure to control for the drivers to be constantly watching the video and not monitoring driving, and so a state of complete disengagement among the drivers was not ensured.

In addition, Clark and Feng (2017) implemented driving simulator study to investigate the effect of age, engagement in secondary tasks and two time buffers of 4.5s and 7.5s on takeover performance of 18 older drivers (aged 62-81 years) and 17 younger drivers (18-35 years). They found that, in general 4.5s was enough for both younger and older drivers to take over control in the HAV, but 7.5 was perceived to be more preferable by the participants. In addition, older drivers were more easily engaged heavily in secondary tasks during automation and they reacted faster with 7.5s time buffers. However, as with the study of Mok et al. (2015a), Clark and Feng (2017) allowed participants to have the freedom to choose which non-driving tasks to perform, which may not have guaranteed that all participants were completely disengaged from driving at all times. Moreover, Melcher et al. (2015) found that a lead time of 10s resulted in a median takeover time of 3.5s for participants, and that this was an sufficient time for drivers to take over control of the vehicle from the HAV.

The above studies regarding the lead time for takeover generated different findings due to the different experimental conditions adopted. It is still not clear how long a lead time is enough for drivers who are completely disengaged from driving to safely and effectively take over control in HAVs.

2.3.7 Effect of traffic density on takeover performance

Previous studies have also investigated the effect of traffic density on takeover performance in HAVs and have provided consistent findings indicating that the presence of traffic would negatively influence takeover performance. Radlmayr et al. (2014) explored driver's takeover performance in different traffic density situations. The results showed that, compared to taking over control in the no-traffic situations, drivers showed significantly higher takeover times, lower values of TTC, greater longitudinal acceleration and greater number of collisions, indicating that high density traffic situations negatively affect the driver's takeover performance. Later research has confirmed these findings, Körber et al. (2016) concluded that both younger and older drivers manifested lower takeover times, higher TTC, and lower lateral acceleration in no-traffic situations than in higher traffic. In addition, Gold et al. (2016) conducted a driving simulator investigation to examine the effect of traffic density and verbal tasks on takeover performance in an HAV and found that the presence of traffic during takeover situations resulted in slower takeover time and worse takeover quality.

2.3.8 Effect of the human-machine interface (HMI) of the HAV on takeover performance

Previous research has also explored whether or not the design of the HMI in the HAV is associated with differences in takeover performance. The importance of the takeover situation in HAVs has been widely recognized, and therefore existing studies have generally focused on the design of the HMI during the takeover of control situations in HAVs.
A great number of studies have looked at the effect of the modalities of delivering information in the takeover request on drivers' takeover behaviour. Naujoks et al. (2014b) conducted a driving simulator investigation to compare the effect of purely visual takeover requests and visual combined with sound takeover requests on takeover performance among 16

participants. They found that the visual combined with sound takeover request led to a mean reaction time of 2.29s, while the purely visual modality led to a significantly longer reaction time of 6.19s. In addition, takeover quality was better with the visual and sound takeover request modality than purely visual. Therefore, it was concluded that the purely visual takeover request modality was not enough, especially for drivers who were performing non-driving-related tasks. This conclusion was supported by later research which suggested that a visual takeover request should be provided together with an acoustic takeover request (Clark and Feng, 2017). In addition, Forster et al. (2017) implemented a driving simulator investigation with 17 participants aged between 22 to 56 years to evaluate the impact of two types of visual and auditory takeover requests, and it was found that the visual and auditory takeover request with additional speech output resulted in faster reaction times and more positive subjective ratings among participants. Previous research has not only been limited to visual and sound takeover requests however, for example, Melcher et al. (2015) evaluated the effect of four types of takeover requests: a visual and sound takeover request, and three enhanced visual and sound takeover requests (integrated with mobile phone, integrated with sudden brake, and integrated with mobile phone combined with sudden brake). The results showed that these types of takeover requests had no significant effect on takeover time, but did have an effect on the driver's type of response. A takeover request with a sudden brake led to reactions of acceleration instead of steering and braking. Also it was suggested that, as long as the driver is provided with a sufficient lead time of 10s to reassume control of the vehicle, the designs of the takeover requests would not play a critical role in determining takeover performance. Also, Petermeijer et al. (2017) conducted a driving simulator-based study with 24 participants aged 24 to 35 years old to investigate the effects of single-mode (sound or vibration) and double-mode (sound and vibration) takeover requests on participants' takeover performance in an HAV. They found that the double-mode sound and vibration takeover request led to faster reaction times and higher satisfaction among the participants compared to the single-mode sound or vibration takeover requests.

Apart from studying the modalities used to deliver information to drivers in the takeover request, previous research has also explored the designs of takeover requests in the HAV. Gold et al. (2013b) evaluated a new form of takeover request which enables drivers to monitor HAV driving for two seconds and then they are asked to take over the control of the vehicle. They found that this type of takeover request slightly speeded up the driver's takeover time by 0.3s. Also, Merat et al. (2014) conducted a study on a driving simulator with 37 participants aged 28 to 67 years to assess two designs of HMIs in HAV, including a fixed

HMI that transfers control of the vehicle from the automation system to the driver after a fixed duration of 6 minutes, and a variable HMI that transfers control to the driver as long as it detects that the driver has shifted visual attention away from the road centre. They found that the fixed HMI led to better takeover performance compared to the variable HMI and drivers generally took 35s to 40s to stabilise the lateral control of the car. In addition, Lorenz et al. (2014) carried out a driving simulator investigation with 46 participants to investigate the effect of integrating augmented reality (AR) technology into the takeover request in an HAV. Two AR takeover requests were examined: one projecting a restricted corridor and another projecting a safe corridor in issuing the takeover request. The results showed that the type of request had no significant effect on takeover time, but the safe corridor projection led to improved takeover quality by leading to more consistent steering action.

The findings of the above studies have provided evidence suggesting that carefully designed HMIs for the takeover process in HAVs can play an important role and could have the potential to improve drivers' takeover performance. However, the above studies mainly focused on testing and evaluating the effects of HMIs in the HAV on takeover performance. It is still unclear how these HMIs were designed and whether the designs fully considered the preferences and requirements of end users. In addition, these studies only considered HMIs during takeover situations in HAVs. Studies regarding the effects of HMIs in HAVs during automated driving on drivers' takeover performance are still limited.

2.4 Older Drivers and HAV

2.4.1 Older drivers and existing ADAS

The human-machine interaction in a vehicle generally includes the driver's operation of the primary vehicle controls as well as interaction and communication with a variety of in-vehicle systems and applications (Norman, 1984). At the present time, the design of in-vehicle advanced driver assistance systems (ADAS) supporting human-machine interaction in a conventional vehicle focuses on giving feedback, information and support to drivers at the time when they are manually driving the car (Damiani et al., 2009). These systems could have the potential to benefit older drivers.

Previous studies have identified several ADAS that are able to meet older drivers' needs and requirements and potentially enhance their driving safety. A range of ADAS were identified to be able to offer tailored support to older drivers in terms of compensating for some aspects of their age-related functional decline, including impaired motion perception, peripheral vision, selective attention and speed of information processing and decision making, including collision warning systems, automated lane changing and merging systems, blind spot and obstacle detecting systems, in-vehicle signing systems, adaptive cruise control systems and driving information systems (Mitchell and Suen, 1997; Davidse, 2006). In addition, Musselwhite and Haddad (2007) conducted several focus groups with older drivers and identified three areas of ADAS which potentially correspond to older drivers' requirements, including in-vehicle speed limit information systems, in-vehicle road signs information systems and night vision systems. Moreover, Guo et al. (2010a) assessed a variety of ADAS for their potential to reduce the influence of age-related functional decline on older drivers' driving performance and suggested that ADAS which offer feedback and support to older drivers have the potential to improve their safety and mobility.

Previous studies have also tested the effectiveness of these age-friendly ADAS with older drivers. For example, Kramer et al. (2007) conducted a driving simulator investigation with 40 participants aged 18 to 82 years to investigate the effect of several collision warning systems on participants' collision avoidance performance. They found that the collision warning system with a visual and auditory warning modality yielded the best performance. Furthermore older drivers and younger drivers benefited from this system in the same ways. Also, Sullivan (2004) conducted a test-track study with 16 participants aged 20 to 73 years old to examine the effectiveness of night vision systems on driving performance. They found that such systems enhanced the distance of target detection among both younger and older participants. In addition, Edwards et al. (2016) conducted a driving simulator study with 30 older drivers to test the effectiveness of an in-vehicle navigation system which provided landmark-based route guidance, and they found that providing landmark route information by an audio and visual modality reduces the risks of distraction and led to better navigation performance. Jenness et al. (2008) conducted a survey which found that older drivers exhibited more positive attitudes towards adaptive cruise control and adapted to it better in their daily life compared to younger drivers. Finally, Guo *et al.* (2013a) conducted a study on a driving simulator with 26 older and 16 younger drivers to investigate the effect of three different levels of intelligent speed adaption (ISA) systems on older drivers' driving performance. Results showed that ISA informing older drivers of the local speed limit and forthcoming changes, as well as ISA automatically braking when the car exceeded the speed limits significantly improved older drivers' speed limit compliance performance.

2.4.2 Older drivers and HAVs

The review of the above studies suggests the importance of current ADAS in improving older driver's driving performance and safety and potentially increasing their mobility. However, these ADAS generally fall into the category of lower levels of vehicle automation systems (SAE levels 0 and 1).With the development of vehicle automation technologies, the potential rollout of higher level automation systems such as HAVs (SAE level 3) would extend the human driver's role from being solely an active driver to including passive monitoring and being more of a passenger. Drivers will also have the freedom to engage in various types of non-driving-related tasks during automated driving. In terms of takeover situations, however, they need to take over control of the vehicle effectively and promptly. These new functionalities of HAVs could potentially deliver huge benefits in terms of enabling older drivers to drive for longer more safely and thus enhance their mobility and wellbeing (Chan, 2017; Young et al., 2017; Bellet et al., 2018). These changes in the driver's role in HAVs have created an urgent need to explore what this new type of human-machine interaction may mean for older drivers. Only a limited number of studies have attempted to investigate older drivers' interactions with HAVs.

Miller et al. (2016) implemented a driving simulator study with 36 drivers aged between 15 and 81 years to explore the effect of age on takeover performance in the HAV. During automated driving in the HAV, one of three non-driving-related tasks was given to the participants: watching a film, reading a story from a tablet in their hands, and monitoring driving. A lead time of 6.5s was provided to participants to take over control and react to a critical event. No significant effect was found of performing the different non-driving-related tasks on takeover performance. Although age itself did not have a significant effect on takeover performance, participants aged 70 and over years were found to have more problems in hearing and understanding the experimental tasks. Also, Molnar et al. (2017) conducted a driving simulator study with 72 participants aged between 16 to 75 years old to examine age-related differences in takeover performance in the HAV. They did not apply any non-driving-related tasks for the participants to perform during the automated driving period in the HAV. Participants experienced seven different takeover situations and a lead time of 5s was provided to participants to reassume control over the vehicle and to react to the critical event in each situation. After each takeover situation, participants were given the power to choose when to activate the automated system. They found that found that older drivers aged 65-75 exhibited similar takeover performance to the comparison group of drivers aged 25-45. In addition, Körber et al. (2016) carried out a driving simulator investigation with 72 participants aged between 19 to 79 years old to investigate the effect of age on takeover performance in an HAV. Participants were asked to perform tasks of verbally answering twenty questions presented by a hands-free mobile phone. A lead time of 7s was provided for them to take over control of the vehicle. Although, no effect of age on takeover time was found, older drivers braked more frequently and harder, and left higher times to collision. It was suggested that older drivers were safer and more cautious when taking over control from the HAV, which was deemed to be due to their greater driving experience. In addition, Clark and Feng (2017) conducted a driving simulator study with 35 participants aged between 17 and 81 years to study age differences in preferences for non-driving-related tasks as well as takeover performance in an HAV. Two lead times of 4.5s and 7.5s were adopted for participants to reassume control over the vehicle. Age differences were found in terms of the preferences for non-driving-related tasks during automated driving. Younger drivers were more likely to use electronic devices. However, older drivers were more likely to speak to other people, and they were more likely to become heavily engaged in non-driving-related tasks. Despite that, older drivers showed more cautious and stable takeovers than the younger drivers. In addition, it was also found that older drivers, but not younger drivers, responded faster to the longer lead time.

The above studies have provided important information to understand how older drivers interact with HAVs and some age differences have been observed in terms of drivers' behaviour of interacting with HAVs. However, there are still limitations in these studies. To begin with, the lead time adopted for participants to take over control of the vehicle were limited to the range of 4.5s to 7.5s (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017). These relatively short lead times may result in high levels of stress, which has been found to have a negative influence on older people's decision making abilities (Earles et al., 2004). So Clark and Feng (2017) found that older drivers benefited more than younger drivers from the longer length of lead time when taking over control from HAV. The above studies may not reflect how older drivers interact with HAVs when they have sufficient time. Therefore, there is a need to explore older drivers' takeover performance when significantly larger lead times are provided to reassume control in the HAV. In addition, the review of previous research with HAV involving older drivers indicates that the effects of complete disengagement from driving among older drivers have not been fully investigated. For example, Molnar et al. (2017) did not apply any non-driving-related tasks to disengage older drivers from driving in the HAV before taking over control, whilst Clark and Feng

(2017) offered the participants the freedom to choose what tasks they would like to perform and how much they would like to be involved in these tasks. Although both Körber et al. (2016) and Miller et al. (2016) adopted mandatory non-driving related tasks for participants to perform during automated driving, the verbal question-answering task used by Körber et al. (2016) could only distract the participants but not completely disengage them from driving during automated driving in the HAV. Similarity, Miller et al. (2016) asked participants to perform the task of watching a film or reading a story; however, the participants were able to interrupt the tasks at any time before they were asked to take over control of the vehicle. Thus, the influence of complete disengagement from driving on the older drivers' takeover performance in HAVs has not been fully investigated.

2.5 Key Research Gaps

This review of existing knowledge concerning older drivers and HAVs suggests that considerable efforts have been made to understand how drivers interact with HAVs, as well as to identify age-related differences in takeover performance in the HAV. However, there are still significant knowledge gaps in this field, as follows:

- Firstly, the majority of the studies concerning the takeover process in the HAV have focused on drivers in general, and only limited research has focused on older drivers. Considering that elderly drivers could potentially be an important group of end users that would benefit from the revolutionary human-machine interactions in HAVs (DfT, 2015c; Chan, 2017; Young *et al.*, 2017; Bellet *et al.*, 2018), therefore the effect of age on drivers' performance in interacting with HAVs during the process of taking over control needs to be further investigated.

- Secondly, the potentially negative impact of a state of complete disengagement from driving in the HAV on drivers' takeover performance has been widely recognized (Merat et al., 2012; Gold et al., 2013a; Radlmayr et al., 2014; Louw et al., 2015; Zeeb et al., 2016; Zeeb et al., 2017). However the review of previous studies of HAVs involving older drivers indicates that the effects of a state of completely disengagement from driving on older drivers' takeover behaviour in HAVs have not been fully investigated (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017).

- Thirdly, a common situation is that older driver have reduced mobility in terms of driving in adverse weather conditions which reduce the visual clarity of the driving environment (Kline et al., 1992; Marottoli et al., 1993; Persson, 1993; Hennessy, 1995; Ball et al., 1998; Kostyniuk and Shope, 1998; Lyman et al., 2001; Charlton et al., 2006; Bellet et al., 2018). As the new human-machine interaction in HAV could release drivers from driving for some part of the journey, thus it may have the potential to enhance older drivers' mobility in adverse weather conditions. However, existing studies of drivers' takeover in HAVs have neglected the effect of weather conditions and mainly focused on drivers' interaction with HAVs in good weather conditions. Therefore, there is an important need to investigate older drivers' takeover performance from HAVs in adverse weather conditions.

- In addition, changes in the role of driver in HAVs have created a need to explore the design of new types of human-machine interaction for HAVs, especially during automated driving periods and in takeover periods. However, the review of the literature suggests that current studies of HAVs involving older drivers tend to focus on quantifying their performance during the process of retaking control in HAVs (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017), but knowledge regarding what are older drivers' needs and requirements towards the human-machine interactions in HAVs are still under-researched.

- Finally, although existing research has recognised the importance of a carefully designed HMI in the HAV for the takeover process in improving drivers' performance (Lorenz et al., 2014; Naujoks et al., 2014b; Radlmayr et al., 2014; Melcher et al., 2015; Clark and Feng, 2017; Forster et al., 2017; Petermeijer et al., 2017), it is still not clear whether the design of these HMIs fully considers the needs and requirements of end users. Given that the majority of these studies did not directly focus on older drivers, knowledge about how to design the HMIs of HAVs so as to meet the older driver's needs and requirements is still limited. And it is still not clear whether or not the HMIs designed based on older drivers' requirements would affect their takeover performance in HAVs.

2.6 Conclusions

This literature review has shown that driving is important for older drivers to maintain mobility and independence. The effect of age-related functional decline negatively affects older drivers' safe driving ability. In order to deal with these difficulties, some older drivers have to adjust their driving by reducing their presence in some specific situations or completely giving up driving. These self-regulatory activities significant reduce their mobility, independence and wellbeing. In the meantime, with the development of levels of vehicle automation, the forthcoming HAVs could potentially benefit older drivers by releasing them from driving tasks for some part of the journey. HAVs would deliver new human-machine interactions that enable drivers to be completely disengaged from driving during automated driving periods. However, there are still situations where the HAV would require input from the drivers. Drivers will then be provided with a sufficient time to take over control of the vehicle in some situations. However, a state of complete disengagement from driving in HAV has been found to have a negative impact on drivers' takeover performance. Other factors such as the length of lead time, traffic density and the HMI in the HAV have been found to be associated with driver performance.

Although a small number of studies have attempted to study older drivers' performance in interacting with HAVs, the literature review has identified significant knowledge gaps in research into older drivers and HAVs. The presence of these gaps generally reflects the fact that the existing research on HAVs has not fully considered older drivers' performance, capabilities, needs and requirements. The lack of this knowledge could potentially prevent older drivers from benefiting from HAVs. Therefore, this study aims to fill these gaps and to generate new knowledge to facilitate a safe and comfortable human-machine interaction for older drivers in HAVs and to eventually enhance their mobility, independence and wellbeing. The findings of this study will provide novel insights into older drivers' interactions with HAVs. To achieve this aim, a review of available methods and explanations of the methods used in this study are detailed in Chapter 3.

Chapter 3. Methodology

3.1 Introduction

The review of the literature regarding older drivers and HAVs in Chapter 2 has revealed that clear knowledge gaps exist in regard to how older drivers interact with HAVs, what their needs and requirements are concerning HAVs, and how HAVs could be designed to be friendly to the older drivers and potentially deliver benefits in enhancing their mobility and wellbeing. In order to address these gaps in knowledge and fulfil the defined aim and objectives of this study (Section 1.6), data is required firstly to examine the takeover performance of older drivers in the HAV, and secondly to explore their needs and requirements concerning the human-machine interactions in HAVs. Based on these findings, some specific requirements of older drivers could be implemented on the HAV and then evaluated and tested with the older drivers. The chapter reviews the available methods to collect data required and explains the selection of methods for this thesis.

3.2 Review of the Available Methods for Assessing Drivers Performance of interacting with the HAV

The first part of the aim of this study focuses on investigating older drivers' takeover performance in the HAV in order to generate an understanding of what would be required to facilitate an effective and safe human-machine interaction in the HAV from an older driver perspective and furthermore to understand whether these requirements would be different from those of the general driving population. This part of the research is quantitative in nature, which attempts to draw statistically significant conclusions about a whole population by investigating a representative sample of that population (Lowhorn, 2007; Polit and Beck, 2010). In order to achieve the above aim, quantitative data of drivers' performance of interacting with HAVs needs to be collected. The data requirements have been reviewed in Section 2.3.3. And a wide range of potential methods are available to collection the data required, include driving simulator, test tracks, on-road tests, field operational tests and completely naturalistic study (McLaughlin *et al.*, 2009).

3.2.1 Driving simulator

A driving simulator is an effective tool for research into driving and driver training (Hoffman et al., 2002; De Winter et al., 2007). There are various types of driving simulators which differ in their fidelity to real world conditions. For example, a basic driving simulator consists of a desktop computer and a set of imitative vehicle controls, while high fidelity driving simulators are equipped with 360-degree screens and authentic vehicle controls which could provide a multidimensional driving experience and a variety of types of visual, auditory and haptic feedback to users (Hoffman et al., 2002; McLaughlin et al., 2009). Driving simulators have been proved to be useful and effective in evaluating the effectiveness of advanced driver-assistance systems (Seppelt and Lee, 2007; Guo *et al.*, 2013a; Edwards *et al.*, 2016). With the emergence of vehicle automation technologies, driving simulators have also been widely used in previous studies for assessing and quantifying driver behaviour and performance when interacting with the HAVs (Merat *et al.*, 2012; Gold *et al.*, 2013a; Gold *et al.*, 2013b; Gouy *et al.*, 2014; Radlmayr *et al.*, 2014; Gold *et al.*, 2015; Mok *et al.*, 2015b; Gold *et al.*, 2016; Körber *et al.*, 2016; Miller *et al.*, 2016; Zeeb *et al.*, 2016; Eriksson and Stanton, 2017; Molnar *et al.*, 2017; VENTURER, 2017; Zeeb *et al.*, 2017).

There are many advantages of the use of driving simulators. To begin with, a wide range of factors and conditions can be customised according to the research aims and they can also be precisely manipulated and controlled, such as type of vehicle, driving mode (manual driving or automated driving modes), in-vehicle technology functionalities, traffic, pedestrians, cyclists, buildings, weather conditions, road layout and design, and road vegetation. This would enable the research to focus on studying the factors relating to the research questions, while the extraneous factors can be controlled as much as possible (McLaughlin et al., 2009; De Winter et al., 2012). Secondly, using a driving simulator can increase the repeatability of research, as it could provide identical experimental condition from one test to another, and it could enable participants based in different physical locations to experience precisely the same experimental conditions. This would potentially make the results and findings of the research more reproducible (De Winter et al., 2012). Thirdly, a large volumes of synchronized data could be automatically recorded by the driving simulator itself, such as measurements of speed, speed variation, lateral positon, steering wheel angle, longitudinal and lateral acceleration, reaction time and time to collision (TTC), such data collection capabilities can make the process of data collection much more easier, effective and efficient (Godley *et al.*, 2002; Stevens *et al.*, 2002; McLaughlin *et al.*, 2009; De Winter *et al.*, 2012). In addition, another major advantage of using a driving simulator is safety. It is suitable for performing driving-related experiments that could be potentially dangerous and risky to the researchers and participants if undertaken on roads in real-world environment, including experiments regarding the exposure of participants to dangerous and risky driving tasks for example, collision avoidance, drink driving and driving while using a mobile phone; and in experiments concerning the testing and evaluation of new technologies related to driving, such as assessing the safety of HAVs. These tasks could be much more safely conducted on a driving simulator (McLaughlin et al., 2009; Underwood et al., 2011; De Winter et al., 2012). Finally, research using a driving simulator is cost-effective compared to research involving real vehicles in a real-world condition (De Winter *et al.*, 2012). For example, testing and evaluating a wide range of advanced-driver-assistance systems and automated vehicles on a driving simulator could be more cost-effective compared to testing them with a real vehicle on real road conditions which may entail substantial monetary cost. Furthermore a driving simulator does not take up much room compared to a test track or real road tests.

However, using a driving simulator could have some limitations and challenges. Firstly, conducting research with low-fidelity driving simulators may demotivate participants and result in non-reliable driving performance, thus reducing the validity of the results (De Winter et al., 2012). In addition, it may be difficult to ascertain how much the performance participants exhibited in a driving simulator could be transferred to their performance when driving an authentic vehicle in real road conditions (McLaughlin et al., 2009; De Winter et al., 2012). Moreover, simulator sickness and symptoms of discomfort may potentially affect the performance of participants or even resulted in their withdraw from the test, and thus reduce the effectiveness of the outcomes of research (McLaughlin et al., 2009; Brooks et al., 2010; De Winter et al., 2012; Keshavarz et al., 2018). This is especially a problem when the research involves older drivers as participants, as they have been found to more commonly experience simulator sickness compared to younger drivers (Brooks et al., 2010; De Winter et al., 2012).

3.2.2 Test track

Apart from driving simulators, performing controlled driving experiments on a test track is also a common method used in driving-related research. It measures driving performance by allowing participants to drive authentic vehicles in controlled testing environments. Compared to using a driving simulator, research using test tracks is closer to real-road driving conditions as it often measure drivers' performance in operating a real vehicle; however, the testing environment can still be controlled according to experimental design or safety considerations (Wooldridge *et al.*, 2000; McLaughlin *et al.*, 2009; Guo *et al.*, 2013b). Test tracks have been used to study driver behaviour and to evaluate in-vehicle technologies in research into conventional vehicles (Ranney et al., 2000; Wooldridge et al., 2000; Ranney et al., 2005). In addition, several studies have adopted this method to investigate driver interaction with vehicle automation technologies (Stanton *et al.*, 2011; Llaneras *et al.*, 2013; Albert *et al.*, 2015; VENTURER, 2017). The strength of the test track lies in the involvement of real vehicles, which enhances the fidelity of the research to real life while the testing environment and experimental conditions can still be controlled and customised to specifically focus on the research questions of a particular study (McLaughlin et al., 2009). For example, if the research questions concerns the measurement of driver alertness, the test tracks could be designed to involve other vehicles, pedestrians or cyclists. However, there are still some challenges in using the test track method. Firstly, although real vehicles are used, the fidelity of the research to real life could still be compromised if some factors were not carefully considered, such as participants' expectations, the existence of researchers and the design of the driving environment (McLaughlin et al., 2009). Secondly, a major challenge of a test track method is that it could be potentially complicated and high-cost. The test track could take up a large space and the involvement of participants operating real vehicles may require a complete development of a prototype testing system and its successful implementation on the testing car, which would be complicated and require large manpower resources and generate substantial monetary cost (Stanton et al., 2011; Llaneras et al., 2013; Albert et al., 2015). This could make test track methods unrealistic for studies with limited time or relatively low research budgets.

3.2.3 On-road test

Driving simulators and test tracks can provide tailored experimental design and precise safety controls based on the nature and aims of research. However, such controls may not be important for some studies, they could be undertaken in public road conditions (McLaughlin et al., 2009). Some studies have adopted on-road research to investigate drivers' interaction with automated vehicles (Eriksson et al., 2017; Banks et al., 2018; VENTURER, 2018). The major benefit of conducting driving-related research on real road conditions is that the road rules and regulations could enhance the face validity of the research, as the participants are being tested and measured in a driving task on a public road and they know that the common risks of driving on real-road exist, so they must keep careful watch for possible danger and maintain alertness just as they normally do when driving in daily life (McLaughlin et al., 2009). However, there are still several limitations and challenges of on-road research. Firstly, the repeatability of results would be reduced compared to those from driving simulators or test tracks, as the experimental environment, such as the traffic and weather conditions, under which each driver is tested will not remain identical when repeating the research each time (McLaughlin et al., 2009; De Winter et al., 2012). Secondly, on-road research allows participants to operate a real vehicle in a real world environment, which could make it more difficult to collect a large amount of synchronized data for driving performance compared to controlled research using driving simulators (Godley et al., 2002; De Winter et al., 2012). Moreover, due to the existence of risks and danger of driving in real world environments, on-road research could be potentially unsafe and risky to participants and experimenters, which would increase the difficulty of the research, especially when the research is in relation to assessing dangerous driving behaviour, testing the safety of new driving technologies and examining the driving behaviour of elderly drivers (Ball et al., 1998; De Winter et al., 2012; Bellet et al., 2018). Finally, the successful implementation of some on-road research, especially when it relates to new driving-related technologies such as vehicle automation, would require substantial monetary and policy support. For example, for an on-road test of an HAV, the design and development of a prototype HAV could potentially require considerately financial and human resources, and policy and legislative support would be necessary to permit the research to be undertaken on public roads. This could make on-road research less feasible when the budget of the research is relatively low or when the legislation of on-road testing for new driving-related technologies has not been fully established.

3.2.4 Field operation test and naturalistic study

Finally, a field operation test refers to a type of research in which a vehicle equipped with a testing system or a prototype of a new vehicle are deployed in everyday use on public road and relevant data is gathered according to the research aim and questions (McLaughlin et al., 2009). This is similar in many ways to on-road research, except that it normally takes longer duration and requires the testing vehicle to drive much longer distances (Kiefer et al., 2003; McLaughlin et al., 2009). Similar to field operation test, naturalistic driving studies concern investigating participants' driving behaviour and performance in driving their own cars in daily life over a prolonged duration (McLaughlin et al., 2009). The advantages of these two methods are that they are capable of investigating, capturing and observing participants' behaviour and performance when interacting with the testing technologies or vehicles in more routine circumstances in daily life (McLaughlin et al., 2008; McLaughlin et al., 2009; Guo et al., 2010b). However, using these methods requires the testing technologies to be in the near-market stages or to have been already widely popularised in order to allow the data collection to be undertaken during the participants' usage of the technologies on public roads on a daily basis (McLaughlin et al., 2008; McLaughlin et al., 2009; Guo et al., 2010b). Also, these methods require experiments to be implemented in real world environments for an extended duration, which could make them difficult and complicated to manage and implement.

In summary, the review of the potential available methods for studying driving performance has indicated that each method has its strengths and limitations. The selection of methods should correspond to the research questions and take account of factors such as the financial and human resources needed in the research, the characteristics of participants, the development stage of the testing systems and technologies, as well as relevant policy and legislative support.

3.3 Selection of Methodology for Investigating Takeover Performance in HAVs of this Thesis

3.3.1 Driving simulator investigations

Section 3.2 has provided a detailed review of the available methods for investigating older drivers' takeover performance from the HAV, including driving simulators, test-tracks, on-road tests, field operation tests and naturalistic studies. When selecting the method for this study, there were several important considerations. Firstly, although legislation regarding testing automated vehicles on public roads in the UK has been established in 2018 (legislation.gov.uk, 2018), during the data collection period for this thesis (2015-2017), a review of the legislation suggested that all existing UK driving laws regarding driver behaviour of operating conventional vehicles continued to apply and drivers of automated vehicles were not allowed to be completely disengaged from driving even if the testing vehicle was operating in an automated driving mode (DfT, 2015c). Therefore, this indicated that potential methods that involve testing HAVs on public roads, including on road tests, field operation trials and naturalistic tests were not feasible. Secondly, due to the limited time, financial budget and manpower resources for this PhD project, designing and developing a full-scale HAV and setting up a test track on a large site were also not possible for this study. Thirdly, corresponding to the aim of this thesis, the method chosen for this research should be capable to collect a large volume of completely synchronized data to quantify drivers' takeover performance in HAVs. Last and most importantly, the method selected for this thesis must ensure the safety for both participants and researchers when performing the experiments with HAVs. The review of method options in Section 3.2 suggests that a driving simulator is not only more effective and efficient in terms of collecting driving performance data but also is the most cost-effective and safest option compared to other methods involving real vehicles (Godley et al., 2002; De Winter et al., 2012); In addition, the review of the existing literature of HAVs in Section 2.4 suggested that driving simulators are also the most common and effective method to quantify drivers' interaction with the HAV. Therefore, according to the above consideration, a driving simulator was the most appropriate method for this research to investigate older drivers' takeover performance in the HAV.

3.3.2 Fixed-based ST Software Jentig50 driving simulator

The investigations took place at the Newcastle University driving simulator laboratory (Appendix J) using a fixed-based ST Software Jentig50 driving simulator (Figure 4.1). This driving simulator consists of an aluminium cabin equipped with five 50-inch LCD screens and all of the controls of a real vehicle, including a dynamic force feedback steering wheel, accelerator pedal, brake pedal, clutch, adjustable car seat and safety belt. The dashboard and the rear-view and side mirrors are displayed on 5 LCD screens. The system has a 5.1 surround-sound system which provides drivers with a relatively authentic 3D driving experience.

This particular driving simulator is able to provide a high fidelity driving experience. It has been used in a number of studies and has been proven to be reliable and valid in investigating older people's interaction with in-vehicle technologies (Guo *et al.*, 2013a; Edwards *et al.*, 2016). All the drivers who participated in previous research using this driving simulator have evaluated its fidelity as good enough compared to driving their own vehicle (Guo *et al.*, 2013a).

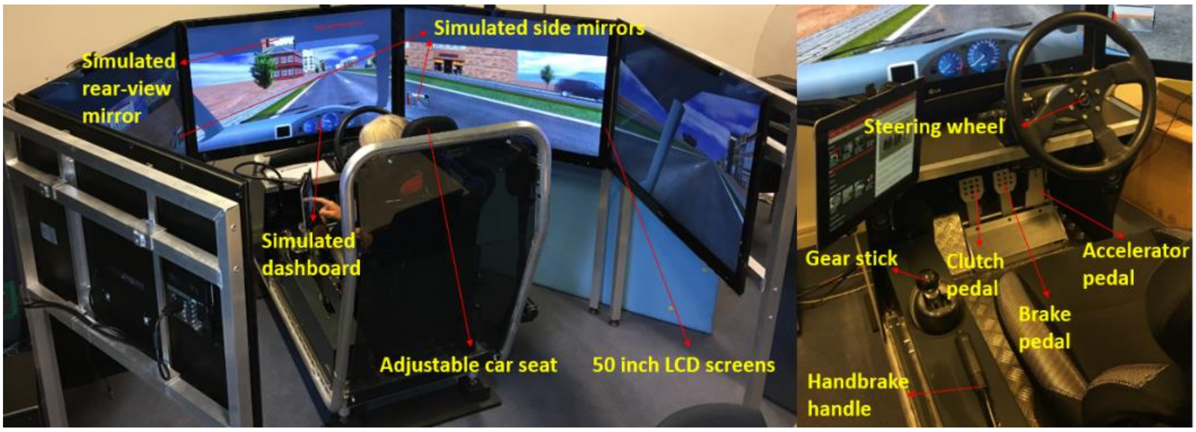


Figure 3.1 Newcastle University Fixed-based ST Software Jentig50 driving simulator

3.3.3 Design of the HAV scenario

After selecting driving simulator as the main method for the quantitative part of this thesis, the next step was to carefully design and create a HAV scenario on it. As discussed in Section 2.3.1, the definition of the HAVs in this study was derived from the DfT's definitions of high automation (DfT, 2015c) and SAE level 3 automation (SAE, 2014). It refers to a level of automation for a vehicle in which the drivers need to be present but is allowed to completely disengage from driving and to safely perform other non-driving related tasks, however, the drivers are required to take over manual control of the vehicle in some situations and it is this takeover procedure this study aims to explore. The HAV scenario was designed through the following steps:

- To design the takeover situation;
- To design the takeover task;
- To select the duration of automated driving;
- To design the takeover request;
- To select the lead time for takeover request; and
- To design the road types involved.

3.3.3.1 Design of the takeover situation

The first step in designing the HAV scenario is to select the takeover situation. A takeover situation in the HAV happens when the driver's control of the vehicle replaces automated driving. The review in Section 2.3.2 indicates that takeover situations in HAVs could be broadly divided into two types: HAV system-initiated takeovers and driver-initiated takeovers (Flemisch *et al.*, 2008; DfT, 2015c; Melcher *et al.*, 2015; Lu *et al.*, 2016). Both situations rely on the driver to effectively reassume the control of the vehicle. However, compared to the driver-initiated takeover, the HAV system-initiated takeover is more demanding and complicated as the drivers could have been disengaged from driving and involved in other non-driving related tasks at the moment of receiving the takeover request and they then have to effectively take over the control of the vehicle within the lead time provided by the HAV system before the HAV reaches system limitations (Melcher et al., 2015; Lu et al., 2016). It represents an important feature of HAVs and has been widely adopted by research of HAVs (Gold *et al.*, 2013a; Gold and Bengler, 2014; Melcher *et al.*, 2015; Gold *et al.*, 2016; VENTURER, 2017). Therefore, a HAV system-initiated approach was chosen as the takeover situation in the HAV scenario in this study.

3.3.3.2 Design of the takeover task

After determining the takeover situation, the next step was to design the takeover tasks for the drivers. In HAV system-initiated takeover situations, after the drivers receive a takeover request from the HAV, the tasks they are required to perform could be a simple task where the drivers just needs to keep driving the vehicle. Alternatively, it could be a more complicated task where they need to reassume the control of the vehicle first and then avoid a potential collision. Compared to the task of continuing to drive the vehicle, a collision avoidance takeover task requires the drivers to take over the control of the vehicle first and then overcome the HAV system limitations by adopting an effective strategy such as to conduct a lane change to avoid an obstacle in the driving lane. It has been widely used in previous studies of HAVs and has been proven to be effective in quantifying subjects' takeover performance (Gold et al., 2013a; Gold et al., 2016; Körber et al., 2016). Therefore, a collision avoidance takeover tasks were chosen for the HAV scenario.

3.3.3.3 Design of the duration of automated driving

After selecting the takeover task, the next step was to determine the duration of the automated driving of each HAV scenario before HAV initiating the takeover request to the driver. When determining the length of automated driving, there are two considerations. Firstly, one of the key features of the HAV is allowing the drivers to completely disengage from driving for some part of the journey (SAE, 2014; DfT, 2015c), and so the duration of automated driving in the HAV scenario should be carefully selected to ensure that the participants could be completely disengaged from the driving. And Endsley (1995a) pointed out if the system operators were disengaged from the task for 30 seconds to 60 seconds, they may not be able to recall the information of the task and thus be completely disengaged from the task. The second consideration is that, due to the usage of the driving simulator, the length of the automated driving period should be carefully chosen to facilitate a comfortable and effective experimental environment for participants. As Kennedy et al. (2000) argued, task duration is positively related to simulator sickness and discomfort. In addition, older drivers are more likely to experience simulator sickness than younger drivers, and adopting short sessions with breaks would reduce or even completely avoid simulator sickness (De Winter et al., 2012; Keshavarz et al., 2018). Furthermore, this investigation intends to ask the participants to experience several HAV driving sessions differentiated in terms of non-driving related tasks, and type of road as well as weather conditions. Therefore, the length of each HAV scenario should not be too long in order to prevent the participants from potentially getting motion sickness, losing attention and becoming too tired (Purchase, 2012). Taking into account the above considerations, each HAV scenario was designed with an automated driving period lasting one minute before initiating the takeover request.

3.3.3.4 Design of the takeover request

The next step was to design the takeover request (TOR) in the HAV scenario. A review of the previous literature concerning in-vehicle systems suggests that the visual and auditory modalities are recommended as they lead to fewer errors and better performance (Campbell et al., 1998; Liu, 2001; Stevens et al., 2002; Naujoks et al., 2014a; Edwards et al., 2016). In terms of the visual element of the modality, the design guidelines of collision warnings (Campbell et al., 1998; Campbell et al., 2007) suggest that a predominantly red display could be used to represent high criticality. Therefore, the visual element of the takeover request is red writing on the screen. Regarding the auditory element, voice messages can deliver more information compared to messages using an audio alert such as a tone or an alarm of pure sound (Campbell et al., 2007), and therefore could be suitable for issuing a takeover request. When considering the type of voice message, previous research suggests that a female voice is found to be the most suitable and realisable auditory interface for takeover requests in HAVs (Bazilinskyy and de Winter, 2015). Also previous literature recommend that the voice should be a machine-generated voice, rather than a voice of a real person (Campbell et al., 2007), so it enables the drivers to easily distinguish the system warning especially in a noisy environment, such as there are other passengers talking loudly in the car or voices from a radio station. It is also suggested that the volume level of the voice message should be 75 dB and about 2000Hz as it is found to be most effective (Campbell et al., 2007; Heinrich, 2012). According to the above considerations, the takeover request of the HAV scenario has been designed. As Figure 4.2 shows, the HAV informs the driver using a visual and auditory takeover request consisting of bold red writing on the screen reading “Take over control” and a computer-generated female voice message (2000Hz, 75 dB) saying “Attention! Please take over the vehicle control”.

Figure 3.2 Takeover request on city road (left) and motorway (right).

3.3.3.5 Design of the lead time for takeover

The next step was to determine the lead time that the HAV provides to the drivers to take over control of the vehicle. The lead time is the time between the moment when the HAV informs the driver to reassume control with a takeover request and the moment when the vehicle encounters the system limitations if it continues at its automated driving speed. A review of the literature shows that previous studies concerning older drivers' takeover in HAVs have adopted a relatively short lead time in the range between 1.5s to 10s (van den Beukel and van der Voort, 2013; Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017). Although, some studies suggested that between 7.5s and 10s seemed to be enough lead times for drivers to take over the vehicle control from automated vehicles (Melcher et al., 2015; Clark and Feng, 2017), the relatively short lead time may result in high level of stress, which has been found to have negative effects on older people's decision-making abilities (Earles et al., 2004). Also, Clark and Feng (2017) reported that older drivers benefited more than younger drivers from a longer length of lead time when taking over control from the HAV. Therefore, it is necessary to adopt a lead time that is longer than the previous studies' when exploring older drivers' takeover performance in HAVs. To select the length of lead time, Merat *et al.* (2014) found that 15 to 20s is enough for disengaged drivers to redirect their attention back to the centre of the road when being required by the automation system to reassume control of the vehicle. Although their study is not strictly comparable to the current investigation, 20 seconds may have the potential to initiate a less time-critical takeover of control from the HAV for the older drivers.

3.3.3.6 Design of the roads

After designing the HAV scenario, the final step was to design the roads that the HAV scenario would be driven on. Ideally the simulated HAV could be tested on six types of roads corresponding to the six common national speed limits in the UK from 20mph to 70mph (GOV.UK, 2018). However, due to the limited timeframe and recourse of the PhD project, designing and developing six road scenarios to reflect all common speed limits were not practical for this study. Instead, the study attempted to select roads that can reflect typical HAV use cases in the real world. The presence of automated vehicles is predicted to potentially benefit road traffic in urban areas by reducing emissions, traffic congestion and accidents (Litman, 2017). And driving in urban build-up areas potentially represents an important HAV use case in the real world (DfT, 2015c; Catapult, 2017; Litman, 2017). Therefore a road in urban build-up areas was chosen for the HAV scenario and the common speed limit of 30mph was identified for this road (GOV.UK, 2018). It was referred as "city road' in this study. In addition, driving on major roads (motorways and 'A' roads) not only represent an important proportion (65%) of the total traffic in the UK (DfT, 2016; DfT, 2017), but also has been one of the early application scenarios for automated driving (DfT, 2015c). Therefore, a major road was chosen as the second type of road for the HAV scenario in this thesis. A common speed limit of 60mph for was identified (GOV.UK, 2018). It was referred as 'motorway' in this study. The two road scenarios are an effective plan to represent significant HAV use cases. The next consideration is that this experiment may be the first time for most of the participants to interact with an HAV on a simulator, and the roads for the HAV scenario should be carefully designed to ensure an efficient and comfortable testing environment for all the participants. De Winter et al. (2012) argued that avoiding complicated road layouts such as sharp curves potentially reduces the likelihood of simulator sickness among participants, especially in research involving the older drivers. In addition, factors related to the driving environment for the HAV scenario may potentially affect drivers' performance in interacting with the HAV, such as road layout and traffic conditions (WAARD et al., 1995; Gold et al., 2016). In order to ensure that participants were in the optimal state during the experiments, and to minimise the effects of road layout and traffic on their driving performance which may potentially compromise the primary targets of this investigation which focuses on examining the effects of age and disengagement from driving on drivers' takeover performance, the roads were designed as straight roads with no other traffic in the lanes in the driving direction. Finally, as discussed in section 3.4.2.2, the HAV scenario has adopted a collision avoidance task to quantify the takeover performance of the participants, which would need the drivers to execute a lane change to overcome a collision. Therefore, both the road in build-up areas and major road for the HAV scenario are designed as dual carriageways to allow this type of takeover task, as illustrated in Figure 4.2. The map of the two types of roads were outlined in Appendix I.

3.3.3.7 Overview of the HAV scenario

The above design considerations have shaped the design of the HAV scenario for this study. As Figure 3.3 shows, the HAV scenario starts with the driver turning on the engine and the HAV starting to perform longitudinal and lateral vehicle control and to drive from 0mph to 30mph (13.41m/s) when driving on the city road or to 60mph (26.82m/s) on the motorway, and then maintaining an even speed of 30mph or 60mph in the central of the left-hand lane of the dual carriageway for a duration of one minute. During the one minute of automated driving, the drivers are allowed to take their hands off the steering wheel, and their feet off the pedals, and to be completely disengaged from driving and to safely perform other non-driving related tasks. At one minute, the system detects a stationary red vehicle blocking the driving lane ahead, and then it informs the driver of this using a visual and auditory takeover request (a red sentence on the screen "Take over control" and a computer-generated female voice saying "Attention, please take over the vehicle control"). Meanwhile, the HAV system continues to drive at its steady speed. On the city road, the HAV detects the stationary car with an advance range of 268.20m and informs the drivers with a lead time of 20 seconds. On the motorway, it detects the stationary car with an advance range of 536.4m and informs the drivers with a lead time of 20 seconds. The driver has to reassume the control of the vehicle within the 20 seconds before the HAV reaches the stationary car. As long as the HAV system detects active input (at least 2 degrees of steering wheel input or/and 10% of pressing accelerator or brake pedals) from the driver, it transfers control of the vehicle to the driver. Then, the driver needs to overtake the stationary car by conducting a lane change. After the driver has passed the stationary car, they are asked to pull over in the left hand lane and the scenario ends.

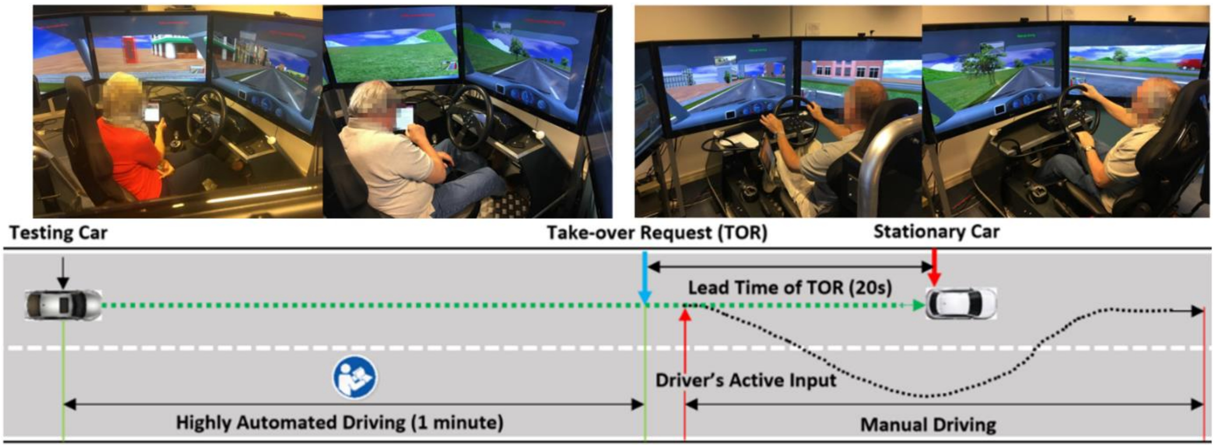


Figure 3.3 Illustration of the HAV scenario

3.3.4 Quantification of Takeover Performance

Having designed the HAV scenario, this section focuses the selection of the dependent variables in order to quantify takeover performance. As reviewed in Section 2.3.3, the data required to quantify the takeover performance are generally categorised into two groups; time aspects of takeover and takeover quality (Gold et al., 2013a; Radlmayr et al., 2014; Gold et al., 2015; Gold et al., 2016; Körber et al., 2016; Clark and Feng, 2017).

3.3.4.1 Time aspect of takeover

The time drivers take to react to events is an important measure of the safety and usability performance of in-vehicle systems (Stevens et al., 2002). In terms of the time aspects of takeover in HAVs, three measurements were selected, consisting of reaction time, takeover time and indicator time, as illustrated in Figure 4.4.

To begin with, reaction time attempts to quantify how quickly the driver reacts to the takeover request. Previous research has defined reaction time as the time between the point of the system's initiation of a takeover request and the point that the driver's hands are back on the steering wheel or the feet touch the pedal, whichever comes first (Clark and Feng, 2017; VENTURER, 2017). However, only having the hands on the steering wheel or feet on the pedal does not mean that a driver has switched to a safe and ready position to manually drive the car. Thus, in this study, the reaction time is defined as the time between the takeover control request and drivers switching back to a safe and ready manual driving position. This position refers to that when subjects' eyes are on the road, hands are on the steering wheel and feet are on the pedals.

Takeover time describes the time between the point the HAV initiates a takeover request and the point that the HAV receives the driver's first active input to the vehicle control. First active input is defined as a manoeuvre which changes the steering wheel by 2 degrees or/and movement of 10% of accelerator or brake pedals (Gold et al., 2013a; Radlmayr et al., 2014). Takeover time measures how fast subjects execute the first conscious input to the vehicle after receiving the takeover request initiated by the HAV.

Finally, indicator time attempts to measure how quickly the participants makes the decision to conduct a lane change to avoid the stationary vehicle in the takeover process in the HAV. It is defined as the time between the points the HAV initiates a takeover request and the point the driver's initiation of an indicator light signal warning fellow road users that the driver intends to change lanes to avoid the stationary car ahead. It is assumed that, the faster their indicator time, the more quickly they have made the decision to change lane. There is no traffic behind the HAV so that the overtaking manoeuvre is not delayed after indicator initiated by a vehicle close behind stopping the HAV overtaking.

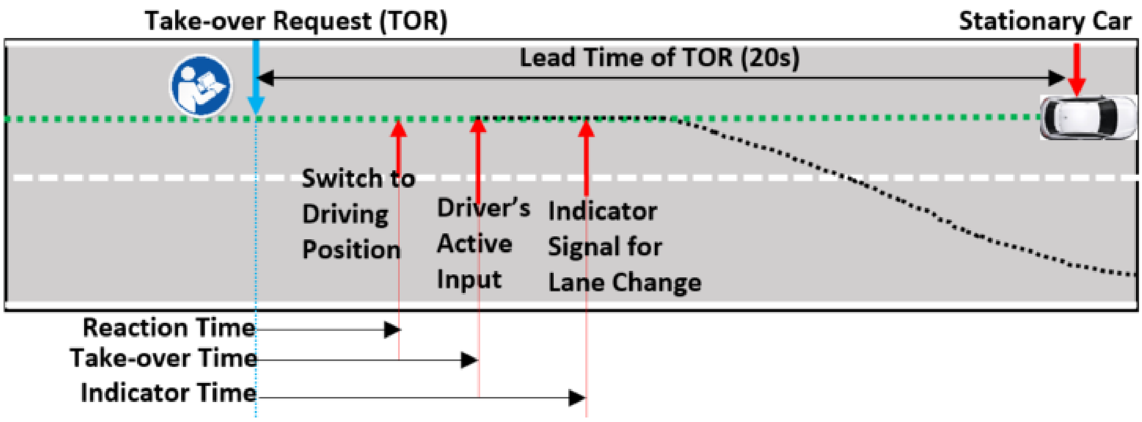


Figure 3.4 Illustration of the time aspects of takeover

3.3.4.2 Takeover quality

In terms of measuring takeover quality. Firstly, the minimum time to collision (TTC) has been recognized as an effective measure in assessing the severity of the risk of potential collisions (van der Horst and Hogema, 1993; Stevens et al., 2002) and has been also an important measure of the safety and usability of in-vehicle systems (Stevens et al., 2002). In the context of the present research, the minimum TTC is defined as the time required for the HAV to collide with the stationary red vehicle ahead in the driving lane if it continues at its current speed at the point it has successfully avoided the stationary car. The lane width is 3.6m and both the HAV and stationary red car have a defined width of 1.8m and they are located in the centre of the lane as a default. Therefore, the point when the value of the lane position of the HAV is lower than 1.8m is defined as it having successfully avoided the stationary vehicle following the manual takeover of the driving task. The minimum TTC is calculated as shown in equation 1, and the higher the minimum TTC, then the less critical the takeover performance is.

$$Min\ TTC = (d_s - d_c)/v_c \qquad (1)$$

Where: d_s is the distance when the stationary car shows up, d_c is the distance when the HAV has successfully avoided the stationary car, and v_c is the speed when the HAV avoided the stationary car.

In addition, as equation 2 indicates, the driver's resulting acceleration after the TOR has been proven to be an effective measure of the quality of a driver's takeover of control, reflecting the force that the car tyre has to transfer to the ground. The higher this value is, the bigger the chance that it could reach the maximum physical limit of the braking manoeuvres centred on the car tyre; and therefore in this case the driving is considered to be less stable and more dangerous (Gold et al., 2013a; Radlmayr et al., 2014).

$$Resulting\ Acc = \sqrt{Max\ Longitudinal\ Acc^2 + Max\ Lateral\ Acc^2} \qquad (2)$$

Steering wheel angle is used as a measure of the stability of the driver's takeover, and it is also an useful measure to reflect the safety performance of in-vehicle systems (Stevens et al., 2002). It is quantified as the standard deviation in degrees from the centre-line of the steering wheel. This measure has been well-used to quantify takeover quality in previous studies (Mok et al., 2015a; Körber et al., 2016; Clark and Feng, 2017). A higher value represents a less stable takeover performance.

Also, previous research has monitored the types of reaction of the driver to check what strategy they used to responses to the system limitations of the HAV (Gold et al., 2013a; Gold and Bengler, 2014). For example, if the system limitation concerns an obstacle in the driving lane, responses to this could be to change lane or to brake and change lane.

Moreover, the numbers of collisions and critical encounters which occurred were used to assess the success of the takeover. Number of collisions involves all the crashes which happened during takeover, and the number of critical encounters includes any takeover with a minimum TTC of less than 1.5s, which is deemed as a time threshold for which human drivers are highly likely to be involved in collisions (van den Beukel and van der Voort, 2013). This reflects potentially dangerous takeover behaviour among the participants. And importantly, it could be used as a performance measure to assess the level of driver's simulation awareness during the takeover control process (Salmon et al., 2006).

Finally, a hasty takeover is defined as any takeover where drivers' takeover time is smaller than the reaction time, reflecting that they execute the first active input to the HAV before they have completely switched to the a safe and ready position to manually drive the car, thus representing abrupt and risky takeovers.

3.3.5 Measurements of mental workloads and subjective attitudes

As Section 1.6 suggests, the sixth objective of this study focuses on testing older drivers' requirements by evaluating several HMI designs for HAVs. Apart from assessing the drivers' performance, the mental workload required and subjective attitudes are also important measurements in the evaluation of in-vehicle systems (Young and Stanton, 2002a; Vlassenroot et al., 2010).

3.3.5.1 NASA-RTLX questionnaire

There are several ways to assess participants' mental workload, broadly encompassing subjective measures, physiological measures and performance measures (Cain, 2007). Among these, a subjective method- The National Aeronautics and Space Administration Task Load Index (NASA-TLX), has been widely used. This examines mental workload in terms of six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration (Hart and Staveland, 1988; Hill et al., 1992). However, the NASA-TLX can be potentially time-consuming and complex to analyse, mainly because it involves a weighting process of the six dimensions with paired comparisons (Byers et al., 1989). To simplify the this method, Byers et al. (1989) proposed the NASA-RTLX, which uses a simple average of the six scales in the NASA-TLX and does not require a weighting process. The results are as valid and reliable as those of the NASA-TLX, but the test is now more convenient in terms of implementation and data analysis (Byers et al., 1989). Therefore the NASA-RTLX was selected for this study (Appendix F).

3.3.5.2 Seven-point Likert scale questionnaire

To measure participants' attitudes, the use of questionnaires with Likert scales is an effective and reliable and widely adopted method (Symonds, 1924; Cohen et al., 2000; Norman, 2010). A Likert scale examines participants' attitudes and asking them to answer how much they agree with a statement and offering a number of response options (Croasmun and Ostrom, 2011). Typically, 5-point and 7-point Likert scales are most common Likert scales (Symonds, 1924; Cohen et al., 2000; Norman, 2010; Croasmun and Ostrom, 2011). The 7-point Likert scale is more widely used and reliable (Symonds, 1924; Cohen et al., 2000). It has been adopted here to examine participants' attitudes (Appendix G).

3.3.6 General procedure of driving simulator investigations

This study conducts three driving simulator investigations (Chapters 4, 5 and 7) to study older drivers' takeover behaviour in HAVs, corresponding to the thesis objectives 3, 4 and 6 listed in Section 1.6. The procedure of the driving simulator investigations was, firstly, the method was selected and experiments were designed. And the investigations were evaluated by the Newcastle University's ethical committee. After the ethical approval for the study was received (Appendix H), the researcher conducted a risk assessment following advice from Newcastle University's lone working safety policy as well as the guidance in *The Pathway to Driverless Cars: Code of Practice for testing* (DfT, 2015c) before starting to work in the driving simulator laboratory. The potential risks to participants when taking part in the study were identified and corresponding risk management plans were carried out which were then reviewed by the researcher together with the supervision team. Then participant recruitment started and data collection began.

3.3.7 Participant recruitment and sample size selection for driving simulator investigations

To be eligible for the study, a participant was required to have a valid UK driving licence for at least one year; to be an active drivers (driving at least once per week) at the time they participated in the study; with normal or correct vision and hearing; and do not experience motion sickness (Guo *et al.*, 2013a; Edwards *et al.*, 2016).

Older drivers aged 60 years and over were recruited as the experimental group for the driving simulator investigations. The age limit was determined according to the definition of 'older person' by the WHO (2016). In order to ensure the sample is representative to the population of older drivers, they were recruited through the VOICE North older driver user group (Guo *et al.*, 2013a; Edwards *et al.*, 2016). It was established at Newcastle University and aims to make use of the valuable experience of the elderly public (people aged 60 years and over) to address the challenges and opportunities of an ageing society. The strength of recruiting participants through the VOICE North is that the cohort is managed by the Ageing Institute at Newcastle University and thus the welfare and ethics issues of the older drivers are managed by a trusted third party. The group have approximately 1000 users which form a representative sample of the population older drivers in the UK. Younger drivers aged 20 to 35 years were recruited as a control group to compare with the experimental group, and they were recruited from the local community in Newcastle upon Tyne. The participant recruitment information is in Appendix A.

When determining the sample size for the driving simulator investigations, the following considerations were taken into account. Firstly, the nature of the driving simulator investigation in this study is quantitative research which attempts to yield statistically significant results that can be generalised to a wider population (Elliott and Woodward, 2007; Lowhorn, 2007; Polit and Beck, 2010). It has been found that the sampling distribution would be approximately normal for studies with 30 participants or more (Hays, 1988; Elliott and Woodward, 2007; Norman, 2010; Ghasemi and Zahediasl, 2012; Field, 2013). This potentially enables parametric tests to be used for data analysis, and these have greater statistical power and are more flexible than non-parametric tests (McCrum-Gardner, 2008; Field, 2013). Secondly, the review of previous driving simulator studies investigating older drivers' interactions with in-vehicle systems and vehicle automation systems showed that the number of participants recruited varied: Guo *et al.* (2013a) recruited 42 participants (26 older and 16 younger drivers); Gouy et al. (2014) 30 (age between 20 and 63 years); Edwards et al.

(2016) 30 (all older drivers); Clark and Feng (2017) 35 (18 older and 17 younger drivers); Körber et al. (2016) 72 (36 older and 36 younger drivers); Gold et al. (2016) 72 (36 older and 36 younger drivers); Miller et al. (2016) 36 (12 drivers aged 15-18, 12 drivers aged 17-69 and 12 drivers aged 70-81); and Molnar et al. (2017) recruited 72 participants (48 younger drivers and 24 older drivers). Therefore according to the above considerations, this study set a target of sample size of 74, with 37 older drivers and 37 younger drivers. This sample size would potentially enable the research to yield results which would be likely to be approximately normally distributed (Hays, 1988; Elliott and Woodward, 2007; Norman, 2010; Ghasemi and Zahediasl, 2012; Field, 2013) and it also exceeds the sample sizes adopted in the previous studies mentioned above. The target sample size of 74 was achieved. A total of 76 drivers participated in the experiments who were aged between 20 and 81 years (mean = 49.21 years, SD = 23.32 years; 33 female, 43 male). 37 subjects were younger drivers aged between 20 and 35 years (mean = 26.05 years, SD = 4.47 years; 17 female, 20 male), and 39 were older drivers aged between 60 and 81 years (mean = 71.18 years, SD = 6.06 years; 16 female, 23 male).

3.3.8 Experimental design considerations

Generally, there are two primary options for a researcher in designing an experiments: a within-subjects design or a between-subjects design (Seltman, 2009; Charness et al., 2012; Field, 2013). The within-subjects design only has within-subjects factors, which are categorical independent variables where each participant is exposed to all the levels of the variable. The within-subjects design is a popular type of experimental design. The key advantage of adopting this design is that it allows each participant to experience all levels of the independent variable, and data for several outcomes for each participant enable each participant to act as his or her own baseline condition. This effectively reduces participant-to-participant variations and thus substantially enhances the statistical power of the findings. However, the disadvantage of within-subjects designs is the possible order effects which arises when each participant experiences all levels of a variable (Seltman, 2009; Charness et al., 2012). For example, after a participant experiences one level of the experimental conditions, they have gained some knowledge towards the task, which could possibly affect their performance of participating the subsequent conditions. Solutions to this problem can include providing rest breaks between trials to eliminate the influence of previous trials, and randomising the order of the experimental conditions for each participants (Lewis, 1989; Seltman, 2009). On the other hand, a between-subjects design only involves between-subjects factors, which are categorical independent variables where each participant only experiences one of the levels of the variable; (Seltman, 2009; Charness et al., 2012). Compared to within-subjects designs, the key advantages of adopting a between-subjects design is that it minimizes order effects across different levels of a variable and it can be used when it is impossible to apply within-subjects variables (Seltman, 2009; Charness et al., 2012). For example, when studying the effect of age or gender, it is not possible to assign multiple levels of age or gender to each subject. A mixed within- and between-subjects design involves both within-subjects factors and between-subjects factors, taking advantage of the benefits of both types of design, and the use of within-subjects factors enhance statistical power whereas the between-subjects factor minimize the threats of order effects (Lewis, 1989; Seltman, 2009; Field, 2013). Therefore, a mixed within-and between- subjects experimental design was chosen for the three driving simulator investigations in this study, and detailed review of the experimental design for each investigation are provided in Sections 4.2.2 , 5.2.1 and 7.2.1.

3.3.9 Statistical analysis of data from driving simulator investigations

This section describes the statistical analysis of the quantitative data collected in the driving simulator investigations. The aim of the use of statistical tests is to determine whether or not there are statistically significant differences between two or more groups. The selection of correct statistical tests is determined by the data type and purpose of analysis (McCrum-Gardner, 2008). Prior to the selection of the statistical tests for a study, it is important to determine the scale of measurements of nominal, ordinal, and continuous data (McCrum-Gardner, 2008; Field, 2013). Table 3.1 provides an overview of the scale of measurements of the data collected in the driving simulator investigations.

Table 3.1 Overview of the scale of measurements of the data in driving simulator investigations

Dependent variables	Unit	Scale of measurements
Reaction time	s	Continuous
Takeover time	s	Continuous
Indicator time	s	Continuous
Time to collisions	s	Continuous
Resulting acceleration	m/s^2	Continuous
Steering wheel angle	degree	Continuous
Collisions and critical encounters	Count	Nominal
Hasty takeover	Count	Nominal
Braking and steering behaviour	Count	Nominal
NASA RTLX score	N/A	Continuous
7 Point-Likert Scale score	N/A	Ordinal

For continuous data, the first step is to assess whether or not the data is normally distributed by plotting a histogram of the data and looking at whether it forms a symmetrical bell shape or using normality tests such as the Kolmogorov-Smirnov and Shapiro-Wilks tests (Elliott and Woodward, 2007; McCrum-Gardner, 2008; Field, 2013). If the data is approximately normally distributed, they could be analysed using parametric methods, otherwise non-parametric tests are used. After determining to use paramedic or non-parametric tests, the final decision to choose which test to use depends on the purpose of analysis. (McCrum-Gardner, 2008; Field, 2013)

For the data to be analysed with parametric tests, when assessing whether or not there are statistically significant differences between two independent groups, the independent sample t-test was considered suitable (McCrum-Gardner, 2008; Field, 2013). For example, in Section 5.3.3, several independent sample t-tests were carried out to compare the mean takeover times of older and younger drivers in a specific weather condition. In situations when two paired groups were to be compared, the paired sample t-test was considered suitable (McCrum-Gardner, 2008; Field, 2013). For instance, in Section 4.3.4, several paired sample t-tests were implemented to compare the older drivers' mean reaction times when completely disengaged from driving as opposed to when monitoring driving. When comparing several groups from a mixed factorial between- and within-subjects experimental design (see Section 3.3.7), a mixed factorial analysis of variance (ANOVA) is recommended in literature (for example, McCrum-Gardner, 2008; Field, 2013) and has been regarded as a suitable method for data analysis by previous driving simulator studies that have adopted a mixed factorial experimental design (Gouy et al., 2014; Gold et al., 2015; Körber et al., 2016). For example, in Section 5.3.5, a mixed factorial ANOVA was used to examine the effects of weather, age and road type on drivers' reaction time. In addition, in order to use the mixed factorial ANOVA, it is important that the data meets the assumption of sphericity, which refers to the condition that the variance of the differences of all possible combinations of related groups are equal (Field, 2013). The assumption of sphericity was examined using Mauchly's test of sphericity, and if the assumption was not met, a correction was implemented and reported in the results (Field, 2013). And the assumption of variance homogeneity was assessed using the Levene test (Field, 2013). In addition, when assessing the correlation between two variables with continuous data, Pearson's correlation was used (McCrum-Gardner, 2008; Field, 2013); for example, in Section 4.3.10, it was used to examine the correlation between drivers' reaction time and takeover time.

Non-parametric tests have less statistical power and are less flexible compared to parametric tests, they are used in the analysis of nominal and ordinal data (McCrum-Gardner, 2008). In terms of analysing nominal data, the Chi-square (X^2) test of independence was conducted when the purpose of analysis is to assessing statistically significant relationship between two independent groups (McCrum-Gardner, 2008; Field, 2013); for example, in Section 4.3.3, the Chi-square (X^2) test was used to assess if there was statistically significant difference in the numbers of collisions and critical encounters among older and younger drivers. When comparing two paired groups, McNemar test was used (McCrum-Gardner, 2008; Field, 2013); for instance, in Section 5.3.3, a McNemar test was conducted to examine if there was a significantly significant difference in drivers' numbers of collisions and critical encounters recorded in clear weather and in rain. In regard to analysis the ordinal data, when comparing two independent groups, the Mann-Whitney U test was adopted (McCrum-Gardner, 2008; Field, 2013); for example, in Section 7.3.9, Mann-Whitney U tests were implemented in assessing whether or not there were statistically significant difference in attitudes towards the HMI designs between older and younger drivers. When comparing two paired groups, the Wilcoxon signed-rank test was used (McCrum-Gardner, 2008; Field, 2013); for instance, in Section 7.3.9, it was used to examine if the participants' attitudes towards two HMI designs were significantly different. Finally, when comparing more than two paired groups, the Friedman test was used (McCrum-Gardner, 2008; Field, 2013); for example, in Section 7.3.9, it was used to check if participants' attitudes towards the four HMI designs were statistically significant different. All the descriptive and inferential statistical analysis were carried out using IBM SPSS Statistics software.

The simulator collects data on the participants' driving performance at a frequency of 20 sample per second (20 Hz). The data from the driving simulator was in binary form and converted into ASCII format. Then, values of all of the dependent variables were calculated following the definitions in Section 3.3.4.

3.4 Review of the Available Methods for Investigating Older Drivers' Needs and Requirements of HAVs

The quantitative driving simulator investigations discussed in the above sections attempted to quantify older drivers' takeover performance in HAVs, whereas another important part of this study aims to broaden and deepen the understanding of what older drivers' needs and requirements towards the human-machine interactions in HAVs are. In light of this, the nature of the research in this stage is qualitative and exploratory. Qualitative research does not focus on generalization but attempts to yield a rich, contextualized understanding of human experience (Polit and Beck, 2010). In order to achieve this aim, qualitative data of older drivers' requirements towards HAVs needs to be collected. A wide range of methods are potentially available to collect qualitative data, including questionnaires, focus groups, individual interviews, observation and self-report diaries.

3.4.1 Questionnaires

The questionnaire is a common research method consisting of a number of closed-ended questions with fixed response options, although it could also include open-ended questions. The questionnaire is useful for collecting rich quantitative and qualitative data from large numbers of participants (Maguire and Bevan, 2002; Mathers et al., 2007; Bird, 2009). Previous studies have used questionnaire surveys to examine drivers' attitudes, needs and requirements towards advance driver-assistance systems as well as vehicle automation systems (Van Driel and van Arem, 2005; Sodnik et al., 2008; Kyriakidis et al., 2015; Piao et al., 2016; Liljamo et al., 2018). The use of questionnaires has several benefits. Firstly, a questionnaire survey can be administered in a variety of ways; for example by post, telephone or online. This enables participants based in different physical locations to be able to take part in the research. So it can allow participants to take part in the survey easily (Kelley et al., 2003; Mathers et al., 2007; Rice et al., 2017). Secondly, questionnaires could be implemented using random sampling techniques which have the potential to yield results that could be generalised to a larger population (Kelley et al., 2003; Mathers et al., 2007; Rice et al., 2017). In addition, some questionnaires, such as postal questionnaires and online questionnaires, allow the participants to take part in a survey privately at their home or workplace so that they do not have to be exposed to a specific experimental environment. This would bring ethical advantages and flexibility for using questionnaires (Mathers et al., 2007). Finally, questionnaires are efficient and economical in collecting data from large samples compared lab based research or research conducted using focus groups or interviews (Kelley et al., 2003; Mathers et al., 2007; Rice et al., 2017). However, there are also a number of limitations of and challenges in using questionnaires. A major disadvantage is that although substantial amounts of quantitative data can be collected, the data collected is likely to be insufficient in terms of depth and detail in clearly describing participants' feelings and expectations so as to fully explain the issue being examined (Kelley et al., 2003; Mathers et al., 2007). Though the inclusion of open-ended questions does allow a questionnaire to collect qualitative data, this cannot match that gained from qualitative research methods such as focus groups and interviews in term of the depth and detail of data (Mathers et al., 2007). Also, the validity of results could be affected by the design and administration of questionnaires, for example, in situations when there is a lack of detailed explanations or information concerning the background of the study or the participants were not given enough time to fully comprehend the research topic (Mathers et al., 2007; Rice et al., 2017), the validity of results could be affected.

3.4.2 Focus groups

In addition to questionnaires, focus groups are a research method that has been widely used to collect qualitative data. A focus group consists of a range of different number of participants (such as six to nine in each focus group) who are brought together by a researcher to investigate their attitudes towards and opinions and ideas about a research topic (Morgan, 1996; Gibbs, 1997; Rabiee, 2004; Gorman and Clayton, 2005; Gill et al., 2008; Dilshad and Latif, 2013). Focus groups have been widely adopted by previous studies in exploring the attitudes, perceptions and requirements of older drivers (Rogers et al., 1998; Herriotts, 2005; Musselwhite and Haddad, 2010; Emmerson et al., 2013). There are several strengths of using focus groups. Firstly, comparing to questionnaires, they are capable of yielding rich qualitative data in a reasonable time, as one to two hours is sufficient (Gorman and Clayton, 2005; Dilshad and Latif, 2013). In addition, a key advantage is that the focus group allows participants to not only communicate with the researcher but also interact with other participants in the group. Such interaction enables participants to share their ideas and to both ask questions of each other and give answers and explanations to each other, which may greatly enhance the range and depth of the qualitative data gathered (Morgan, 1996; Gibbs, 1997; Gorman and Clayton, 2005; Dilshad and Latif, 2013). However, there are also some limitations of focus groups. To begin with, a number of different participants are required in each focus group (Morgan, 1996; Rabiee, 2004; Herriotts, 2005; Dilshad and Latif, 2013), and it could be extremely difficult to arrange for different participants to meet for each focus group (Gibbs, 1997; Gorman and Clayton, 2005). Also, as the nature of interaction in the focus group is to provide conversation and discussion, there could be risks that a small number of participants may dominate proceedings (Gorman and Clayton, 2005; Dilshad and Latif, 2013). In addition, some focus groups are designed based on the homogeneous features of a particular type of participants, such as gender, age, occupation and preferences (Morgan, 1996; Gibbs, 1997; Gorman and Clayton, 2005; Dilshad and Latif, 2013). It could be a challenge for researchers to successfully recruit participants with the required common features within the available time (Gorman and Clayton, 2005; Dilshad and Latif, 2013).

3.4.3 Individual interviews

The individual interview is another commonly used research method for the collection of quantitative data (DiCicco-Bloom and Crabtree, 2006; Gill et al., 2008; Alshenqeeti, 2014; Guest et al., 2017). It is similar in several ways to focus groups, except a major difference is that it collects qualitative data from each participant individually. Individual interviews are known to be an effective method in investigating issues of older drivers' mobility and their reactions to technology (Siren and Hakamies-Blomqvist, 2005; Vrkljan and Polgar, 2007; Fofanova and Vollrath, 2012; Gitelman et al., 2017; Prat et al., 2017; Buckley et al., 2018). Compared to focus groups, individual interviews have several advantages (Alshenqeeti, 2014; Guest et al., 2017). Firstly, an individual interview allows the researcher to collect data from each participant individually, and therefore the process is more flexible and convenient compared to a focus group (Gill et al., 2008; Guest et al., 2017), as the researcher saves the effort in gathering several participants together, setting a common time and arranging a large enough venue for a focus group session. This strength becomes especially obvious when a convenient time slot for all participants in research is difficult to reach, or in situations where the qualitative interview investigation is a part of mixed methods research (Johnson and Onwuegbuzie, 2004), so that it may be subsequent to or followed by the use of another piece of quantitative research in which only one participant could be tested at a time. Secondly, another advantage of individual interviews is that they completely avoid one of the major drawbacks of focus groups where discussion could be dominated by some participants (Gorman and Clayton, 2005). In addition, each participant in an individual interviews has a longer time to fully comprehend the interview questions and express themselves compared to in focus groups, and the researcher can thus concentrate on each participant and give them equal opportunities to fully express themselves in more depth and detail concerning topics and issues that they have more ideas about or opinions on (Gill et al., 2008; Alshenqeeti, 2014; Guest et al., 2017). This advantage becomes especially important when the research topic concerns a field that the participants have limited experience and information about. Although a major limitation of using individual interviews is the lack of interaction between participants which occurs in focus groups; however individual interviews may get participants to give responses that they cannot do in a group environment, they have been found to be as effective as focus groups in exploring and generating new ideas and topics in a specific research field (Guest et al., 2017).

Individual interviews can be categorised in three types, including structured, unstructured and semi-structured interviews (DiCicco-Bloom and Crabtree, 2006; Harrell and Bradley, 2009; Alshenqeeti, 2014). Structured interviews consist of a number of predetermined close-ended questions and participants are required to answer the questions directly. This type of interview is like a quantitative questionnaires with little flexibility and freedom in terms of the researchers' questions and the participants' answers (DiCicco-Bloom and Crabtree, 2006; Harrell and Bradley, 2009; Alshenqeeti, 2014). Unlike structured interviews, an unstructured interview is more like a conversation in which the researcher and participant can be flexible in terms of question, content and answers given, this could create a comfortable atmosphere between the researcher and the participant. However, it could be potentially time-consuming and the content of interview may face a risk of easily straying away from the purpose of the research (Harrell and Bradley, 2009; Alshenqeeti, 2014). Another type of interview is the semi-structured interview, which consists of a set of predefined questions which ensure that certain topics must be covered, while in the meantime also allowing the researcher to ask new questions based on the participants' responses. The strength of a semi-structured interview is that it combines the benefits of both structured and unstructured interviews (DiCicco-Bloom and Crabtree, 2006; Alshenqeeti, 2014; Guest et al., 2017). It uses the predefined structured questions to ensure that the content of the interview covers the research interests and it is also flexible enough to allow the researcher to explore and expand on participants' responses to ensure greater range, depth and detail in the qualitative data collected. Individual interviews could be administered in several ways using different techniques, including face-to-face, over the telephone, online chart (for example, WhatsApp or Facebook messenger) and e-mail interviews (Opdenakker, 2006). Among these, a face-to-face interview is the most common, and it allows the communication between the researcher and participants to be taken place at the same time and location, but the cost is relatively high (Opdenakker, 2006). Telephone and online chat interviews can only ensure real time communication between the researcher and participants but they may not at the same location. An e-mail interview provides neither synchronous conversation in time nor in location, but they generally require lower cost compared to a face-to-face interview (Opdenakker, 2006).

3.4.4 Observation

Observation is also a useful methods available in investigating users' needs and requirements towards a system (Gulian et al., 1990; Maguire and Bevan, 2002; Shinar and Compton, 2004). Observation involves a researcher observing the participants using and interacting with a system or technology and information about their activities and behaviours are noted by the researcher (Maguire and Bevan, 2002; Shinar and Compton, 2004). There are two types of observations: the first is the direct observation where the researcher is physically present during the investigation to observe participants' behaviour directly; and the second is the indirect observation where the video footage of participants' behaviour is recorded and reviewed by the researcher later (Maguire and Bevan, 2002). A major benefit of using observation is that it allows the researcher to view how participants actually behave instead of what they state (Kawulich, 2005; Rosenbloom, 2006). However there are also important problems in using this method. It is potentially costly and time-consuming; its ability of collecting rich qualitative data is limited compared to focus groups and interviews; and researchers may have subjective bias concerning the participants' activities they have observed, which could potentially affect the validity of the results (Gulian et al., 1990; Maguire and Bevan, 2002; Rosenbloom, 2006).

3.4.5 Self-report diary

Similar to observation, a self-report diary requires that participants take notes of their activities when interacting with a system or using a technology throughout a day over a specific period of time, and information about their opinions, needs and requirements towards the systems or technologies could be derived from the diary entries (Maguire and Bevan, 2002). The strength of this method lies in the fact that it is able to effectively capture rich data of users' actual behaviour of interacting with a system or technology during their daily life. However, it could be potentially costly in terms of time and money and the task of writing a diary could potentially become a burden to participants and result in their withdrawal from the research (Wood et al., 2005).

3.5 Selection of Methodology Exploring Older Drivers' Requirements of HAVs of this Thesis

3.5.1 Semi-structured interview

The review of the available method options in Section 3.4 above has clearly indicated that, compared to questionnaires, observation and self-report diaries, focus groups and individual interviews are not only the most popular methods used in previous studies to qualitatively investigate the opinions, attitudes and requirements of older drivers, but they are also more cost-effective and are able to yield rich, in-depth and detailed qualitative data (Rogers et al., 1998; Herriotts, 2005; Siren and Hakamies-Blomqvist, 2005; Vrkljan and Polgar, 2007; Musselwhite and Haddad, 2010; Fofanova and Vollrath, 2012; Emmerson et al., 2013; Gitelman et al., 2017; Prat et al., 2017). Therefore they were initially chosen as two suitable method options for this study to use in exploring older drivers' requirements towards HAV. When deciding between these two, the following factors were considered: Firstly, given that hands-on experience is important to enable older adults to develop a spontaneous and realistic understanding of a new technology (Eisma et al., 2003; Davies and Lam, 2009; Buckley et al., 2018), the qualitative data collection of this study was to be undertaken after each participant had experienced several HAV driving sessions on the driving simulator, and the driving simulator only allows one participants to be tested at a time (see Section 3.3). Secondly, the HAV is an emerging technology that has not been introduced on real road yet, and so taking part in this research could be the first time most of the participants had ever experienced and interacted with an HAV, and therefore each of them should be provided with enough time to become familiar with the HAV and to fully express their opinions, ideas, needs and requirements. Therefore based on the considerations above, individual interviews were chosen over focus groups as the main method for exploring older drivers' requirements of the HAV in this study. In terms of choosing the type of individual interviews and the method of implementation, the review in Section 3.4.3 clearly showed the benefits of semi-structured face-to-face interviews. Therefore this has been chosen as the main qualitative method for this study in order to fulfil the fifth objective of this thesis. The design of the interview investigation is presented in Section 6.2.1.

3.5.2 Participants for the interview investigation

The widely used method to determine the sample size for the qualitative interview investigation is by the time when data reached saturation where data collection completed at the point when limited new information could be gained from additional interview sessions (Guest *et al.*, 2006; Mason, 2010; O'reilly and Parker, 2013; Steinberger *et al.*, 2016; Vaezipour *et al.*, 2017; Saunders *et al.*, 2018). However, this method would not reveal the sample size until data collection finishes.

In order to build an understanding on the sample size needed before the start of data collection, this study has considered recommendations proposed in previous studies and also reviewed the sample sizes adopted by previous qualitative interview studies involving older drivers. The recommendations from previous research suggested that a sensible sample size for a qualitative interview study should be between 5 to 30 participants. Specifically, Luborsky and Rubinstein (1995) suggested that 12 to 26 participants are generally accepted as enough for qualitative interviews, while a larger range of sample sizes was proposed by Creswell (1998), who suggested adopting a sample size of 5 to 30 participants in quantitative studies. Guest et al. (2006) concluded that interviewing 12 participants is a big enough sample size for qualitative interview research. Also Marshall et al. (2013) made an recommendation of 15 to 30 interviews as a sufficient sample size for qualitative interview studies. In addition, a number of previous qualitative interview studies concerning older drivers were reviewed, they adopted a sample size between 2 to 68 (Siren et al., 2004; Siren and Hakamies-Blomqvist, 2005; Vrkljan and Polgar, 2007; Musselwhite and Haddad, 2010; Meng et al., 2013; Trübswetter and Bengler, 2013; Broberg and Willstrand, 2014; Mårdh, 2016; Gish et al., 2017; Mueller et al., 2017; Buckley et al., 2018; Lin et al., 2018). Older drivers who participated in the driving simulator investigations were randomly selected to be interviewed after completing the HAV experiments on the driving simulator, a sample size of 24 was determined by the time when data reached saturation.

3.5.3 Thematic analysis of interview data

In qualitative research, data interpretation and analysis can run concurrently or overlap with data collection in order to facilitate the drawing of conclusions (Cassell and Symon, 1994; Braun and Clarke, 2006; Cohen and Morrison, 2011). Therefore, it is necessary in qualitative research to determine a clear qualitative analytical framework before starting. Also, the framework selected should correspond with the research purpose so that results allow the research questions to be answered (Braun and Clarke, 2006). With respect to the exploratory nature of the qualitative interview investigation in this study, thematic analysis was deemed the most suitable choice. Thematic analysis is a widely-used method used to identify and analyse themes within qualitative data, and while it is independent of pre-existing theoretical frameworks, it allows the interpretation of diverse aspects of a research topic and can potentially offer rich and detailed qualitative findings (Boyatzis, 1998; Braun and Clarke, 2006). The implementation of thematic analysis in this study followed the guidance given by Braun and Clarke (2006), which is explained in detail in Section 6.2.3.

Thematic analysis can be broadly administered in two ways. To begin with, it could be conducted manually, where the researcher reads through all the transcripts and codes the data and identifies themes by manually searching, copying, and cutting and pasting sentence by sentence through all of the participants' transcripts (Zamawe, 2015). However, qualitative research can generate a great amount of qualitative textual data (Zamawe, 2015; Castleberry and Nolen, 2018), and for instance there were 24 transcripts in the study. Therefore manual thematic analysis could be very time-consuming, burdensome, demanding and complex and may increase the probability of error which could potentially reduce the validity of the results (Zamawe, 2015; Castleberry and Nolen, 2018). The second way to implement thematic analysis is using computer-assisted qualitative data analysis tools such as NVivo (Richards and Richards, 1994; Zamawe, 2015; Castleberry and Nolen, 2018). NVivo is a software suite which assists the researcher in analysing the semantic features of qualitative data and is capable of storing, organizing, categorizing, analysing and visualizing qualitative data (Richards and Richards, 1994; Zamawe, 2015). There are several advantages of using NVivo. Firstly, NVivo is flexible and does not have any specific requirements in terms of the design of a quantitative study (Richards and Richards, 1994; Zamawe, 2015). Secondly, NVivo makes the thematic analysis easier and more efficient by allowing the researcher to simply code data and identify themes in a more structured and effective way (Zamawe, 2015). For example, if the researcher wants to find out how many participants have mentioned a specific issue or topic, manual searching could take a very long time and be less accurate compared to using NVivo. Finally, NVivo can reduce the likelihood of data loss, as NVivo is able to store the entire qualitative dataset together with all the codes and themes created by the researcher. Compared to conducting thematic analysis manually with paper transcripts, this significantly reduce the risk of data loss (Richards and Richards, 1994; Zamawe, 2015). Therefore, the thematic analysis of the qualitative interview data in this study was implemented using NVivo, and the process is explained in detail in Section 6.2.3.

3.6 Overview of the Methodology Adopted For This Thesis

Table 3.2 Overview of the methodology of this thesis

	Chapter 4 ***1st Driving Simulator Investigation***	***Chapter 5*** ***2nd Driving Simulator Investigation***	***Chapter 6*** ***Semi-structured Interview Investigation***	***Chapter 7*** ***3rd Driving Simulator Investigation***
Objectives	• To investigate effect of age and complete disengagement from driving on takeover performance	• To Investigate effect of age and adverse weathers on takeover performance	• To explore older drivers' opinions and requirements towards the human-machine interaction of HAV	• To test older drivers' requirements • To investigate effect of age and different types of HMIs on takeover performance
Nature of study	• Quantitative	• Quantitative	• Qualitative	• Quantitative
Methods adopted	• Driving simulator	• Driving simulator	• Semi-structured interview	• Driving simulator • NASA RTLX questionnaire • 7 Likert scale questionnaire
Data collected	• Data of takeover performance	• Data of takeover performance	• Data of individual interview	• Data of takeover performance • NASA RTLX score • 7 Point-Likert Scale score
Data analysis	• Mixed Factorial ANOVA • Chi-square (X^2) test • Paired sample t-test • Pearson correlation coefficient	• Mixed Factorial ANOVA • Chi-square (X^2) test • McNemar test • Independent sample t-test • Paired sample t-test	• Thematic Analysis	• Mixed Factorial ANOVA • Chi-square (X^2) test • McNemar test • Paired sample t-test • Mann-Whitney U test • Wilcoxon signed-rank test • Friedman tests • Pearson correlation coefficient
Data analysis technique	• SPSS	• SPSS	• NVivo	• SPSS

3.7 Conclusion

This chapter has reviewed the methods that are potentially available for use in achieving the aim and objectives of this study, and then discussed the methods adopted in this thesis. In general, this study has adopted a mixed quantitative and qualitative methodological approach to study HAVs with older drivers. The investigations undertaken in this thesis included two driving simulator investigations to quantitatively investigate older drivers' takeover performance in the HAV, and then an individual semi-structured interview investigation was chosen to qualitatively explore older drivers' opinions and requirements concerning the human-machine interaction in the HAV. Finally some of their requirements were quantitatively tested in another driving simulator investigation. These investigations are highlighted in the following chapters 4, 5, 6 and 7.

Chapter 4. Investigation of the effects of age and disengagement in driving on drivers' takeover performance in HAV

4.1 Introduction

Chapter 2 pointed out that research focusing on older drivers' interaction with HAVs is still limited. Therefore, it is necessary to examine older drivers' interactions with HAV to build knowledge that can potentially inform the design of age-friendly human-machine interaction in the HAV. In addition, one of the key features of the HAV is that drivers are allowed to be completely disengaged from driving. However, the review of the literature showed that the effects of complete disengagement from driving on older drivers' takeover performance in the HAV have not been fully investigated. A lack of knowledge here could potentially become a barrier that stops older drivers from being assisted by HAVs.

In response to these knowledge gaps, Chapter 4 details a driving simulator investigation aimed to address two key areas: firstly, to investigate the effect of age on drivers' takeover performance in the HAV; and secondly, to examine the effect of complete disengagement from driving on drivers' takeover performance in the HAV.

4.2 Method

The justification and selection of the main methodologies for using the driving simulator (figure 4.1), the detailed review of the HAV scenario (figure 4.1), the dependent variables collected, the statistical methods selection, the sample size selection as well as the participant recruitment of the driving simulator investigations have been provided in Section 3.3. This section reviews the experimental design, the design of non-driving related tasks, and experimental procedure of this specific driving simulator investigation.

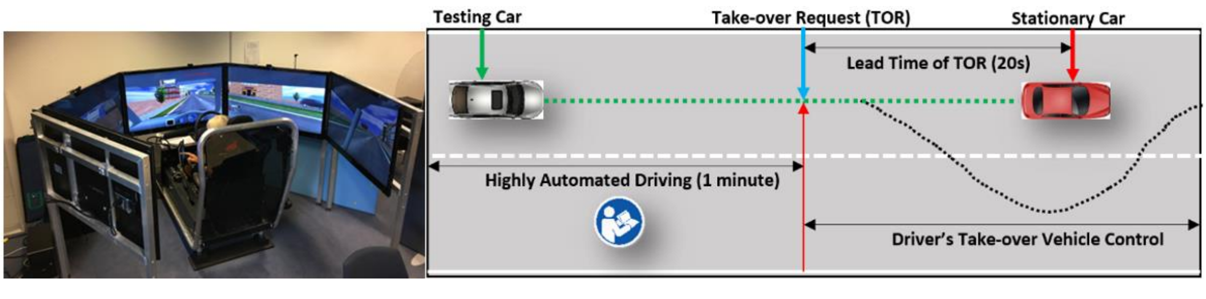


Figure 4.1 Fixed-based ST Software Jentig50 driving simulator and HAV scenario.

4.2.1 Experimental design considerations

Corresponding to the aims of this investigation, firstly, age was selected as an independent variable in this investigation and it consists of two levels. Older drivers aged ≥ 60 years are the experimental group. Younger drivers (aged ≤ 35 years) have been widely adopted as a control group in studying the effect of age on drivers' performance using automated vehicles in previous research (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017), and it was selected as a control group.

Secondly, driving disengagement level (DDL) was adopted as another independent variable. It consists of two levels: the experimental condition of complete disengagement from driving; and the baseline condition of monitoring driving, which represents a state where drivers are not manually controlling the vehicle but are engaged in the driving loop of the HAV.

In addition, as Section 3.3.3.6 suggested, the HAV scenario runs on two types of roads. It would be valuable to investigate the effect of different road types on takeover performance in the HAV. Therefore, road type is adopted as the third independent variable, consisting of two levels: a city road and the motorway.

Having determined the independent variables for this investigation, the next step is to design the experiments. According to the review of experimental design considerations in section 3.3.8, it is clear that age could not be a within-subjects factor, and so it was adopted as a between-subjects factor. The driving disengagement level (DDL) was adopted as the within-subjects independent variable. So each participant experiences both complete disengagement from driving and the condition of monitoring driving. In order to reduce the total number of drives for each participants, road type was selected as an additional between-subjects independent variables. The participants were divided into two groups, one for the city road and the other for the motorway. In order to reduce order effects, the order of the driving sessions was randomised for participants and they were provided with time to rest between each sessions. In summary, this investigation adopts a mixed within- and between-subjects experimental design. An overview of the experimental design was shown in Table 4.1.

Table 4.1 Experimental design overview

Between-subjects independent variable		***Within-subjects independent variables***
Road Type	**Age**	**Driving Disengagement Level (DDL)**
City Road	Younger drivers	Monitoring driving, Disengagement from driving
City Road	Older drivers	Monitoring driving, Disengagement from driving
Motorway	Younger drivers	Monitoring driving, Disengagement from driving
Motorway	Older drivers	Monitoring driving, Disengagement from driving

A detailed review of the selection of the dependent variables (Table 4.2) was given in Section 3.3.4.

Table 4.2 Overview of the dependent variables for this investigation

Dependent variables	***Unit***
Reaction time	s
Takeover time	s
Indicator time	s
Time to collisions (TTC)	s
Resulting acceleration	m/s²
Steering wheel angle	degree
Collisions and critical encounters (CCE)	Count
Hasty takeover	Count

4.2.4 Design of the non-driving related task

As suggested in section above, this investigation adopted a within-subjects independent variable of driving disengagement level (DDL). In order to effectively test the this independent variable, the non-driving related tasks should be carefully designed to enable the participants to achieve the state of being completely disengaged from driving or monitoring driving representing being engaged in driving in the HAV. The non-driving related tasks refer to the tasks that drivers perform when the HAV is performing automated driving.

As reviewed in Section 2.3.5, to achieve the state of completely disengaged from driving among participants, previous research has adopted standardized tasks such as a cognitive n-back task as well as naturalistic activities such as reading in HAVs. Both of them have been found to be able to completely disengage drivers from driving, resulting in deteriorated take over performance (Radlmayr et al., 2014; Zeeb et al., 2016; Eriksson and Stanton, 2017; Molnar et al., 2017; Zeeb et al., 2017). Compared to standardized tasks, some research indicates the importance of using naturalistic tasks in HAV research to ensure ecological validity (Körber et al., 2016; Zeeb et al., 2017). In the context of this research, naturalistic tasks would enable this test to be closer to the case of the authentic use of HAV in reality for older people. The top three activities that elderly people perform most frequently in their free time are watching television, spending time with friends or family and reading (Seddon, 2011). Among these, watching television and reading seem to be appropriate for this investigation as they can be performed individually in the controlled environment of the driving simulator lab. To ensure that participants are as completely disengaged from driving as possible, a mandatory reading task is more suitable, since by asking subjects to read the material aloud their disengagement from driving could be controlled. The reading material was presented using a tablet, as shown in Figure 4.2. To further guarantee the subjects' disengagement from driving, the tablet was located at an angle of 45 degree left from the central line of the steering wheel to ensure that the subject's face was not aligned with the vehicle's driving direction (VENTURER, 2017).

The status of being engaged in driving by a participant in the HAV was achieved by asking them to constantly monitor the HAV driving while taking their hands off of the steering wheel and that feet off of the pedals. This is the baseline condition in investigating the effect of complete disengagement from driving on takeover performance. In order to ensure that the participants were constantly engaged in the driving, they were asked to describe the driving environment and the traffic situation verbally when they were monitoring the HAV driving. In addition, to make sure that the participants could focus on monitoring driving, the tablet was removed when they were monitoring driving.

Figure 4.2 Participants performing the reading task in the HAV on the city road and the motorway.

4.2.5 Participants

The detailed review of the participants' demographic features and recruitment process is highlighted in Section 3.3.7. In general, 76 drivers (39 older drivers and 37 younger drivers) participated this study. Their annual mileage was shown in Table 4.3.

Table 4.3 Annual mileage driven by participants

Annual mileage (miles)	***0-3000***	***3000-6000***	***6000-10000***	***10000-15000***	***15000+***	***Total***
Younger drivers	15	13	5	2	2	37
Older drivers	6	10	12	10	1	39
Total	21	23	17	12	3	76

4.2.6 Experimental procedure

When the participants arrived, their driving licences were checked and they completed the ethical form (Appendix B) and demographic questionnaire (Appendix E). After that, the reason for the research was briefly explained to them as being to investigate their takeover performance in the HAV. All participants were provided with considerable practice time to become comfortable with the simulator until they confirmed verbally that they were ready. Then the HAV scenario was briefly explained. The participants were told that their performance in each driving session would be assessed; during the automated driving mode, they needed to take their hands off the steering wheel and their feet off the pedals, and they needed to verbally describe the driving environment or read the material on the tablet out loud when required; they need to take over control of the vehicle as soon as they received the takeover request; after taking over control, they needed to keeping driving until being informed to pull over; they needed to obey the speed limit and indicate when changing lanes and drive as they normally would in real life. After that, the experiment started and the sequence of the driving sessions was randomised to avoid order effects.

4.3 Results

This section reports the results of this investigation. The justification of the use of statistical tests is detailed in Section 3.3.9.

4.3.1 Trajectories

Figures 4.5 and 4.6 illustrates participants' average trajectories when they took over from the HAV while being disengaged from driving and monitoring on the city road and the motorway. The average trajectories were generated by positioning each driver's lane position data as vertical coordinates and the driving distance data as horizontal coordinates. The trajectories in different conditions are illustrated by lines of different colours, and the black vertical arrow and a car were used to indicate the takeover request and the stationary car.
In general, younger drivers' average takeover trajectories in monitoring driving and disengaged from driving conditions exhibited relatively similar characteristics. However, there are apparent gaps between older drivers' average take-over trajectories in monitoring driving and disengaged from driving conditions, with those in monitoring driving conditions indicate an earlier intervention and a steeper trajectory than in disengaged from driving condition.

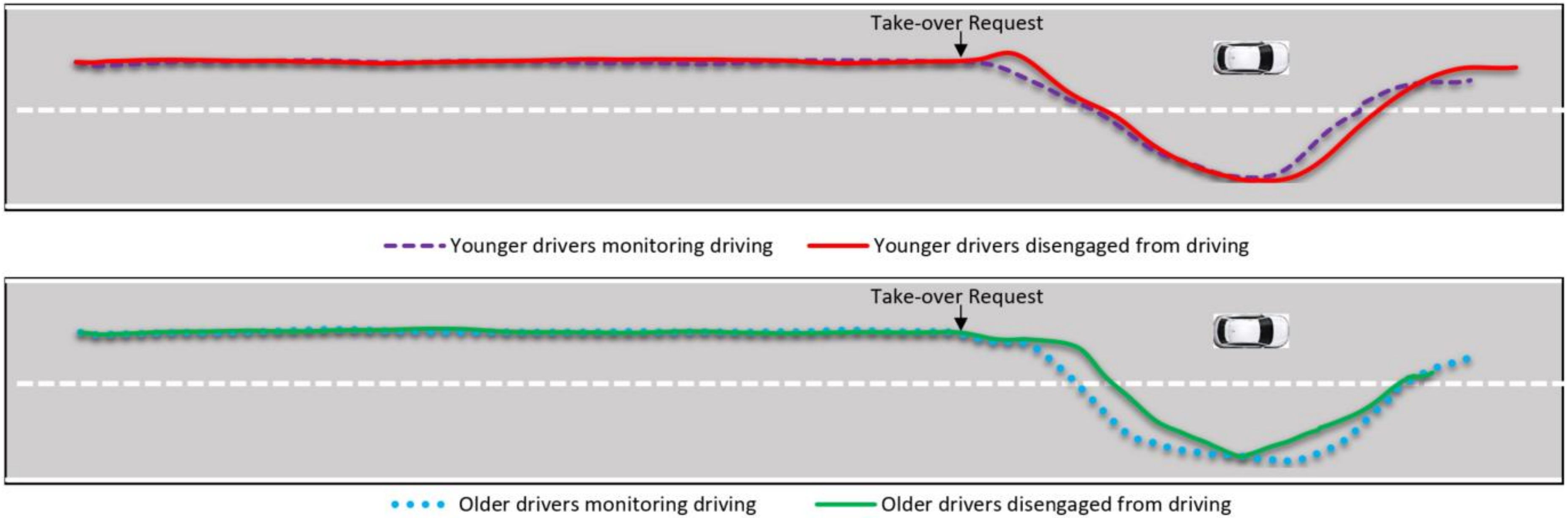


Figure 4.3 Average trajectories when older and younger drivers took over control from HAVs on the city road.

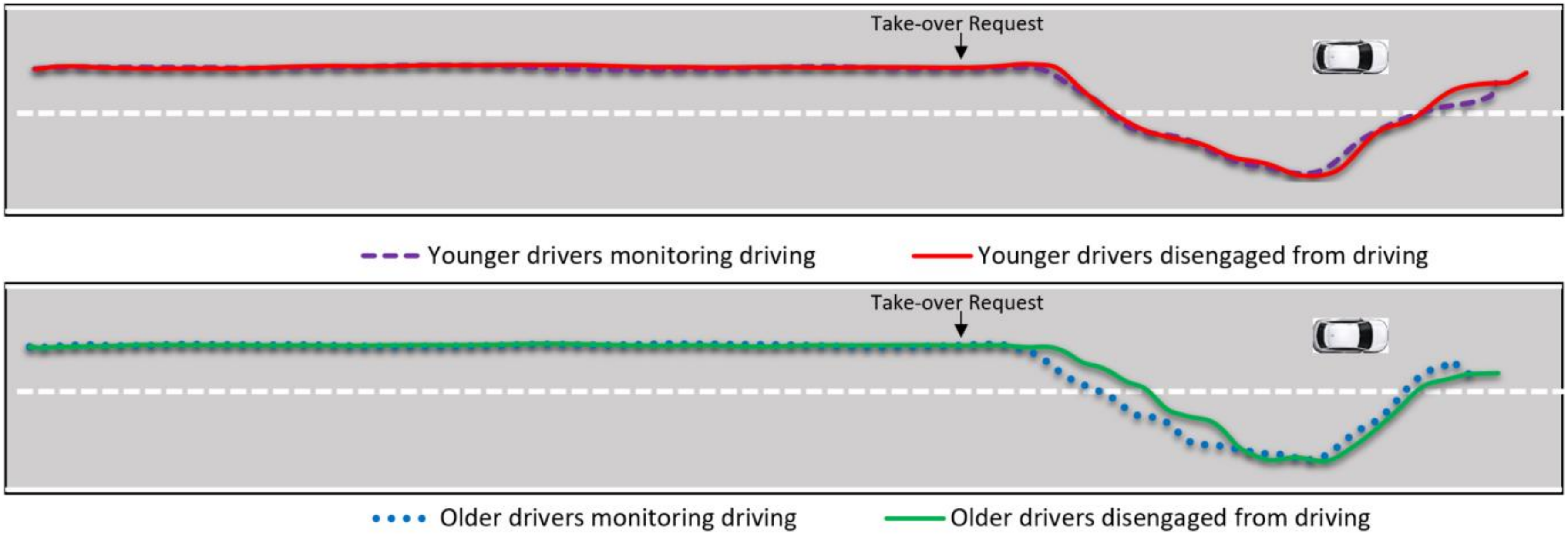


Figure 4.4 Average trajectories when older and younger drivers took over control from HAVs on the motorway

4.3.2 Steering and braking behaviours

This section reports the results of drivers' steering and braking behaviours to avoid the stationary vehicle when taking over control from the HAV. As Table 4.4 indicated, in general, the majority participants avoided the stationary car by only steering into the next lane. And the number of participants who avoided the stationary car by steering and braking showed a consistent trend.

The monitoring driving resulted in 71 drivers who responded to the stationary vehicle by only steering to the next lane, including 36 older drivers and 35 younger drivers. 5 drivers reacted by both braking and steering to the next lane, including 3 older drivers and 2 younger drivers. Chi-square test yielded that there is no significant difference in the reaction type between older and younger drivers when they were monitoring driving, $X^2(1) = 0.162$, p=0.688.
The disengaged from driving condition led to 67 drivers who responded to the stationary vehicle by only steering to the next lane, including 34 older drivers and 33 younger drivers. 9 drivers responded by steering and braking, including 5 older drivers and 4 younger drivers. A Chi-square test yielded that there is no significant difference in the reaction type between older and younger drivers when they were disengaged from driving, $X^2(1) = 0.073$, p=0.768.

Table 4.4 Overview of the steering and braking behaviours

	Monitoring driving		*Disengagement from driving*	
	Steer only	*Steer & brake*	*Steer only*	*Steer & brake*
Older drivers	36	3	34	5
Younger drivers	35	2	33	4
Total	71	5	67	9

4.3.3 CCEs and hasty takeovers

There were no collisions for both younger and older drivers under all the situations. There was only one critical encounter recorded (TTC=1.38s). This was among older drivers cohort and was during the use-case of taking over the control of the HAV when they were disengaged from driving on the city road. This difference was not statistically significant, as assessed by a Chi-square test, $X^2(1) = 2.153$, p=0.142.

Regarding the hasty takeovers, in the monitoring driving condition, there was no hasty takeovers recorded both the younger and older drivers. In the disengagement from driving condition, there was 3 hasty takeovers recorded, all of them were among the older drivers. A Chi-square test revealed that this difference was not statistically significant, $X^2(1) = 2.963$, p=0.085.

4.3.4 Reaction time

This section reports the results of drivers' reaction time when taking over the control of the vehicle in the HAV while monitoring driving and disengaging from driving. Figure 4.5 illustrates the mean reaction time for older and younger drivers. The overall participants had a mean reaction time of 1.93s (SD=0.83). The data of reaction time was analysed by a mixed factorial ANOVA with a within-subjects factor of driving disengagement level (DDL), and between-subjects factors of age and road type. Table 4.5 summarizes the results of ANOVA. Results showed that age had a statistically significant main effect on reaction time, $F(1,72)=27.249$, $p<0.001$, $\eta p^2=0.275$, with older drivers (M=2.14s, SD=0.96s) reacted slower to the takeover request than the younger drivers (M=1.70s, SD=0.59s), a statistically significant difference of 0.43s (95% CI, 0.27s to 0.60s).

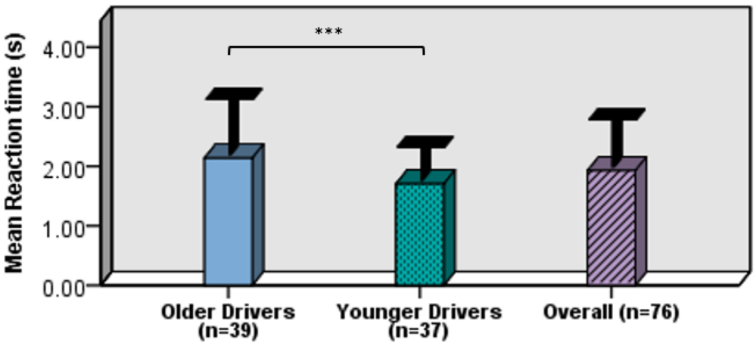


Figure 4.5 Mean reaction time for different age groups (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Figure 4.6 shows the mean reaction time for participants when they monitor driving and disengage from driving. Results of ANOVA shows that DDL had a significant main effect on reaction time, $F(1,72)= 295.761$, $p<0.001$, $\eta p^2=0.804$, with drivers took longer time to react to takeover request when they monitor driving (M=1.33s, SD=0.34s) than they disengage from driving (M=2.53s, SD=0.73s), a statistically significant increase of 1.20s (95% CI, 1.05s to 1.32s) in the reaction time from monitoring driving to disengagement from driving.
In addition, Results of ANOVA showed that road type yielded a significant main effect on reaction time, $F(1,72)=19.354$, $p<0.001$, $\eta p^2=0.212$, with drivers took longer time to react to the takeover request on the motorway (M=2.11s, SD=0.82s) than on the city road

(mean=1.75s, SD=0.80s). This represented a statistically significant increase of 0.36s (95% CI, 0.20s to 0.53s) in the reaction time from the city road to the motorway.

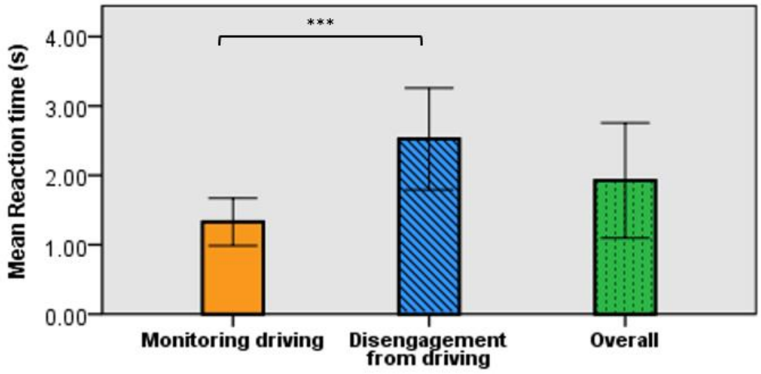


Figure 4.6 Mean reaction time when monitor driving and disengage from driving (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Table 4.5 Results of a mixed ANOVA for reaction time

	df	*F*	*p*	*ηp²*
Age	1,72	27.249***	<0.001	0.275
DDL	1,72	295.761***	<0.001	0.804
Road Type	1,72	19.354***	<0.001	0.212
Age × DDL	1,72	27.289***	<0.001	0.275
Age × Road Type	1,72	0.451	0.504	0.006
DDL × Road Type	1,72	0.103	0.750	0.001
Age × DDL × Road Type	1,72	2.015	0.160	0.027

*Note: *= p ⩽0.05, **= p ⩽0.01, ***= p ⩽0.001*

Moreover, there is a significant interaction effect between age and DDL on the reaction time, $F(1,72)= 27.289$, $p<0.001$, $\eta p^2=0.275$. It indicates that the disengagement from driving affects older and younger drivers in different ways in terms of the reaction time. Figure 4.7 virtualises this interaction. Paired sample t-tests were performed in order to interpret the significant age and DDL interaction on the reaction time. For the older drivers, DDL yielded a significant effect on reaction time, $t(38) = -13.317$, $p<0.001$. Older drivers' reaction time was significantly longer when disengaging from driving (M=2.92s, SD=0.70s), compared to monitoring driving (M=1.37s, SD=0.37), this represents a significant difference of 1.55s (95% CI, 1.31s to 1.79s). For the younger drivers, DDL also yielded a significant effect on reaction time, $t(36) = -11.612$, $p<0.001$, their reaction time was significantly longer when disengaging from driving (M=2.12s, SD=0.52s) than monitoring driving (M=1.30s, SD=0.31s), a significant difference of 0.82s (95% CI, 0.68s to 0.97s). This series of results suggest that although both the older and younger drivers' reaction time increased when switching from the monitoring driving condition to the disengagement from driving conditions, older drivers' reaction time increased much more greatly compared to the younger drivers.

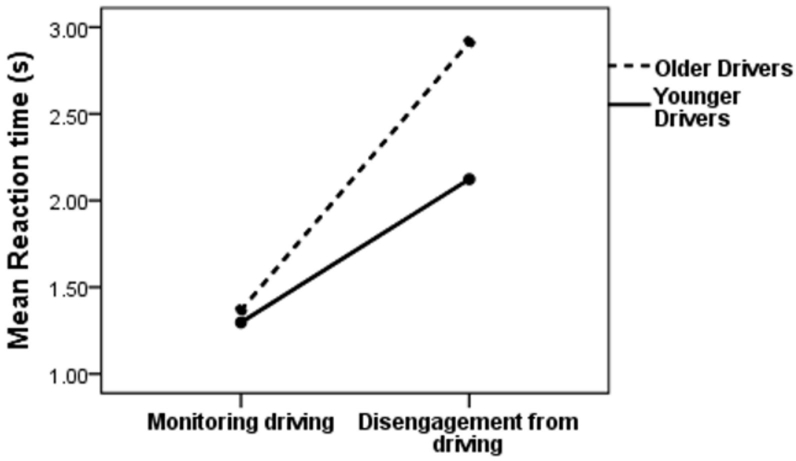


Figure 4.7 Illustration of the significant interaction effect between age and DDL on reaction time.

4.3.5 Takeover time

This section reports the results of drivers' takeover time when reassuming the control of the vehicle in the HAV while monitoring driving and disengaging from driving on different roads. Figure 4.8 indicates the mean takeover time for older and younger drivers. The overall participants exhibited a mean takeover time of 3.13s (SD=1.38s). In order to investigate the effects of age, DDL and road type on the takeover time, a mixed factorial ANOVA was performed. Table 4.6 summarizes the results of ANOVA. Age yielded a statistically significant effect on the takeover time, $F(1,72)= 9.107$, $p=0.004$, $\eta p^2=0.112$, with older drivers having slower takeover times (M=3.38s, SD=1.71s) than younger drivers (M=2.84s, SD=0.86s), a statistically significant difference of 0.55s (95% CI, 0.19s to 0.92s).

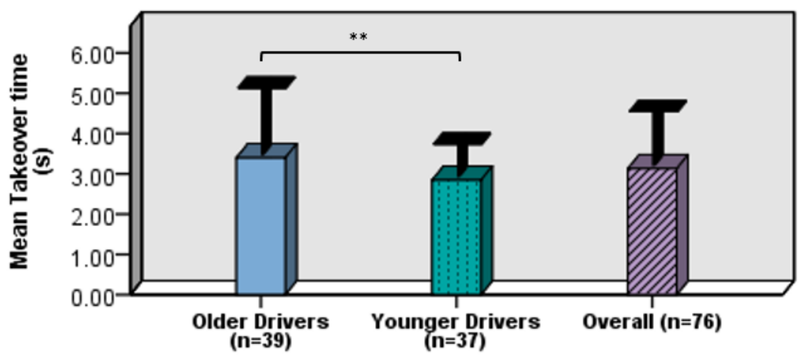


Figure 4.8 Mean takeover time for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Figure 4.9 illustrates the mean takeover time participants exhibited when they monitor driving and disengage from driving. Results of ANOVA shows that DDL had a significant main effect on takeover time, $F(1,72)= 62.517$, $p<0.001$, $\eta p^2=0.465$, with drivers needed longer time to generate the first active input to the vehicle when they monitor driving (M=2.46s, SD=0.87s) than when they disengage from driving (M=3.79s, SD=1.47s), this represents a statistically significant increase of 1.33s (95% CI, 0.98s to 1.64s) in the takeover time from monitoring driving to disengagement from driving.

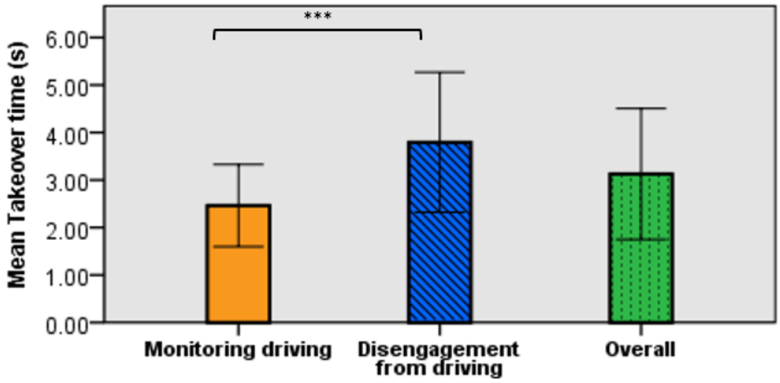


Figure 4.9 Mean takeover time when monitor driving and disengage from driving (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Table 4.6 Results of a mixed ANOVA for takeover time

	df	*F*	*p*	*ηp²*
Age	1,72	9.107**	0.004	0.112
DDL	1,72	62.517***	<0.001	0.465
Road Type	1,72	9.662**	0.003	0.118
Age × DDL	1,72	24.017***	<0.001	0.250
Age × Road Type	1,72	0.230	0.633	0.003
DDL × Road Type	1,72	0.320	0.574	0.004
Age × DDL × Road Type	1,72	1.569	0.214	0.021

*Note: *= p ≤0.05, **= p ≤0.01, ***= p ≤0.001*

Additionally, road type was found to have a significant effect on takeover time, $F(1,72)= 9.662$, $p=0.003$, $\eta p^2=0.118$, with drivers showing longer takeover time on the motorway (M=3.41s, SD=1.45s) than on the city road (M=2.85s, SD=1.27s), this represents a statistically significantly increase of increase of 0.56s (95% CI, 0.21s to 0.94s) in the takeover time from the city road to the motorway.

Moreover, results of ANOVA yielded a significant interaction effect between age and DDL on the reaction time, $F(1,72)= 24.017$, $p<0.001$, $\eta p^2=0.250$. As Figure 4.10 shows, it indicates that the disengagement from driving affects older and younger drivers differently in terms of the takeover time. In order to interpret this interaction, paired sample t-tests were performed. For older drivers, DDL yielded a significant effect on takeover time, $t(38) = -7.903$, $p<0.001$, older drivers' takeover time was statistically longer when disengaging from driving (M=4.47s, SD=1.61s) compared to monitoring driving (M=2.35s, SD=0.95), a significant difference of 2.12s (95% CI, 1.58s to 2.67s). For the younger drivers, DDL showed a significant effect on their takeover time, $t(36) = -2.652$, $p=0.012$, their takeover time was significantly longer when disengaging from driving (M=3.10s, SD=0.89s) compared to monitoring driving (M=2.60s, SD=0.75s), a significant difference of 0.49s (95% CI, 0.12s to 0.87s). This a series of results indicated that both the older and younger drivers' takeover time increased when switching from the monitoring driving condition to the disengagement from driving conditions, however older drivers' takeover time slowed more sharply compared to the younger drivers.

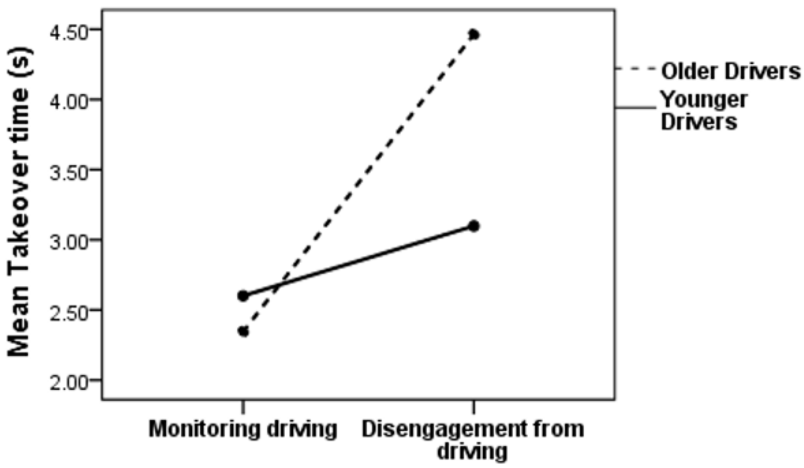


Figure 4.10 Illustration of the significant interaction effect between age and DDL on takeover time.

4.3.6 Indicator time

This section reports the results of drivers' indicator time when retaking the control of the vehicle in the HAV while monitoring driving and disengaging from driving on different roads. Figure 4.11 shows the mean indicator time for different age groups. General, the overall participants had a mean takeover time of 7.67s (SD=3.39s). The data of indicator time was analysed by a mixed factorial ANOVA with a within-subjects factor of driving disengagement level (DDL), and between-subjects factors of age and road type. Table 4.7

shows the results of ANOVA. Age yielded a statistically significant effect on the takeover time, $F(1,72)= 4.538$, $p=0.037$, $\eta p^2=0.059$, with the older drivers cohort taking longer to generate indicator light signal of lane change (M=8.32s, SD=3.48s) compared to the time for the younger drivers cohort (M=6.99s, SD=3.18s), this represents a statistically significant difference of 1.33s (95% CI, 0.85s to 2.57s) in the indicator time between the two age groups.

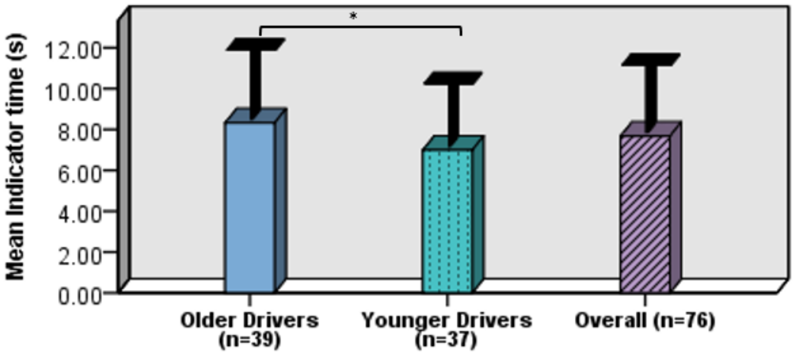


Figure 4.11 Mean indicator time for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Figure 4.12 shows the mean indicator time participants had when they monitor driving and disengage from driving. Results of ANOVA shows that DDL had a significant main effect on indicator time, $F(1,72)= 37.851$, $p<0.001$, $\eta p^2=0.345$, with drivers needing longer to generate indicator signal of lane change when they were disengaged from driving (M=8.79s, SD=3.44s) compared to it when they were monitoring driving (M=6.56s, SD=2.98s), this represents a statistically significant increase of 2.23s (95% CI, 1.48s to 3.89s) in the indicator time from monitoring driving to disengagement from driving.

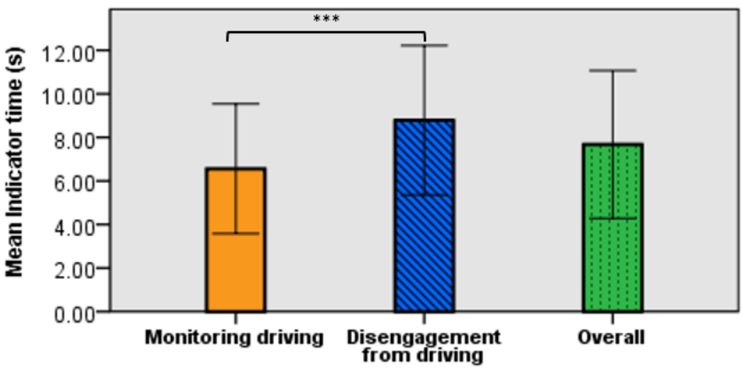


Figure 4.12 Mean indicator time when monitor driving and disengage from driving (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Additionally, the road type did not have a significant effect on indicator time, despite drivers measured taking longer to initiate the manoeuvre indicator light on the motorway (M=7.83s, SD=3.54s) than on the city road scenario (M=7.52s, SD=3.27s).

Table 4.7 Results of a mixed ANOVA for indicator time

	df	*F*	*p*	*ηp²*
Age	1,72	4.538*	0.037	0.059
DDL	1,72	37.851***	<0.001	0.345
Road Type	1,72	0.241	0.625	0.003
Age × DDL	1,72	14.469***	<0.001	0.167
Age × Road Type	1,72	0.061	0.806	0.001
DDL × Road Type	1,72	0.412	0.523	0.006
Age × DDL × Road Type	1,72	0.299	0.586	0.004

*Note: *= p ⩽0.05, **= p ⩽0.01, ***= p ⩽0.001*

Moreover, there was a significant interaction between age and DDL on the indicator time, $F(1,72)= 14.469$, $p<0.001$, $\eta p^2=0.167$. As Figure 4.13 shows, it indicates that the disengagement from driving affects older and younger drivers in different ways in terms of the indicator time. In order to interpret this interaction, paired sample t-tests were performed. For older drivers, DDL yielded a significant effect on indicator time, $t(38) = -6.162$, $p<0.001$, older drivers' indicator was statistically longer when disengaging from driving (M=10.09s, SD=3.33s) compared to monitoring driving (M=6.56s, SD=2.65), a significant difference of 3.55s (95% CI, 2.38s to 4.71s). For the younger drivers, DDL showed a significant effect on their indicator time, $t(36) = -2.127$, $p=0.040$, their takeover time was significantly longer when disengaging from driving (M=7.41s, SD=3.02s) compared to monitoring driving (M=6.58s, SD=3.32s), a significant difference of 0.83s (95% CI, 0.04s to 1.63s). This a series of results shows that both the older and younger drivers' indicator time increased when switching from the monitoring driving condition to the disengagement from driving conditions, but the time taken for older drivers' to initiate the indicator light was slowed much greater than the younger drivers cohort.

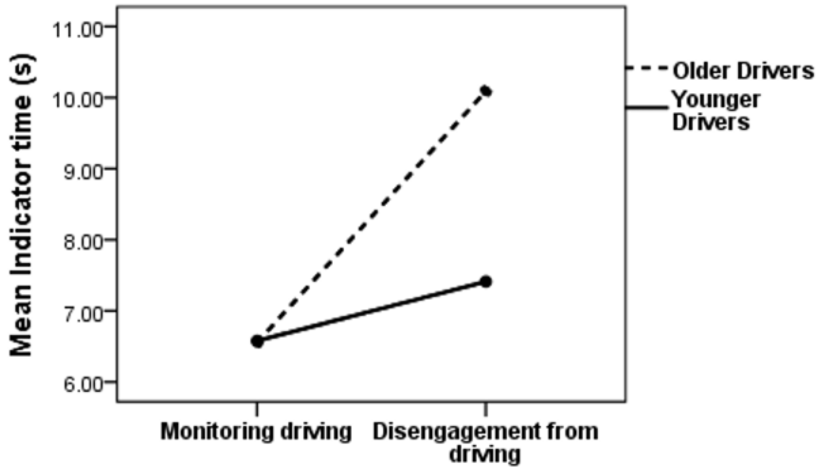


Figure 4.13 Illustration of the significant interaction effect between age and DDL on indicator time.

4.3.7 Time to collision (TTC)

This section reports the results of drivers' time to collision (TTC) when reassuming the control of the vehicle in the HAV while monitoring driving and disengaging from driving on different roads. Figure 4.14 indicates the mean TTC for different age groups. The overall participants had a mean TTC of 10.32s (SD=5.45s). The data of TTC was analysed by a mixed factorial ANOVA with a within-subjects independent variable of driving disengagement level (DDL), and between-subjects independent variables of age and road type. The results ANOVA are summarized in Table 4.8. Results showed that age did not have a statistically significant effect on TTC, older drivers (M=10.32s, SD=5.24s) exhibited similar TTC with the younger drivers (M=10.32s, SD=5.72s).

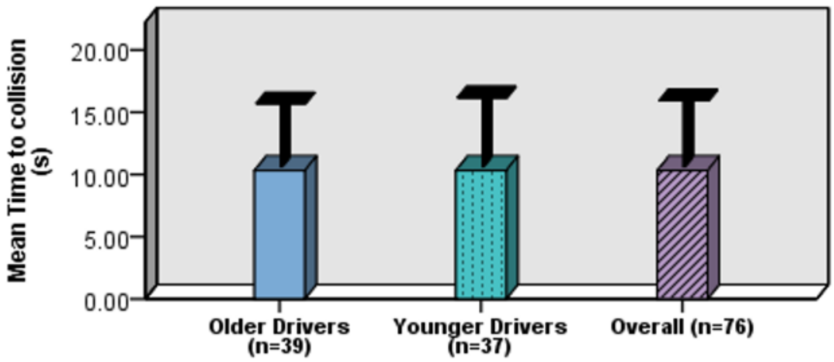


Figure 4.14 Mean TTC for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

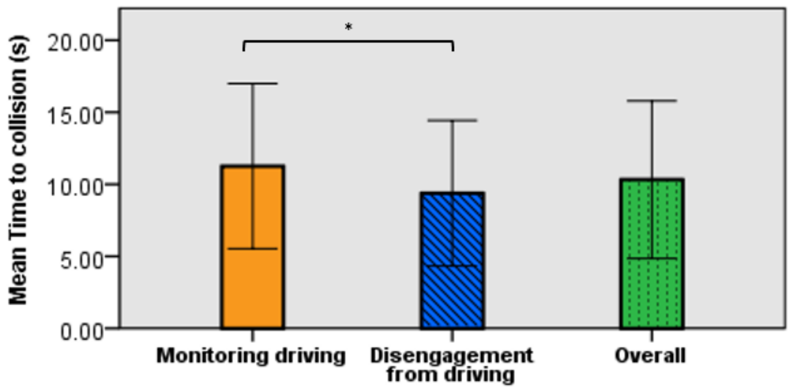


Figure 4.15 Mean TTC when monitor driving and disengage from driving (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Figure 4.15 indicates the mean TTC participants exhibited when taking over control of the HAV while they were monitoring driving and disengaging from driving. Results of ANOVA shows that DDL had a significant main effect on TTC, $F(1,72)= 6.579$, p=0.012, $\eta p^2=0.084$, TTC was longer when they were monitoring driving (M=11.26s, SD=5.73s) than when disengaging from driving (M=9.37s, SD=5.05s), this represents a statistically significant increase of 1.88s (95% CI, 0.41s to 3.25s) in the indicator time from monitoring driving to disengagement from driving. Road type did not have a significant effect on the TTC, despite drivers exhibited slightly shorter TTC on the city road (M=10.04s, SD=5.97s) than the motorway (M=10.61s, SD=4.90s).

Table 4.8 Results of a mixed ANOVA for TTC

	df	*F*	*p*	*ηp²*
Age	1,72	0.000	0.991	0.000
DDL	1,72	6.579*	0.012	0.084
Road Type	1,72	0.323	0.571	0.004
Age × DDL	1,72	4.038*	0.048	0.053
Age × Road Type	1,72	8.681	0.642	0.003
DDL × Road Type	1,72	0.982	0.325	0.013
Age × DDL × Road Type	1,72	0.444	0.507	0.006

*Note: *= p ⩽0.05, **= p ⩽0.01, ***= p ⩽0.001*

Moreover, there was a significant interaction between age and DDL, as indicated in Figure 4.16, it indicates DDL affects the TTC differently between the older and younger drivers. In order to interpret this interaction, paired sample t-tests were performed. For older drivers, DDL yielded a significant effect on TTC, $t(38) = 3.450$, p=0.001, older drivers' TTC was statistically shorter when disengaging from driving (M=8.68s, SD=5.11s) compared to monitoring driving (M=11.96s, SD=4.90s), a significant difference of 3.29s (95% CI, 1.36s to

5.21s). For the younger drivers, DDL did not have a significant effect on their indicator time, $t(36) = 0.381$, p=0.705, although their takeover time was shorter when disengaging from driving (M=10.14s, SD=4.94s) compared to monitoring driving (M=10.53s, SD=6.48s), a difference of 0.40s (95% CI, -1.74s to 2.54s). This a series of results shows when switching between monitoring driving to disengaging from driving, older drivers' TTC was reduced more seriously compare to younger drivers.

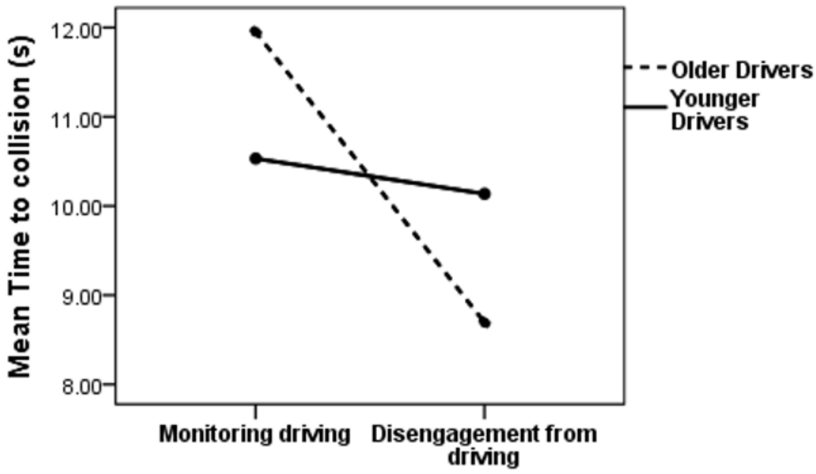


Figure 4.16 Illustration of the significant interaction effect between age and DDL on time to collision.

4.3.8 Resulting acceleration

This section reports the results of drivers' resulting acceleration when taking over the control of the vehicle in the HAV. Figure 4.17 indicates the mean resulting acceleration for both the age groups. In general, the overall participants exhibited a mean resulting acceleration of 2.61 m/s^2 (SD=1.71 m/s^2). A mixed factorial ANOVA was performed to examine the effect of age, DDL and road type on drivers' resulting acceleration. The results of ANOVA was displayed in Table 4.9. Results showed that age exhibited statistically significantly main effect on the resulting acceleration, $F(1,72)= 5.435$, p=0.023, $\eta p^2=0.070$, with older drivers showing significantly higher resulting acceleration (M=2.95m/s^2, SD=1.78m/s^2) than younger drivers (M=2.26m/s^2, SD=1.58m/s^2), this represents a statistically significant difference of 0.69 m/s^2 (95% CI, 0.10m/s^2 to 1.30m/s^2).

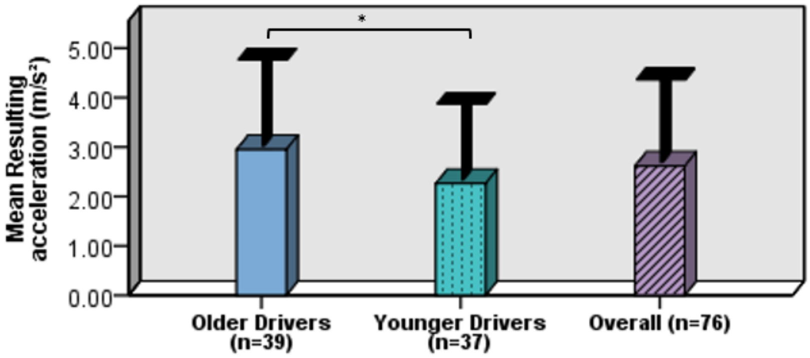


Figure 4.17 Mean TTC for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

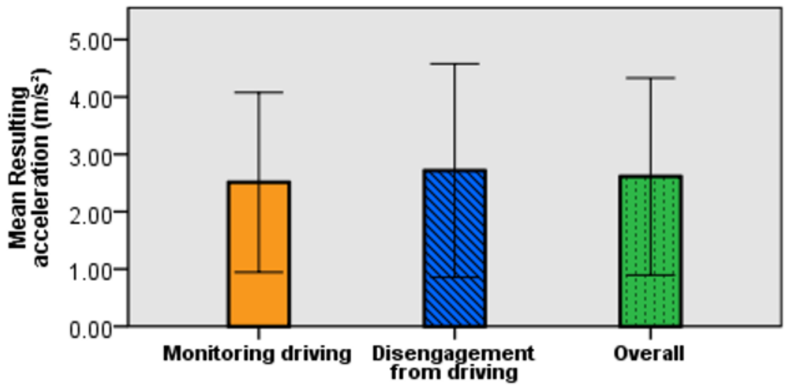


Figure 4.18 Mean resulting acceleration when monitor driving and disengage from driving (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Figure 4.18 shows the mean resulting acceleration that participants exhibited when taking over control of the HAV while they were monitoring driving and disengaging from driving. Results of ANOVA shows that DDL did not yield a significant main effect on TTC, despite drivers exhibited smaller resulting acceleration when monitoring driving ($M=2.51m/s^2$, $SD=1.57m/s^2$) than when disengaging in driving ($M=2.72m/s^2$, $SD=1.86m/s^2$). Road type also did not have a significant effect on the resulting acceleration, despite drivers exhibited stronger resulting acceleration on the motorway ($M=2.76m/s^2$, $SD=1.55m/s^2$) compared to the city road ($M=2.48m/s^2$, $SD=1.86m/s^2$).

Table 4.9 Results of a mixed ANOVA for resulting acceleration

	df	*F*	*p*	*ηp²*
Age	1,72	5.435*	0.023	0.070
DDL	1,72	0.737	0.394	0.010
Road Type	1,72	0.785	0.379	0.011
Age × DDL	1,72	1.104	0.297	0.015
Age × Road Type	1,72	2.539	0.115	0.034
DDL × Road Type	1,72	2.178	0.144	0.029
Age × DDL × Road Type	1,72	0.420	0.519	0.006

*Note: *= p ⩽0.05, **= p ⩽0.01, ***= p ⩽0.001*

4.3.9 Steering wheel angle

This section reports the results of drivers' steering wheel angle when taking over the control of the vehicle in the HAV. Figure 4.19 shows the mean steering wheel angle for younger and older drivers. In general, the overall participants had a mean steering wheel angle of 6.88 degrees (SD=4.47degrees). The data of steering wheel angle was analysed by a mixed factorial ANOVA with a within-subjects factor of driving disengagement level (DDL), and between-subjects factors of age and road type. Results of ANOVA was shown in Table 4.10. It shows that age exhibited a statistically significant effect on the steering wheel angle, $F(1,72)= 15.228$, $p<0.001$, $\eta p^2=0.175$, Older drivers showed larger steering wheel deviation (M=8.46degrees, SD=4.71degrees) than the younger drivers (M=5.20degrees, SD=3.54degrees), this represents a statistically significant difference of 3.26degrees (95% CI, 1.60degrees to 4.92degrees).

Figure 4.20 shows the mean steering wheel angle that participants exhibited when taking over control of the HAV while they were monitoring driving and disengaging from driving. Results of ANOVA showed that DDL did not have any statistically significant effect on the steering wheel angle, although drivers exhibited greater steering wheel angle when they were monitoring driving (M=6.45degrees, SD=3.96degrees) compared to disengaging driving (M=7.30degrees, SD=4.93degrees). In addition, road type did not yield a significant effect on the steering wheel angle, although drivers exhibited greater steering wheel angle on the city road (M=7.35degrees, SD=4.83degrees) compared to the motorway (M=6.38degrees, SD=4.05degrees).

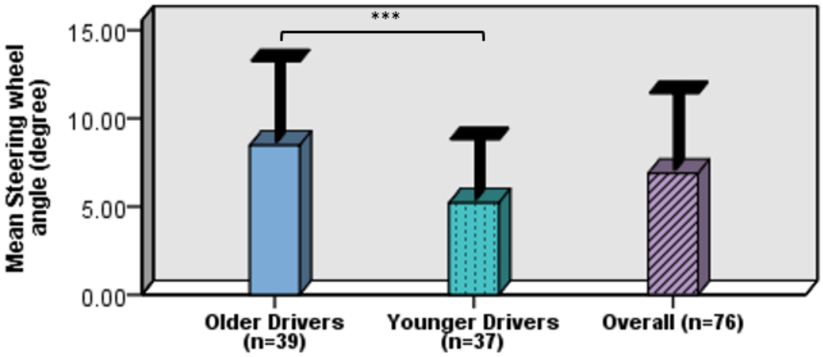


Figure 4.19 Mean steering wheel angle for different age groups (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

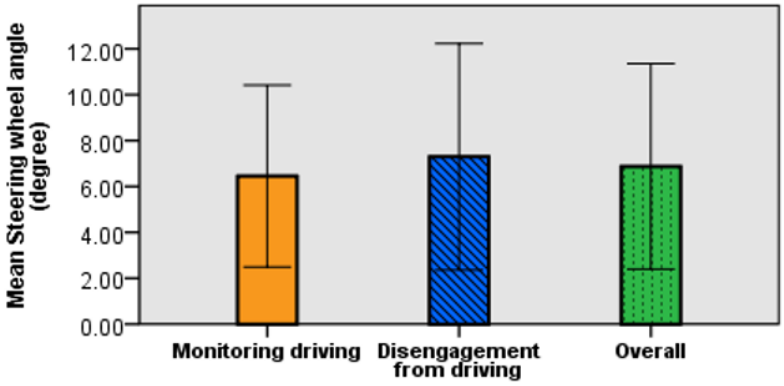


Figure 4.20 Mean steering wheel angle when monitor driving and disengage from driving (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Table 4.10 Results of a mixed ANOVA for steering wheel angle

	df	*F*	*p*	*ηp²*
Age	1,72	15.228***	<0.001	0.175
DDL	1,72	2.901	0.093	0.039
Road Type	1,72	1.343	0.250	0.018
Age × DDL	1,72	0.071	0.790	0.001
Age × Road Type	1,72	0.104	0.748	0.001
DDL × Road Type	1,72	0.302	0.584	0.004
Age × DDL × Road Type	1,72	0.317	0.575	0.004

*Note: *= p ⩽ 0.05, **= p ⩽ 0.01, ***= p ⩽ 0.001*

4.3.10 Correlation analysis

This section reports the Pearson's correlation analysis between the measurements of takeover performance. The results of Pearson's correlation coefficients were shown in Tables 4.11 and 4.12, and were illustrated in the scatterplot matrices in Figures 4.21 and 4.22.

Results showed that there is positive correlation between the value of reaction time and takeover time both when participants were monitoring driving and disengaging from driving in HAV. This suggests that the participants who switched back to the manual driving position faster when receiving the takeover request, also generate the first active input of vehicle control quicker. In addition, there is positive correlation between the takeover time and the indicator time when subjects were monitoring driving. That suggests that subjects who execute conscious input of the vehicle more quickly also indicated the signal for lane change faster.

In terms of the relationship between the takeover time and quality. Results show that when participants were monitoring driving (Table 4.11 and Figure 4.21), there was a significant negative correlation between reaction time and TTC, but there was no significant correlation between the takeover time and measurements of takeover quality. However, when participants were disengaging from driving (Table 4.12 and Figure 4.22), the value of reaction time and takeover time showed significantly negative correlation with the value of TTC. Reaction time also had significantly positive correlation with resulting acceleration and steering wheel angle. In addition, there was a significant positive correlation between takeover time and steering wheel angle. This suggests that when being disengaged from driving, participants who exhibited slower reaction and takeover time also have smaller TTC, stronger resulting acceleration and steering wheel angle.

Table 4.11 Results of Pearson's correlation coefficients of takeover performance when monitoring driving.

		Reaction time (s)	Takeove r time (s)	Indicator time (s)	Time to collision (s)	Resulting acceleration (m/s²)	Steering wheel angle (degree)
Reaction time (s)	Pearson Correlation	1	.564**	.164	-.268*	-.167	-.141
	Sig. (2-tailed)		.000	.156	.019	.149	.223
	N	76	76	76	76	76	76
Takeover time (s)	Pearson Correlation	.564**	1	.245*	-.179	-.089	-.066
	Sig. (2-tailed)	.000		.033	.121	.446	.573
	N	76	76	76	76	76	76
Indicator time (s)	Pearson Correlation	.164	.245*	1	-.525**	.067	-.004
	Sig. (2-tailed)	.156	.033		.000	.568	.976
	N	76	76	76	76	76	76
Time to collision (s)	Pearson Correlation	-.268*	-.179	-.525**	1	.256*	.203
	Sig. (2-tailed)	.019	.121	.000		.025	.079
	N	76	76	76	76	76	76
Resulting acceleratio n (m/s²)	Pearson Correlation	-.167	-.089	.067	.256*	1	.412**
	Sig. (2-tailed)	.149	.446	.568	.025		.000
	N	76	76	76	76	76	76
Steering wheel angle (degree)	Pearson Correlation	-.141	-.066	-.004	.203	.412**	1
	Sig. (2-tailed)	.223	.573	.976	.079	.000	
	N	76	76	76	76	76	76

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

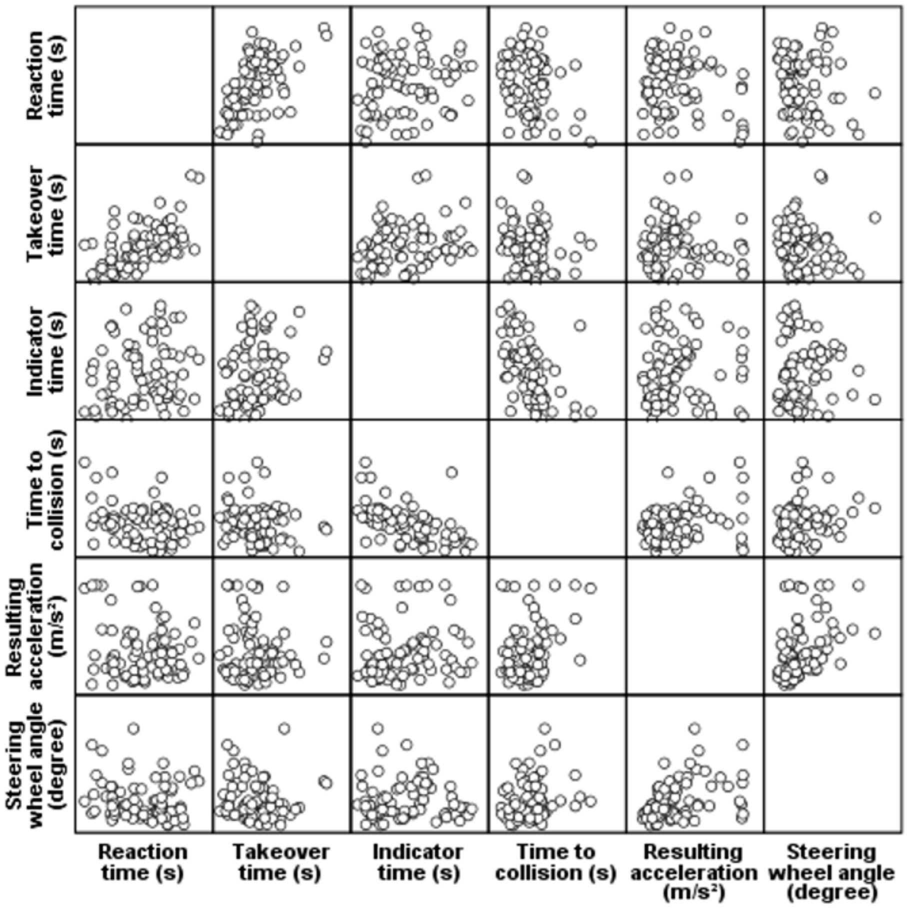


Figure 4.21 Scatter matrix of bivariate correlation analysis of drivers' takeover performance when monitoring driving

Table 4.12 Results of Pearson's correlation coefficients of takeover performance when disengaged from driving.

		Reaction time (s)	Takeover time (s)	Indicator time (s)	Time to collision (s)	Resulting acceleration (m/s²)	Steering wheel angle (degree)
Reaction time (s)	Pearson Correlation	1	.710**	.231*	-.337**	.271*	.291*
	Sig. (2-tailed)		.000	.045	.003	.018	.011
	N	76	76	76	76	76	76
Takeover time (s)	Pearson Correlation	.710**	1	.062	-.245*	.125	.254*
	Sig. (2-tailed)	.000		.597	.033	.282	.027
	N	76	76	76	76	76	76
Indicator time (s)	Pearson Correlation	.231*	.062	1	-.457**	.385**	.200
	Sig. (2-tailed)	.045	.597		.000	.001	.083
	N	76	76	76	76	76	76
Time to collision (s)	Pearson Correlation	-.337**	-.245*	-.457**	1	-.103	.031
	Sig. (2-tailed)	.003	.033	.000		.374	.793
	N	76	76	76	76	76	76
Resulting accelerati on (m/s²)	Pearson Correlation	.271*	.125	.385**	-.103	1	.358**
	Sig. (2-tailed)	.018	.282	.001	.374		.001
	N	76	76	76	76	76	76
Steering wheel angle (degree)	Pearson Correlation	.291*	.254*	.200	.031	.358**	1
	Sig. (2-tailed)	.011	.027	.083	.793	.001	
	N	76	76	76	76	76	76

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

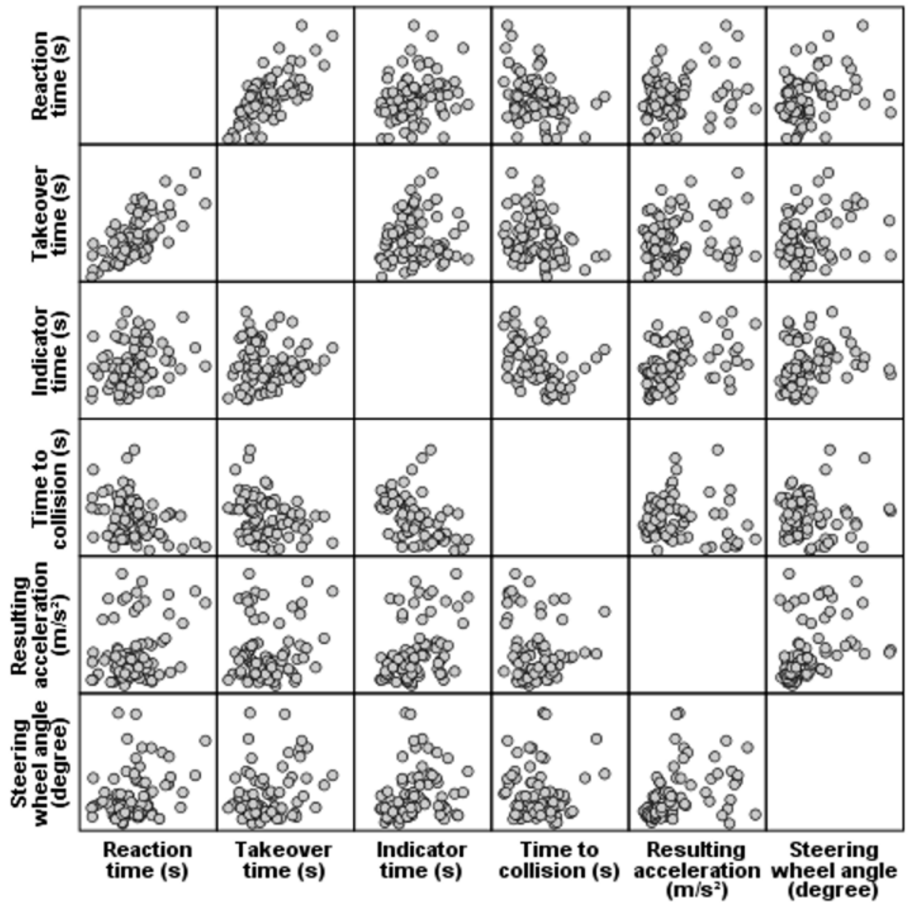


Figure 4.22 Scatter matrix of bivariate correlation analysis of drivers' takeover performance when disengaging from driving.

4.4 Discussion

This investigation aimed to investigate the influence of age, driving disengagement level (DDL) and road type on the time aspects of takeover and takeover quality. In both monitoring driving and disengaged from driving conditions, the majority of participants responded to the stationary car by only steering to the next lane without braking. This may because that in this study they were provided with a relatively long lead time of 20s to take over and respond to the stationary car, and Gold et al. (2013a) found that longer the time that participants have the less likely they use brakes during the takeover process in the HAV. In addition, all participants were able to take over control of the vehicle effectively and successfully responded to the stationary car, so that no collisions occurred.

4.4.1 Effects of age on takeover performance

This investigation adopted the reaction time, takeover time and time to initiate indicator light (to warn drivers of a pending overtaking manoeuvre) as the measurements of the time aspects of subjects' takeover behaviour. They reflect the time that subjects took to switch to manual driving position, generate conscious input of the car and start to conduct lane change, respectively, after the HAV system has sent the takeover request to them. The research evidenced that there are significant differences between the older driver cohort and the younger cohort in all three time-measures with generally the older drivers requiring more time to complete each phase. This finding might be explained as in the literature that there is a tendency of older people to be more cautious and to monitor their responses more carefully and thoroughly (Botwinick, 1966). From another point of view, this finding confirms previous research showing that age-related functional impairments have a significant effect leading to deteriorating driving performance. In the context of this research, this deterioration could be caused by several factors, including slower reaction times (Ferreira et al., 2013b), cognitive impairments, including information processing speed, attention switch, memory and problem solving (Brouwer et al., 1991; Salthouse, 1996; Pollatsek et al., 2012) as well as declining psychomotor abilities (Staplin et al., 1999).

However, although the effect of age on driving has been well recognized, previous research into takeover control of HAV among older drivers has not found any significant effect of age on the driver's takeover time (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017). Körber et al. (2016) explained by arguing that age related differences in driver's cognitive impairments and reaction times are obvious in laboratory experiments but may not be significant enough in naturalistic tasks like taking over control of the vehicle from an HAV system. However, the findings of this research indicate that age effects could be pronounced enough to affect an applied task like taking over control from the HAV. One possible explanation is that this study adopted a larger sample size of older drivers (n=39) and the mean age (mean=71.2 years old) of the older subjects was higher than in previous research. A more important reason may be that this research provided the participants with a lead time of 20s to take-over control of the vehicle, which is much larger than the lead time (4.5s to 7.5s) used in previous studies (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017). A longer lead time reduces the difficulty and complexity of the takeover control task, and age differences in takeover time are more pronounced for less demanding takeover tasks. This conclusion is in accordance with previous findings such as by Vaportzis et al. (2013) who found that in simple reaction time tasks older people are significantly slower, but are just as accurate as younger people. However, in complex reaction time tasks, older people are as fast as younger drivers, but their performance is significantly worse.

In comparison with the current research, which adopted a lead time of TOR of 20s and where the mean takeover time for disengaged participants was 3.79s, previous studies had lead time between 2s to 8s leading to smaller mean values of takeover time between 1.7s-3.66s (Gold et al., 2013a; Melcher et al., 2015; Körber et al., 2016; Zeeb et al., 2016; Clark and Feng, 2017; Molnar et al., 2017; Zeeb et al., 2017). However, a study by Eriksson and Stanton (2017) found a larger mean takeover time (4.46s-6.06s) when an unlimited lead time was adopted. Therefore, this suggests that when more time is available for drivers to take over the vehicle control, the higher their resulting mean takeover time is, which is in line with the conclusion of Gold et al. (2013a) that shorter lead time available for drivers to take over the vehicle of the vehicle result in lower takeover time.

In terms of the effect of age on takeover quality, the present results show that there was no effect of age on the driver's TTC. Also no collision would happen for either older or younger drivers. And there was no critical encounters for the younger drivers and only one for older drivers. This indicates that the older drivers were able to take control over the vehicle as successfully and efficiently as younger drivers when they were provided with a lead time of 20s to take over the vehicle control. Given the finding concerning the significant effect of age on reaction time, takeover time and indicator time in this research, it seems that the effect of age on TTC and collision times is compensated for by the extra time older drivers took. This may be explained by previous research indicates that there is a phenomenon of trade-off between task processing speed and processing accuracy observed among older people (Brébion, 2003; Vaportzis et al., 2013). In addition, the finding could be a negative demonstration of the finding by Gold et al. (2013a) indicates that an inadequate lead time resulted in quicker decisions and responses, but worse takeover quality. Therefore, it may suggests 20s could be an adequate lead time for both younger and older drivers. However, age had a significant effect on the driver's steering wheel angle, with older drivers showing significantly larger steering angle and higher resulting acceleration than younger drivers. These findings could be related to the decline in psychomotor abilities with age. Staplin et al. (1999) indicated that age-related impairments in limb mobility and flexibility affect a driver's ability to effectively operate the steering wheel and accelerator/brake to execute safe manoeuvres.

4.4.2 Effect of completely disengagement from driving on takeover performance

Driving disengagement level was shown to have a significant influence on the driver's reaction time, takeover time and indicator time with drivers needing longer to switch to manual driving position, to generate active input to the vehicle and to start to change lane when they were completely disengaging from driving compared to when monitoring driving. Some previous research found similar results (Radlmayr et al., 2014; Eriksson and Stanton, 2017). However, Zeeb et al. (2016) did not find any effect of disengagement in driving on reaction time and explained this was possibly due to the takeover tasks they used were not time-critical and did not need a prompt driver input. Körber et al. (2016) also did not found any effect of engaging in an additional task on the driver's takeover time. A possible explanation for this could be that they used a 20-question task presented on a hands-free cell phone. Despite this task being able to distract participants to a greater extend, it cannot guarantee that participants constantly keep their eye off the road and it could easily be interrupted. In contrast, standardized tasks, such as the n-back, and naturalistic tasks such as reading tasks, used in the previous studies (Radlmayr et al., 2014; Eriksson and Stanton, 2017) as well as the present research could enable the participants to become completely disengaged from attention to driving, so that 'out-of-the-loop'(OoTL) performance issue results in declining take-over control ability for automation system operators (Endsley and Kiris, 1995).

Results also found that complete disengagement from driving led to worse takeover quality, reflected in significantly shorter TTC, stronger resulting acceleration and greater steering wheel angles, this finding is in accordance with the previous findings showing the negative effect of the state of complete disengagement from driving on the takeover quality in the HAV (Radlmayr et al., 2014; Zeeb et al., 2016; Zeeb et al., 2017). In addition, results indicated that there was no correlation between takeover time and quality when the participants were monitoring HAV system driving before asked to take over control. However, when they were disengaged from driving in the HAV, those participants who took over vehicle control slower also had a smaller TTC and greater steering wheel deviation, which reflects worse takeover quality. This could be explained as when subjects were taking over the control of HAV while monitoring driving, their attention was focused on one task-driving all the time. However, when they took over control of HAV while they were completely disengaged from driving, they need to switch their attention between two tasks-the secondary task and take-over of control. Comparing with repeating one task, task-switches are always linked with longer response time and worse accuracy in the execution of the task (Schmitz and Voss., 2014). This strengthens the effect of complete disengagement in driving on the take-over performance and implies importance of considering the takeover time and quality as a cohort when designing HMI of HAV.

4.4.3 Interaction effect between age and DDL on takeover performance

The results found significant interaction effects between the independent variables of age and DDL on the time aspects of takeover in terms of reaction time, takeover time and indicator time, as well as takeover quality in terms of the TTC. These significant interaction effects suggested that complete disengagement from driving influenced older drivers more seriously than the younger drivers. This finding is in line with the study of Clark and Feng (2017) which found that older drivers were more strongly involved in non-driving related secondary tasks than the younger drivers. A possible explanation could be the negative effect of DDL on takeover performance is enlarged by the age-related physical, cognitive and psychological functional impairments and therefore affects older drivers to a greater extent compared to younger drivers. In addition, when disengaged from driving, older drivers showed a greater variability across all measurements of takeover performance than younger drivers. This corresponds with previous research and indicates that the driving performance of older drivers were more inconsistent than younger drivers (Dykiert et al., 2012).

4.4.4 Effect of road type on takeover performance

Moreover, the results showed that road type has a significant effect on the driver's reaction time, takeover time and indicator time, with drivers taking longer on the motorway than the city road. These findings could be explained in terms of the car's speed. When driving at higher speed, drivers' perception of danger enhanced, which activates a raised endocrine reaction in the brain which induces close attention to be paid to objects in motion around the car, which can result in significant increases in reaction time (Anderson et al., 1997; Zachariou et al., 2011). Thus, it seems that the way that speed affects drivers' manual driving performance is also noticeable in affecting on their take-over performance from the HAV.

4.5 Conclusion

This aim of this driving simulator investigation is twofold; firstly to investigate the effect of age on drivers' takeover performance in HAV; secondly to investigate the effect of complete disengagement in driving on drivers' takeover performance in the HAV.
Firstly, regarding to the effect of age, this investigation found that age significantly affect drivers' takeover performance in the HAV. Older drivers resulted in slower time aspects of takeover in the HAV and worse takeover quality in terms of operating steering wheel and pedals. These conclusions were drawn through the analysis of the following measurements, where older drivers resulted in:

- Significantly slower reaction time (2.14s compared to 1.70s of younger drivers);
- Significantly slower takeover time (3.38s compared to 2.84s of younger drivers);
- Significantly slower indicator time (8.32s compared to 6.99s of younger drivers);
- Significantly stronger resulting acceleration (2.95m/s² compared to 2.26m/s² of younger drivers);
- Significantly greater steering wheel angle (8.46degrees compared to 5.20degrees of younger drivers);

Secondly, complete disengagement from driving has a significant effect on the takeover performance in the HAV. It leads to a slower reaction and decision making and worse takeover quality than engagement from driving (achieved by monitoring driving). When disengaging from driving, drivers who had slower takeover time also had worse takeover quality. These conclusions were drawn through the analysis of the following measurements, where drivers when disengaging from driving resulted in:

- Significantly slower reaction time (2.53s compared to 1.33s when monitoring driving);
- Significantly slower takeover time (3.79s compared to 2.46s when monitoring driving);
- Significantly longer indicator time (8.79s compared to 6.56s when monitoring driving);
- Significantly shorter TTC (9.37s compared to 11.26s when monitoring driving);
- Stronger resulting acceleration (2.72m/s² compared to 2.51m/s² when monitoring driving);
- Greater steering wheel angle (7.30degrees compared to 6.45degrees when monitoring driving);

In addition, this investigation found a significant interaction between age and driving disengagement indicating that complete disengagement in driving affected older drivers' takeover performance more seriously than younger drivers. Moreover, in this investigation all the participants were able to take over the vehicle control successfully and overcome the stationary vehicle effectively, no collision was recorded for both the younger and older drivers. This indicates that 20 seconds seemed to be sufficient for both younger and older drivers to take over control safely and effectively. Furthermore, drivers needed longer time to react and make decision when taking over control from the HAV on the motorway compared to the city road. The implications and recommendations derived from the findings are summarized in Chapter 8.

Chapter 5. Investigation of older driver's takeover performance in highly automated vehicles in adverse weather conditions

5.1 Introduction

The first driving simulator investigation described in Chapter 4 found a significant age difference in terms of performance when interacting with the HAV in clear weather conditions. In Section 2.2.4.1, it was pointed out that driving in adverse weather could be dangerous and the negative effects of adverse weather on older drivers' independence and mobility was highlighted. However, knowledge concerning how older drivers interact with HAVs in adverse weather situations is still limited. Given that older drivers' reduced mobility and independence could potentially be improved by HAV, the question of how adverse weather might affect their takeover performance has to be addressed.

In response to the above gap in knowledge, this chapter details a second driving simulator investigation aiming to address two key areas: firstly, to further examine the effect of age on drivers' takeover performance; and secondly to investigate the effect of adverse weather on takeover performance of drivers who are disengaged from driving in the HAV.

5.2 Method

The explanation and selection of the main methodologies for adopting the driving simulator, the dependent variables measured, and the detailed review of the HAV scenario and the analysis of data were described in Sections 3.2 and 3.3. The participants in this investigation and the experimental procedure are the same as those in Chapter 4 (see sections 4.2.5 and 4.2.6). This section details the experimental design of this specific driving simulator investigation, and the design of the weather conditions.

5.2.1 Experimental design

Corresponding to the aims of this investigation, firstly, age is identified as an independent variable which includes two levels with an experimental group of older drivers and a control group of the younger drivers. In addition, weather is identified as another independent variables, including four levels: the experimental conditions of rain, snow and fog, and the baseline condition of clear weather. A detailed review of the selection of these adverse weathers conditions is provided in the following section. Moreover, two more independent variables of road type and gender were also adopted for this investigation.

Section 3.3.8 has provided a detailed review of the options for experimental design. According to the review, age and gender were selected as between-subjects factors, as they cannot be within-subjects factors. To reduce the total number of drives for each subjects in this investigation, road type was also determined as a between-subjects factor. The weather was adopted as a within-subjects factor which would allow each participant to experience all four types of weather conditions and each participant could act as his/her own control group (Seltman, 2009; Charness et al., 2012). To avoid order effects, the order of the conditions for each driver were randomised and rest breaks were provided to drivers between each condition (Charness et al., 2012). Overall, this investigation adopted a between- and within-subjects mixed-factor experimental design. An overview of the experimental design is shown in Table 5.1.

Table 5.1 Overview of the experimental design

Between-subjects independent variables		***Within-subjects independent variable***
Road Type	**Age**	**Weather**
City Road	Younger drivers	Clear weather, Rain, Snow, Fog
City Road	Older drivers	Clear weather, Rain, Snow, Fog
Motorway	Younger drivers	Clear weather, Rain, Snow, Fog
Motorway	Older drivers	Clear weather, Rain, Snow, Fog

The dependent variables adopted for this investigation have been discussed in Section 3.3.4. Table 5.2 shows an overview of the dependent variables for this driving simulator investigation.

Table 5.2 Overview of the dependent variables for Chapter 5

Dependent variables	***Unit***
Reaction time	s
Takeover time	s
Indicator time	s
Time to collisions (TTC)	s
Resulting acceleration	m/s^2
Steering wheel angle	degree
Collisions and critical encounters (CCE)	Count
Hasty takeover	Count

5.2.2 Weather effects

Figure 5.1 Drivers were disengaged from driving in the HAV in snow and fog conditions.

In selecting the types of adverse weather for this investigation, there are several considerations. To begin with, DfT (2015a) has pointed out several types of adverse weather condition that can make driving dangerous, including rain, ice and snow, wind, fog and hot weather. Secondly, corresponding to the purpose of this investigation, the adverse weathers selected should represent typical situations in which older drivers' independence and motility are commonly reduced. The common adverse weather conditions that older drivers commonly avoid are rain, snow and fog (Owsley et al., 1999; Charlton et al., 2006; Braitman and McCartt, 2008; Donorfio et al., 2008). Simulating these three weathers are within the capability in the specific driving simulator used in this research. And a clear weather was chosen as the baseline condition. In total, the HAV scenario ran four weather conditions: clear weather, rain, snow and fog, as illustrated in Figures 5.1 and 5.2.

Figure 5.2 Weather conditions in the HAV scenario: clear weather, rain, snow and fog from left to right.

Due to limitations in the functionality of the particular driving simulator used in this study, this research only considers visual distractions and reduced visibility due to adverse weather conditions. Some other negative effects of adverse weather, such as slippery surfaces, longer braking distances, cumulative snow, or car window steaming up, were not taken into account when designing the current research. This represents a limitation of this study and has been noted in Section 9.3.

Weather-related visibility reduction is regarded as a significant problem affecting manual driving performance (Mueller and Trick, 2012; NeelimaChakrabartya; Ashley et al., 2015; Bellet et al., 2018). Visibility may vary among rain, snow and fog conditions. Levels of visibility in these adverse weather conditions were determined according to suggestions from the UK Meteorological Office and previous literature (Edwards, 1998; Hautiere et al., 2009; MetOffice, 2018a; MetOffice, 2018b). As Figure 5.2 illustrates, in rainy condition visibility is approximately 400 metres, whereas in snowy conditions it is approximately 200 metres, and in fog approximate 100 metres. In clear weather conditions visibility is approximately 1000 metres. In addition, the driving speed of the HAV before the takeover request was assumed to be the same under different weather conditions in order to set up a controlled experiment.

5.3 Results

This section reports the results of this investigation. The explanation of the use of statistical tests is detailed in Section 3.3.9.

5.3.1 Trajectories

Figure 5.3 and 5.4 show the average takeover trajectories for older and younger drivers in the clear weathers, the rain, the snow and the fog. The figures indicate that drivers' average takeover trajectories in clear weather and in the rain were more smooth and gradual than those in the snow and fog. The average takeover trajectories in the snow and fog were sharper and much closer to the stationary car than those in clear weather and rain. The average takeover trajectories in the fog are closest to the stationary car compared to those in other three weather conditions. In addition, older drivers and younger drivers exhibited similar average trajectories in the clear weather and the rain. However, older drivers' average trajectories were more inconsistent than those of younger drivers in the snow and fog.

City Road 30mph

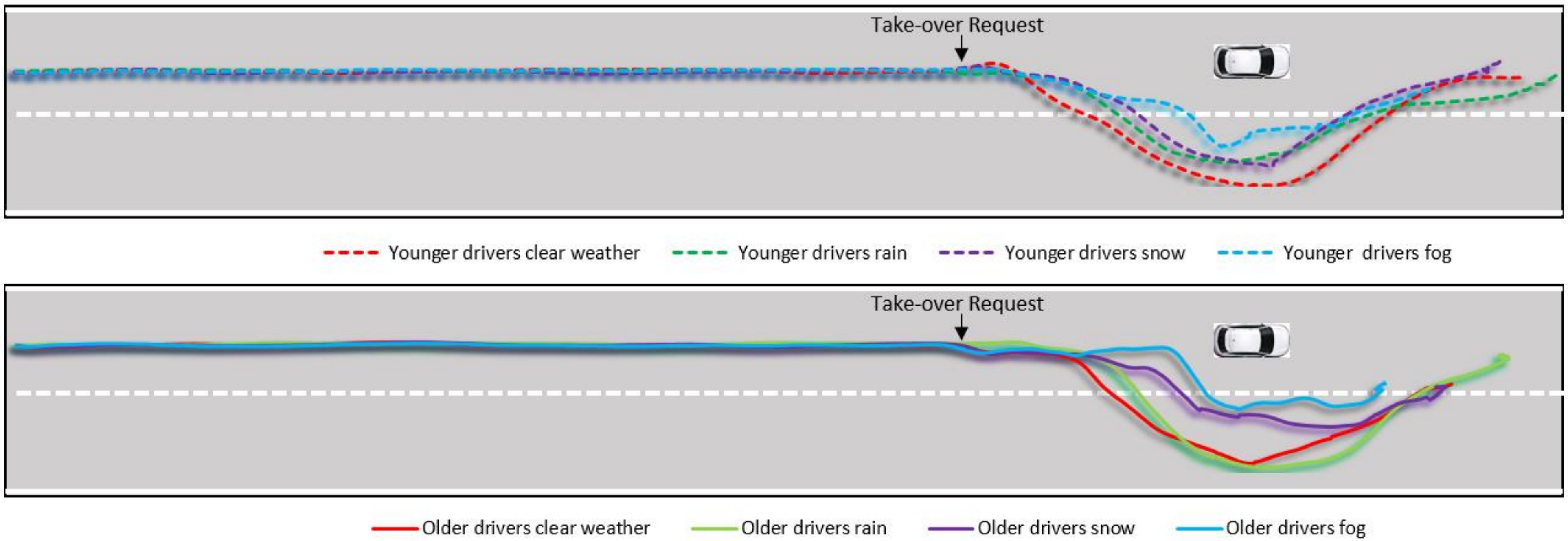


Figure 5.3 Average trajectories when older and younger drivers took over control from HAV on city road in different weather situation

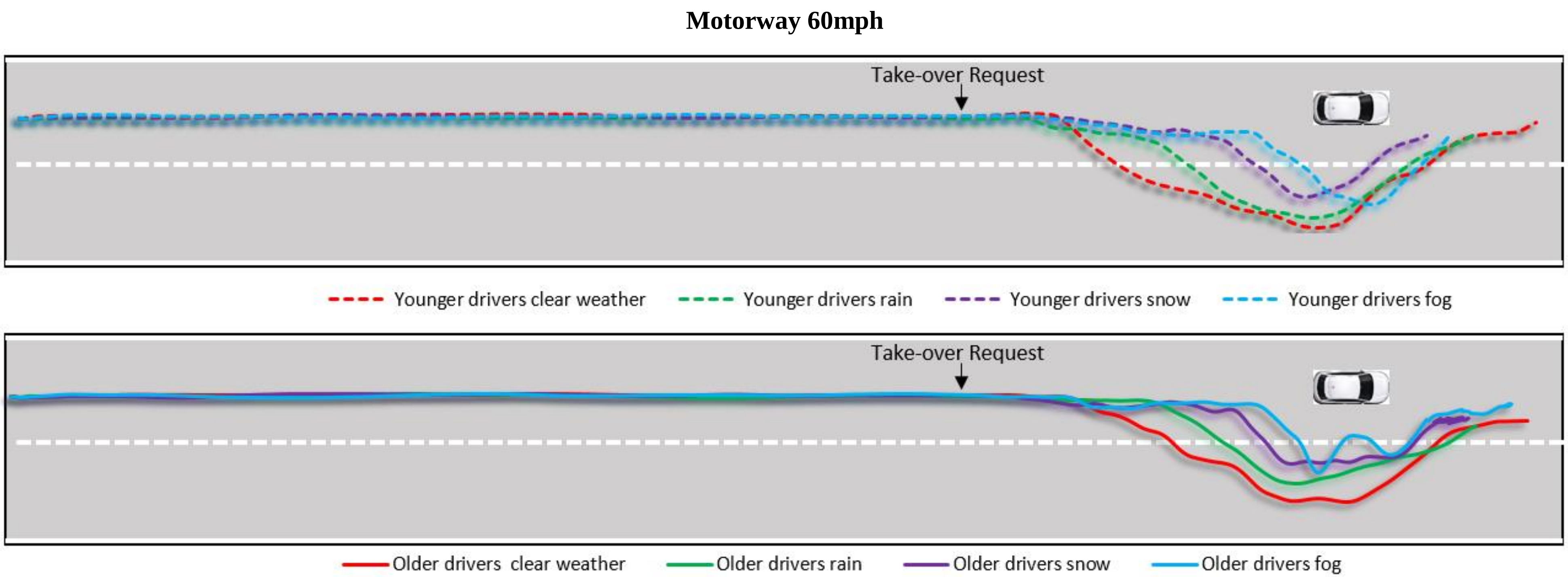


Figure 5.4 Average trajectories when older and younger drivers took over control from HAV on motorway in different weather situations

5.3.2 Steering and braking behaviours

This section reports the results of drivers' steering and braking behaviours to avoid the stationary vehicle. As Table 5.3 indicated, in general, the majority participants avoided the stationary car by only steering into the next lane. And the number of participants who avoided the stationary car by steering and braking showed a trend of consistent increasing from the clear weather to the fog.

In the clear weather, 67 drivers responded to the stationary vehicle by only steering to the next lane, including 34 older drivers and 33 younger drivers. 9 drivers responded by steering and braking, including 5 older drivers and 4 younger drivers. A Chi-square test yielded that there is no significant difference in the reaction type between older and younger drivers in the clear weather, $X^2(1) = 0.073$, $p=0.768$.

In the rain, 68 drivers overcame the stationary car by only steering to the next lane, including 34 older drivers and 34 younger drivers. 8 drivers (5 older drivers and 3 younger drivers) reacted by steering and braking. Age did not have a significant effect on the steering and braking behaviours in the rain as assessed by a Chi-square test, $X^2(1) = 0.448$, $p=0.503$. In addition, a McNemar test ($p=1.000$) revealed there is no significant difference in the drivers' reaction type between the clear weather and the rain.

In the snow, 60 drivers avoided the stationary car by only steering to the next lane, including 29 older drivers and 31 younger drivers. 16 drivers avoided the stationary car by steering and braking, including 10 older drivers and 6 younger drivers. A Chi-square test revealed that age had no effect in the reaction type, $X^2(1) = 1.015$, $p=0.315$. In addition a McNemar test revealed there were no significant difference in the reaction type between clear weather and snow ($p=0.092$). However, the McNemar test ($p=0.039$) found that there was significant difference in the reaction type between in the rain and in the snow.

In the fog, 55 drivers (24 older drivers, 31 younger drivers) avoided the stationary car by only steering to the next lane, while 21 drivers (15 older drivers, 6 younger drivers) reacted by steering and braking. A Chi-square test revealed that age showed a statistically significant effect in the reaction type in the fog, $X^2(1) = 4.699$, $p=0.030$, with the number of older drivers who avoided the stationary car by steering and braking is statistically larger than the younger drivers. In addition, the McNemar tests found that drivers' reaction type in the fog is statistically significant different than it in the clear weather (p=0.012) and in the rain (p=0.007). However, there was no significant difference (p=0.332) in drivers' reaction type in the snow and fog.

Table 5.3 The steering and braking behaviours for different age groups under different weather situations

	Clear		*Rain*		*Snow*		*Fog*	
	Steer only	*Steer & brake*	*Steer only*	*Steer & brake*	*Steer only*	*Steer & brake*	*Steer only*	*Steer & brake*
Older drivers	34	5	34	5	29	10	24	15
Younger drivers	33	4	34	3	31	6	31	6
Total	67	9	68	8	60	16	55	21

5.3.3 Collision or critical encounter (CCE)

This section reports the results of the collisions and critical encounters (CCEs) that participants had when taking over control from HAV in different weather conditions. CCE refers to the participants' takeovers resulted in a collision or a critical encounter (TTC less than 1.5s) to the stationary vehicle. As Figures 5.5 and 5.6 indicate, in general, the CCEs were mostly happened when the participants were taking over the control of the HAV in the snow and fog.

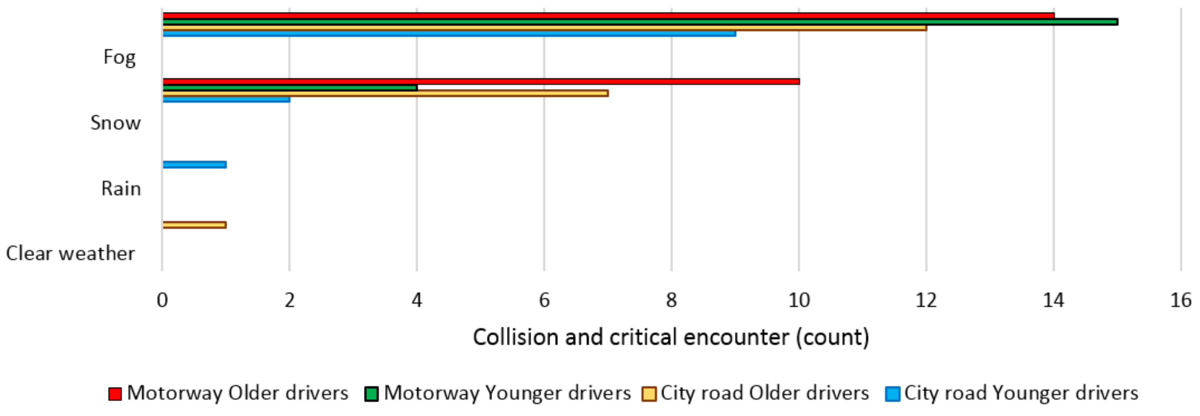


Figure 5.5 CCEs of participants under different weather situations

In total, 75 CCEs were recorded among all the drivers in all the weather situations, including 44 CCEs were among the older drivers and 31 were among the younger drivers. A Chi-square test found that the difference in the CCEs between the younger and older drivers is not statistically significant, $X^2(1) = 2.153$, p=0.142.

In the clear weather, 1 CCE (on city road) was recorded among the older drivers, and no CCE was recorded among the younger drivers. A Chi-square test found that this difference was not statistically significant, $X^2(1) = 0.961$, p=0.327. In the rain, no CCE was recorded for the older drivers, but there was 1 CCE (on city road) happened among the younger drivers. A Chi-square test showed that this difference was not statistically significant, $X^2(1) = 1.068$, p=0.301. In addition, a McNemar test (p=1.000) revealed that there is no statistically significant difference between the number of CCEs recorded in the clear weather and in the rain.

In the snow, there were 23 CCEs were recorded in total. Older drivers had more CCEs (total: n=17, city road: n=7, motorway: n=10) than the younger drivers (total: n=6, city road: n=2, motorway: n=4). A Chi-square test revealed that this difference was statistically significant, $X^2(1) = 6.741$, p=0.009. The McNemar tests revealed that the snow weather (n=23) resulted in statistically significantly more CCEs compared to the clear weather (n=1, p<0.001) and the rain (n=1, p<0.001).

In the fog, 50 CCEs were recorded in total. Among them, 26 CCEs (city road: n=12, motorway: n=14) were from the older drivers and 24 CCEs (city road: n=9, motorway: n=15) were from the younger drivers. A Chi-square test found that the difference in the number of CCEs between the older and younger drivers was not statistically significant, $X^2(1) = 0.027$, p=0.869. The results of several McNemar tests showed that the fog weather (n=50) led to statistically significantly more CCEs compared to the clear weather (n=1, p<0.001), the rain (n=1, p<0.001) and the snow (n=23, p<0.001).

Table 5.4 The CCEs recorded for male and female participants under different weather situations

	Clear	*Rain*	*Snow*	*Fog*	*Overall*
Female	3.0%	0.0%	39.4%	63.6%	26.5%
Male	0.0%	2.3%	23.3%	67.4%	23.3%
Total	1.3%	1.3%	30.3%	65.8%	24.7%

In addition, Table 5.4 and Figure 5.6 shows the CCEs recorded for female and male participants. Overall, 35 CCEs (26.5%) were recorded among the female participants, and male participants had 40 CCEs (23.3%). Chi-square test revealed the difference was not statistically significant, $X^2(1) = 0.427$, p=0.514.

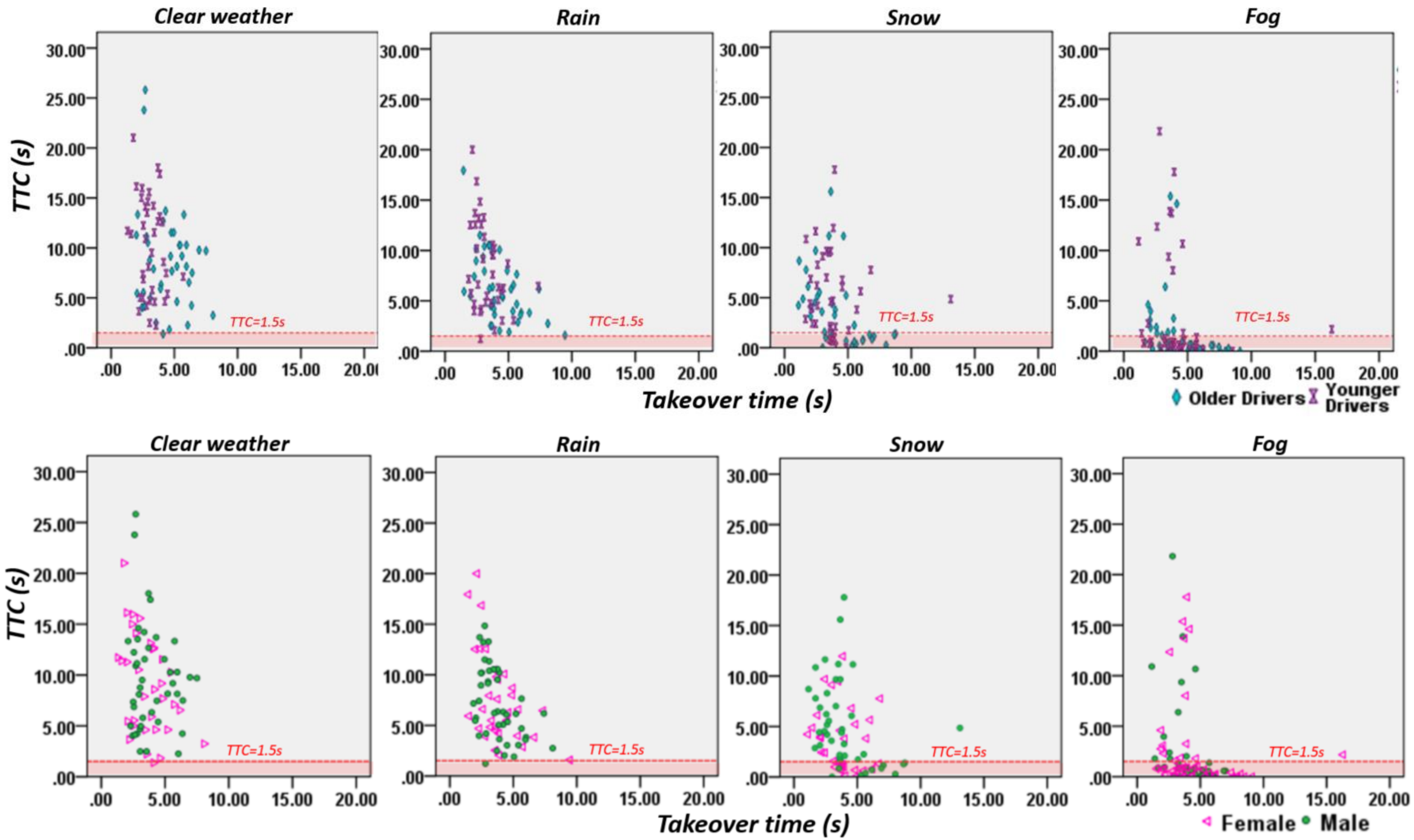


Figure 5.6 Illustration of CCEs of different age and gender groups using scatterplot of TTC and takeover time.

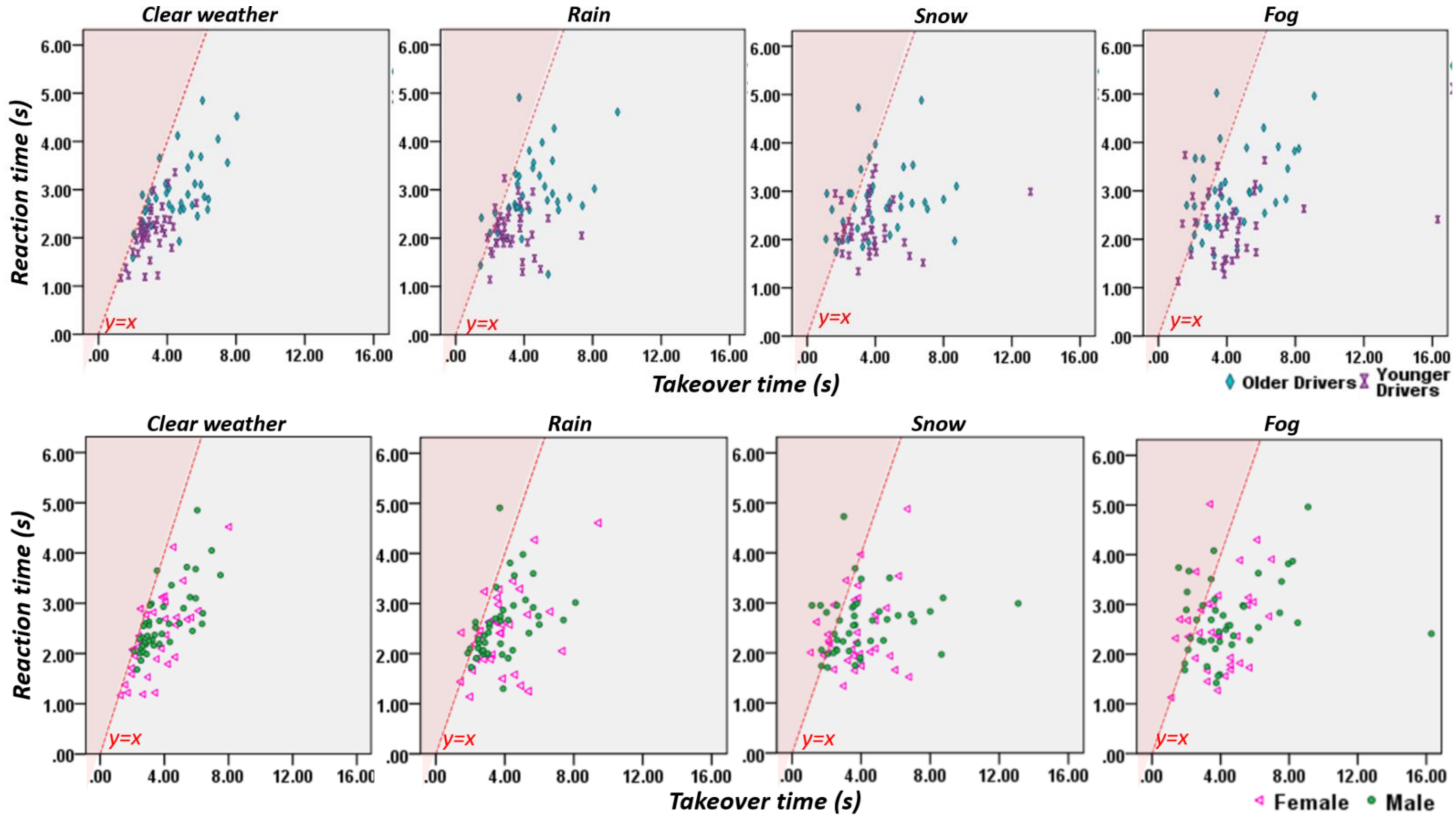


Figure 5.7 Illustration of hasty takeovers of different age and gender groups using scatterplot of reaction time and takeover time.

5.3.4 Hasty takeover

This section of the results reports the number of hasty takeovers that were recorded among the participants when taking over control from the HAV. The hasty takeover is defined as a takeover behaviour that drivers generated the conscious input to the vehicle before they had completely switched to the manual driving position. Figures 5.7 and 5.8 show the hasty takeover that participants had under different weather situations. Generally, participants were recorded fewer hasty takeovers in the clear weather conditions compared to in the rain, snow and fog.

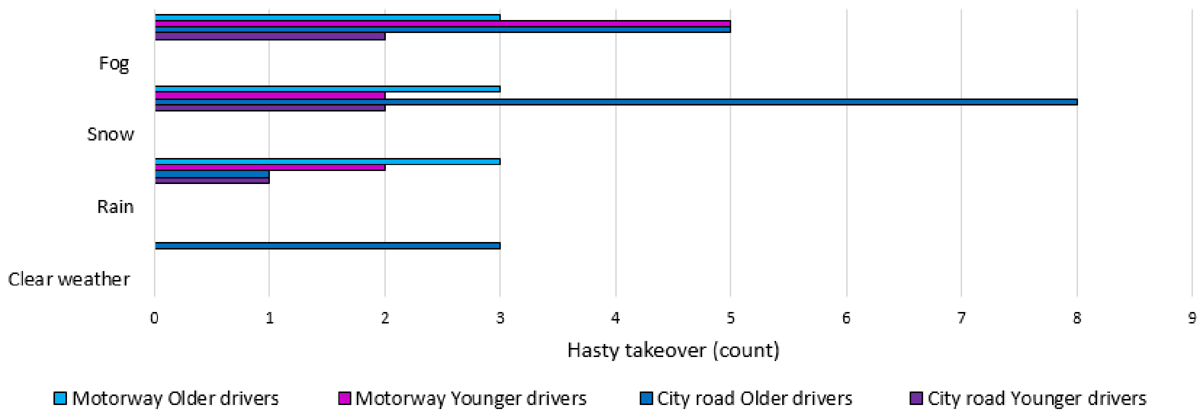


Figure 5.8 Hasty takeovers of participants under different weather situations

In total, 40 hasty takeovers were recorded among all the drivers in all the weather situations, including 26 hasty takeovers were among the older drivers and 14 were among the younger drivers. A Chi-square test found that the difference in the hasty takeovers between the younger and older drivers is not statistically significant, $X^2(1) = 3.452$, p=0.063.
In the clear weather, there were 3 hasty takeovers in total. All of them were recorded among the older drivers. Younger drivers did not have any hasty takeovers. A Chi-square test revealed that this difference was not statistically significant, $X^2(1) = 2.963$, p=0.085.
In the rain, 7 hasty takeovers were recorded. 4 were recorded among the older drivers (city road: n=1, motorway: n=3), and 3 were among the younger drivers (city road: n=2, motorway: n=1). A Chi-square test found that this difference was not statistically significant, $X^2(1) = 0.105$, p=0.746. In addition, in order to test whether the number of hasty takeover is statistically significant between the clear weather (n=3) and the rain (n=7), a McNemar test was conducted, results showed the difference was not statistically significant (p=0.344).
In the snow, 15 hasty takeovers were happened overall. Older drivers had more hasty takeovers (total: n=11, city road: n=8, motorway: n=3) compared to the younger drivers (total:

n=4, city road: n=2, motorway: n=2). Despite the Chi-square test showed this difference was not statistically significant, $X^2(1) = 3.626$, p=0.057, the p value shows the difference towards a certain trend of significant. In addition, the McNemar tests revealed that snow weather (n=15) resulted in statistically significantly more hasty takeovers than the clear weather (n=3, p=0.002), and there was no significant difference between the number of hasty takeover in the snow and in the rain (n=7, p=0.077).

In the fog, there were also 15 hasty takeovers were recorded in total. Older drivers had slightly more hasty takeovers (total, n=8, city road: n=3, motorway: n=5) than the younger drivers (total, n=7, city road: n=2, motorway: n=5). However, this difference was not statistically significant as assessed by a Chi-square test, $X^2(1) = 0.030$, p=0.861. Several McNemar tests found that the number of hasty takeovers in the fog (n=15) is significantly higher than it of the clear weather (n=3, p=0.002), and there were no statistically significant difference in the hasty takeover in the fog compared to the rain (n=7, p=0.096) and the snow (n=15, p=1.000).

Table 5.5 The number of hasty takeovers recorded for different gender under different weather situations

	Clear	*Rain*	*Snow*	*Fog*	*Overall*
Female	2	2	7	6	17
Male	1	5	8	9	23
Total	3	7	15	15	40

In addition, Table 5.5 and Figure 5.7 displays the hasty takeovers for female and male participants. Overall, 17 hasty takeovers were recorded among the female participants, and male participants had 23 hasty takeovers. Chi-square test revealed the difference was not statistically significant, $X^2(1) = 0.016$, p=0.900.

5.3.5 Reaction time

This section reports the results of drivers' reaction time when taking over the control of the vehicle in the HAV under different weather conditions. Figure 5.9 shows the mean reaction time for different age groups. The overall participants had a mean reaction time of 2.55s (SD=0.74). The data of reaction time was analysed by a mixed factorial ANOVA with a within-subjects independent variable of Weather, and between-subjects independent variables of age and road type. The results of ANOVA are summarized in Table 5.6. Results showed that age had a statistically significant main effect on reaction time, $F(1,72)= 26.903$, $p<0.001$, $\eta p^2=0.272$, with older drivers (M=2.88s, SD=0.76s) needed significantly longer time to switch back to the manual driving position compared to the younger drivers (M=2.21s, SD=0.55s), a statistically significant difference of 0.67s (95% CI, 0.41s to 0.93s).

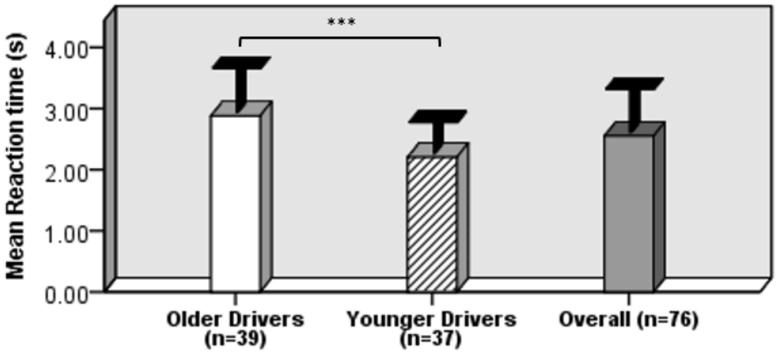


Figure 5.9 Mean reaction time for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

As Figure 5.10 illustrates, drivers exhibited slowest reaction time in the fog (M=2.65s, SD=0.82s), and they had similar reaction time in the clear weather (M=2.52s, SD=0.74s), rain (M=2.52s, SD=0.74s) and snow (M=2.51s, SD=0.68s). In terms of the effect of weather, Mauchly's test of Sphericity showed that the assumption of sphericity was not met, $X^2(5) =11.589$, $p=0.041$, and thus degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon=0.976$). Results of ANOVA showed weather had a significant main effect on the reaction time, $F(2.927,23.930)= 3.168$, $p=0.026$, $\eta p^2=0.042$. Post hoc test with Bonferroni correction ($p \leq 0.05$) indicated that drivers' reaction time showed a significant increase of 0.13s (95% CI, 0.003s to 0.257s) from 2.52s (SD=0.74s) in the clear weather to 2.65s (SD=0.82s) in the fog.

In addition, results yielded that road type had a significant effect on reaction time $F(1,72)= 8.852$, $p=0.004$, $\eta p^2=0.109$, with drivers' reaction time had a significant increase of 0.39s (95% CI, 0.13s to 0.64s) from 2.35s (SD=0.67s) on the city road to 2.74s (SD=0.78s) on the motorway.

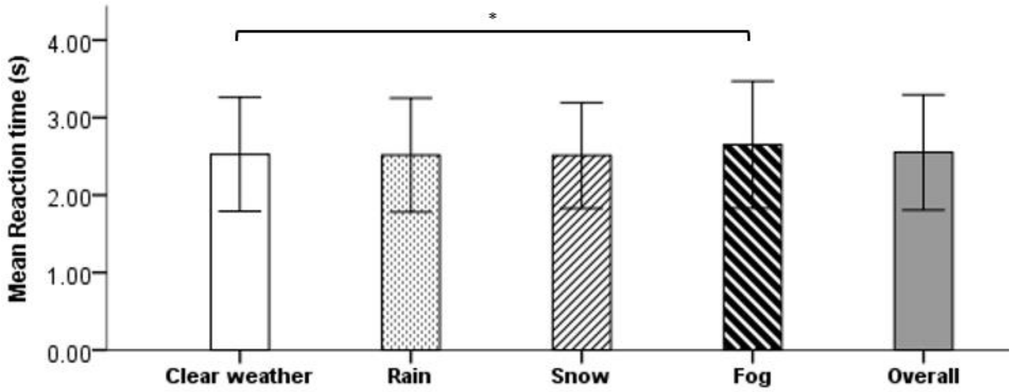


Figure 5.10 Mean reaction time in different weather situations (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Table 5.6 Results of a mixed ANOVA for reaction time

	df	*F*	*p*	*ηp²*
Age	1,72	26.903***	<0.001	0.272
Weather	2.927,23.930	3.168*	0.026	0.042
Road Type	1,72	8.852**	0.004	0.109
Age × Weather	2.927,23.930	2.946*	0.035	0.039
Age × Road Type	1,72	1.816	0.182	0.025
Weather × Road Type	2.927,23.930	2.773*	0.044	0.037
Age × Weather × Road Type	2.927,23.930	0.719	0.538	0.010

*Note: *= p ⩽ 0.05, **= p ⩽ 0.01, ***= p ⩽ 0.001*

Moreover, there is a significant interaction effect between age and weather on the reaction time (Figure 5.11), *F*(2.927,23.930)= 2.946, p=0.035, ηp²=0.039. Several paired sample t-tests were performed to interpret this interaction. For the older drivers, their reaction time showed a relative steady trend across the four weather conditions. Their reaction time in clear weather (M=2.91s, SD=0.70s) is slightly longer than it in the rain (M=2.87s, SD=0.77s), but the difference is not significant, *t*(38)=0.749, p=0.459. Their reaction time in clear weather is also longer than in the snow (M=2.75s, SD=0.73s), the difference was not significant either, *t*(38)=1.777, p=0.084. Lastly, their reaction time in clear weather is faster than it in the fog, but the difference is not significant, *t*(38)=-1.214, p=0.232. For the younger drivers, their reaction time showed a trend of consistent increasing from clear weather to the fog. Their reaction time in clear weather (M=2.12s, SD=0.52s) is faster than in the rain (M=2.15s, SD=0.47s), but the difference is not significant, *t*(36)=-0.448, p=0.656. Their reaction time in clear weather is significantly faster in clear weather than in the snow (M=2.26s, SD=0.52s), t(36)=-2.059, p=0.047, a significant difference of 0.14s (95% CI, 0.002s to 0.28s). In addition, their reaction time is significantly faster in clear weather than in the fog (M=2.29s, SD=0.66s), *t*(36)=-2.440, p=0.020, a significant difference of 0.17s (95% CI, 0.029s to 0.32s). The above series of results suggests that the adverse weather affected older drivers' and younger drivers' reaction time in different ways.

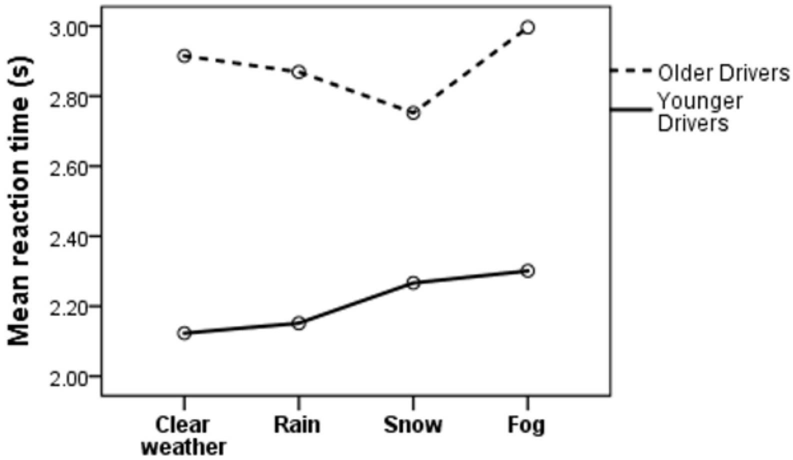


Figure 5.11 Illustration of the significant interaction effect between age and weather on reaction time.

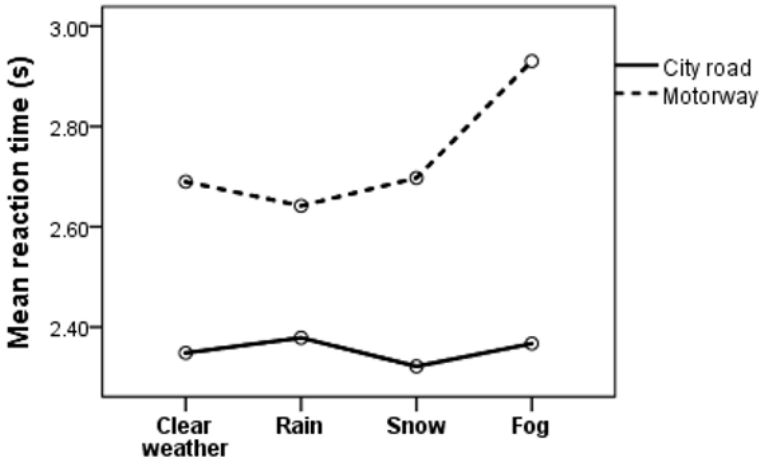


Figure 5.12 Illustration of the significant interaction effect between weather and road type on reaction time.

Finally, there is a significant interaction between weather and road type (Figure 5.12), $F(2.927,23.930)= 2.773$, p=0.044, $\eta p^2=0.037$. This interaction indicates that on the city road, drivers' reaction time was faster in clear weather (M=2.36s, SD=0.67s) than in the fog (M=2.38s, SD=0.75s). Similarly, on the motorway, driver's reaction time was faster in clear weather (M=2.70s, SD=0.77s) than in fog (M=2.94s, SD=0.80s), though the difference was more marked on the motorway.

In addition, An Independent samples t-test showed gender has a statistically significant effect on the reaction time, $t(248.695) = -1.991$, $p=0.048$, with female drivers (M=2.45s, SD=0.82) exhibited faster reaction time compared to the male drivers (M=2.63, SD=0.67),a significant increase of 0.17s (95% CI, 0.002s to 0.35s).

5.3.6 Takeover time

This section reports the results of the takeover time that participants had when taking over control from the HAV under different weather conditions. Figure 5.13 shows the mean takeover time for different age groups. The overall participants had a mean takeover time of 3.98s (SD=1.85s). In order to investigate the effects of age, weather and road type on the takeover time, a mixed factorial ANOVA was performed. The results are summarized in Table 5.7, it showed that that age had a significant effect on takeover time, $F(1,72) = 5.739$, $p=0.019$, $\eta p^2=0.074$, older drivers (M=4.33s, SD=1.84s) had significantly longer takeover time than the younger drivers (M=3.61s, SD=1.79s), a statistically significant difference of 0.72s (95% CI, 0.12s to 1.32s).

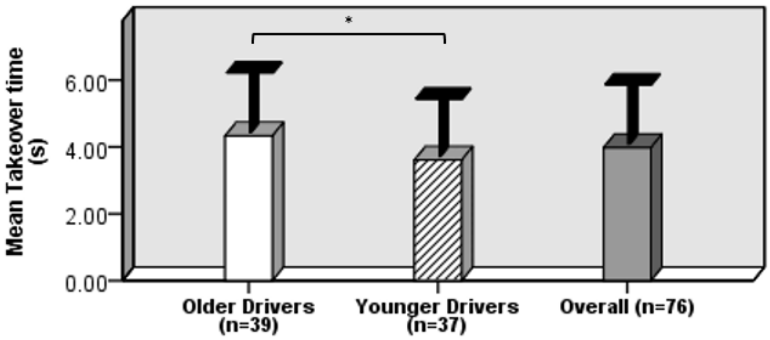


Figure 5.13 Mean takeover time for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

As Figure 5.14 shows, drivers had the slowest takeover time in the fog (M=4.30s, SD=2.26s) and the fastest takeover time in the clear weather (M=3.79s, SD=1.47s), their takeover time is 3.84s (SD=1.54s) in the rain and 3.97s (SD=2.00s) in the snow. In terms of the effect of weather on the takeover time, Mauchly's test showed that the assumption of sphericity was violated, $X^2(5) = 29.018$, $p<0.001$, and therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon=0.875$). ANOVA showed that weather and road type did not have significant effect on takeover time.

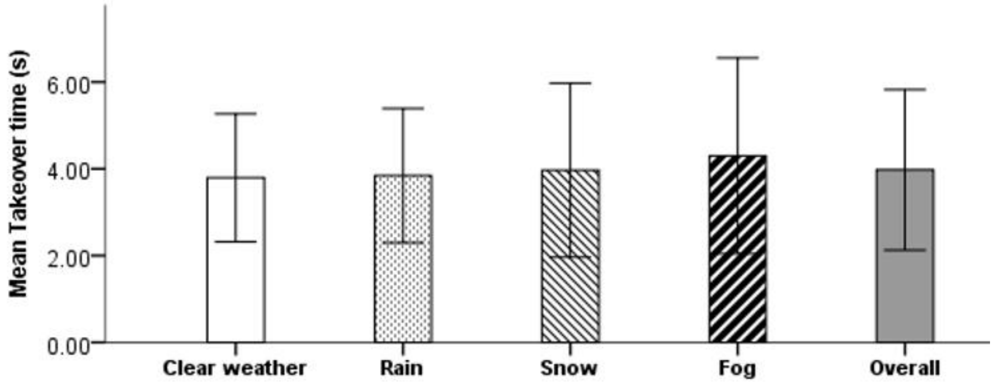


Figure 5.14 Takeover time in different weather situations (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Table 5.7 Results of a mixed ANOVA for takeover time

	df	*F*	*p*	*ηp²*
Age	1,72	5.739*	0.019	0.074
Weather	2.626,189.07	1.947	0.131	0.026
Road Type	1,72	1.149	0.287	0.016
Age × Weather	2.626,189.07	2.771*	0.050	0.037
Age × Road Type	1,72	0.047	0.830	0.001
Weather × Road Type	2.626,189.07	0.227	0.853	0.003
Age × Weather × Road Type	2.626,189.07	0.397	0.728	0.005

*Note: *= p ≤0.05, **= p ≤0.01, ***= p ≤0.001*

However, there was a significant interaction (Figure 5.15) between age and weather, $F(2.626,189.07) = 2.771$, $p=0.050$, $\eta p^2=0.037$. In order to interpret this interaction, several independent sample t-tests were applied. In clear weather, age had significant effect on takeover time, $t(59.868) = 4.614$, $p<0.001$, older drivers' takeover time (M=4.46s, SD=1.61s) was significantly slower than it of younger drivers (M=3.09s, SD=0.89s), a significant difference of 1.37s (95% CI, 0.78s to 1.96s). In the rain, age yielded a significant effect on takeover time, $t(65.302) = 2.952$, $p=0.004$, older drivers (M=4.32s, SD=1.74s) also had significantly slower takeover time than younger drivers (M=3.34s, SD=1.12s), but the difference (0.95s, 95% CI, 0.32s to 1.65s) became less pronounced than in clear weather. In the snow, age did not have a significant effect on takeover time, $t(74) = 0.896$, $p=0.387$, although older drivers' takeover time (M=4.16s, SD=2.04s) is longer than it of younger drivers (M=3.76s, SD=1.98s) and the difference (0.40s, 95% CI, -0.52s to 1.32s) is smaller than it in the rain and clear weather. Finally, in the fog, age did not show a significant effect on takeover either $t(74) = 0.561$, $p=0.809$, despite older driver showed slower takeover time (M=4.36s, SD=2.01s) than that of younger drivers (M=4.24s, SD=2.52s), but the difference

(0.13s, 95% CI, -0.92s to 1.16s) became quite small. In addition, paired sample t-tests were conducted to further examine this interaction between age and weather. For the older drivers, there was no significant difference between their takeover time in clear weather and in the rain, $t(38) = 0.584$, p=0.563. Similarly, there was no significant difference between their takeover time in clear weather and in the snow, $t(38) = 1.114$, p=0.272. Likewise, no significant difference was found between their takeover time in clear weather and in the fog, $t(38) = 0.377$, p=0.708. For the younger drivers, they exhibited faster takeover time in clear weather than in the rain, but difference was not significant, $t(36) = -1.229$, p=0.227. In addition, their takeover time was longer in the snow compared to in the clear weather, and the difference showed a certain trend towards significant, $t(36) = -1.897$, p=0.066. Moreover, their takeover time was significantly longer in the fog compared to in clear weather, $t(36) = -2.722$, p=0.010, a significant difference of 1.15s (95% CI, 0.29s to 2.00s). The above series of results showed that the significant age and weather interaction could be interpreted as the adverse weather affected the takeover time differently between the older and younger drivers.

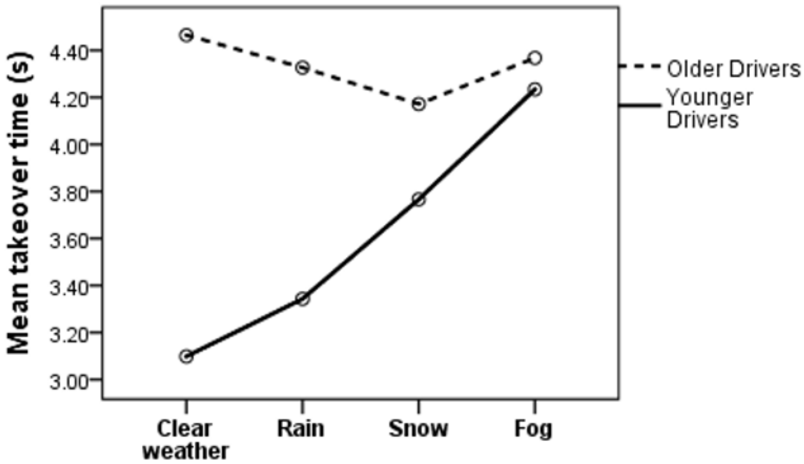


Figure 5.15 Illustration of the significant interaction effect between age and HMI on takeover time.

Moreover, it indicates that male drivers (m=4.10s, SD=2.05s) had slightly slower takeover time than the female drivers (m=3.82s, SD=1.55s). An Independent samples t-test revealed that the difference is not statistically significant, $t(302) = -1.275$, p=0.203.

5.3.7 Indicator time

This section reports the results of drivers' indicator time when reassuming the control of the vehicle in the HAV under several weather conditions. Figure 5.16 shows the mean indicator time for older and younger drivers. The overall participants had a mean takeover time of 13.66s (SD=6.59s).

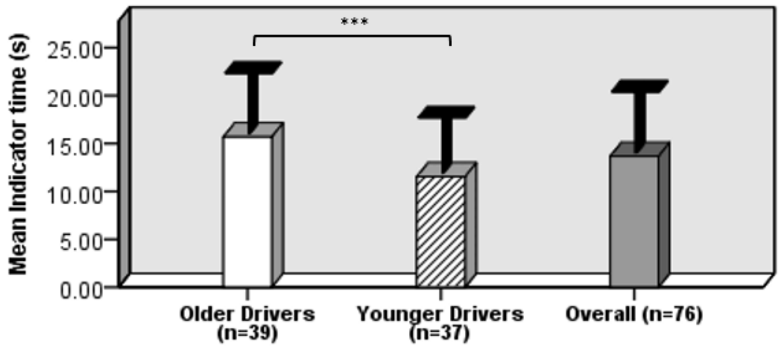


Figure 5.16 Mean indicator time for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

A mixed factorial ANOVA was performed on the indicator time comparing the values of older and younger drivers in four types of weather conditions on two types of road. The results are summarized in Table 5.8. Results showed that age had a significant effect on indicator time, $F(1,72)= 37.023$, $p<0.001$, $\eta p^2=0.340$, with the indicator time showed a statistically significant decrease of 4.15s (95% CI, 2.78s to 5.48s) from 15.68s (SD=6.50s) of older drivers to 11.53s (SD=6.01s) of younger drivers.

As Figure 5.17 indicates, drivers exhibited fastest indicator time in the clear weather (M=8.79s, SD= 3.44s) and longest indicator time in the fog (M=18.77s, SD=6.49s). Regarding the effect of weather on the indicator time, Mauchly's test showed that the assumption of sphericity was not satisfied, $X^2(5) =36.949$, $p<0.001$, and therefore the Huynh-Feldt correction was conducted ($\varepsilon=0.869$). Results of ANOVA showed that weather elicited a significant effect on the indicator time, $F(2.606,187.652)= 107.338$, $p<0.001$, $\eta p^2=0.599$. Post hoc test with Bonferroni correction ($p<0.001$) indicates that driver's indicator time in clear weather (M=8.79s, SD= 3.44s) is faster than it in the rain (M=10.84s, SD=3.85s), snow (M=16.27s, SD=6.41s) and fog (M=18.77s, SD=6.49s). This represents significant increases in the indicator time from clear weather to the rain (2.02s, 95% CI, 1.01s to 3.09s), to the snow (7.48s, 95% CI, 5.66s to 9.35s), and to the fog (10.00s, 95% CI, 8.08s to 11.95s).

Also, the post hoc test (p<0.001) shows driver's indicator time in the rain is faster than it in the snow and fog. This represents the indicator time showed significant increase of 5.46s (95% CI, 3.81s to 7.10s) from the rain to the snow and significant increase of 7.96s (95% CI, 6.10s to 9.83s) from the rain to the fog.

Lastly, the post hoc test (p<0.001) shows indicator time in the snow is faster than it in the fog, which represents the indicator time showed a significant increase of 2.51s (95% CI, 0.66s to 4.36s).

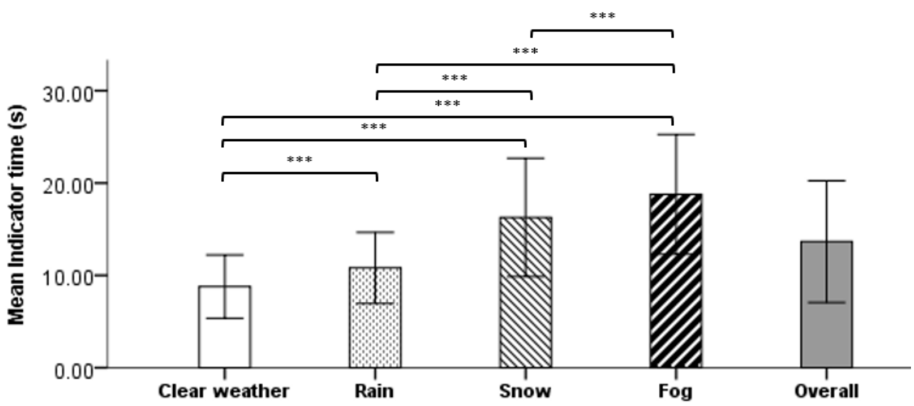


Figure 5.17 Mean indicator time in different weather situations (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Table 5.8 Results of a mixed ANOVA for indicator time

	df	*F*	*p*	*ηp²*
Age	1,72	5.739*	0.019	0.074
Weather	2.626,189.07	1.947	0.131	0.026
Road Type	1,72	1.149	0.287	0.016
Age × Weather	2.626,189.07	2.771*	0.050	0.037
Age × Road Type	1,72	0.047	0.830	0.001
Weather × Road Type	2.626,189.07	0.227	0.853	0.003
Age × Weather × Road Type	2.626,189.07	0.397	0.728	0.005

*Note: *= p ≤0.05, **= p ≤0.01, ***= p ≤0.001*

Road type yielded a statistically significant effect on the indicator time, $F(1,72)= 5.118$, p<0.001, ηp²=0.206, with drivers' indicator time exhibited a significant increase of 2.92s (95% CI, 1.58s to 4.29s) from 12.24s (SD=5.65s) on the city road to 15.15s (SD=7.18s) on motorway.

Also, there is a significant interaction between weather and road type on the indicator time, $F(2.606,187.652)= 107.338$, p=0.003, $\eta p^2=0.066$, as Figure 5.18 shows, this interaction could be interpreted as the effects of adverse weather, especially snow and fog, were more pronounced on the motorway than the city road.

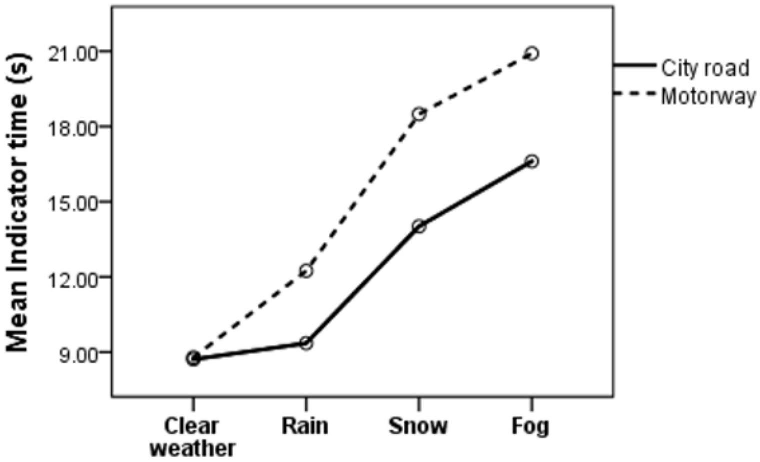


Figure 5.18 Illustration of the significant interaction effect between weather and road type on indicator time.

In addition, in general, the male drivers (M=13.76s, SD=6.71s) elicited slightly higher indicator time compared to the female drivers (M=13.52s, SD=6.46s). An Independent samples t-test showed that the difference is not statistically significant, $t(302) = -0.321$, p=0.748.

5.3.8 Time to Collision (TTC)

This section reports the results of drivers' TTC when taking over the control of the vehicle in the HAV under several weather conditions.

Figure 5.19 shows the mean TTC for older and younger drivers. The overall participants had a mean TTC of 5.99 (SD=5.11s). The data of TTC was analysed by a mixed factorial ANOVA with a within-subjects independent variable of weather, and between-subject independent variables of age and road type. The results ANOVA are summarized in Table 5.9. Results showed that age had a statistically significant effect on TTC, $F(1,72)= 6.278$, p=0.014, $\eta p^2=0.080$, with older drivers (M=5.13, SD=4.70s) had significantly shorter TTC than the younger drivers (M=6.90s, SD=5.38s), a statistically significant difference of 1.77s (95% CI, 0.36s to 3.17s).

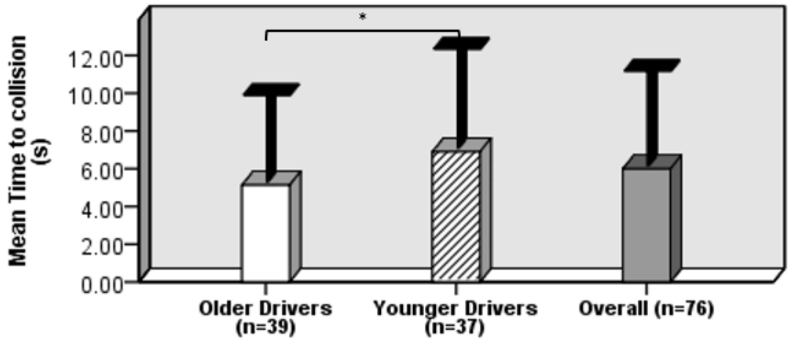


Figure 5.19 Mean TTC for different age groups (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

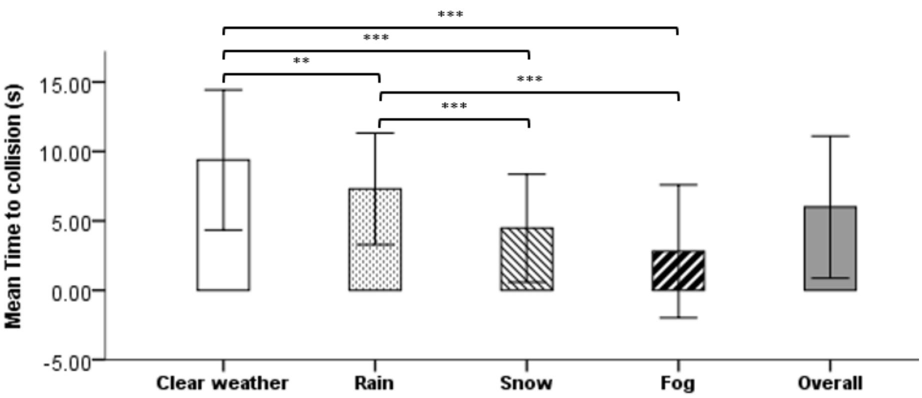


Figure 5.20 Mean TTC in different weather situations (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Figure 5.20 shows drivers' TTC in different weather situations. In terms of the effect of weather on the TTC, Mauchly's test showed that the assumption of sphericity was not met, $X^2(5) = 12.449$, p=0.029, and therefore the Huynh-Feldt correction was conducted (ε=0.962). Results of ANOVA showed that weather yielded a significant effect on the value of the driver's TTC, $F(2.885,207.74) = 47.974$, $p<0.001$, $\eta p^2=0.400$. Post hoc test with Bonferroni correction (p<0.01) shows that driver's TTC in clear weather (M=9.38s, SD=5.05s) is larger than it in the rain (M=7.30s, SD=4.01s), significant decrease of 2.08s, (95% CI, 0.61s to 3.55s) in the TTC from clear weather to the rain. It (p<0.001) also shows that the TTC in clear weather is larger than it in the snow (M=4.47s, SD=3.89s) and in the fog (M=2.81s, SD=4.79s), which represents that the TTC showed significant decrease of 4.91s (95% CI, 3.43s to 6.43s) from the clear weather to the snow and significant decrease of 6.57s (95% CI, 4.63s to 8.54s) from the clear weather to the fog. Moreover, it (p<0.001) indicates the TTC in the rain is larger than it in the snow and in the fog, which means that the TTC showed significant decrease of 2.83s (95% CI, 1.49s to 4.22s) from the rain to the snow and significant decrease of 4.50s (95% CI, 2.79s to 6.22s) from the rain to the fog.

Regarding the effect of road type on the TTC, results of ANOVA showed that it did not have any significant effect on the TTC, $F(1,72)= 0.138$, $p=0.711$, $\eta p^2=0.002$.

Table 5.9 Results of a mixed ANOVA for TTC

	df	*F*	*p*	*ηp²*
Age	1,72	6.278*	0.014	0.080
Weather	2.885,207.74	47.974***	<0.001	0.400
Road Type	1,72	0.138	0.711	0.002
Age × Weather	2.885,207.74	0.078	0.968	0.001
Age × Road Type	1,72	0.002	0.966	0.000
Weather × Road Type	2.885,207.74	1.363	0.256	0.019
Age × Weather × Road Type	2.885,207.74	0.522	0.661	0.007

*Note: *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001*

In addition, male drivers (M=6.12s, SD=5.13) exhibited slightly longer TTC than the female drivers (M=5.82, SD=5.10s), however, an Independent t-test revealed that this difference was not significant, $t(302) = -0.514$, $p=0.607$.

5.3.9 Resulting Acceleration

This section focuses on the results of drivers' resulting acceleration when reassuming the control of the vehicle in the HAV. Figure 5.21 shows the mean resulting acceleration for older and younger drivers. The overall participants had a mean resulting acceleration of 3.45m/s² (SD=2.25 m/s²).

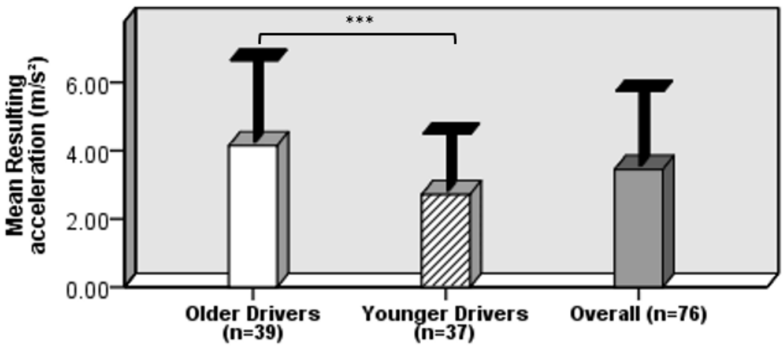


Figure 5.21 Mean resulting acceleration for different age groups (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

A mixed factorial ANOVA was performed to examine the effect of age, weather and road type on drivers' resulting acceleration. The results of ANOVA was shown in Table 5.10. Results showed that age has a significant effect on drivers' resulting acceleration, $F(1,72)=$

27.268, $p<0.001$, $\eta p^2=0.275$, with older drivers (M=4.14m/s², SD=2.46m/s²) exhibiting significantly greater resulting acceleration than younger drivers (M=2.71m/s², SD=1.74 m/s²), a statistically significant difference of 1.43m/s² (95% CI, 0.89m/s² to 1.99m/s²).

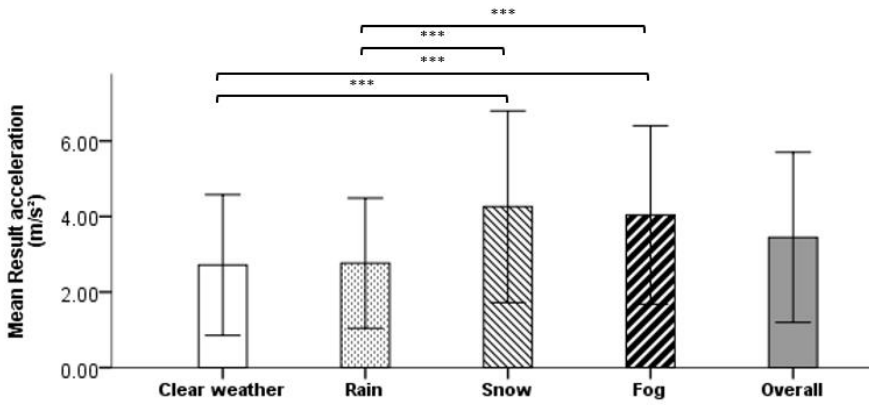


Figure 5.22 Mean resulting acceleration in different weather situations (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Figure 5.22 shows the mean resulting acceleration in the four weather situations. Regarding the effect of weather, Mauchly's test showed that the assumption of sphericity was violated, $X^2(5)$ =4.012, $p=0.048$, and therefore the Huynh-Feldt correction was conducted ($\varepsilon=0.964$). Results of ANOVA showed that weather yielded a significant effect on the value of the driver's resulting acceleration, $F(3,216)= 14.982$, $p<0.001$, $\eta p^2=0.172$. Post hoc with Bonferroni correction ($p<0.001$) shows that the driver's resulting acceleration showed a statistically significant increase of 1.54m/s² (95% CI, 0.70m/s² to 2.34 m/s²) from 2.72m/s² (SD=1.86m/s²) in the clear weather to 4.26 m/s² (SD= 2.46m/s²) in the snow. It ($p=0.001$) also shows that the resulting acceleration exhibited a significant increase of 1.33m/s² (95%CI, 0.44m/s² to 2.21m/s²) from 2.72m/s² (SD=1.86m/s²) in clear weather to 4.04 m/s² (SD=2.36m/s²) in the fog. In addition, it ($p<0.001$) indicates the resulting acceleration showed significant increases of 1.48m/s² (95% CI, 0.67 m/s² to 2.29 m/s²) and 1.28m/s² (95% CI, 0.49m/s² to 2.06m/s²) from 2.77m/s² (SD=1.72m/s²) in the rain to 4.26 m/s² (SD= 2.46m/s²) in the snow and to 4.04 m/s² (SD=2.36m/s²) in the fog respectively.

In addition, road type also yielded a significant effect on the resulting acceleration, $F(1,72)= 5.170$, $p=0.026$, $\eta p^2=0.067$, with the motorway (M=3.77m/s², SD=2.26m/s²) resulted in significantly greater resulting acceleration than the city road (M=3.14m/s², SD=2.21m/s²), a statistically significant difference of 0.64m/s² (95% CI, 0.08m/s², to 0.1.18m/s²).

Moreover, female drivers (M=3.41m/s², SD=2.25m/s²) generated slightly smaller resulting acceleration compared to the male drivers (M=3.47m/s², SD=2.26m/s²). In regard to the effect of gender on the resulting acceleration, an Independent sample t-test showed that there was no significant effect of gender on the resulting acceleration, $t(302) = -0.234$, p=0.815.

Table 5.10 Results of a mixed ANOVA for resulting acceleration

	df	*F*	*p*	*ηp²*
Age	1,72	27.268***	<0.001	0.275
Weather	3,216	14.982***	<0.001	0.172
Road Type	1,72	5.170*	0.026	0.067
Age × Weather	3,216	2.609	0.052	0.035
Age × Road Type	1,72	1.490	0.226	0.020
Weather × Road Type	3,216	1.158	0.327	0.016
Age × Weather × Road Type	3,216	1.315	0.270	0.018

*Note: *= p ≤0.05, **= p ≤0.01, ***= p ≤0.001*

5.3.10 Steering Wheel Angle

This section reports the results of drivers' steering wheel angle when taking over control from the HAV. Figure 5.23 shows the mean steering wheel angle for older and younger drivers. The overall participants had a mean steering wheel angle of 8.93decrees (SD=6.19decrees).

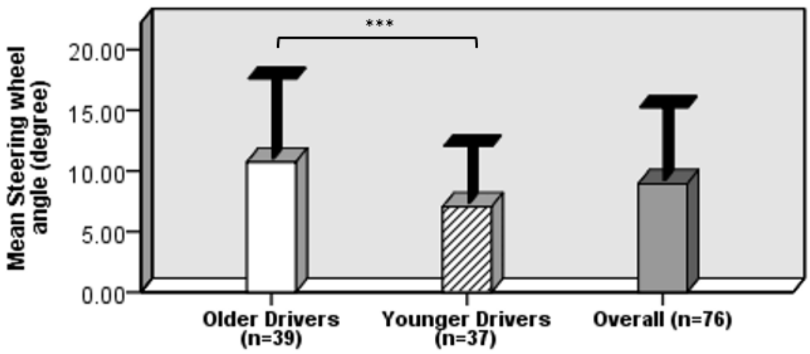


Figure 5.23 Mean steering wheel angle for different age groups (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

A mixed factorial ANOVA was performed to investigate the effect of age, weather and road type on drivers' steering wheel angle. The results of ANOVA was shown in Table 5.11. Results showed that age has a significant effect on drivers' steering wheel angle, $F(1,72)= 17.870$, p<0.001, ηp²=0.199, with older drivers (M=10.73 degrees, SD=6.75 degrees) exhibited significantly greater steering wheel angle than younger drivers (M=7.04 degrees, SD=4.89 degrees), a statistically significant difference of 3.69 degrees (95% CI, 1.95 degrees to 5.43 degrees).

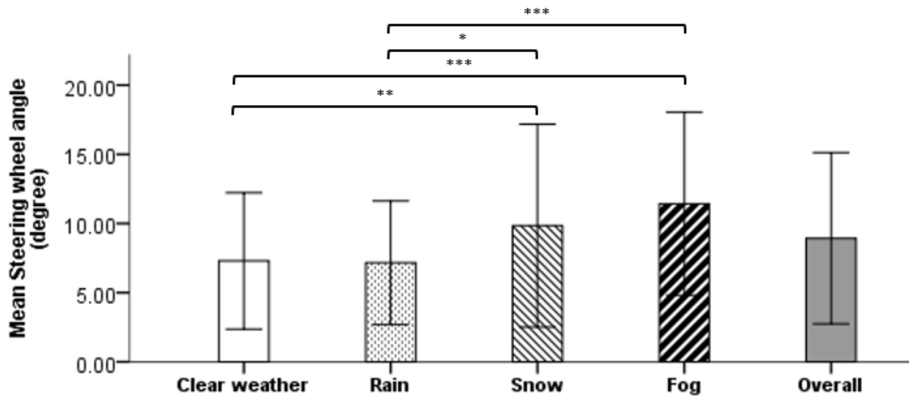


Figure 5.24 Mean steering wheel angle in different weather situations (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Figure 5.24 shows the mean steering wheel angle in the different weather situations. Regarding the effect of weather, Mauchly's test showed that the assumption of sphericity was violated, $X^2(5) = 41.362$, $p<0.001$, and therefore the Huynh-Feldt correction was conducted ($\varepsilon=0.844$). Results of ANOVA showed that weather yielded a significant effect on the value of the driver's resulting acceleration, $F(2.532,182.3)= 13.496$, $p<0.001$, $\eta p^2=0.158$. Post hoc with Bonferroni correction ($p<0.01$) shows that drivers' steering wheel angle in clear weather (M=7.30 degrees, SD=4.93 degrees) is smaller than it is in the snow (M=9.85 degrees, SD=7.33 degrees), a statistically significant difference of 2.55 degrees (95%CI, 0.47 degrees to 4.57 degrees). Moreover, it ($p<0.001$) shows the steering wheel angle in the clear weather is smaller than it in the fog (M=11.43 degrees, SD=6.62 degrees), a statistically significant difference of 4.13 degrees (95%CI, 1.89 degrees to 6.39 degrees). In addition, it ($p<0.05$) indicates that the steering wheel angle in the rain (M=7.16 degrees, SD=4.47 degrees) is smaller than it in the snow, a statistically significant difference of 2.69 degrees (95%CI, 0.41 degrees to 4.89 degrees). And it ($p<0.001$) indicates the steering wheel angel in the rain is smaller than it in the fog, a statistically significant difference of 4.27 degrees (95%CI, 2.10 degrees to 6.43 degrees).

In terms of the effect of road type on the steering wheel angle, results of ANOVA showed that it did not have any statistically significant effect on the steering wheel angle, $F(1,72)= 2.081$, $p=0.153$, $\eta p^2=0.028$.

Moreover, an Independent sample t-test was performed to determine if there is statistically significantly difference in the steering wheel angle between the female and male drivers, results revealed a significant effect of gender on the steering wheel angle, $t(302) = -2.024$, $p=0.044$, with female drivers (M=8.13 degrees, SD=5.55 degrees) exhibited significantly smaller steering wheel angle compared to the male drivers (M=9.55 degrees, SD=6.60 degrees), a statistically significant difference of 1.41 degrees (95% CI, 0.04 degrees to 2.78 degrees).

Table 5.11 Results of a mixed ANOVA for steering wheel angle

	df	*F*	*p*	ηp^2
Age	1,72	17.870***	<0.001	0.199
Weather	2.532,182.3	13.496***	<0.001	0.158
Road Type	1,72	2.081	0.153	0.028
Age × Weather	2.532,182.3	1.098	0.345	0.015
Age × Road Type	1,72	0.004	0.947	0.000
Weather × Road Type	2.532,182.3	0.683	0.539	0.009
Age × Weather × Road Type	2.532,182.3	0.102	0.750	0.001

*Note: *= p ⩽0.05, **= p ⩽0.01, ***= p ⩽0.001*

5.4 Discussion

5.4.1 Effect of Age

When comparing the takeover performance between older and younger drivers. The time aspects of takeover were used to reflect how quickly the participants reacted to the takeover request from the HAV, executed active input and made the decision to change lane. Significant effects of age on all three measurements were found, with older drivers needing longer in all three of the time components measured for the takeover than younger drivers. These findings could be explained in terms of the fact that the takeover control process in this research requires participants to first perceive and understand the system takeover request while disengaged from driving, then to stop engaging in non-driving tasks and take over control of the vehicle, and finally to perceive the environment, process information and make decisions. Therefore, a variety of physical, cognitive and psychomotor abilities and their interactions and coordination were needed from the drivers during this take over process. A series of age-related functional impairments may lead to slow reactions and decision making among older drivers during this takeover process, including declines in age-related visual and hearing (Attebo et al., 1996; Helzner et al., 2005) and cognitive abilities (Brouwer et al., 1991; Pollatsek et al., 2012), slower reaction times (Myerson et al., 2007; Ferreira et al., 2013a) and reduced psychomotor abilities (Stelmach and Goggin, 1988). Also, age was shown to have significant effects on the measurements of takeover quality, in terms of the resulting acceleration and steering wheel angle, with older drivers having greater resulting acceleration and greater steering wheel angle than the younger drivers. These findings correspond to those of previous research that also observed stronger acceleration and braking among older drivers when taking over control from the HAV (Körber et al., 2016; Clark and Feng, 2017). In addition, age had a significant effect on TTC, with older drivers had smaller TTC values than the younger drivers. Also, the total number of collisions and critical encounters as well as hasty takeovers involving older drivers (CCE: 44; Hasty takeover: 26) was larger than for younger drivers (CCE: 31; Hasty takeover: 14). Taken together, these findings indicate that older drivers' takeover is less effective and more critical than that of younger drivers. However, these findings are contrary to those of another study (Körber et al., 2016) which found that older drivers had fewer collisions and critical encounters and reflected a longer TTC than younger drivers. A possible explanation for this could involve the fact that the non-driving task that participants were asked to undertake in this research was "reading out loud", which requires constant attention and leads drivers to be completely disengaged from driving. However, the previous study (Körber et al., 2016) adopted a questioning task delivered via a hands-free phone, which may not be compelling enough to disengage older drivers completely from driving. In addition, compared to previous studies that focused on investigating drivers' takeover from HAVs in clear weather conditions (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017), the current research adopted clear weather condition together with a series of adverse weather conditions (rain, fog and snow) which may have made the takeover task more difficult, therefore resulting in worse takeover quality among the older drivers.

5.4.2 Effect of Weather on the Takeover Performance

Another important area for investigation in this research is the effect of weather conditions on the driver's takeover performance. With regards to the time aspects of takeover, the results showed that a driver's reaction time in clear weather is significantly faster than it is in fog. This is consistent with the findings of a previous study (Fotios et al., 2017), and even though it is not quite comparable with the current research, similar results were found in that enhanced luminance and decreasing fog thickness also led to faster reaction times. Weather conditions had significant effects on the driver's indicator time, which increased progressively from clear weather, to rain, snow, and fog. One possible explanation could be that drivers drive more cautiously in adverse weather conditions, and therefore they take a longer time to make decisions about changing lane. A more important reason for this could be that, in this research, the drivers' visibility was reduced successively during clear weather, to rain, snow and fog conditions (each with an incremental reduction in visibility). Therefore after the drivers took control of the vehicle from the HAV, the time they needed to catch sight of the stationary vehicle ahead was increased progressively as weather conditions, and thus visibility worsened. Concerning the effect of weather on takeover quality, there was a significant effect on the TTC, with drivers taking over control during clear weather showing the longest TTC among the four weather conditions. And drivers taking over control during rain showed longer TTC values than during snow and fog. In addition, the resulting acceleration and steering wheel angle were higher in conditions of snow and fog compared to in clear weather and rain. Besides this, the majority of CCEs happened during snow (30.7%) and fog (66.7%). These findings, taken together, indicate that drivers' takeover was less effective and more dangerous in adverse weather conditions, especially in the conditions of snow and fog, compared to those in clear weather. Again, one important contributor to these findings may be reduced visibility in adverse weather conditions, which may have resulted in more critical takeover behaviours and collisions. Another possible explanation may be that, compared with taking over control in clear weather, the visual effects of the simulated adverse weather conditions in this research may increase the difficulty of the takeover tasks as well as the amount of information that drivers have to process, and therefore this may result in mental overload among drivers that would be highly linked with deteriorating and more dangerous takeover quality (Brookhuis and de Waard, 2010).

5.4.3 Interaction between Age and Weather on Takeover Performance

In addition, this research has found that there is a significant interaction effect between age and weather on the time aspects of takeover in terms of reaction time (RT) and takeover time (TOT). Younger drivers' RT and TOT showing a continuous growing trend and older driver's RT and TOT showed a relatively steady trend across the four weather conditions from the clear weather to the fog. This could be interpreted together with the number of collisions and critical encounters (CCEs) and hasty takeovers which occurred for each group. In general, younger drivers' time aspects of takeover were faster than those of the older drivers. In clear and rainy conditions, despite the greater differences in the mean value of time aspects between younger drivers (RT: 2.12s in clear weather, 2.15s in the rain; TOT: 3.09s in clear weather, 3.34s in the rain) and the older drivers (RT: 2.91s in clear weather, 2.87s in the rain; TOT: 4.46s in clear weather, 4.32s in the rain), both groups exhibited similar safe and effective takeover behaviours, with 1 CCE for each group and 7 hasty takeovers among the older drivers and 3 hasty takeovers among the younger drivers. However, in snowy conditions, the differences in the time aspects between the younger drivers (RT: 2.26s; TOT: 3.76s) and older drivers (RT: 2.75s; TOT: 4.16s) become much smaller and older drivers' takeover was more dangerous (17 CCEs; 11 hasty takeovers) than that of the younger drivers (6 CCEs; 4 hasty takeovers). In addition, in foggy conditions, the gap in the time aspects of takeover, and especially the takeover time, between the younger drivers (RT: 2.29s; TOT: 4.24s) and the older drivers (RT: 2.99s; TOT: 4.36s) becomes smaller, and older drivers again showed more dangerous takeover (26 CCEs; 8 hasty takeovers) than the younger drivers (23 CCEs; 7 hasty takeovers). In addition, in the fog situation, the number of number of drivers who avoided the stationary car by steering and braking is statistically larger among older drivers (n=15) than among the younger drivers (n=6). These findings could be because the takeover tasks were less difficult in clear weather and rain conditions, as drivers had greater visibility and less cognitive demand so that they were able to catch sight of the stationary car earlier after taking over control from the HAV. With less time and cognitively demanding tasks, older drivers took a longer time to perceive and understand system's takeover request, to process information and to generate active input than the younger drivers, so that their takeover was as safe and effective as the younger drivers. These behaviours correspond with findings from previous research which indicates the phenomenon of a trade-off between task processing speed and accuracy among older people for simple tasks (Brébion, 2003). However, in snowy and foggy conditions, the tasks of taking over control became more difficult as drivers' visibility was seriously reduced and their mental workload increased. In these conditions, younger drivers' reaction time and takeover time showed a dramatic increase in the snow and fog compared to in clear weather and rainy conditions, and they had a substantial increase in the number of CCEs and hasty takeovers. This could also be explained in terms of the enhanced levels of task difficulty resulting in slower and less accurate task performance (Shumway-Cook and Woollacott, 2000). However, in the same conditions, older drivers' time aspects did not increase much further, but more CCEs and hasty takeovers were recorded than with younger drivers. This could possibly be explained by the previous finding that older people's already slower reaction time involved a "protective" mechanism which prevented that from slowing down even further in the more difficult tasks; the price of maintaining reaction time is reduced accuracy (Vaportzis et al., 2013). In general, this finding corresponds with those of previous studies which suggest that older drivers interact with technologies differently compared to younger drivers, and their needs should be carefully considered in the design of new technologies (Pangbourne *et al.*, 2010; Guo *et al.*, 2013a).

5.4.4 Effect of Gender on Takeover Performance

Regarding the effect of gender on the takeover performance, this investigation found that the female and male drivers exhibited similar takeover performance in terms of most of the measurements. However, gender showed a significant effect on reaction time and steering wheel angle, with female drivers exhibited slightly faster reaction time (a significant difference of 0.17s) and slightly smaller steering wheel angle (a significant difference of 1.41 degrees) compared to the male drivers. This finding is different from previous study by Blough and Slavin (1987) who also found that females have better performance than males in performing visual tasks, but their reaction time is slower than male. The possible reason could be that as in this investigation, the reaction time measures the time between the HAV system's takeover requests to the point when drivers have completely switched to the manual driving position. During the moment that HAV initiates a takeover request, the drivers were completely disengaged from driving and had little information about the driving situation. In terms of dealing with uncertain situations, females are more cautious and less confident compared to the males (Croson and Gneezy, 2009), which may resulted in a slightly more urgent switch back to the manual driving position, thus faster reaction time. In addition, female drivers (CCEs: 35, hasty takeovers: 17) exhibited less number of CCEs and hasty takeovers compared to the male drivers (CCEs: 40, hasty takeovers: 23). However, the difference was not statistically significant. This is in accordance with a previous study by Crizzle et al. (2013), although this study is not very comparable with the current research but they found similar results that male drivers had slightly more driving mistakes compared to female, but the differences was not statistically significant.

5.5 Conclusion

This investigation studied the takeover performance of younger and older drivers in HAV during clear weather, rain, snow, and fog. The aim of this investigation is twofold; firstly to further examine the effect of age on the drivers' takeover performance in HAV; secondly to investigate the effect of adverse weathers (rain, snow and fog) on older and younger drivers' takeover performance in the HAV.

Firstly, in regard to the effect of age, the results of this investigation showed that age significantly affect drivers' takeover performance, resulted in slower time aspects of takeover and worse takeover quality. This conclusion was drawn through the analysis of the following measurements, where older drivers resulted in:

- Significantly slower reaction time (2.88s compared to 2.21s of younger drivers);
- Significantly slower takeover time (4.33s compared to 3.61s of younger drivers);
- Significantly slower indicator time (15.68s compared to 11.53s of younger drivers);
- Significantly smaller TTC (5.13s compared to 6.90s of younger drivers);
- Significantly stronger resulting acceleration (4.14m/s² compared to 2.71m/s² of younger drivers);
- Significantly greater steering wheel angle (10.73 degrees compared to 7.04 degrees);
- More CCEs (44 compared to 31 of younger drivers), significantly more CCEs in snowy weather (17 compared to 6 of younger drivers);
- More hasty takeovers (26 compared to 14 of younger drivers);

Secondly, in terms of the effect of adverse weather, the results revealed that weather significantly affected the takeover performance. Adverse weather conditions, particularly snow and fog, led to slower reaction and decision making as well as a less effective and more dangerous takeover among the HAV drivers. This conclusion was drawn through the analysis of the following measurements:

To begin with, the rain weather resulted in:

- Slower takeover time (3.84s compared to 3.79s of the clear weather);
- Significantly slower indicator time (10.84s compared to 8.79s of the clear weather);
- Significantly smaller TTC (7.30s compared to 9.38s of the clear weather);
- Stronger resulting acceleration (2.77m/s² compared to 2.72m/s² of the clear weather)
- More hasty takeover (7 compared to 3 in the clear weather)

And the snow weather resulted in:

- Slower takeover time (3.97s compared to 3.79s of the clear weather);
- Significantly slower indicator time (16.27s compared to 8.79s of the clear weather);

- Significantly smaller TTC (4.47s compared to 9.38s of the clear weather);
- Significantly stronger resulting acceleration (4.26m/s² compared to 2.72 m/s² of the clear weather), and strongest resulting acceleration among the four weathers;
- Significantly greater steering wheel angle (9.85 degrees compared to 7.30 degrees of the clear weather);
- Significantly more CCEs (23 compared to 1 in the clear weather);
- Significantly more hasty takeovers (15 compared to 3 in the clear weather);

Lastly, the fog weather resulted in:

- Significantly slower reaction time (2.65s compared to 2.52s of the clear weather), and the slowest reaction time among the four weathers;
- Slowest takeover time among the four weathers (4.30s compared to 3.79s of the clear weather);
- Significantly slower indicator time (18.77s compared to 8.79s of the clear weather) and the slowest indicator time among the four weathers;
- Significantly shorter TTC (2.81s compared to 9.38s of the clear weather), and the shortest TTC among the four weather;
- Significantly stronger resulting acceleration (4.04m/s² compared to 2.72m/s² of the clear weather);
- Significantly greater steering wheel angle (11.43 degrees compared to 7.30 degrees of the clear weather), and the greatest steering wheel angle among the four weathers;
- Significantly more CCEs (50 compared to 1 in the clear weather);
- Significantly more hasty takeover (15 compared to 3 in the clear weather);

In addition, this research found a significant interaction between age and weather. This interaction indicates that younger drivers and older drivers were affected differently by the adverse weather. Adverse weather resulted in slowed time aspects of takeover and worse takeover quality among younger drivers. For older drivers, their already slower time aspects of takeover were not slowed down much further by adverse weather, but their overall takeover became much more dangerous. Moreover, this research found gender differences exists in terms of the takeover performance from the HAV. The recommendations yielded from the findings are shown in Chapter 8.

Chapter 6. Investigation of older drivers' opinions of and requirements towards the human-machine interaction in highly automated vehicles

6.1 Introduction

Chapters 4 and 5 described older drivers' first-hand experience of interacting with the HAV. The findings of these two chapters highlighted age differences in performance in interacting with the HAV and emphasized the necessity of considering older drivers' needs and requirements in the design of human-machine interaction in the HAV. However, the review of literature in Chapter 2 pointed out that knowledge regarding older drivers' requirements concerning the human-machine interaction in HAVs is still limited. This knowledge gap may potentially prevent older drivers from benefitting from HAVs.

In response to this gap in knowledge, Chapter 6 details a qualitative interview investigation which aimed to investigate older drivers' opinions of and requirements towards the human-machine interaction in the HAV.

6.2 Method

In order to investigate older drivers' requirements towards the human-machine interaction in HAVs. The method adopted was semi-structured interview. The detailed justification of the selection of this method was provided in Sections 3.4 and 3.5. This section firstly discusses the experimental design of this interview investigation in Section 6.2.1 and then provides an overview of the participants of the investigation in Section 6.2.2. After that, the detailed process of the thematic analysis of the interview data is provided in Section 6.2.3.

6.2.1 Experimental design

This investigation aims to build a qualitative understanding of older drivers' interaction with HAVs. Quantitative data were collected in Chapters 4 and 5 from the use of the driving simulator which provided the participants with hands-on experience with a simulated HAV. Hands-on experience is crucial in developing technologies for older people and can help them to gain a spontaneous and realistic understanding of the new technology as well as laying the foundations for the collection of data about their attitudes and needs (Eisma et al., 2003; Davies and Lam, 2009; Buckley et al., 2018).

Therefore, the data collection in the interview investigation was undertaken after each participant had participated in the quantitative driving simulator experiments for Chapters 4 and 5, which lasted for approximately 45 minutes. Then they fill the ethical consent form for this interviews study (Appendix C). After that, the interviews begin. Each interview lasted no longer than 30 minutes in order to restrict the duration of the overall experiment to less than 75 minutes to prevent the participants from losing attention and becoming fatigued (Purchase, 2012).

Figure 6.1 Semi-structured interviews

As Section 3.4.3 highlights, the interviews were semi-structured in that they were structured by a group of predetermined open-ended questions which also allowed the researcher to follow up other questions derived from the dialogue between the researcher and participants (DiCicco-Bloom and Crabtree, 2006). The careful and clear design of the predetermined questions is important in semi-structured interviews, and thus the design of the predetermined questions in this investigation followed advice and guidance in the literature suggesting that the questions should correspond to the research aims and be able to address the research questions appropriately and easily understandable by the participants (DiCicco-Bloom and Crabtree, 2006; O'Keeffe et al., 2016). Corresponding to the advice, the questions were centred on older drivers and the two new types of human-machine interaction in the HAV highlighted in the literature (SAE, 2014; DfT, 2015c; Gold *et al.*, 2016): first, when the HAV is performing automated driving and the drivers are completely disengaged from driving; and second, when drivers are reassuming control of the vehicle back from the HAV. The interviews were semi-structured format. Interview questions (Appendix D) were in plain language and cover the following topics: driving behaviour in daily life and opinions of automated vehicles; preferred tasks instead of driving in HAVs; expectations from the HAVs during automated driving and taking over control processes; and advice to HAV manufacturers. Figure 6.1 illustrates the semi-structured interviews, which were audio-recorded. At any point in the interview, the participants were free to withdraw from the investigation.

6.2.2 Participants

The simple size determination of this investigation was explained in Section 3.5.3. 24 older drivers (mean = 71.50 years, SD = 5.93 years; 12 female, 12 male) who participated in the quantitative driving simulator experiments were interviewed. Their annual driving mileages are shown in Table 6.1.

Table 6.1 Annual mileage driven by participants

Annual mileage (miles)	*0-3000*	*3000-6000*	*6000-10000*	*10000-15000*	*15000+*	*Total*
Female	2	4	5	1	0	12
Male	1	1	5	4	1	12
Total	3	5	10	5	1	24

6.2.3 Thematic analysis

The purpose of this qualitative investigation is to build new knowledge to understand older drivers' opinions of and requirements towards the human-machine interaction in emerging HAVs. Therefore, the nature of this investigation is exploratory research which attempts to address issues and questions that have not yet been defined clearly or fully explored (Jaeger and Halliday, 1998). Considering the exploratory nature of the research, the most suitable method to use for the data analysis is thematic analysis (Braun and Clarke, 2006). The thematic analysis was conducted using the computer-assisted qualitative data analysis software NVivo (Figure 6.2), the explanation of selecting this technique was highlighted in 3.5.4. Using such software tool for qualitative research ensures that the data analysis is performed in a continuous and transparent way, and therefore could potentially enhances the rigour of the research (Richards and Richards, 1994; Castleberry and Nolen, 2018). NVivo does not automatically analyse the data but assists in organizing large amount of qualitative data in order to code it and to observe the patterns of codes and connections between codes and the data in a clear and transparent way (Castleberry and Nolen, 2018).

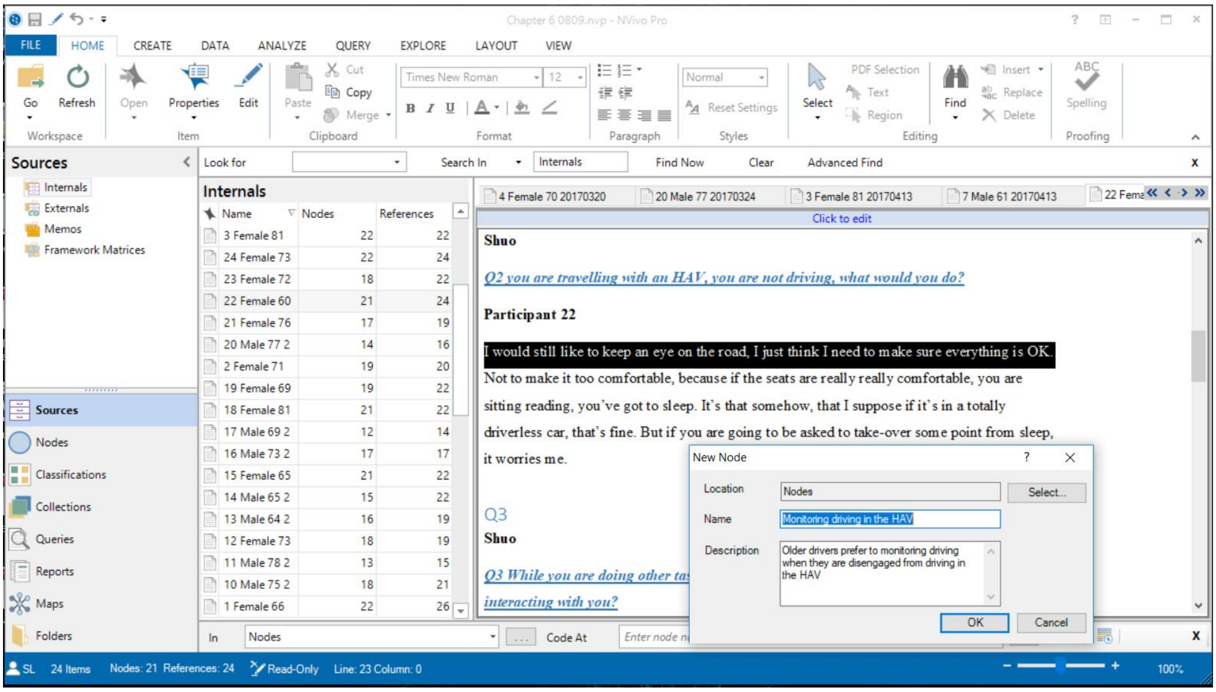


Figure 6.2 Thematic analysis coding with NVivo software

The thematic analysis was conducted according to the step-by-step outline proposed by Braun and Clarke (2006). To begin with, the interview recordings were transcribed and then the transcripts were read through to enable the researcher to be familiar with the data. During this process, the initial thoughts and ideas for the coding of the data were noted.

Secondly, a new project was created in the NVivo and the interview transcripts were imported. Then, the interview scripts were coded in NVivo. A code is a label assigned to a phrase or a sentence to identify the semantic features of the participants' answers (Braun and Clarke, 2006). Thematic analysis includes two primary ways to code the data and identify themes in an inductive way or a deductive way (Braun and Clarke, 2006; Guest et al., 2011). An inductive approach codes the data and identifies the themes based on the quantitative data themselves. However, a deductive approach generates themes based on pre-existing theories, such as pre-exiting coding frameworks, pre-defined codebook or the researcher's analytic preconceptions (Braun and Clarke, 2006; Nowell et al., 2017). Considering the exploratory nature of this investigation which is attempting to build a fundamental understanding towards older drivers' requirements of the human-machine interactions of a forthcoming technology-HAV, inductive thematic analysis was more appropriate.

As Figure 6.2 illustrates, the coding process using NVivo software is convenient and efficient in that a code could be generated by using the mouse cursor to highlight the relevant content of a transcript and then assign a name for the code. In order to code the data in a robust and rigorous way and ensure the codes reflect the qualitative richness of the phenomenon, a thematic analysis coding advice proposed by Vaismoradi et al. (2016) was adopted to facilitate coding (see Appendix K for details). This advice facilitates the researcher to better code the data and to clearly and efficiently identify the semantic features of the participants' comments. Also, it could also allow the researcher to compare and group the codes clearly and effectively (Vaismoradi et al., 2016). Following the advice, each participants' comment was reviewed, the code was identified inductively based on the semantic features of the data. Then, a label was assigned to the code. In regarding to the way to name the codes, Sandelowski and Leeman (2012) suggested that using a phrase or sentence could be more clearly to show the complete ideas to the reader than a single word. The entire dataset was coded in this manner. The coding process was conducted by one researcher. In order to prevent bias and to ensure the codes are valid and reliable, it was highly recommended that the codes should be cross-checked by one or two other researchers (Boyatzis, 1998; Fereday and Muir-Cochrane, 2006). Therefore, the codes were verified by two other academics. Finally, the above coding process resulted in 62 codes (see Figure 7.4).

The next step is to discover themes. Themes are discovered by combining fragments or components of issues, topics, ideas or experiences, which may often have less meaning or significance when inspected alone (Aronson, 1995). An important consideration is what counts as a theme. It is possible to identify a theme based on the number of participants who refer to a topic or the frequency that a topic is mentioned. However Vaismoradi et al. (2016) suggested that despite the more times a same code was mentioned by the participants the more likely it could form a theme, but researchers' judgement is more important. Braun and Clarke (2006) argued that greater number of instances of an issue do not necessarily suggest that the issue is more important, as in qualitative analysis there is no definition of what proportion of the data is a criterion for being considered as a theme. This is in accordance with the belief of Musselwhite and Haddad (2010) that the qualitative depth and significance of an issue is much more important than how often this issue is discussed. In addition, Fereday and Muir-Cochrane (2006) argued that a single comment may be as important as those that have been mentioned multiple times by other participants. The judgement of the researcher is crucial in identifying and developing the themes (Braun and Clarke, 2006). Therefore, in this investigation, counts of the frequency or instances of an issue were only used to describe the data rather than to identify themes. Instead of generating themes by counting instance of a topic, Fereday and Muir-Cochrane (2006) indicated that grouping codes and generating themes is performed in accordance with the research questions. This is in accordance with Braun and Clarke (2006) who believed a theme represents patterned responses in the data corresponding to the purpose of the research. In addition, Vaismoradi et al. (2016) augured that a theme is generated by grouping the codes with a similarity with regard to the research questions.

Therefore, the 62 codes were reviewed carefully under the context of the research question of this study which is to explore older drivers' opinions and requirements towards the human-machine interaction of HAVs. Some important codes were recognized and have formed initial themes directly. For example, the codes "First-hand experience with the HAV", "Physical control of HAV" and "Psychological control of HAV". Some codes refer to similar topics, issues and ideas, so they were grouped together, which had shaped other initial themes. For example, the initial theme of "Relaxing tasks" was generated by grouping the codes "relaxing not demanding tasks", "listening to the radio", "reading", "looking at scenery", "talking to others in the car", "using mobile phone", "watching TV and movies", "doing exercise", "thinking", "doing crosswords" "meditation and breathing". This process has resulted in twenty initial themes, and they were further collapse into several core themes according to the similarity of the ideas they are representing under the context of the research questions (see Figure 6.3 and Appendix I). The next step is to review the themes. As suggested by Nowell et al. (2017), the researcher reviewed the codes for each theme to check whether they followed a coherent pattern in the theme. The themes were also checked against the original interview transcripts to make sure that data of each theme fit together meaningfully and different themes are clearly distinguishable (Braun and Clarke, 2006). If themes fit the data and no important new themes could be identified, this step finishes, and at this point the comprehensive story of the data that the themes are telling has become clear (Braun and Clarke, 2006). Finally, the names and definitions of the core themes were generated. Based on the process of thematic analysis, seven core themes were generated.

6.3 Results

In total, the 24 interview transcripts resulted in 62 codes. The 62 codes as well as the number of participants each code were coded from and the frequency that each code was mentioned was highlighted in Figure 6.4. It shows that the two most frequently mentioned codes by the participants in this research were 'Informing what's happening' and 'Reasons for takeover'. Figure 6.3 illustrates the thematic analysis, it shows that the 62 codes were then classified into 20 initial themes. Finally, the 20 initial themes were further grouped into 7 core themes. A more detailed summary of thematic analysis was in Appendix L.

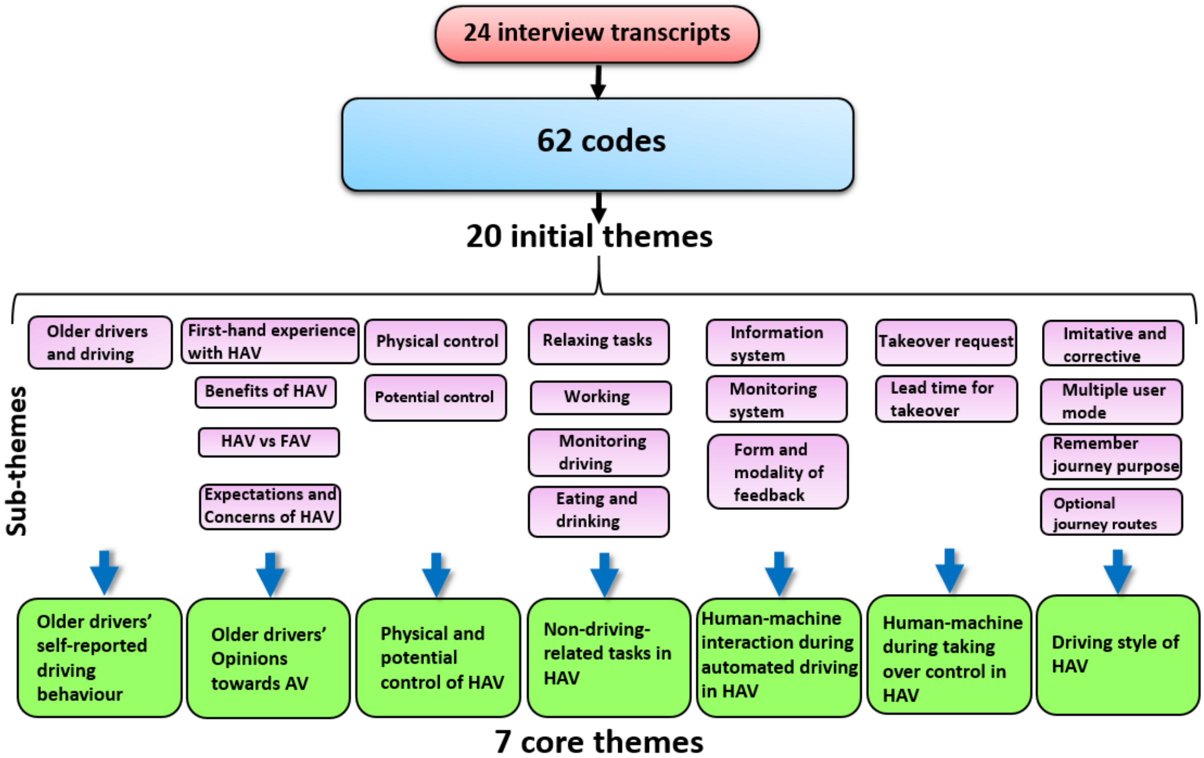


Figure 6.3 Thematic map showing the process of thematic analysis.

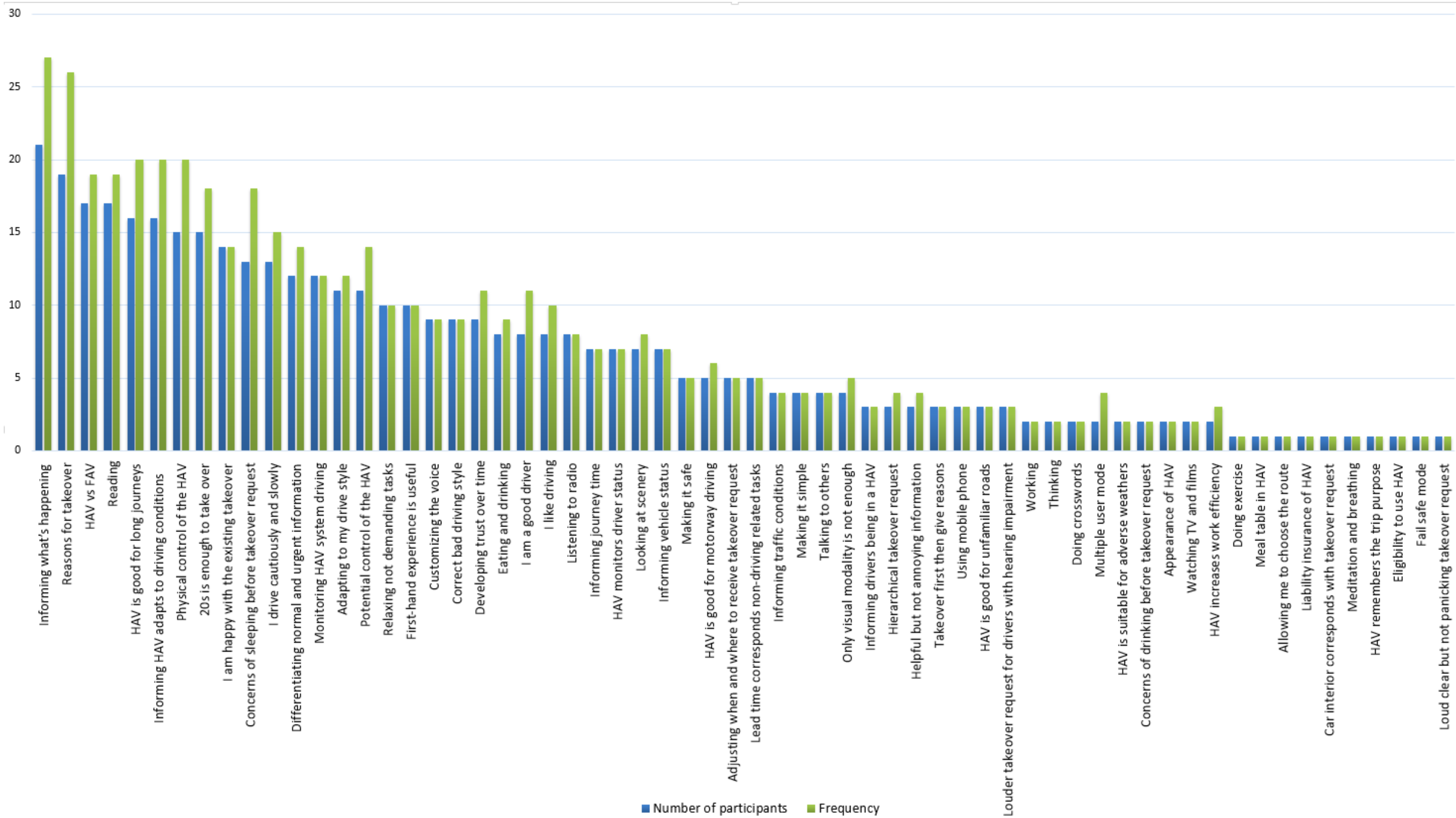


Figure 6.4 Summary of the 62 codes of the thematic analysis of the interview scripts

6.3.1 Theme 1-Self-reported driving behaviour of older drivers

The first themes is about the older drivers' self-reported driving behaviour. The coding map of this theme is shown in Figure 7.5. It shows the codes that this themes consists. The light blue dots represent the codes that construct the theme. The multi-coloured dots represent the interview scripts of each participants. The black arrows extended from the codes point to the participants' scripts that the code were coded from. In general, the participants believed that older drivers are safe drivers. More than half of the participants indicated that they drove cautiously and more slowly than others (n=13, 7 female, 6 male) For example:

"When I drive, I am watching what's going on around me, dogs on the pavement, children on the pavement, it's windy, and it's a bit of plastic bags blowing across the road. What's the condition of the road? I am continually scanning everything and thinking about it. I am not doing it for fun, I am doing it because I am going from A to B and I want to get there safely." (No.6, Male, age 79)

"They say older people are slow, slow still gets you there, you don't break speed limit."(No.18, Female, age 81)

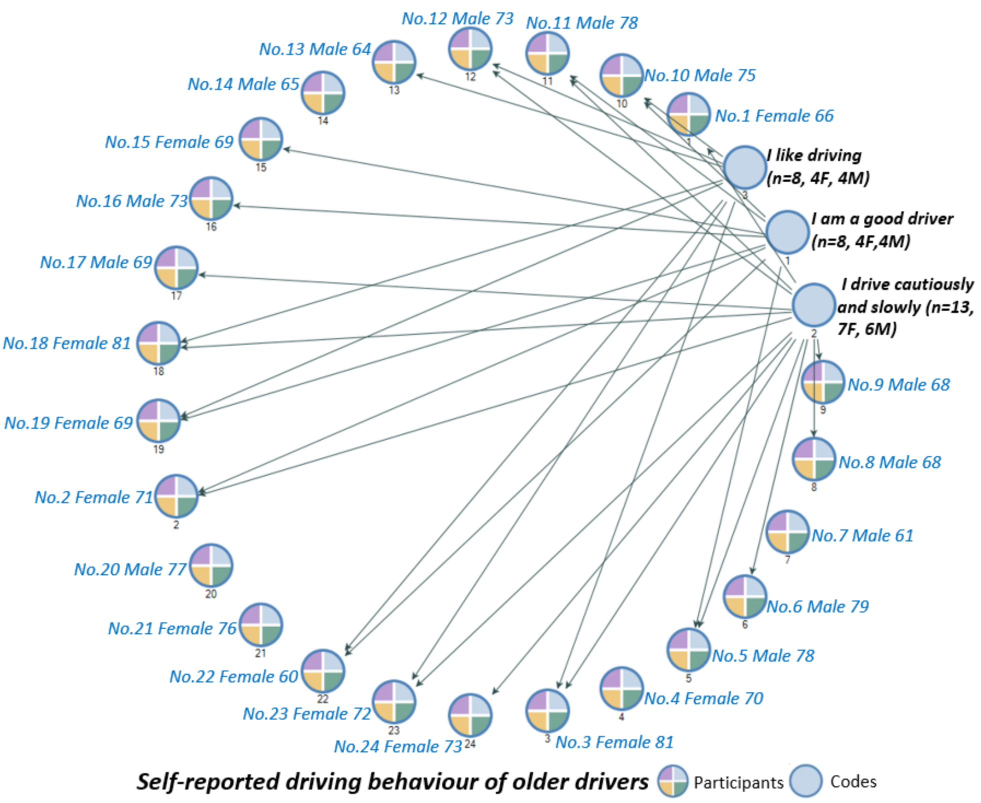


Figure 6.5 Coding map of theme one, F=female, M=male

Some participants indicated they are good drivers (n=8, 4 female, 4 male) and they like driving (n=8, 4 female, 4 male).

6.3.2 Theme two-Older drivers' opinions towards the automated vehicles

The second theme was older driver's opinions towards automated vehicles. The themes consists several sub-themes including their first-hand experience with the HAV, comparison between the HAV and the FAV (fully automated vehicle), benefits and concerns of the HAV. Figure 6.6 illustrates the coding map of this theme. It shows the codes that this theme consists and which participants' script each code was coded from.

First-hand experience of interaction with the HAV

Participants (n=10, 6 female, 4 male) pointed out that the first-hand experience of interaction with the HAV on the simulator is really important for them to build a realistic understanding of HAVs. They stated that it is completely different with the HAV that they imagined when they first heard about it on the news. Also, participants (n=9, 4 male and 5 female) indicated that their trust and confident in HAVs have improved over several driving sessions on the simulator, they believed their trust of automated vehicles could be developed over time. For example:

"Before I came here this afternoon, I thought it would be terrifying to drive an automated car, I'll be frightened to keep my eyes off the road, but now I know I can do it, it's quite smooth." (No.15, Female, age 69)

"I felt more confident by the end than I did in the first couple, I could see in a day, I would be better." (No. 20, male, age 77)

Perceived benefits of the HAV

Participants also discussed the impact of HAVs on their quality of life, they generally positive about HAV and believed it would enhance their mobility and help them to stay independent. One common response was that HAV could enable them to drive long journeys confidently and comfortably (n=16, 11 female, 5 male). For example:

"Now I don't do much long-distance driving any more, but I do enjoy it. I think, with the highly automated vehicle, what I would do is I wouldn't get tired as much, cos sometimes it's quite tired driving long-distance. I think that would be a big advantage where you just going down the motorway, you can sit and have a rest. And you won't be that tired when you get there."(No. 13, male, age 64)

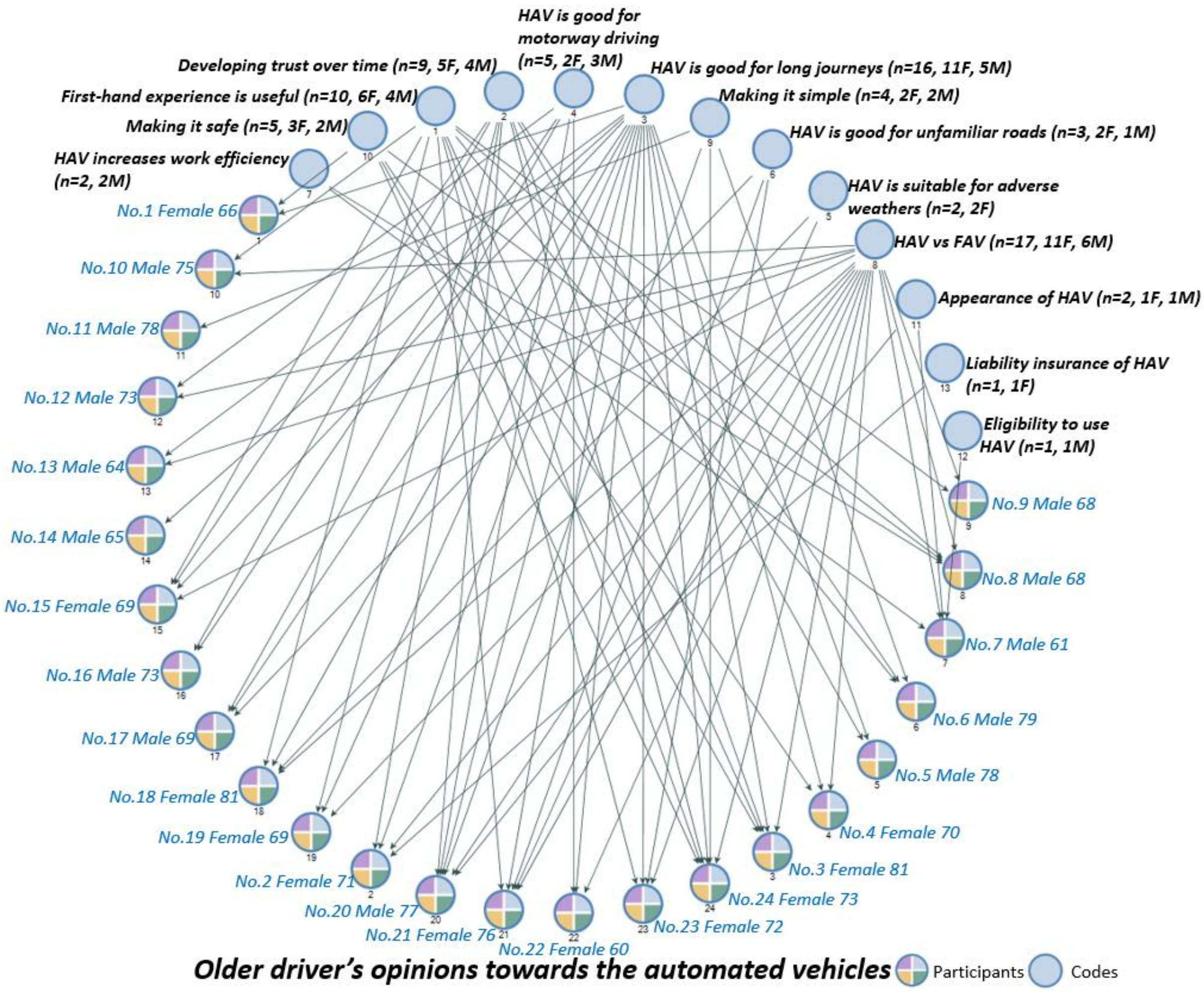


Figure 6.6 Coding map of theme two, F=female, M=male

In addition, participants perceived that HAV would help them to drive safely and comfortably in situations in which they felt it was difficult to drive, such as motorway driving (n=5, 2 female, 3 male), in adverse weather conditions (n=2, 2 female) and on unfamiliar roads (n=3, 2 female, 1 male). For example:

"When I drive to visit my son, I never really stop going down, I feel fine. But coming back at night is very tiring, that takes more out of you physically, and every other way. So I found on the way back, I need to stop, have a drink, and have a break. This is the time I need an automated car." (No. 12, female, age 73)

"Driving in the fog and snow conditions, I would just park and wait until it stops. That appeals to me that the HAV would know better for what speed to drive at when I didn't know what the conditions were like, so that's a big bonus point. (No. 18, female, age 81)

"I don't like driving in unknown cities or countries, I don't like planning navigating sort of thing, that would be the time I'll let the car to take-over."(No. 23, female, age 72).

HAV vs FAV

The participants (n=17, 11 female, 6 male) also specified that they currently preferred HAVs as they still allow them to have some control over the vehicle. However, they were aware when they become older, their physical, mental and cognitive conditions may not allow them to drive safely. By that time, they would need a fully automated vehicle (FAV) to enable them to stay mobile and independent. For example:

"I like driving, I like the abilities to make decisions. So, currently I may choose a highly automated car. But, ten, twenty years from now, I'll be much older, my functionalities will be slower I would imagine, then a fully automated car may benefit me." (No.8, male, age 68)

"I would like a highly automated vehicle now. But the fully automated might be useful when as you get older and the DVLA says you shouldn't be driving any more, then you can still have a fully automated car, because taking my car away that would like taking my legs away."(No. 12, female, age 72)

Expectations and Concerns of the HAV

Moreover, some participants indicated that they expected the HAV to be designed to be simple (n=4, 2 male, 2 female) and safe (n=4, 2 male and 2 female). In addition, two participants (1 male, 1 female) exhibited expectations about the appearance of the HAV, they believed it should be designed like the traditional vehicles. However, some participants showed concerns about the eligibility to use the HAV (n=1, 1 male) and the liability insurance of HAV (n=1, 1 female).

6.3.3 Theme three- Physical and potential control of the HAV

Notwithstanding the positive attitudes towards and the benefits of HAV that the participants perceived, the third theme shows that they would still like to retain certain levels of control of the HAV, both physical and potential control.. The coding map of this theme is displayed in Figure 7.7. It illustrates the codes that this theme contains and which participants' script each code was coded from.

Physical control of the HAV

Participants (n=15, 9 female, 6 male) indicated that they would still like to remain active drivers and to retain control over their lives. Participants stated that it is important to remain the physical control of the vehicle as driving is a habit of a lifetime and they love it. For example:

"Old habits die hard, our driving habit has been inculcated over 50 years, and it would be very difficult just sort of pretending I was a complete passenger, it's not about not trusting automated cars, but I like to be in control." (No.5, male, age 78)

"I think I would like a bit of control, maybe not complete control. If it's on motorway, it drove for you, you can sit there and take a break. Like I was driving up to Edinburgh on A1, I am quite happy to let the car drive. But when I am getting into Newcastle, I need to drive, I want control." (No.16, male, age 73)

"I like to think I could intervene, if I know I can intervene at any time, then I feel I have some responsibility over this car and I feel control."(No. 15, female, age 69)

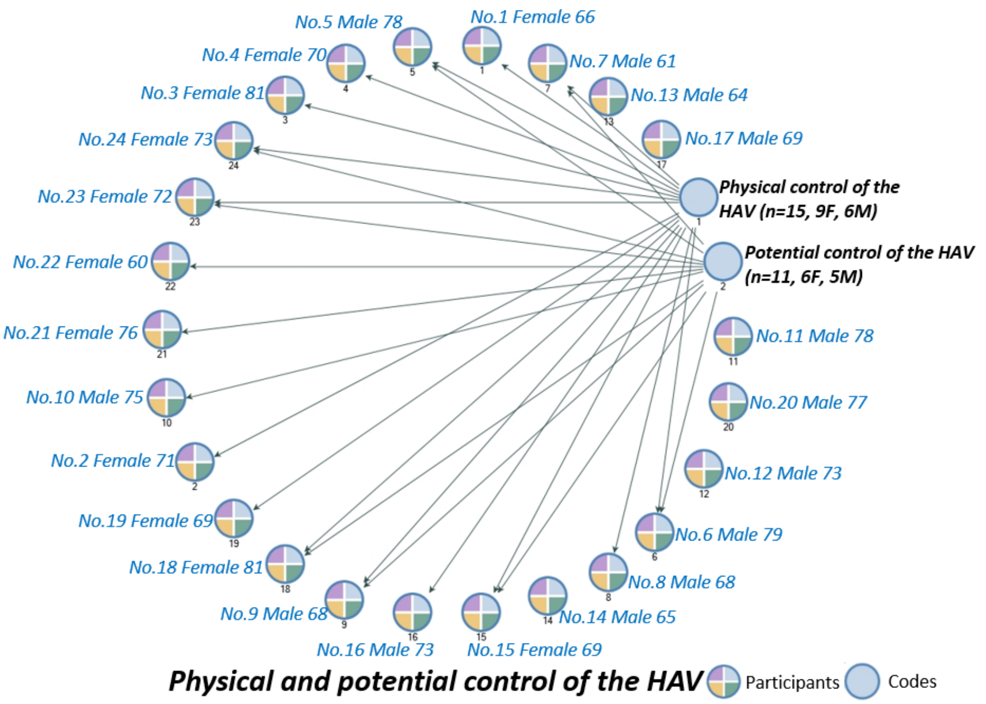


Figure 6.7 Coding map of theme three, F=female, M=male

Potential control of the HAV

In addition, participants (n=11, 6 female, 5 male) participants (n=11, 6 female, 5 male) indicated that they wanted to retain potential control, of the car as well. They described that they needed to perceive themselves as having potential control over the HAV, which means to be able to intervene at any time they wanted when the car is driving automatically. For example:

"I would still like to have some control, just for mental, to make sure that you still have some reason for being in the car."(No.10, male, age 75)

"I would still prefer to have some control over the car, just don't take it out of the driver's hands totally. The control I mean is more mental, nor physical. I would like to use an automated vehicle, but I need to know I am able to take over it when I feel I want to."(Male, older drivers)

6.3.4 Theme four-Non-driving-related tasks in HAV

The forth theme was regarding the activities older drivers would like to perform instead of driving when the HAV is automated driving. Figure 7.8 shows the coding map of this theme. It displays the codes that this theme includes and which participants' script each code was coded from.

Relaxing tasks

Some participants indicated that when they are not driving in HAV they would like to do the tasks which are relaxing and do not require massive attention (n=10, 5 female, 5 male), such tasks may include listening to the radio (n=8, 4 female, 4 male), reading (n=16, 10 female, 6 male), looking at scenery (n=7, 5 female, 2 male), talking to others in the car (n=4, 3 female, 1 male), using mobile phone (n=3, 1 female, 2 male), watching TV and movies (n=2, 1 female, 1 male), doing exercise (n=1, 1 male), thinking (n=2, 1 female, 1 male) and meditation and breathing (n=1, 1 female), doing crosswords (n=2, 1 male, 1 female). For example:

"I would listen to music or listen to the radio, but not answering emails, perhaps looking at an iPad a little." (No. 20, male, age 77)

"I would read a book perhaps, talk to somebody who is in the car with me, just something not requiring massive attention." (No.8, male, age 68)

"I would like to be doing something where I can get relief. Because I need to know a bit of what's happening. It would be OK reading the iPad, reading a bit of news that you didn't have to concentrate on." (No.1, female, age 66)

"I'd probably look around me, enjoy the scenery, because you can't really appreciate the scenery around you when you are driving yourself." (No.12, female, age 73)
"I think we can do something beneficial, like a kind of meditation, breathing exercise."(No.3, female, age 81)

Working

Some older drivers said they would like to work in the highly automated vehicle, such as working (n=2, 2 male), For example:

“If I was going to a business, maybe preparing, I think you could send emails or texts.”(No.11, male, age 78)

Monitoring driving

Half of the participants (n=12, 5 female, 7 male) mentioned that they would still like to monitor the HAV system driving to make sure everything is fine, especially in heavy traffic conditions. For example:

“I would still like to keep an eye on the road, I just think I need to make sure everything is OK.”(No.22, female, age 60)

“I would probably be watching the car driving at first, and then if it was not busy traffic. I’ll probably watch an iPad or read newspaper.” (No.14, male, age 65)

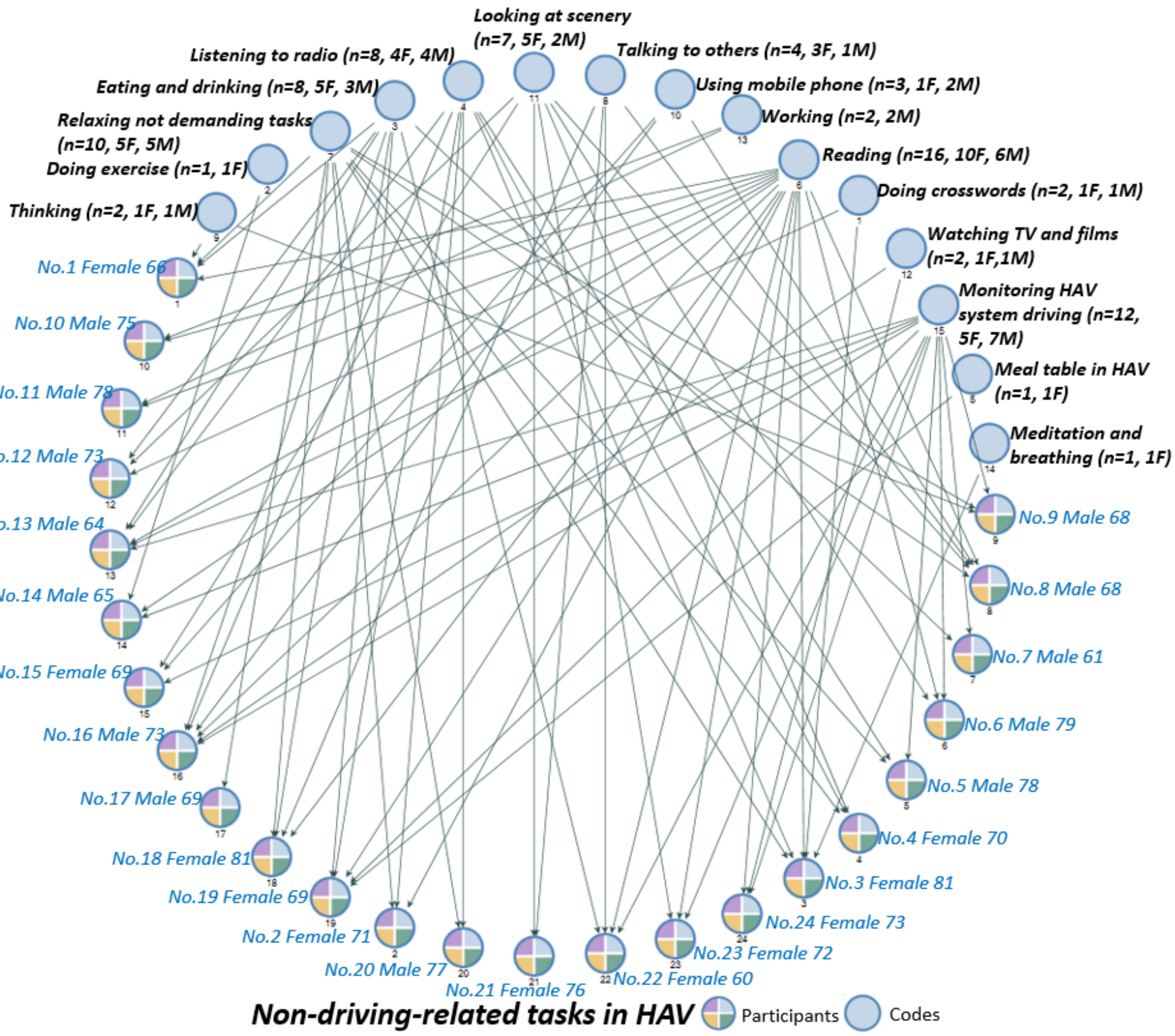


Figure 6.8 Coding map of theme four, F=female, M=male

Eating and drinking in the HAV

In addition, a large proportion (n=8, 5 female, 3 male) of older drivers expressed a wish to eat and drink in the HAV. For example:

"If it's allowed to eat and drink, that would be brilliant, at the moment it's illegal, isn't it. But if you could actually have a cup of tea or whatever, that would be nice." (No.7, male, age 61)

"If I could be having my lunch or a cup of coffee in the car, I don't need to stop at the motorway service station." (No.13, male, age 64)

"I may not have lunch in my HAV, cos I don't like my car in a mess, but I would have a piece of food, a chocolate bar, something like that."(No.12, female, age 73)

One female older driver mentioned that a meal table would make eating and drinking more convenience in the HAV.

"If I am hungry I may have a slice of bread. I may not drink tea of coffee cos I don't want to spill anything on my car, you know I hate cleaning up spills, unless there is a table in my car, like the one on a plane." (No.19, female, age 69)

6.3.5 Theme five-Human-machine interaction during automated driving in HAV

In addition to the non-driving-related activities that older drivers prefer to undertake instead of driving in the HAV, the fifth theme was about what they expected the HAV to do in terms of interacting with the driver during automated driving. Generally, their requirements towards the human-machine interaction during automated driving were grouped into two categories. Firstly, they would like an information system in the HAV to keep them updated about what is happening when they are disengaged from driving. Secondly they require the HAV system to be able to monitor on their status to ensure safety. In addition, the type of information they would like the HAV system to inform them, and the preferred form and modality of the feedback were also discussed.

Information system in the HAV

A majority of participants (n=21, 12 female, 9 male) expressed a requirement that they would like the HAV system to inform them about what is happening to keep them updated when the HAV is automated driving. The types of information they would like the HAV to inform them include journey (n=7, 3 female, 4 male), vehicle status (n=7, 2 female, 5 male), traffic conditions (n=4, 1 female, 3 male). For example:

"I am going to somewhere 150 miles away. I'm reading the morning paper. And time passes, I would love it if the HAV said to me: we'll be there in five minutes, so you can put your tie on, neat and tidy, comb you hair when you get it. I would like to be kept updated on where the car is, how much time we got left before the end of the journey."(No.6, male, age 79)

"I need the car to tell me what it is doing if I am not watching it, just basic information would do, like speed, journey time."(No.9, male, age 68)

"I presume, for automated vehicles, there will be some sort of alarm or something to say fuel is low, so we are not gonna get there without fuel then so we need to refuel within the next half an hour, which would be great." (No. 13, male, age 64)

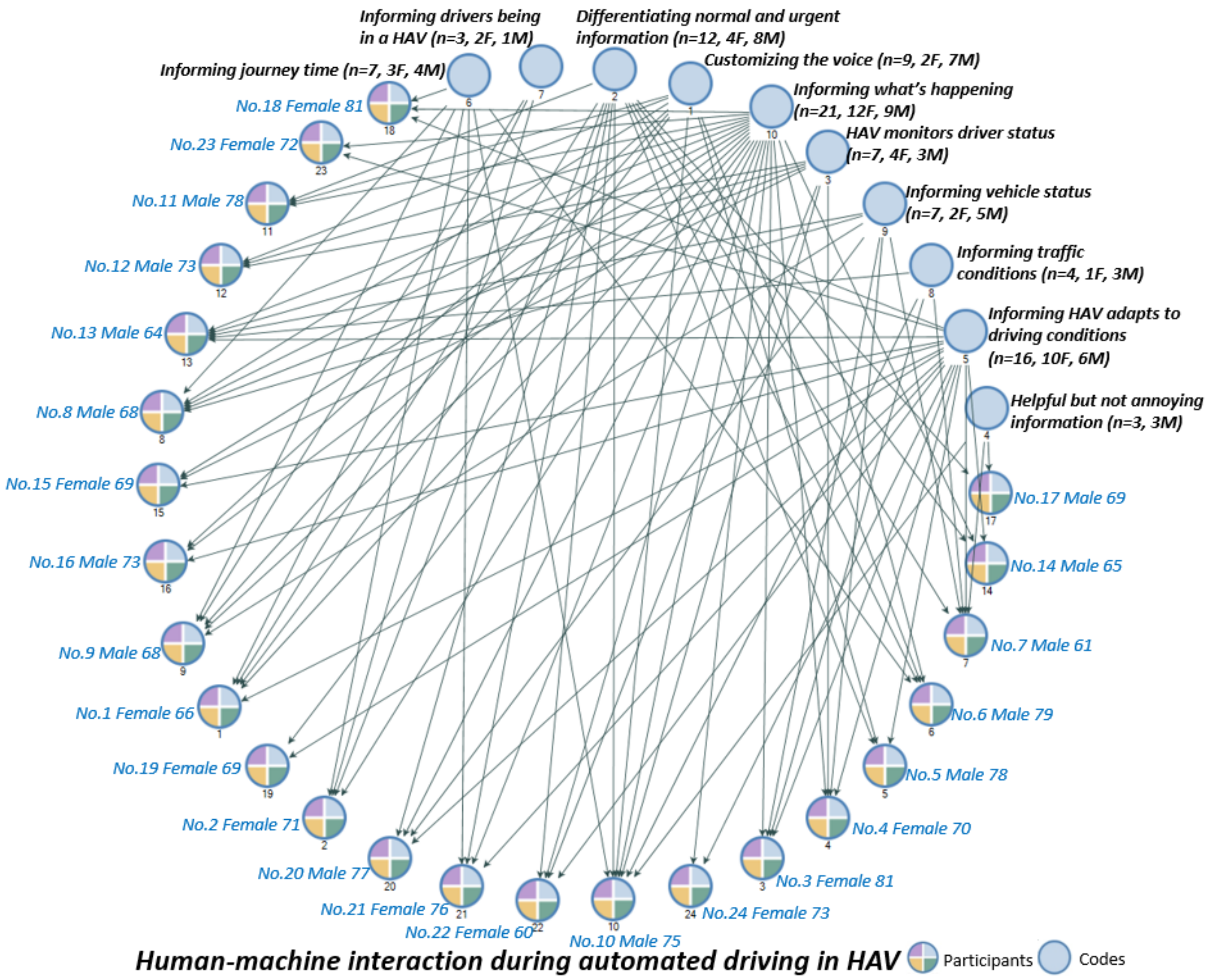


Figure 6.9 Coding map of theme five, F=female, M=male

In addition, some participants (n=3, 2 female, 1 male) mentioned that some drivers may forget they are in the HAV when they are not driving. Consequently, this may pose a safety threat when it comes to the situations when the drivers' input is required. Therefore, the HAV system should remind the drivers that they are in an automated car when they are not driving. For example:

"It worries me that some people may forget they are sitting in an automated car if it's too cosy, they may think they are in the living room and doze off."(No.8, male, age 68).

In addition, the majority of participants (n=16, 10 female, 6 male) stated a strong need that their HAV should inform them that it is adapting the way it drives to suit the conditions it is driving in, especially when driving in adverse weather conditions. For example:

"I want to know that the vehicle knows, and I would like some kind of display that let me know the vehicle knows it is very foggy. So I want to know that the vehicle knows it is the one definite thing."(No. 1, female, age 66)

"I would want to be very sure that the car has adapted to the degree of penetration into the bad weather conditions, and was it adjusting its braking for wet and slushing conditions? I want it to say: Hey it is little bit slippery, just gonna slow down a little bit." (No.5, male, age 78)

"I suppose the car is advanced far enough to know what to do in situations like snow and fog. I want to know the car knows, the electronic brain knows. If it lets me know, that will make me feel a lot better. (No.16, Male, age 73)

Monitoring system in the HAV

Apart from the requirement of requiring the HAV to keep the drivers updated, some older drivers (n=7, 4 female, 3 male) indicated that the HAV should be able to monitor their status and take action accordingly. A common concern was that the driver falls asleep and may not be able to response to an emergency promptly and effectively, such as to a takeover request. The HAV system, then, should be able to detect this and warn the driver, such as by an additional alert, a higher-volume alert or a vibration alert.

"It could be useful if the system knows what you are doing, for example, if it knows I am going to sleep, maybe then it knows that the volume needs to go up to wake me up, or it gonna to send some vibration to the seat." (No.22, female, age 60)

Form and modality of the feedback

In terms of the form and modality of the feedback of HAV system, a great number older drivers (n=12, 4 female, 8 male) indicated that they generally wanted to differentiate between modalities of normal and urgent information.

"I think it probably would be a screen showing everything that happens. For the urgent messages, it should be both visual and auditory." (No.2, female, age 71)

"For the less important information I would like it to be shown on a display, such as how far is it to the journey destination, or the current speed. But for important information I want it to be audible, for example, for fuel or a take-over request." (No.14, male, age 65)

"The sort of messages that are not crucial to the car's safety, such as where you are, how far you are from the destination, why it takes a different route. Pleasant soft voice for that. But if we've got a problem here, it needs to be a loud, clear and straightforward voice. There should be an emergency voice and a routine voice." (No.5, male, age 78)

Some participants (n=3, 3 male) also mentioned the form of the driver feedback in the HAV should be able to draw a balance between being annoying and being helpful. And it should minimise false alarms to avoid "crying wolf".

"You got to draw the balance between being over-annoying and being helpful. If it's so annoying, you may not pay enough attention, oh here it goes again, and here it goes again. In England we have thing called 'crying wolf'." (No. 17, male, age 69)

Regarding the voice of the HAV system, more than one third of the participants (n=9, 2 female, 7 male) showed a desire to be able to customize the voice to fit individual requirements.

"It would be good if I can customize the voice, because it might be an irritating voice." (No.8, male, age 68)

"I think it is very import to customize the voice of the vehicle because I have a satellite, the voice I could pouch her, I just want her to be somebody else. It is important because if you have all of that, and all sort of messages and things, the voice that you hear has to be friendly and something that you like (No.1, female, age 66)

6.3.6 Theme six-Human-machine interaction during taking over control in HAV

The sixth theme focuses on the older drivers' requirements towards the human-machine interaction during taking over control in HAV centred on the takeover request as well as the lead time provided for takeover in the HAV. In general, they would like the takeover request to be adjustable, explanatory and hierarchical. The coding map of this themes was displayed in Figure 7.10. It shows the codes that this theme has and which participants' script each code was coded from.

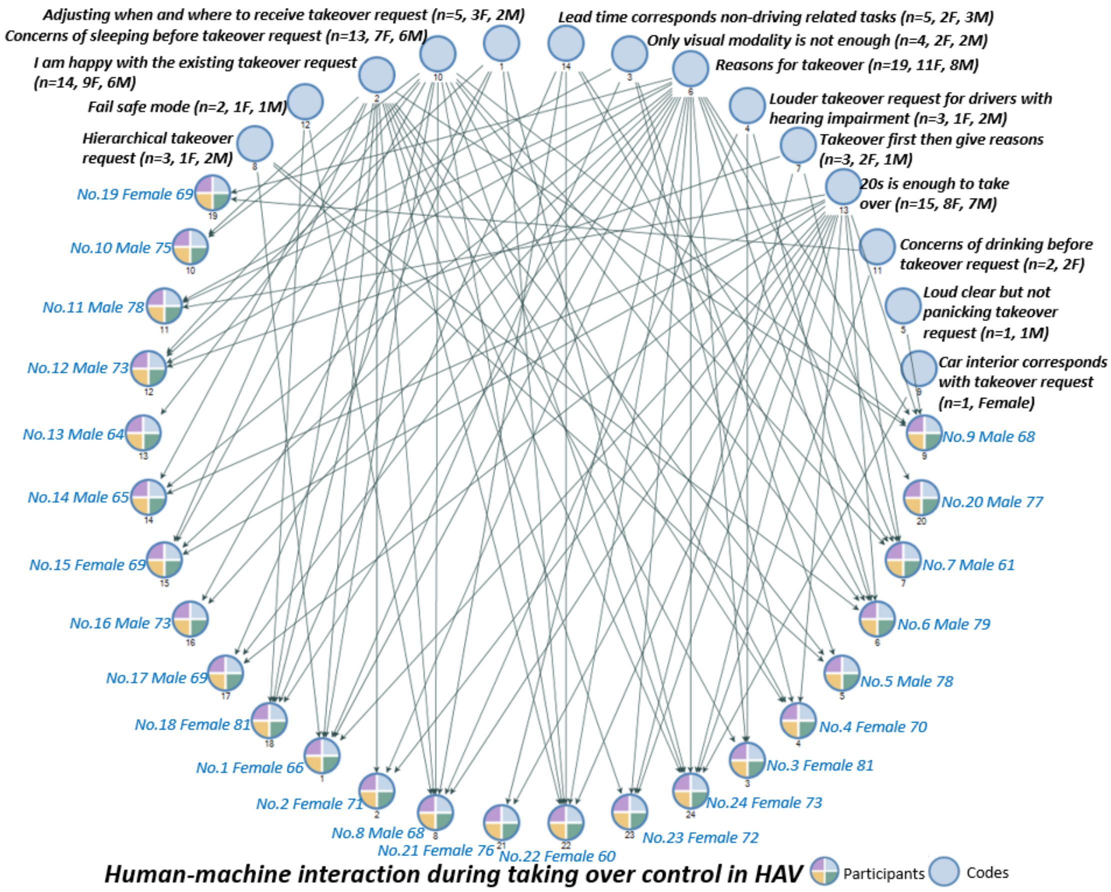


Figure 6.10 Coding map of theme six, F=female, M=male

Takeover request in the HAV

To begin with, some older drivers (n=5, 3 female, 2 male) expressed a desire that, apart from receiving the urgent takeover request which the HAV encounters a system limitation and relies on the drivers to take over control, they would need to be able to adjust when and where the HAV sends them take over request according to their preferences. For example, to enable the HAV to always send drivers take-over requests when driving on familiar routes, or when it comes to the pre-defined situations that the HAV detects the traffic and weather conditions are suitable to drive manually for the drivers.

"I am happy to let the car drive on unfamiliar roads, but it should remind me to take over when it drives in the places I'm familiar with." (No.17, male, age 69)

"I do want my automated car to tell me when it is the best time for me to drive. Maybe when it detects the weather and traffic is suitable for me."(No.4, female, 70)

The majority of the participants (n=14, 9 female, 6 male) evaluated the existing visual and audible takeover request in the current research as nice and effective. Some participants (n=4, 2 female, 2 male) indicated that if the takeover request only has the visual message, that would not be considered as satisfactory. It should include a loud and clear but not panicking audible message. In addition, three participants mentioned that a louder takeover request would benefit the older drivers who suffers hearing impairments. Moreover, the majority of the older drivers (n=19, 11 female, 8 male) showed a strong requirement that the takeover request should include the reason for taking over. For example:

"I think it would be useful to tell you why you need to take-over, then you know you got to be prepared for, because obvious take over control means there is something ahead, which could be bad weather, bad visibility, stationary vehicle, person, it is good if it gives you a hint, because if otherwise you will be thinking I don't know what it is." (No.11, male, age 78)
"It says 'please take over' and you look up and you wonder um, boom, you hit something. Because it didn't tell you or indicate the severity of the reason why it wanted you to take over."(No.6, Male, age 79)

"If the car's driving down the road and tells me to take over, my eyes would go everywhere, everywhere at the same time, why did it tell me to do that? If the car said to me I am very tired, please take over, you drive for the next half an hour, now the car has given me a reason for wanting me to take over."(No.20, male, age 77)

And some older drivers (n=3, 2 female, 1 male) also emphasized that the sequence is important, where the takeover request should inform the driver about taking over control first and then explaining the reason.

"The first think I would say is you need to take over the car, then, once the person has taken over, then give the reason, cos you don't need to know the reason immediately, you need to know immediately take over." (No.12, female, age 73)

Another requirement highlighted concerning the takeover request that older drivers expressed (n=3, 1 female, 2 male) was that the HAV should adopt a hierarchical take over request mechanism based on how urgent their input is needed. For an urgent takeover request, such as when encountering a system limitation, the visual message could be in red, and the voice message should be clear, serious and straightforward. For non-urgent takeover requests, such as a user's predefined takeover request on familiar routes, the visual message could be in green and the voice message could be relaxed and soft.

"If it's a predefined one in familiar places, it could be a soft voice. If it is an emergency, like the red car in the front, I would expect a more serious and excited voice "XXX, take over the bloody car now!" It would have to be short and clear." (No.6, male, age 75)

"It could be a hierarchical thing, it could be a message come up in red, yellow or green to give you an idea how serious it is, if it comes up in red, you got to do something now. If it comes up in green, you know it's not very urgent." (No.1, female, age 66)

One older driver indicated that the screen for performing non-driving related tasks, should be shut down or moved away from the driver automatically following an urgent takeover request. More than half of the older drivers (n=13, 7 female, 6 male) showed a concern that if the drivers fall asleep they may not be able to respond to the takeover request safely and effectively. And one participant indicated that HAV should adopts a fail-safe mode to ensure safety when the driver fails to take over the vehicle control effectively.

Lead time for takeover control in HAV

In regard to the time needed to take over control, older people in general, believed it varies between individuals. The majority of the participants (n=15, 8 female, 7 male) thought that the 20 seconds used in the current research was generally adequate and comfortable for taking over the control of the vehicle. In foggy situations, a longer time than 20s could be better for them.

"20s is quite a long time, better than 10s. I mean 20s gives you the time to feel the car. I think 10s may give you enough time to get the hold of the wheel, but not feel the car." (No.9, male, age 68)

"I found the 20s is an adequate time, it was only once when in the fog, it just seemed to be hard, but for the rest of the times, I felt pretty comfortable with it. (No.11, male, age 78)

In addition, some older drivers (n=5, 2 female, 3 male) believed that the lead time needed depends on the non-driving related tasks the drivers were doing. And they indicated the requirement that the HAV should monitor what the drivers are doing during automated driving and adapt the lead time to take over control accordingly. They suggested that a longer lead time to take over control would be necessary if the driver had fallen asleep or their hands were occupied.

"20 seconds might be enough. But it depends on what the person's doing, if they are sitting there, reading a book, chatting on Facebook, then 20s is long enough. But if they are doing something more complicated and personal, such as dozing or sleeping, 20s might not be long enough." (No.6, male, age 79)

"20s is enough unless you got a hot cup of tea and sandwich in your hand. It depends on what you're doing. Even 10 seconds is fine if you're only sort of sitting and watching scenery. But 10 seconds isn't fine if you got a hot cup of coffee in one hand and a bite and pint in another." (No.7, male, age 61)

6.3.7 Theme seven-Driving style of HAV

The last theme of older drivers' requiems towards the human-machine interaction of HAV is driving styles of the highly automated vehicles. The coding map of this theme is illustrated in Figure 7.11 which shows the codes that this theme contains and which participants' script each code was coded from.

Imitative and corrective driving style of HAV

Nearly half of the older drivers (n=11, 4 female, 7 male) in this study indicated that their HAVs should be able to adapt their driving style to "drive like them", which would make them feel more assured and comfortable.

"If the computer can learn from me, in the way I normally think under varying road conditions and re-adjust itself, which would be brilliant."(No.6, male, age 79)
"It would great if it's driving like you're driving, it's imitating you. Adapting to my driving style."(No.12, female, age 73)

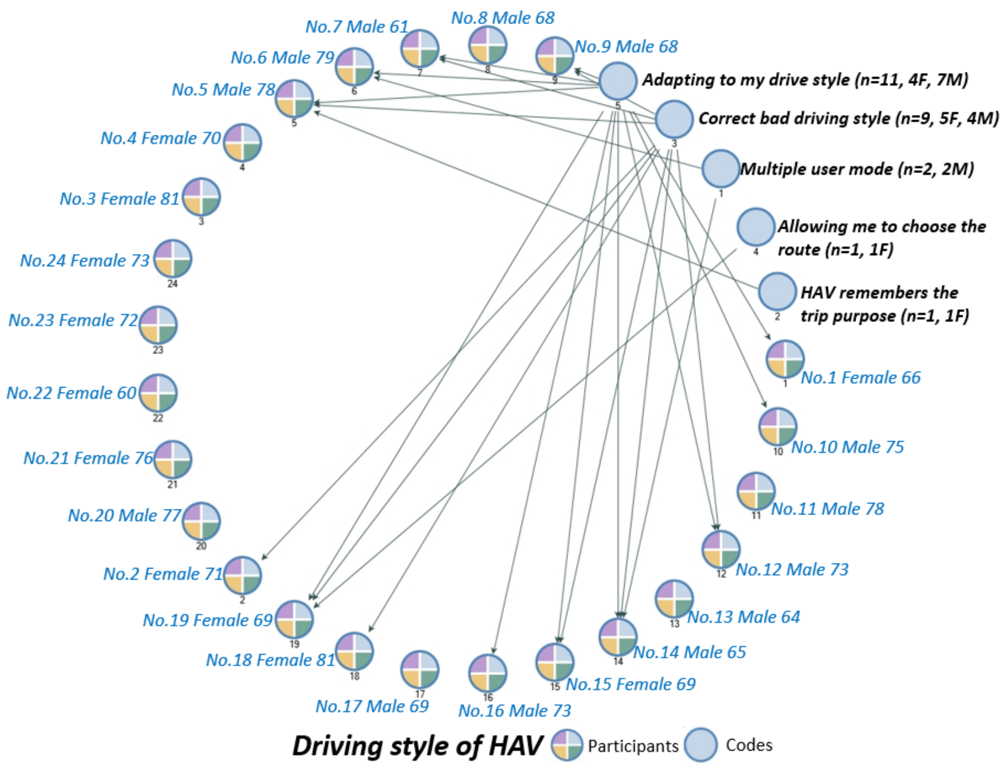


Figure 6.11 Coding map of theme seven, F=female, M=male

Some other participants (n=9, 5 female, 4 male) realized that they have poor driving habits, and were concerned that these bad habits maybe copied by their HAV. But they still liked the idea of their HAV driving like them. Therefore, they pointed out that their HAV should be able to adapt to their driving style as much as possible but correct the bad driving habits. For example:

"The HAV system might have to be able to differentiate between good and bad. For example, if it realizes that I tend to brake more gently and a little earlier, it would be good if it adapted to that habit. It wouldn't be good if I drove right up to the car in front and slammed down the brakes. So it needs to be able to make a judgement on what is better than the standard and adjust it that way." (No. 5, male, age 78)

"I've got bad driving habits same as everybody else. That would be brilliant if my automated vehicle drives like me but corrects the bad habits, I wish it could." (No.9, male, age 68)

Multiple user mode

Two male older drivers suggested that the driving style of HAV should be able to adapt to different users. It should be allowed to have multiple user mode.

"If you had a highly automated car, then anyone could drive it, so how would it adapt to different drivers? If it drove like you. And I got into your car, and it drove like you, would I be happy? So it should have a "host mode" which is your mode, "guest mode" would be someone else's mode. (No. 14, male, age 65)

Remembering journey purpose

In addition older drivers also staged that they would like the HAV to remember the purpose of the trip (n=1, 1 male).

"It would be brilliant if the AV can remember the purposes of the trip, for example, if it can remember every Monday I am going for shopping, it could remind me of buying something that would make me feel more independent."(No.5, male, age 78)

Optional journey routes of HAV

One older driver mentioned that she would like to be able to choose the route of the journey (n=1, 1 female).

"When you get into an automated car. You will say: right, I am going somewhere, and you put in the postcode, so whatever it is where you going. Then the car asks you that we will go the pretty way, will go the fast way, will go whichever the way it is, and it will take us extra number of minutes, have a nice day kind of thing." (No.19, female, age 69).

6.4 Discussion

This investigation aimed to provide understanding of older driver's opinions towards the HAV and outlined their requirements towards the human-machine interaction of the HAV. Seven key themes were identified by semi-structured interviews.

In terms of their self-reported driving behaviour. Generally, the older drivers in this research believed that they drove more safely and much more cautiously than others. This is in line with previous findings which indicate that the main issue with younger drivers is risk-seeking and lack of skills, but older drivers have the strength of being cautious drivers (McGwin Jr and Brown, 1999).

The present study has found that the first-hand experience of interacting with an HAV plays an important role in facilitating older drivers in building a realistic and spontaneous understanding of and improving trust in HAVs. The abundant information about older drivers' requirements provided by this research may also be credited to the first-hand experience, which has been proven to be effective in helping participants deepen their understanding and develop a more critical perspective of the subject (Davies and Lam, 2009). These findings are in line with those of Eisma et al. (2003), who reported that first-hand experience can enable older people to clearly understand the possibilities of technology more than with a verbal explanation or demonstration. In summary, these findings provide evidence supporting the necessity of providing sufficient 'test-drive' opportunities for the older drivers to help them to gain their first-hand experience towards the HAV.

In respect of opinions towards HAV, in general older drivers were positive towards HAVs and believed that has potential to improve their quality of life. Their perceived benefits of HAV on their lives are mainly focused on improving their mobility. This corresponds to the fact that maintaining mobility is a privilege for older drivers, and is invaluable for their independence, quality of life and wellbeing (Charlton et al., 2006; Levasseur et al., 2016). Older drivers perceived that HAV would enhance their mobility in helping them to drive long-distance journeys and in adverse weather conditions, which are common examples of the challenging situations that older drivers avoid in their driving self-regulation (Charlton et al., 2006). Moreover, the older people also indicated that they would prefer to use a HAV to extend their mobility at the moment, but they would like to use a FAV to help them to stay mobile when they were not entitled to drive any longer due to their physical and mental capacities. This finding was in accordance with those of Bellet et al. (2018), who reported that older drivers were interested in vehicle automation and would consider using the FAV in the future when they were not able to drive safely anymore. These findings pointed out the importance for the OEMs and policy makers to distinguish the different requirements between those older people who are still active drivers and who have already given up driving. For example, the Level 3 or 4 HAV with good manoeuvrability that still allows the drivers to enjoy the pleasure of manually driving may be more easily adopted by some older active drivers, while for those who have ceased driving, a complete driverless car may appeals to them as it may help them to fulfil their daily travel demands and to maintain mobility.

In spite of the fact that older drivers perceived that their mobility could be improved by the HAV, this research has also found that they expressed a strong requirement to retain some physical and mental control over their HAVs. They indicated they still wanted to have the ability to manually drive the HAV, as driving is not only a lifelong habit for them but also creates a sense of control over their lives (Gabriel and Bowling, 2004). In addition, older drivers had a need to retain potential control of the HAV, and they expressed a need to know that they could intervene in controlling the vehicle at any time even they are not controlling the vehicle in HAV. This need for potential control is very close to the concept of potential travel proposed by Metz (2000), who reported that it is important for older people's mobility that they are aware that a trip could be made even if it is not actually undertaken. Considering the older adults who were active drivers when participated in this study, these findings provide an implication on a suitable way to introduce and explain the HAV to the older drivers. Instead of overemphasizing the 'self-driving' features of the HAV which may result in the misapprehension by some older drivers that their abilities of driving could be taken away, an appropriate standpoint to introduce the HAV to the older drivers may be a new type of vehicle that they can drive it exactly as a conventional vehicle but it can drive for them under the circumstances that they do not feel like to or are not able to drive in.

In terms of the non-driving related tasks in HAVs, the current research has found that some older people would like to perform tasks that allow them to relax but do not require massive attention, including reading, communicating with family/friends in the car, listening to the radio, looking at the scenery and monitoring the system driving. Among these activities, reading, communicating with family or friends and listening to the radio are also the most common activities that older people reported as doing in their free time (Seddon, 2011). In addition, previous research into HAVs involving older drivers yielded a similar finding that older drivers tended to spend their time having conversations with other people during automated driving in HAVs (Clark and Feng, 2017). Moreover, older drivers showed a desire to eat and drink (tea or coffee) in the HAV. In general, these requirements should be taken into account when designing the interior of the HAVs. For example, a compact bookshelf or a tablet dock could be provided for the convenience of those who want to use one, and a rotatable seat may allow older drivers to talk with family and friends without constantly turning their head; A panorama windscreen could also enhance their experience while monitoring driving or looking at the scenery, and a foldable meal table may help them better enjoy their food and drink during automated driving.

While performing relaxing non-driving activities during automated driving, this research found that older drivers would still like to know what the HAV is doing. They desired the HAV system to provide them with information about the journey, vehicle status, traffic conditions and road conditions when they are disengaged from the vehicle. Most importantly, they needed to be informed that the HAV is adjusting its driving to adapt to the conditions it is driving in, especially in adverse weather conditions. This need may partially arise because the HAV is a new system which has yet to be introduced in road traffic and older drivers had spent only a limited time interacting with it, and so they may still want to be updated to make sure that everything is fine. From another point of view, this could also be deemed as a need for potential control of the HAV among older drivers, reflecting the fact that they need to know the HAV is doing exactly as they expected and nothing is beyond their mastery even they are not driving the car themselves. This emphasizes the importance of the sense of self-mastery and control over life to older people's wellbeing (Gabriel and Bowling, 2004). In addition, a driver feedback system has been identified as being useful in improving older drivers' safety in manual driving (Guo et al., 2010a), and thus it may also have potential to enhance older drivers' performance when interacting with the HAV.

Together with the need of the driver for feedback, this research also found that older drivers would expect the HAV to monitor them to keep track of their status and to take action accordingly. The older drivers explained that the major reason for this was that they worried they may not be able to react in time in cases of an emergency, for example if they fell asleep in the HAV. A possible reason for this requirement could be because older drivers have a stronger awareness of the danger of the driver's sleepiness and they are less likely to drive while sleepy than younger drivers (Obst et al., 2011). When monitoring the sleepiness of the driver, the older drivers expected that the HAV should be able to issue an alert with a stronger stimuli, such as a voice at higher volume or vibrations in the seat. Also there should be a safe mode if the driver fail to respond appropriately.

In terms of the form and modality of the system feedback, this research found that older drivers needed different modalities for normal as opposed to urgent information. In addition, the older people indicated that the system feedback should strike a balance between being irritating and useful. Normal information, such as road status and speed, should not be reported too frequently. These findings are generally in line with those of previous research that has reported that visual combined with audio modality is recommended when designing in-vehicle systems for older drivers (Edwards et al., 2016).

Regarding the taking over of control in the HAV, this research highlights that the older drivers believed that taking over control in the HAV was an advantage rather than a drawback, as it would still allow them to manually drive the vehicle and remain active drivers while enjoying automated driving when needed. This is in line with the results of research in other fields which has identified that older people prefer to receive support and assistance without compromising their control over their lives (Burton, 2012). In addition, apart from receiving take over requests when HAV encounters system limitation, the older drivers indicated a strong need to be able to adjust in advance when they receive a TOR from the HAV, especially when on familiar roads or when traffic or other conditions are suitable for them to drive.

Regarding the form and modality of takeover requests, this research found that older drivers had a strong requirement for including the reason for taking over in the take-over request itself. Engaging in non-driving related tasks may result in the driver's complete disengagement from driving , which would lead to a longer take-over time being needed and possibly worse take-over quality among drivers (Eriksson and Stanton, 2017; Zeeb et al., 2017). Therefore an explanation of the reason for taking over control may have the potential to facilitate a quicker and more effective take-over. Apart from the reasons for take-over, older drivers had a requirement for a hierarchical system of take-over requests that would differentiate between urgent take-over situations and non-urgent situations. Moreover, older drivers also indicated that the specially designed car interior features for performing non-driving related tasks should be coordinated with the TOR to ensure the safety and efficiency of the take-over. For example, following an urgent take over request, the tablet should be turned off or moved away from the driver automatically; or the rotatable seat should turn back to the driving direction if the driver was facing to the back talking with other people in the car. In terms of the lead time for taking over control, the older drivers thought that 20 seconds would generally be enough. However, they indicated that the lead time should be variable to adapt to different driving environments or the driver's status.

Finally, this investigation found that older drivers had a specific requirement in terms of the driving style of their HAV. They would like their HAV to drive like them as much as possible, but it should only adopt the good driving habits and correct bad driving habits. This could be a reflection of one of the older drivers' strengths of being cautious divers (McGwin Jr and Brown, 1999). Additionally, they believed that the HAV should have multiple user accounts as to accommodate different people's driving styles and preferences.

6.5 Conclusion

The aim of the interview investigation has been to investigate older drivers' opinion and requirements concerning human-machine interaction in HAVs. The key findings were:

- Older drivers indicated that they like driving and they drive slow and cautiously.
- The first-hand experience of interaction with the HAV on the driving simulator is useful to help older people to build in-depth understanding about the HAVs, and to enhance their trust and confidence.
- Older drivers had positive opinions towards the HAV. They were able to perceive the potential benefits of HAV in enhancing their mobility, especially when driving on long journeys, motorways, in adverse weather conditions and on unfamiliar roads.
- Older drivers currently preferred highly automated vehicles to help them to drive longer and safer. When they have to give up driving, they would prefer to use a fully automated vehicle to stay mobile and independent.
- Older drivers prefer to remain active drivers, and they want to retain physical control of the HAV. Besides, they need to perceive that they have potential control in HAV, which means knowing that they would be able to intervene and take over the control back at any time when the HAV is driving automatically.
- When older drivers are completely disengaged from driving in the HAV, they would like to perform a variety type of non-driving-related tasks, including relaxing tasks such as listening to radio, reading, looking at scenery, talking with others, using mobile phone, watching TV and movies, doing exercise, thinking, and mediation and

breathing; other tasks including working, doing crosswords, monitoring HAV driving, and eating and drinking.

- During automated driving in HAV, older drivers need the HAV systems to keep them updated about what is happening and to inform them about their journey, vehicle status and road conditions. Essentially, it should inform them that the HAV was adapted its driving to suit the conditions it is driving in. Additionally, older drivers need the HAV system to monitor the driver's status and to take action accordingly. The modalities of system feedback should differentiate between normal and urgent information.
- During the take-over control process in the HAV, older drivers need to be able to adjust when and where to receive takeover requests. The takeover request should include a description of the reasons for take-over. Also, the modality of the takeover request should be hierarchical, based on how urgent the takeover situation is. In addition, specially designed car interiors should coordinate with the takeover request to ensure a safe and effective takeover. Twenty seconds is considered a long enough lead time for older drivers to take over control of the HAV, but it should be adapted to weather conditions and the driver's status.
- The HAV should be able to adapt to the driver's driving style, but only safe aspects of the style, while correcting dangerous ones. And the HAV should allow the drivers to choose the routes and remember the purpose of the trips.

The findings of this investigation provided evidence showing the semi-structured interviews have been an effective way to collect information of the requirements of HAVs from the end-users such as the older drivers. Older drivers expressed a range of needs and requirements towards the human-machine interaction in the HAV. In general, they believed it should be designed to be friendly and helpful. Most significantly, it should be designed to be smart and adaptive to offer tailored solutions based on various traffic, road and weather conditions as well as driver status. Above all, the HAVs that older people required would be automated cars that would enable them to drive safely for longer, facilitate comfortable driving, and ultimately maximise their independence and mobility, rather than being a new vehicle that simply took away their ability to drive. Finally, the findings of this investigation emphasize the necessity to consider the needs and requirements of the ageing population during the design process of new in-vehicle technologies and vehicle automation systems (Guo *et al.*, 2013a). If the HAV can be designed to be age-friendly, then the potential advantages to older drivers and their subsequent enhanced mobility, independence and freedom could have profoundly positive effects and implications for society and the economy. The implications of the findings of this interview investigation to inform OEMs and policy makers in relation to forthcoming roll-out of HAV are summarized in Chapter 8.

Chapter 7. Evaluation of Effect of Human Machine Interfaces (HMIs) on the Driver's Performance when Taking Over Control in HAVs

7.1 Introduction

The review of literature in Chapter 2 showed that limited research has considered older drivers' needs and requirements in the design of HMIs in HAVs. In addition, the findings from Chapter 4 and 5 have provided a clear indication that the HMIs in HAVs should take into account older drivers' capabilities and requirements in order to better support their interaction with HAVs. Moreover, the findings of Chapter 6 yielded clear requirements among older drivers in terms of the design of the human-machine interaction in HAVs. Therefore, it is important to develop knowledge in terms of incorporating older drivers' requirements into the design of HMIs in HAVs and evaluation of the effect of these HMIs on drivers' takeover performance, considering if this is good design for older drivers it is good design for all. Such knowledge is important in facilitating a safe and comfortable human-machine interaction in HAVs for older drivers.

In order to address the above research gap, this chapter details the third driving simulator investigation that aimed to address two key areas; firstly, to implement older drivers' requirements into the design of the HMIs in HAVs and then investigate the effects of these HMIs on older driver's takeover performance, the perceived workload and subjective attitudes; and secondly, to further examine the effect of age on the drivers' takeover performance.

7.2 Method

The justification and selection of the main methodologies for using the driving simulator, the design of HAV scenario, and the selection of dependent variables in this research is provided in Sections 3.2 and 3.3. This investigation used the same participants as in Chapters 4 and 5, and the participant recruitment process has been discussed in see Section 3.3.7. Their demographic characteristics and annual mileages have been highlighted in Section 4.2.5. This section details the explanation of the design of three HMIs based on older drivers' requirements, as well as the experimental design and procedure of this investigation.

7.2.1 Design of HMIs based on the requirements of older drivers

The usability and safety of in-vehicle systems are closely associated with the design of HMIs in these systems and it is important for the design of HMIs to enable the users to feel safe, confident and comfortable when interacting with them (Stevens, 2000). Chapter 6 has yielded a wide range of requirements among older drivers concerning a variety of aspects of the human-machine interactions in HAVs (see Section 6.3 for detail). However, due to the limited timeframe, resources and budget, testing all the requirements yielded in Chapter 6 is not practicable for this study. Therefore, this study decides to focus on testing two important requirements raised by older drivers as follows:

- Informing drivers about the reasons for takeover in the takeover request in HAVs.
- Providing drivers with information about their journey, vehicle status and road conditions when they are disengaged from driving during the automated driving process in HAVs.

Following a mapping exercise, these two requirements were chosen because they were the two most frequently stated requirements among older drivers (see Section 6.3). More importantly, they correspond to the two most important human-machine interactions in HAVs- the takeover control and automated driving processes. In order to test these two requirements, they would be integrated into the design of the HMI in the HAV. As Figure 7.1 indicates, the existing HMI in the HAV of this study is a visual and audible takeover request. The Baseline HMI was used to refer to this original design.

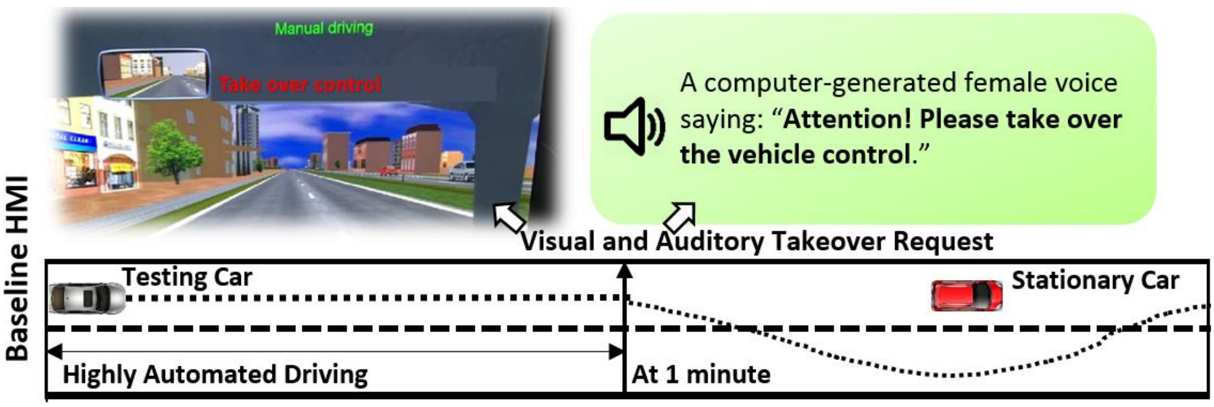


Figure 7.1 Illustration of the Baseline HMI in the HAV.

7.2.1.1 Design of the R HMI

In terms of the first requirement raised by older drivers, the reasons for takeover in HAVs depends on the nature of the takeover, whether it is a driver-initiated or a HAV system-initiated takeover (see the detailed review in Section 2.3.2). The HAV scenario in this study adopted a HAV system-initiated takeover requiring drivers to perform collision avoidance manoeuvre (see Section 3.3.3.1). Therefore, the reason for takeover refers to a stationary red car suddenly appearing which blocked the driving lane. Such a reason was not mentioned in the Baseline takeover request of the HAV.

When integrating the reason for takeover into the existing baseline HMI, an important consideration is the sequence of the takeover control command and the reason for takeover. Some older drivers expressed a view that that there would be no point in the driver knowing what is in front of them before they have completely got the vehicle under control, therefore the takeover request should tell the driver about taking over control of the vehicle first and then explain the reason for requesting this intervention (see Section 6.5.2.), thus this requirement was built into the HMI. When the existing baseline HMI is followed by the indication of that there is a parked car ahead, a new type of HMI has been formed. An abbreviation of 'R HMI' is used to refer to this HMI, which is illustrated in Figure 7.2.

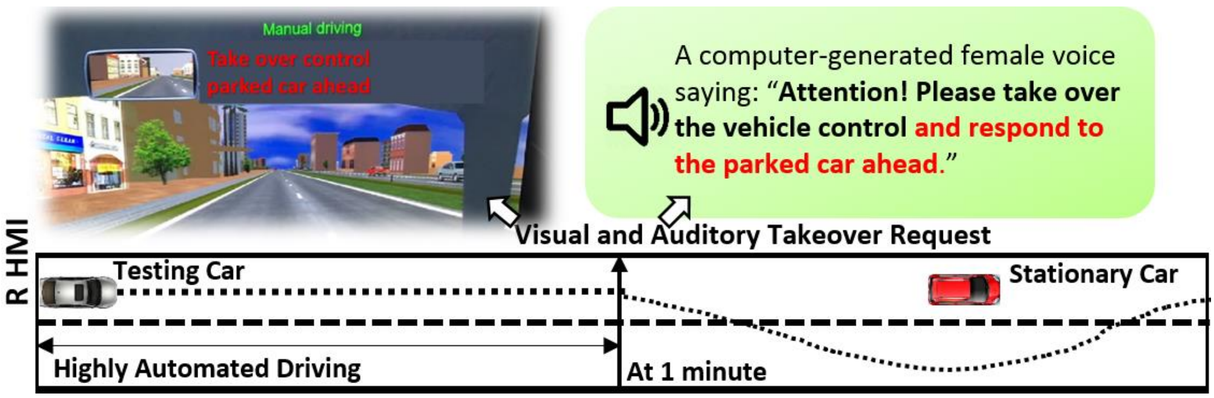


Figure 7.2 Illustration of the R HMI in the HAV.

7.2.1.2 Design of the V HMI

A second requirement from older drivers regarding the HMI was a strong desire to receive some information about their journey from the HAV when they are disengaged from driving while the HAV is performing automated driving (see Section 6.3.5). This requirement is also consistent with the findings of Chapter 4 and 5 suggesting that more assistance should be offered to drivers who are disengaged from driving during the automated driving mode in order to facilitate the safer and more effective takeover of control from the HAV. Therefore, this requirement would be tested by incorporating it into the existing HMI. The results in Chapter 6 indicate that there are three types of information that older drivers would like to be informed when they are disengaged from driving and the HAV is automatically driving the vehicle, these are: vehicle-journey time; traffic conditions and vehicle status (see Section 6.3.5).

When deciding which information should be included in HMI messages, there are several considerations. Firstly, in order to effectively test the newly designed HMI, it needs to correspond with the existing user-case of the HAV scenarios in this research. The HMI that provides the drivers with journey time during the automated driving may be suitable to be evaluated in the HAV scenarios that simulates long-distance journey with the HAV. Since the current user case of the HAV scenarios in this research allows the drivers to have a relatively short duration (one minute) of automated driving before asking them to take over the control of the vehicle. The inclusion of journey time in the design of the HMI was not considered in this investigation, which represents a limitation of this study and has been highlighted in Section 9.3 to enlighten future research. Similarly, providing drivers with traffic information may be suitable to be tested in scenarios where the HAV is driving in busy traffic. However, in order to minimise the impact of extraneous factors on the drivers' performance, in the existing HAV scenarios used in this study, there is no other traffic, apart from the car which represents the HAV and the stationary red car on the lanes in the direction of driving. Therefore, this requirement was not considered in this study either, nevertheless it could be tested in future research. The second consideration for designing the HMI was that the information provided by the HMI messages during automated driving should have the potential to improve the drivers' takeover performance. Endsley and Kiris (1995) suggested that providing information about the current status of the system has the potential to enhance operators' situation awareness and thereby would benefit their performance. And the information of vehicle status of study is the car is highly automated driving at 30mph or 60mph at the time when drivers were disengaged from driving. Such information is used as indications of the status of the HAV in the design of HMI in HAV.

In determining at which time the HMI should present this information to the drivers, an important consideration is that allowing drivers to be completely disengaged from driving is a key feature of HAVs (SAE, 2014; DfT, 2015c). Therefore, it is important to ensure that the time point when participants receive the information about vehicle status from the HMI, they should already have been completely disengaged from driving in HAVs. Endsley (1995a) argued that if the operator has been disengaged from the task for more than thirty seconds, they may hardly be able to recall the situation awareness information. Therefore, the information is presented after the drivers have been disengaged from driving task through performing a non-driving reading tasks for 50 seconds to ensure the status of completely disengagement from driving. The above considerations have shaped a new design of the HMI in HAVs. An abbreviation of 'V HMI' was used to refer to this HMI, as illustrated in Figure 7.3.

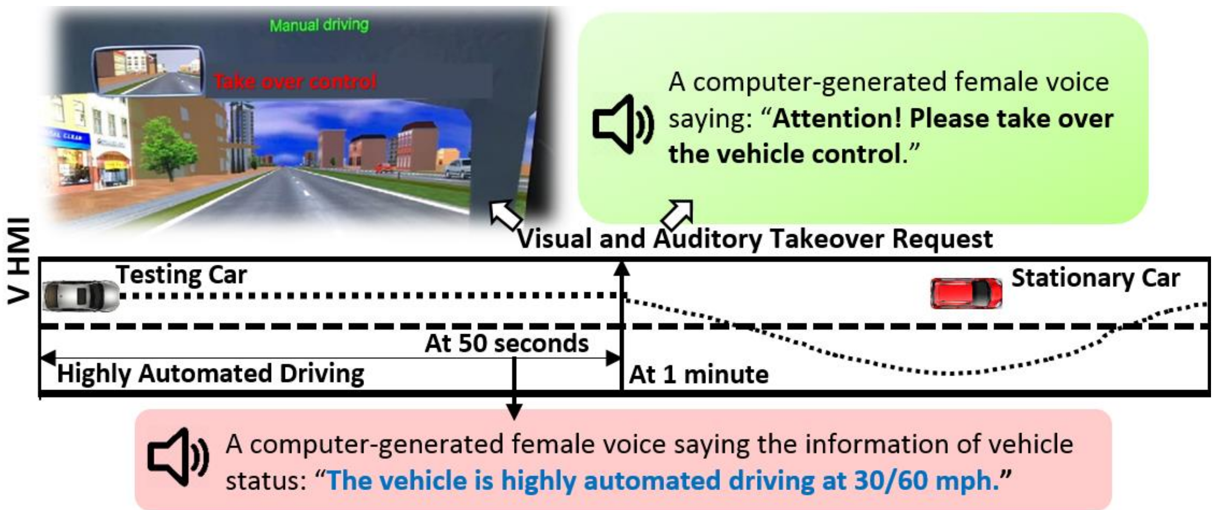


Figure 7.3 Illustration of the V HMI in the HAV.

7.2.1.3 Design of the R+V HMI

Finally, it would be worthwhile to design and test an HMI which fulfils both requirements to investigate if this has a more positive impact on user performance or not. Therefore, by combining the R HMI and V HMI, a new type of HMI that provides the reasons for takeover in the takeover request together with giving information about vehicle status was designed. An abbreviation of 'R+V HMI' was adopted to refer to this HMI, which is illustrated in Figure 7.4.

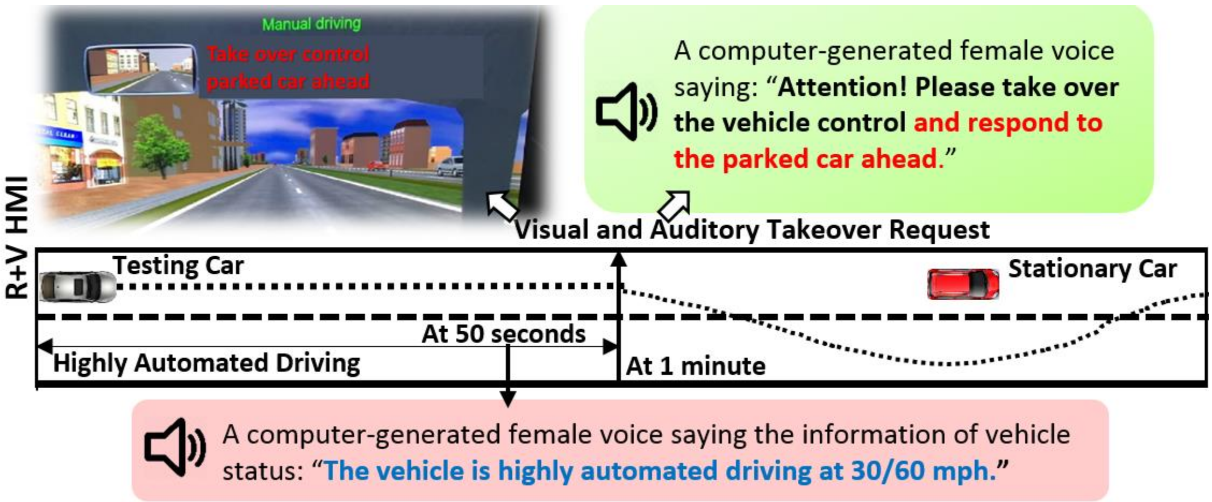


Figure 7.4 Illustration of the R+V HMI in the HAV.

7.2.2 Experimental design

According to the experimental considerations highlighted in Section 3.3.7, this investigation adopted a 2 × 4 between-and within-subjects mixed factor experimental design. The between-subjects independent variable is age (younger drivers, older drivers). The within-subjects independent variable is HMI type (Baseline HMI, R HMI, V HMI and R+V HMI). Each participant experiences all the types of HAV situations. In order to reduce the number of driving sessions for the participants, they were divided into two groups according to the type of road involved. An overview of the experimental design is displayed in Table 7.1.

Table 7.1 Experimental design overview

Between-subjects independent variables		***Within-subjects independent variable***
Age	**Road type**	**HMI**
Older drivers	City road	Baseline HMI, R HMI, V HMI, R+V HMI
Younger drivers	City road	Baseline HMI, R HMI, V HMI, R+V HMI
Older drivers	Motorway	Baseline HMI, R HMI, V HMI, R+V HMI
Younger drivers	Motorway	Baseline HMI, R HMI, V HMI, R+V HMI

Table 7.2 shows an overview of the dependent variables for this driving simulator investigation, they were reviewed in more detail in Sections 3.3.4 and 3.3.5.

Table 7.2 Overview of the dependent variables

	Dependent variables	***Unit***
Time aspects of takeover	Reaction time	s
Time aspects of takeover	Takeover time	s
Time aspects of takeover	Indicator time	s
Takeover quality	Time to collisions (TTC)	s
Takeover quality	Resulting acceleration	m/s^2
Takeover quality	Steering wheel angle	degree
Takeover quality	Hasty takeover	Count
Workload	NASA RTLX score	N/A
Attitude	7-likert scale score	N/A

7.2.3 Experimental procedure

- When the participants arrived, their driving licences were checked, and they completed the ethics form and the demographic questionnaire. The investigation was explained to them verbally.
- The participants were provided with considerable practice time to become comfortable with the simulator until they confirmed verbally that they were ready.
- The HAV scenario was explained briefly. The participants were told that they needed to put their hands off the steering wheel, with feet off the pedals and to read the material on the tablet out loud, that their performance in each driving session would be assessed, and they needed to take over control of the vehicle as soon as they received the TOR. Then, after taking over control, they needed to keeping driving until being told to stop; they needed to obey the speed limit, indicate (using indicator) when changing lanes and drive as they normally would in real life.
- After that, the experiment started and the participants completed several takeover sessions in the HAV differentiated by different types of HMI. The order of the driving sessions for each participants were randomised.
- After each driving session, participant was given a five to ten-minutes break, and then they completed the NASA-RTLX and 7-Likert scale questionnaires.

The logic and procedure for selection of statistical tests were highlighted in the Section 3.3.9. The following section presents the results of this chapter.

7.3 Results

7.3.1 Trajectories

Figures 7.5 and 7.6 show the average trajectories of the older and younger drivers when taking over control from the HAV using different types of HMIs on the two simulated road environment: the city road; and motorway. They could provide a general illustration showing drivers' takeover behaviour.

The average trajectories were generated by positioning each driver's lane position data as vertical coordinates and the driving distance data as horizontal coordinates. The trajectories for each HMI use case are illustrated by lines of different colours, while each figure further divides the experiments parameters by both road type and the cohorts of older and younger drivers. The black vertical arrow and a red car were used to indicate the takeover request and the stationary car. In general, both younger and older drivers were able to take over control of the vehicle and pass the stationary vehicle successfully. Apart from one CCE was recorded among older drivers when using the Baseline HMI, no CCEs were recorded for participants when suing the other HMIs.

In general, participants showed similar average trajectories when using different HMIs. The R+V HMI resulted in the smoothest trajectories among the four HMIs. For the younger drivers, on the city road, their mean trajectories under the four types of HMI exhibited similar pattern, with the one using the Baseline HMI showed a slight deviation to the left after takeover request. On the motorway, their average trajectories when using the R and V HMIs were slightly sharper compared to the ones using the Baseline and R+V HMI. For the older drivers, on the city road, their average trajectory when using the Baseline HMI exhibited a slower lane change comparing to those using the R, V and R+V HMIs. In addition, the trajectory when using the R HMI exhibited the earliest lane change. On the motorway, their average trajectories exhibited similar patterns.

City road

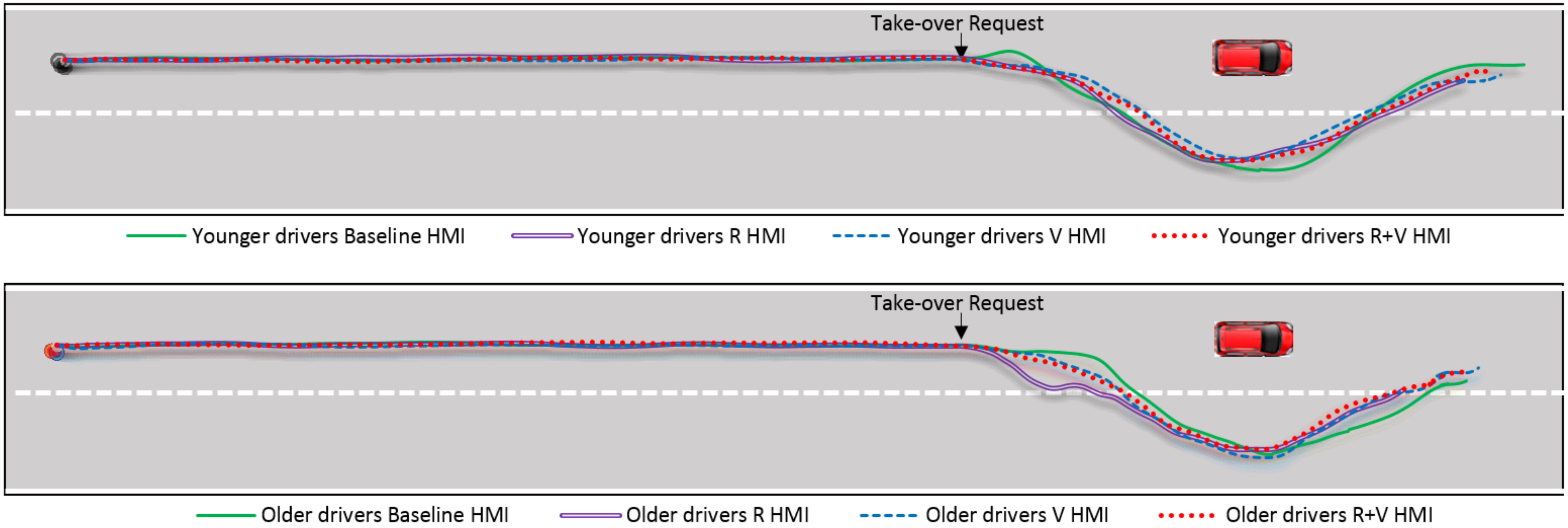


Figure 7.5 Average trajectories when older and younger drivers took over control from HAV on city road in different HMI situations

Motorway

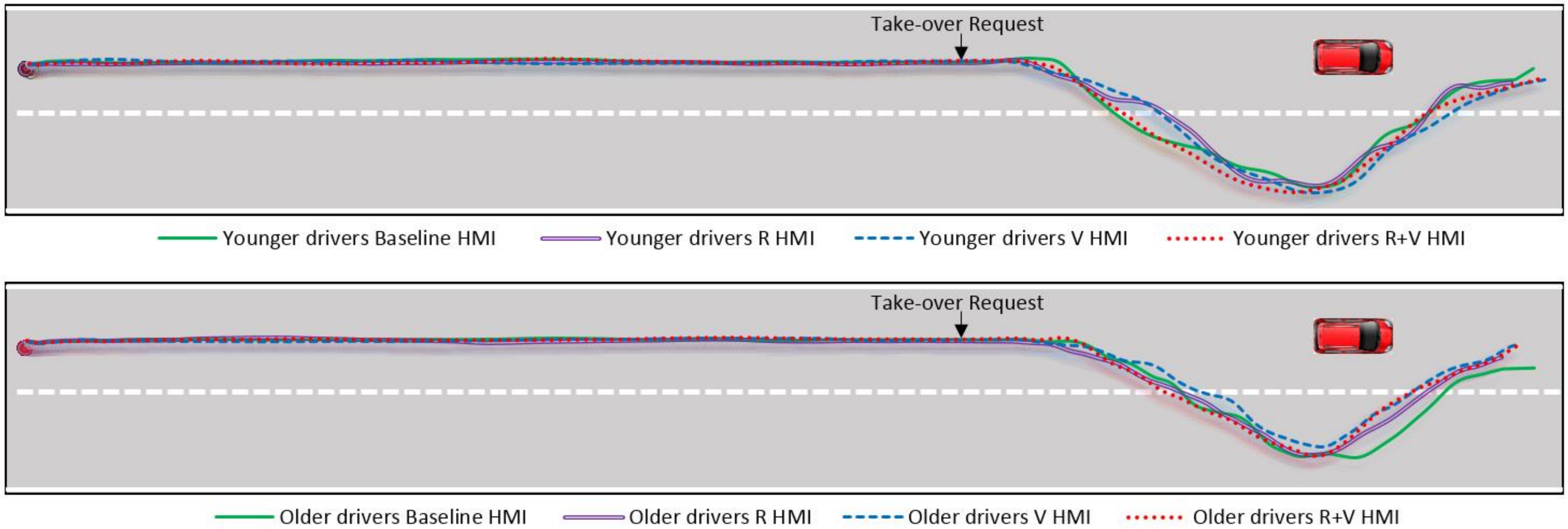


Figure 7.6 Average trajectories when older and younger drivers took over control from HAV on motorway in different HMI situations

7.3.2 Steering and braking behaviour

This section reports the results of drivers' steering and braking behaviour to overcome the stationary vehicle when taking over control from HAVs in different HMI conditions. As shown in Table 7.3, when using the Baseline HMI, the majority of participants reacted the stationary vehicle by only steering into the next lane. However, when using the R HMI, V HMI and R+V HMI, the majority of participants avoided the stationary vehicle by breaking and steering into the next lane.

When using the Baseline HMI, 67 drivers (34 older and 33 younger drivers) avoided the stationary vehicle only steering to the next lane, but not using the brake. 9 drivers (5 older and 4 younger drivers) reacted by steering and braking. A Chi-square test showed that there is no significant difference in the steering and braking behaviour between older and younger drivers in the clear weather, $X^2(1) = 0.073$, $p=0.768$.

When using the R HMI, 71 drivers avoided the stationary car by braking and steering into the next lane, including all the older drivers and the majority of younger drivers. 5 younger drivers reacted by only steering into the next lane. A Chi-square test showed that there is significant difference in the steering and braking behaviour between older and younger drivers when using the R HMI, $X^2(1) = 5.641$, $p=0.018$. In addition, a McNemar test ($p<0.001$) showed that there is a significant difference in the steering and braking behaviours among participants when using the Baseline HMI and the R HMI.

When using the V HMI, 68 drivers (36 older and 32 younger drivers) reacted to the stationary vehicle by braking and steering into the next lane. 8 drivers (3 older and 5 younger drivers) reacted by only steering into the next lane. There was no significant difference in the steering and braking behaviour between the older and younger drivers as assessed by a Chi-square test, $X^2(1) = 0.683$, $p=0.409$. A McNemar test ($p<0.001$) revealed that there is a significant difference in the steering and braking behaviours among the participants when using the Baseline HMI and the R HMI. Also, there was no significant difference in the steering and braking behaviours when using the R HMI and the V HMI, as tested by a McNemar test ($p=0.453$).

Finally, when using the R+V HMI, 66 drivers (38 older and 28 younger drivers) avoided the stationary vehicle by braking and steering into the next lane. 1 older drivers and 9 younger drivers reacted by only steering into the next lane. A Chi-square test revealed that there is significant difference in the steering and braking behaviour between the older and younger drivers, $X^2(1) = 7.868$, p=0.005. A McNemar test (p<0.001) showed that there is a significant difference in the steering and braking behaviours among the participants when using the Baseline HMI and the R+V HMI. In addition, McNemar tests revealed that there is no significant difference in the steering and braking behaviour when using the R+V HMI compared to the R HMI (p=0.063) and V HMI (p=0.774).

Table 7.3 the steering and braking behaviours for different age groups in different HMI conditions

	Baseline HMI		*R HMI*		*V HMI*		*R+V HMI*	
	Steer only	*Steer & brake*	*Steer only*	*Steer & brake*	*Steer only*	*Steer & brake*	*Steer only*	*Steer & brake*
Older drivers	34	5	0	39	3	36	1	38
Younger drivers	33	4	5	32	5	32	9	28
Total	67	9	5	71	8	68	10	66

7.3.3 Reaction time

This section reports the results of drivers' reaction time, it measures how quickly drivers reacts to the takeover request (see Section 3.3.4.1 for details). Figure 7.7 illustrates that older drivers had slower reaction time compared to the younger drivers. To investigate whether or not there were statistically significant effects of age and HMI type on drivers' reaction time, a mixed factorial ANOVA was conducted. As Table 7.4 indicates, age had a statistically significant effect on reaction time, $F(1,74)= 16.678$, p=0.001, $\eta p^2=0.139$, with older drivers (M=2.41s, SD=0.79s) needing statistically significantly longer reaction times than younger drivers (M=2.04s, SD=0.50s), a significant difference of 0.37s (95% CI, 0.16s to 0.58s).

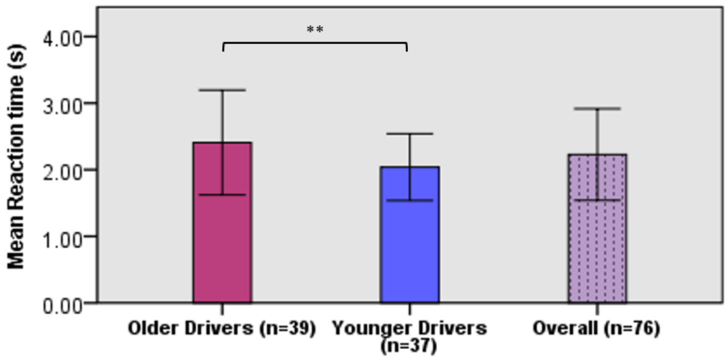


Figure 7.7 Mean reaction time for different age groups (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Figure 7.8 shows that participants exhibited the longest reaction time when using the Baseline HMI and the fastest reaction time when using the R+V HMI. The results of ANOVA revealed that the HMI type had a statistically significant effect on reaction time, $F(1.989,147.184)=11.941$, $p<0.001$, $\eta p^2=0.184$. The assumption of sphericity was not met, $X^2(5)=126.097$, $p<0.001$, and the Greenhouse-Geisser correction ($\varepsilon<0.75$) had been applied. Post-hoc test using the Bonferroni correction revealed that significant difference were between:

- Baseline HMI (M=2.53s, SD=0.73s) to V HMI (M=2.07s, SD=0.60s,), a decrease of 0.45s (95% CI, 0.21s to 0.69), p<0.001.
- Baseline HMI (M=2.53s, SD=0.73s) to R+V HMI (M=2.02s, SD=0.62s), a decrease of 0.49s (95% CI, 0.23s to 0.75s), p<0.001.
- R HMI situation (M=2.30s, SD=0.69s) to V HMI, a decrease of 0.23s (95% CI, 0.20s to 0.44s), p=0.024.
- R HMI to R+V HMI, a decrease of 0.27s (95% CI, 0.06s to 0.49s), p=0.006.

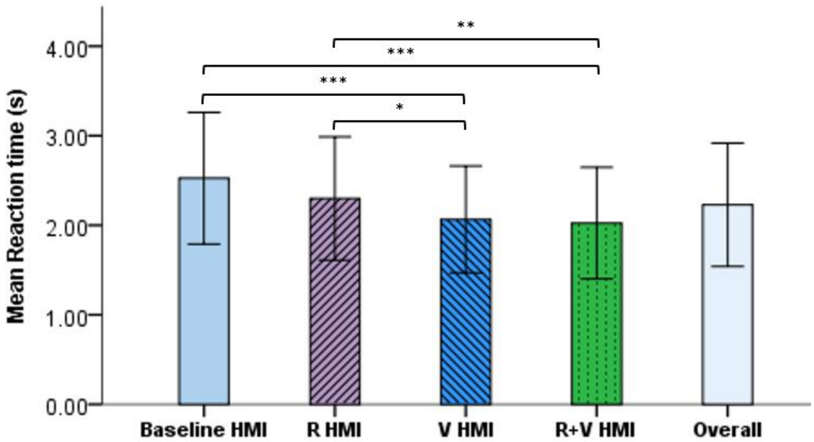


Figure 7.8 Mean reaction times for different HMI conditions (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

In addition, the mixed factorial ANOVA with Greenhouse-Geisser correction revealed a significant interaction effect between age and HMI type, $F(1.989,147.184)= 6.768$, p=0.002, $\eta p^2=0.084$. As illustrated in Figure 7.9, this interaction indicates that HMI affected older drivers' and younger drivers' reaction time in different ways. In order to interpret this interaction, several paired sample t-tests were performed.

Table 7.4 Results of a mixed ANOVA for reaction time

	df	*F*	*p*	*ηp²*
Age	1,74	11.941***	0.001	0.139
HMI Type	1.989,147.184	16.678***	<0.001	0.184
Age × HMI Type	1.989,147.184	6.768**	0.002	0.084

Note:= p ⩽0.05, **= p ⩽0.01, ***= p ⩽0.001*

For the older drivers, their reaction time showed a trend of consistent reduction from the Baseline HMI to the R HMI, V HMI and R+V HMI conditions. The difference between HMI conditions were as follows:

- Baseline HMI (M=2.91s, SD=0.70s) to R HMI (M=2.45s, SD=0.81s), a significant decrease of 0.46s (95% CI, 0.13s to 0.80s), *t*(38)=2.80, p=0.008.
- Baseline HMI to V HMI (M=2.16s, SD=0.67s), a significant decrease of 0.75s (95% CI, 0.43s to 1.08s), *t*(38)=4.699, p<0.001.
- Baseline HMI to R+V HMI (M=2.11s, SD=0.73s), a significant decrease of 0.80s (95% CI, 0.45s to 1.15s), *t*(38)=4.585, p<0.001.
- R HMI to V HMI, a significant decrease of 0.29s (95% CI, 0.002s to 0.58s), *t*(38)=2.042, p=0.048.
- R HMI to R+V HMI, a significant decrease of 0.33s (95% CI, 0.41s to 0.63s), *t*(38)=2.304, p=0.027.
- No significant difference between V HMI and R+V HMI, *t*(38)=1.015, p=0.316.

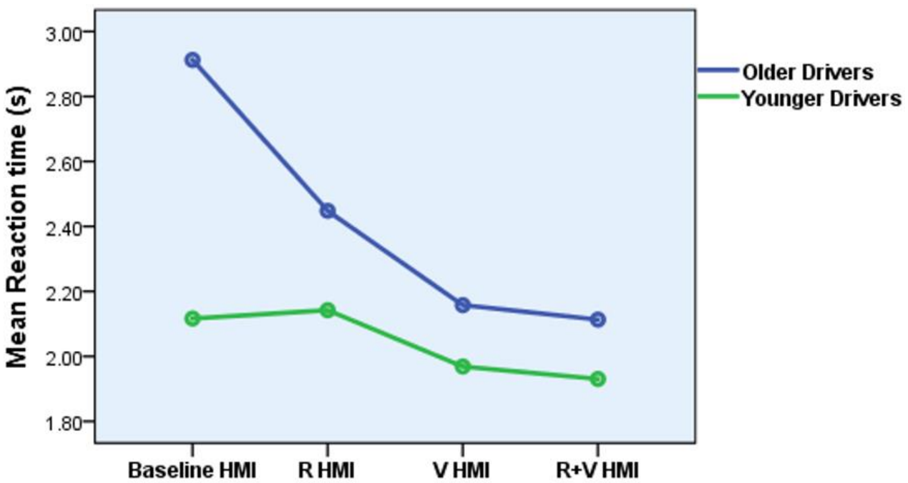


Figure 7.9 Illustration of the significant interaction effect between age and HMI on reaction time.

For the younger drivers, their reaction time showed a slight increase from Baseline HMI to R HMI and then exhibited a consistent decrease from R HMI to R+V HMI. The difference between HMIs were as follows:

- Baseline HMI (M=2.12s, SD=0.52s) to R HMI (M=2.14s, SD=0.50s), there is no significant difference, $t(36)=-1.423$, p=0.163.
- Baseline HMI to V HMI (M=1.97s, SD=0.50s), a significant decrease of 0.15s (95% CI, 0.016s to 0.28s), $t(36)=2.279$, p=0.029.
- Baseline HMI to R+V HMI (M=1.93s, SD=0.48s), a significant decrease of 0.19s (95% CI, 0.045s to 0.33s), $t(36)=2.680$, p=0.011.
- R HMI to V HMI, a significant decrease of 0.17s (95% CI, 0.057s to 0.29s), $t(36)=3.027$, p=0.005.
- R HMI to R+V HMI, a significant decrease of 0.21s (95% CI, 0.09s to 0.33s), $t(36)=3.511$, p=0.001.
- V HMI to R+V HMI, there is no significant difference between $t(36)=1.724$, p=0.093.

The above findings are expanded upon in Section 7.4.1.

7.3.4 Takeover time

This section reports the results of participants' takeover time, it measures how quickly they generate their first active input to the vehicle (see Section 3.3.4.1 for detail). Figure 7.10 shows that older and younger drivers exhibited similar takeover times when reassuming control from the HAV.

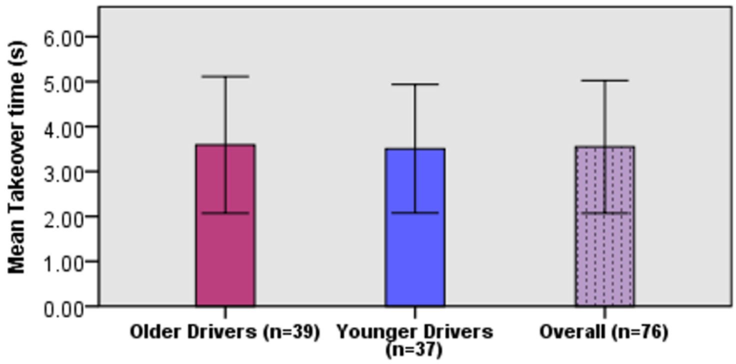


Figure 7.10 Mean takeover time for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

To explore the effect of age and the HMI type on the participants' overall takeover time, a mixed factorial ANOVA was performed. As Table 7.5 shows that age did not have a significant effect on takeover time, although older drivers (M=3.59s, SD= 1.52s) exhibited slightly slower takeover time compared to the younger drivers (M=3.51, SD=1.43s).

Figure 7.11 shows that, generally, participants had the longest takeover time when using the Baseline HMI (M=3.79s, SD=1.47s) and the fastest takeover time in the R+V HMI situation (M=3.26s, SD=1.30s). The mixed factorial ANOVA with Huynh-Feldt correction ($X^2(5)=36.699$, $p<0.001$, $\varepsilon>0.75$) revealed that HMI type showed a significant effect on participants' takeover time, $F(2.470,182.779)= 0.177$, $p=0.043$, $\eta p^2=0.039$. A post-hoc test using the Bonferroni correction revealed that takeover times in the R HMI situation (M=3.75s, SD=1.60s, p= 0.045) were significantly longer than in the R+V HMI situation; a significant difference of 0.49s (95% CI, 0.01s to 0.98s). There were no statistically significant differences in takeover time among the other HMI conditions.

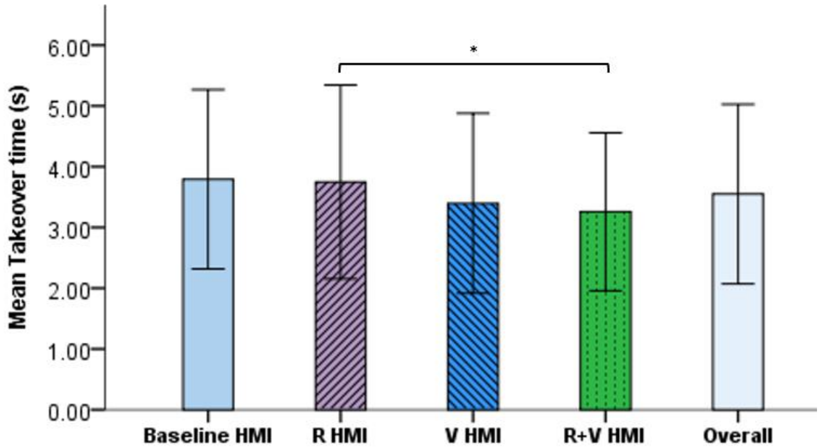


Figure 7.11 Takeover time for different HMI conditions (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

In addition, as Table 7.5 shows, the mixed factorial ANOVA with Huynh-Feldt correction yielded a statistically significant interaction effect between age and HMI type on takeover time, $F(2.470,182.779)= 8.381$, $p<0.001$, $\eta p^2=0.102$. Figure 7.12 visualizes this interaction. In order to interpret his interaction, several paired sample t-tests were performed.

Table 7.5 Results of mixed ANOVA for takeover time

	df	*F*	*p*	ηp^2
Age	1,74	0.177	0.675	0.002
HMI Type	2.470	2.963*	0.043	0.039
Age × HMI Type	2.470	8.381***	<0.001	0.102

Note:= p ⩽0.05, **= p ⩽0.01, ***= p ⩽0.001*

For older drivers, their takeover time highest when using the Baseline HMI, and then showed a trend of consistent reduction when using the R HMI, V HMI and R+V HMI. The difference between their takeover times of different HMIs were as follows:

- Baseline HMI (M=4.46s, SD=1.61s) to R HMI (M=3.61s, SD=1.65s), a significant decrease of 0.85s (95% CI, 0.03s to 1.67s), *t*(38)= 2.092, p=0.043.
- Baseline HMI to V HMI (M=3.17s, SD=1.34s), a significant decrease of 1.29s (95% CI, 0.53s to 2.05s), *t*(38)= 3.446, p=0.001.
- Baseline HMI to R+V HMI (M=3.12s, SD=1.07s), a significant decrease of 1.34s (95% CI, 0.64s to 2.03s), *t*(38)= 3.889, p<0.001.
- R HMI to V HMI, there is no significant difference, *t*(38)= 1.468, p=0.150.
- R HMI to R+V HMI, no significant difference, *t*(38)= 1.795, p=0.081.
- V HMI to R+V HMI, no significant difference, *t*(38)= 0.241, p=0.811.

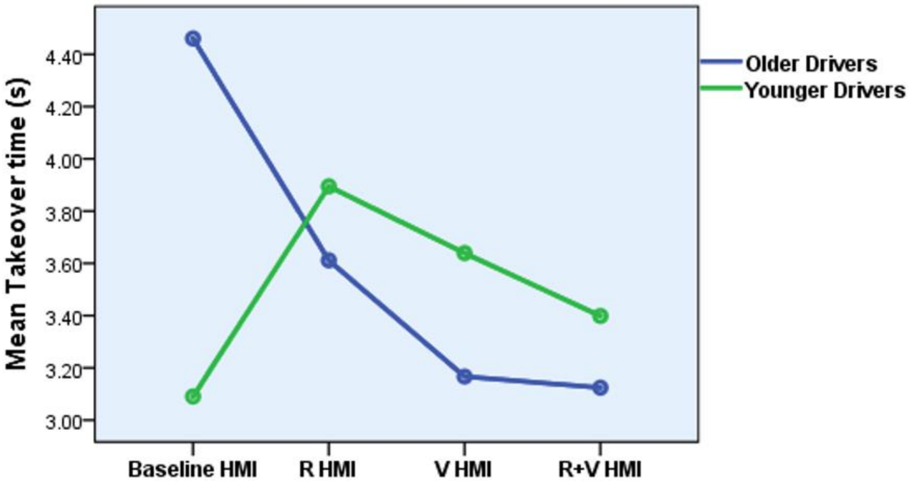


Figure 7.12 Illustration of the significant interaction effect between age and HMI on takeover time.

For the younger drivers, they exhibited the shortest takeover time in the Baseline HMI and then it showed sharp increase to in the R HMI situation, after that it showed a consistent decrease across the R HMI, V HMI and R+V HMI. The difference between HMIs were:

- Baseline HMI (M=3.09s, SD=0.89s) to R HMI (M=3.89s, SD=1.55s), a significant increase of 0.80s (95% CI, 0.17s to 1.44s), $t(36)= -2.572$, p=0.014.
- Baseline HMI to V HMI (M=3.64s, SD=1.60s), there is not significant difference, $t(36)= -1.869$, p=0.07.
- Baseline HMI to R+V HMI (M=3.40s, SD=1.51s), there is no significant difference, $t(36)=-1.053$, p=0.300.
- R HMI to V HMI, there is no significant difference, $t(36)= 0.983$, p=0.332.
- R HMI to R+V HMI, a significant decrease of 0.50s (95% CI, 0.03s to 0.96s), $t(36)= 2.150$, p=0.038.
- V HMI to R+V HMI, there is no significant difference $t(36)=1.195$, p=0.240.

The above findings are discussed in Section 7.4.1.

7.3.5 Indicator Time

This section reports the results of drivers' indicator time, it measures how quickly the participants makes the decision to conduct a lane change to avoid the stationary vehicle and indicate their intention to change lane (see Section 3.3.4.1 for detail). Figure 7.13 shows that older drivers had longer indicator times than younger drivers.

To investigate whether or not there were statistically significant differences in indicator time between older and younger drivers when using different types of HMI, a mixed factorial ANOVA was performed. As Table 7.6 shows that age had a statistically significant effect on indicator time, $F(1,74)= 5.594$, p=0.021, $\eta p^2=0.070$, with older drivers (M=8.96s, SD=3.75s) exhibiting significantly longer indicator times than younger drivers (M=7.63s, SD=3.17s); a significant difference of 1.33s (95% CI, 0.21s to 2.46s).

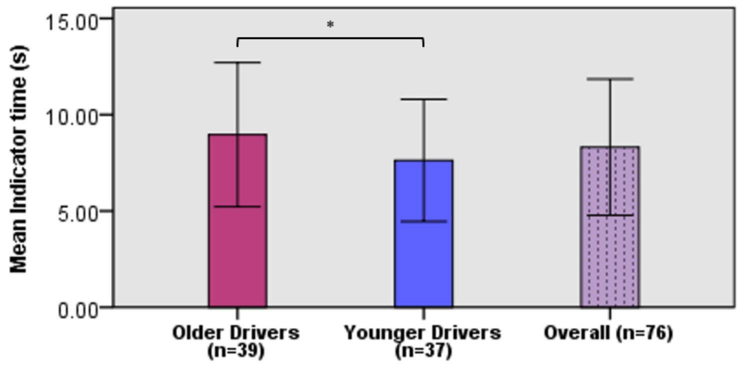


Figure 7.13 Mean indicator time for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Figure 7.14 shows that participants had the longest indicator time when using the Baseline HMI and the fastest when using the R HMI.

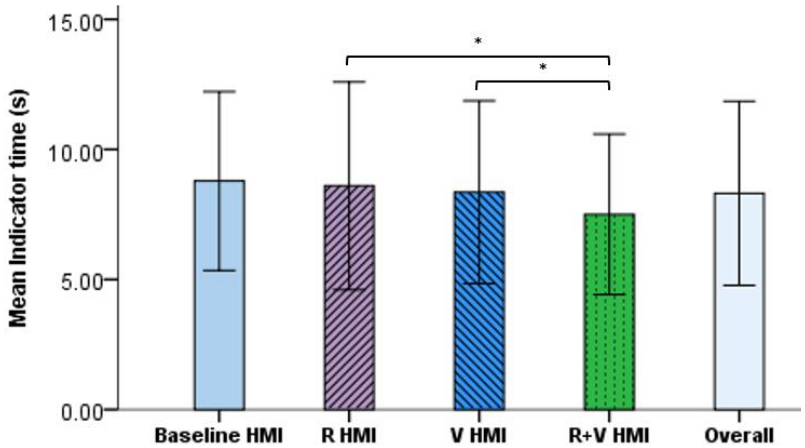


Figure 7.14 Indicator time for different HMI conditions (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

In testing whether or not there were statistically significant differences in the participants' indicator time when using the different types of HMI, the mixed factorial ANOVA with Huynh-Feldt correction ($X^2(5)$ =45.761, p<0.001, ε>0.75) yielded a statistically significant effect of HMI type on the indicator time, $F(2.315,171.3051,74)$= 3.067, p=3.067, ηp^2=0.040. Post-hoc test using the Bonferroni correction revealed that significant difference were between:

- Baseline HMI (M=8.79s, SD=3.44s, p=0.087) to R+V HMI (M=7.50s, SD=3.08s), there is no significant difference, but p value (p=0.087) shows a certain trend towards significant.

- R HMI (M=8.60s, SD=3.99s) to R+V HMI, a significant decrease of 1.11s (95% CI, 0.11s to 2.10s), p=0.021.
- V HMI (M=8.36s, SD=3.52s) to R+V HMI, a significant decrease of 0.86s (95% CI, 0.11s to 1.6s), p=0.016.

Table 7.6 Results of a mixed factorial ANOVA for indicator time

	df	*F*	*p*	*ηp²*
Age	1,74	5.594*	0.021	0.070
HMI Type	2.315,171.305	3.067*	0.042	0.040
Age × HMI Type	2.315,171.305	2.261	0.099	0.030

Note:= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001*

7.3.6 Time to collision (TTC)

This section reports the results of drivers minimum TTC, it measures how critical drivers' takeover in terms of colliding to the stationary vehicle (see Section 3.3.4.2 for detail). Figure 7.15 illustrates that older drivers generally exhibited slightly longer TTC compared to the younger drivers.

In order to test whether or not there were statistically significant differences in TTC between the older and younger drivers in different types of HMI situations, a mixed factorial ANOVA was performed. As Table 7.7 shows, there was no significant effect of age on TTC, $F(1,74)= 0.742$, p=0.392, $\eta p^2=0.010$.

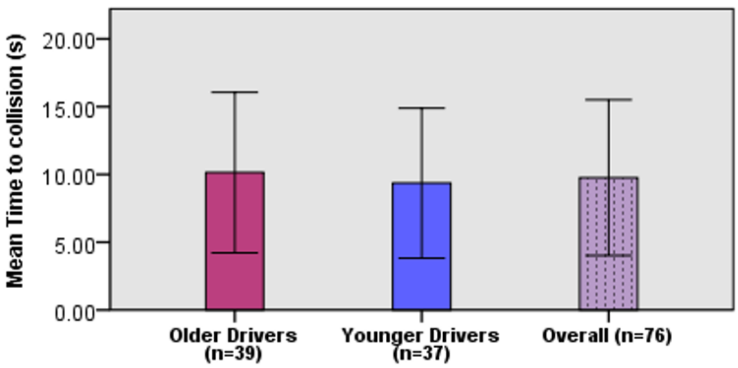


Figure 7.15 Mean TTC for different age groups (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Figure 7.16 illustrates that in general, participants exhibited similar TTCs when using the Baseline HMI, V HMI and R+V HMI. The TTC for R HMI was higher than for the three other types of HMI.

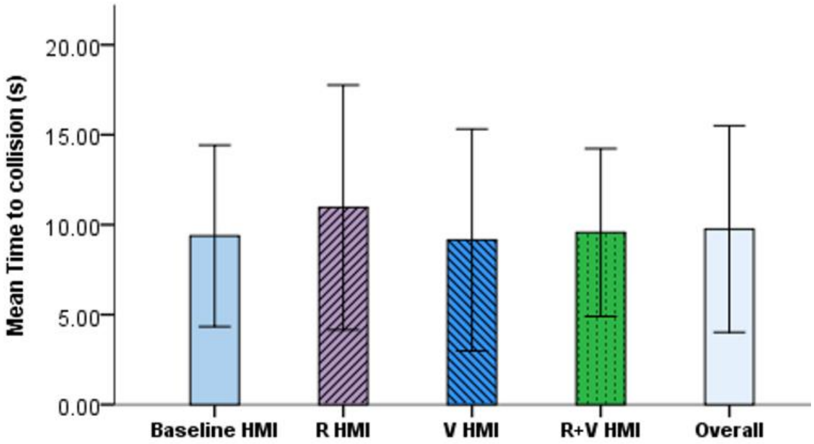


Figure 7.16 TTCs for different HMI conditions (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

The results of the mixed factorial ANOVA shown in Table 7.7 indicates that there were no significant effect of HMI type on the TTC. In addition, the interaction between age and HMI type was non-significant.

Table 7.7 Results of a mixed factorial ANOVA for TTC

	df	*F*	*p*	*ηp²*
Age	1,74	0.742	0.392	0.010
HMI Type	2.356,174.348	2.168	0.108	0.028
Age × HMI Type	2.356,174.348	2.055	0.122	0.027

Note:= p ⩽0.05, **= p ⩽0.01, ***= p ⩽0.001*

7.3.7 Resulting acceleration

This section reports the results of drivers' resulting acceleration, it measures the maximum force drivers generate during the takeover (see Section 3.3.4.2 for detail). Figure 7.17 shows that older drivers had stronger resulting acceleration than the younger drivers.

To test whether or not there were statistically significant difference between the younger and older drivers when using different types of HMI, a mixed factorial ANOVA was carried out. As Table 7.8 shows, the results indicate a significant effect of age on the resulting acceleration, $F(1,74)= 7.794$, $p=0.007$, $\eta p^2=0.095$, with older drivers (M=2.82m/s², SD=1.80m/s²) exhibiting significantly greater resulting acceleration than younger drivers (M=2.21m/s², SD=1.56m/s²), a significant difference of 0.61s (95% CI, 0.17s to 1.04s).

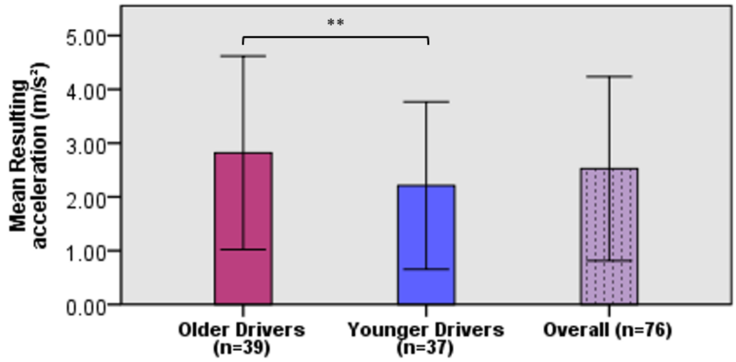


Figure 7.17 Mean resulting acceleration for different age groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Figure 7.18 illustrates that participants exhibited the greatest resulting acceleration when using R HMI. Also, participants had higher resulting acceleration in the Baseline HMI and R HMI situations than in V HMI and R+V HMI situations. And participants had similar resulting acceleration when using the V HMI and R+V HMI.

To investigate whether or not there were significant differences in the resulting acceleration that participants generated during the takeover control process in HAV, a mixed factorial ANOVA was conducted. The assumption of sphericity was not met, as assessed by Mauchly's test of Sphericity $X^2(5) =46.504$, $p<0.001$ and the Huynh-Feldt correction ($\varepsilon>0.75$) was applied. Results revealed that HMI type had a statistically significant effect on the resulting acceleration, $F(2.473, 182.975)= 14.451$, $p<0.001$, $\eta p^2=0.163$.

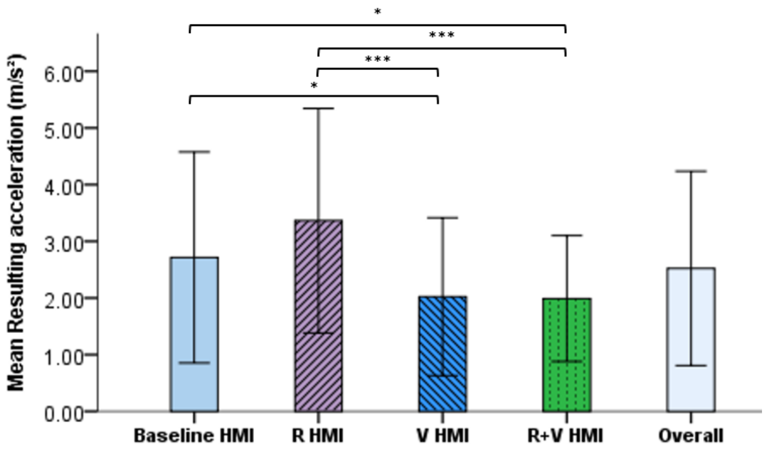


Figure 7.18 Resulting acceleration for different HMI conditions (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Post-hoc test using the Bonferroni correction revealed that significant difference were between:

- Baseline HMI (M=2.72m/s², SD= 1.86m/s²) to V HMI (M=2.02m/s², SD= 1.39m/s²), a significant decline of 0.69s (95% CI, 0.001s to 1.37s), p=0.049.
- Baseline HMI to R+V HMI (M=1.99m/s², SD= 1.11m/s²), a significant difference of 0.72s (95% CI, 0.12 m/s² to 1.32 m/s²), p=0.011.
- R HMI (M=3.36m/s², SD= 1.98m/s²) to V HMI, a significant decline of 1.34m/s² (95% CI, 0.63m/s² to 2.05m/s²), p<0.001.
- R HMI to R+V HMI, a significant decline of 1.37m/s² (95% CI, 0.69m/s² to 2.05m/s²), p<0.001.

Table 7.8 Results of a mixed factorial ANOVA for resulting acceleration

	df	*F*	*p*	*ηp²*
Age	1,74	7.794**	0.007	0.095
HMI Type	2.473,182.975	14.451***	<0.001	0.163
Age × HMI Type	2.473,182.975	0.610	0.578	0.008

Note:= p ⩽ 0.05, **= p ⩽ 0.01, ***= p ⩽ 0.001*

7.3.8 Steering wheel angle

This section reports the results of drivers' steering wheel angle, it measures how stable their takeovers are (see Section 3.3.4.2 for detail). Figure 7.19 shows that generally older drivers exhibited greater steering wheel angles than the younger drivers.

In order to determine whether or not there were statistically significant differences among the steering wheel angles that participants had when taking over control from the HAV in different HMI situations, a mixed factorial ANOVA was performed. As Table 7.9 shows, the results revealed a statistically significant effect of age on steering wheel angle, $F(1,74)= 30.282$, $p<0.001$, $\eta p^2=0.290$, with older drivers (M=8.83 degrees, SD=5.50 degrees) showing significantly greater steering wheel angles than the younger drivers (M=5.41 degrees, SD=2.85 degrees); a significant difference of 3.43 degrees (95% CI, 2.17 degrees to 4.67 degrees).

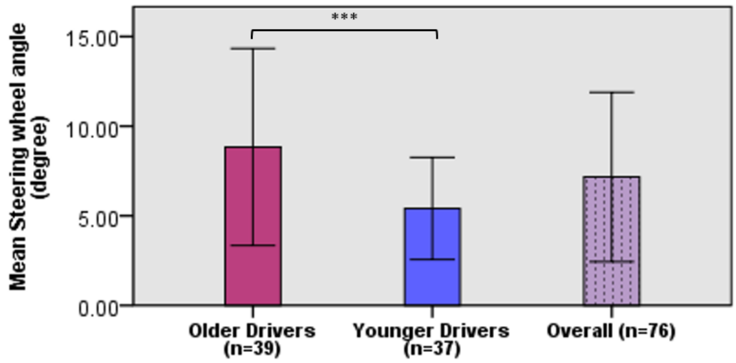


Figure 7.19 Mean steering wheel angle for different age groups (error bars=±1 SD, *= $p \le 0.05$, **= $p \le 0.01$, ***= $p \le 0.001$).

Figure 7.20 shows the steering wheel angles that participants had during taking over control from the HAV in the four types of HMI situations. Overall, participants showed the greatest steering wheel angle when using R HMI. Also, participants' steering wheel angle was higher when using Baseline HMI and R HMI compared to when using V HMI and R+V HMI. And V HMI and R+V resulted in similar steering wheel angles.

With regard to whether or not participants exhibited statistically significantly different steering wheel angles, a mixed factorial ANOVA was performed. The assumption of sphericity was violated, as assessed by Mauchly's test of Sphericity $X^2(5) =38.491$, $p<0.001$ and the Huynh-Feldt correction ($\varepsilon>0.75$) was applied. The results of ANOVA with Huynh-

Feldt correction showed that the HMI type resulted in statistically significant effect in the steering wheel angle, $F(2.556,189.128)= 4.990$, p=0.004, $\eta p^2=0.063$.

Post-hoc test using the Bonferroni correction revealed significant difference between:

- R HMI (M=8.52 degrees, SD=5.72 degrees) to V HMI (M=6.26 degrees, SD=4.18 degrees), a significant decline of 2.25 degrees (95% CI, 0.36 degrees and 4.14 degrees), p=0.011.
- R HMI to R+V HMI (M=6.56 degrees, SD= 3.57degrees), a significant decline of 1.96 degrees (95% CI, 0.52 degrees to 3.41 degrees), p=0.003.

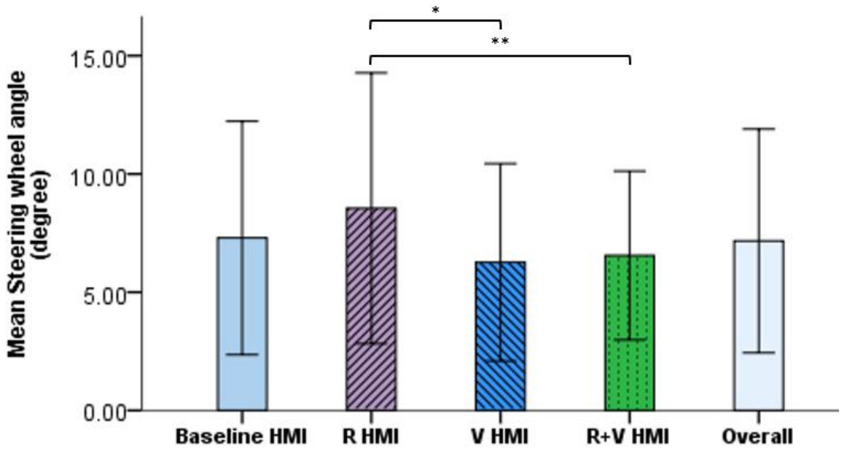


Figure 7.20 Steering wheel angle for different HMI conditions (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Table 7.9 Results of a mixed ANOVA for steering wheel angle

	df	*F*	*p*	*ηp²*
Age	1,74	30.282***	<0.001	0.290
HMI Type	2.556,189.128	4.990**	0.004	0.063
Age × HMI Type	2.556,189.128	1.294	0.278	0.017

Note:= p ⩽ 0.05, **= p ⩽ 0.01, ***= p ⩽ 0.001*

7.3.9 Correlation between reaction time and takeover time

In order to investigate the relationship between drivers' reaction time and takeover time under difference HMI conditions, several Pearson's correlation analysis were carried out. Table 7.10 summarized the correlation coefficients, showing that there was a large and statistically significant positive correlation between reaction time and takeover time in the Baseline HMI situation, and a significant small positive correlation for V HMI. In addition, the R+V HMI resulted in a significant moderate positive correlation between the two variables. Lastly, there was no significant correlation between the two variables for the R HMI.

The scatterplots of reaction time correlates takeover time in the four types of HMI situations are shown in Figure 7.22. A qualitative inspection of the plots indicates that there is a clear trend for younger drivers to have smaller reaction and takeover times than older drivers when using the Baseline HMI. However, this trend became less obvious when participants were using the R HMI, V HMI and R+V HMI.

Table 7.10 Results of Pearson's correlation of reaction time (s) and takeover time (s)

Correlation between reaction time (s) and takeover time (s)	***Correlation coefficients***
Baseline HMI	r (76) = 0.710, p< 0.001
R HMI	r (76) = -0.008, p=0.946
V HMI	r (76) = 0.243, p=0.034
R+V HMI	r (76) = 0.361, p=0.001

7.3.10 Hasty takeover

In addition, the red dotted lines in the Figure 7.22 are y=x. If a data point falls on the left-hand side of the y=x line (The highlighted red area), it suggests a driver has exhibited a longer reaction time than takeover time. Drivers of this type generated active input to the vehicle before they had completely switched to the manual driving position. A hasty takeover could reflect an abrupt and potentially risky takeover behaviour. The number of hasty takeovers were illustrated in Figure 7.21.

When participants were taking over the control of HAV using the Baseline HMI, 3 drivers exhibited hasty takeover. All of them were older drivers. A Chi-square test showed there is no significant difference in the hasty takeover between the older and younger drivers, X^2 (1) = 2.963, p=0.085.

When using the R HMI, 13 drivers (8 older and 5 younger drivers) exhibited hasty takeover. A Chi-square test revealed that there is no significant effect of age on hasty takeover in R HMI condition, X^2 (1) = 0.656, p=0.418. In addition, a McNemar test (p=0.013) revealed that R HMI led to significantly greater number of participants with hasty takeover compared to the Baseline HMI.

When using the V HMI, 9 participants (7 older and 2 younger drivers) exhibited hasty takeover. A Chi-square test revealed that there is no significant effect of age on hasty takeover in V HMI condition, X^2 (1) = 2.861, p=0.091. Also, there is no significant difference in the number of participants with hasty takeover in the V HMI condition compared to in the Baseline HMI condition (p=0.070) and the R HMI condition (p=0.454) as assessed by McNemar tests.

Finally, when using the R+V HMI, 4 participants (3 older and 1 younger drivers) exhibited hasty takeover. There is no significant effect of age on hasty takeover as tested by a Chi-square test, X^2 (1) = 0.948, p=0.330. In addition, there is no significant difference in the number of participants with hasty takeover in the R+V condition compared to in the Baseline HMI condition as examined by a McNemar test (p=1.000). However, a McNemar test (p=0.022) revealed that the R+V HMI led to significant fewer participants with hasty takeover compared to the R HMI. There was no significant difference on hasty takeover between the R+V HMI and the V HMI as tested by a McNemar test (p=0.227).

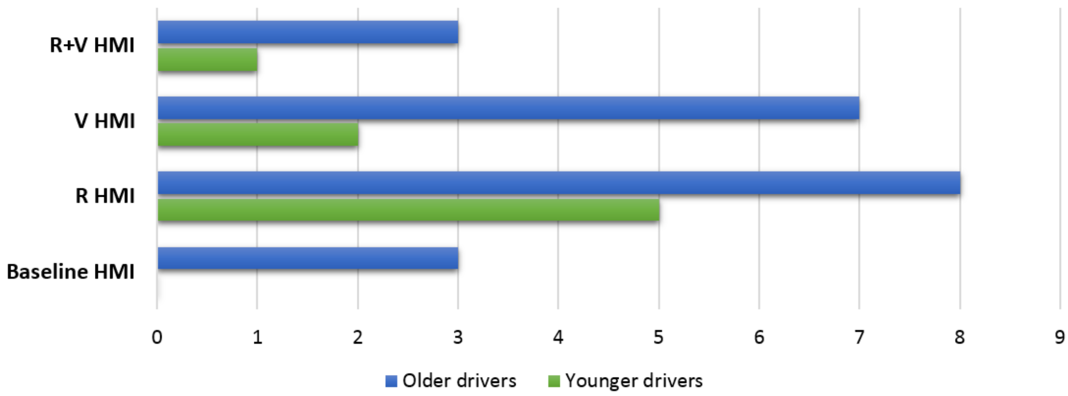


Figure 7.21 Hasty takeovers of participants in different HMI conditions.

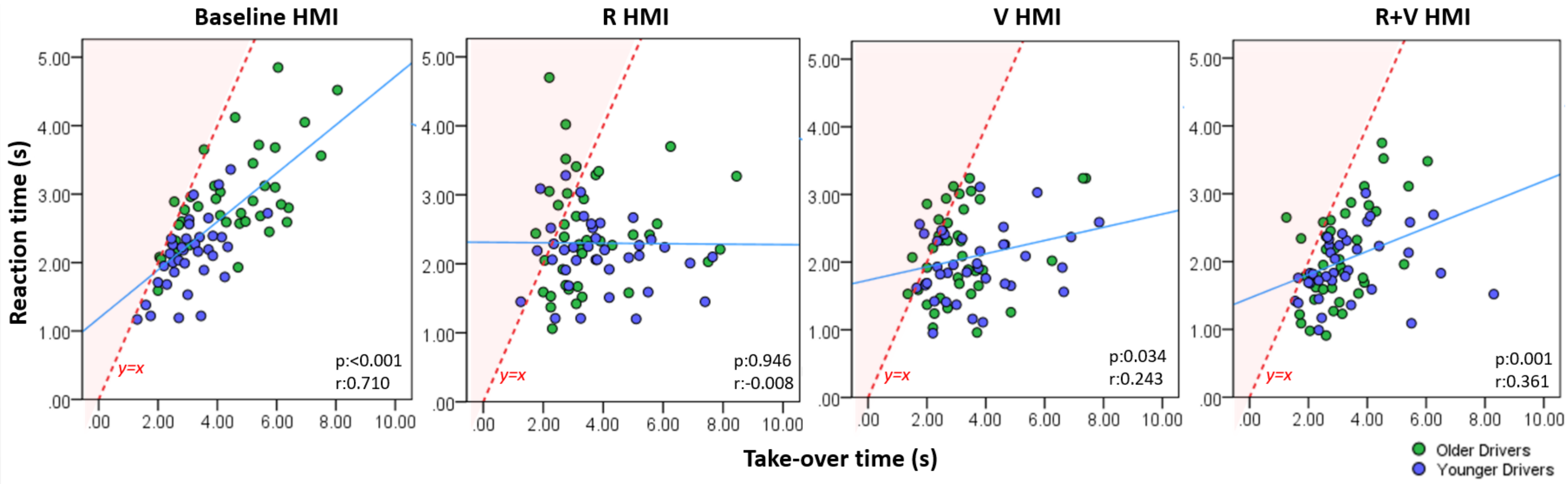


Figure 7.22 Scatter plot of reaction time (s) relative to takeover time (s) for different age groups in the four HMI situations.

7.3.11 Correlation between TTC and resulting acceleration

In order to investigate the relationship between the participants' TTC and the resulting acceleration when using different HMI conditions, several Pearson's correlations were carried out. Table 7.11 summarizes the results which show that there was a significant positive correlation between TTC and the resulting acceleration when participants were using the R HMI and V HMI. For the Baseline HMI and R+V HMI no significant correlation was found between these two variables.

Table 7.11 Results of Pearson's correlation of TTC(s) and resulting acceleration (m/s^2)

Correlation between TTC (s) and Resulting Acceleration (m/s^2)	*Correlation coefficients*
Baseline HMI	$r(76) = -0.103$, $p=0.374$
R HMI	$r(76) = 0.300$, $p=0.009$
V HMI	$r(76) = 0.374$, $p=0.001$
R+V HMI	$r(76) = -0.006$, $p=0.960$

The scatterplots of the TTC correlates resulting acceleration in the four types of HMI situations are shown in Figure 7.23. The purple dotted vertical lines show the point when the resulting acceleration equalled 2.52 m/s^2, which is the mean value of resulting acceleration of the four HMI situations. The upper red dotted horizontal lines represent the point when the TTC equalled 6s, which has been previously recognized as the threshold value for a safe headway time between the lead and the following cars (Vogel, 2002; Vogel, 2003). Each scatterplot is divided into four segments by the vertical and horizontal lines. If a data point falls into the upper right segments (highlighted grey), this suggests that the driver has a safe TTC and the resulting acceleration was smaller than the overall mean value, which is defined as a safe driver. However, if a data point is shown into the lower right segments (highlighted red), this indicates that the driver has a critical TTC and also exhibited a strong resulting acceleration (greater than the mean value), which could be potentially unsafe (Table 7.12).

Table 7.12 Number of participants falling into safe and critical segments of TTC correlates resulting acceleration

	Baseline HMI		*R HMI*		*V HMI*		*R+V HMI*	
	Safe	*Critical*	*Safe*	*Critical*	*Safe*	*Critical*	*Safe*	*Critical*
Older drivers	16	9	13	7	22	6	23	5
Younger drivers	21	2	13	3	18	2	26	2
Total	37	11	26	10	40	8	49	7

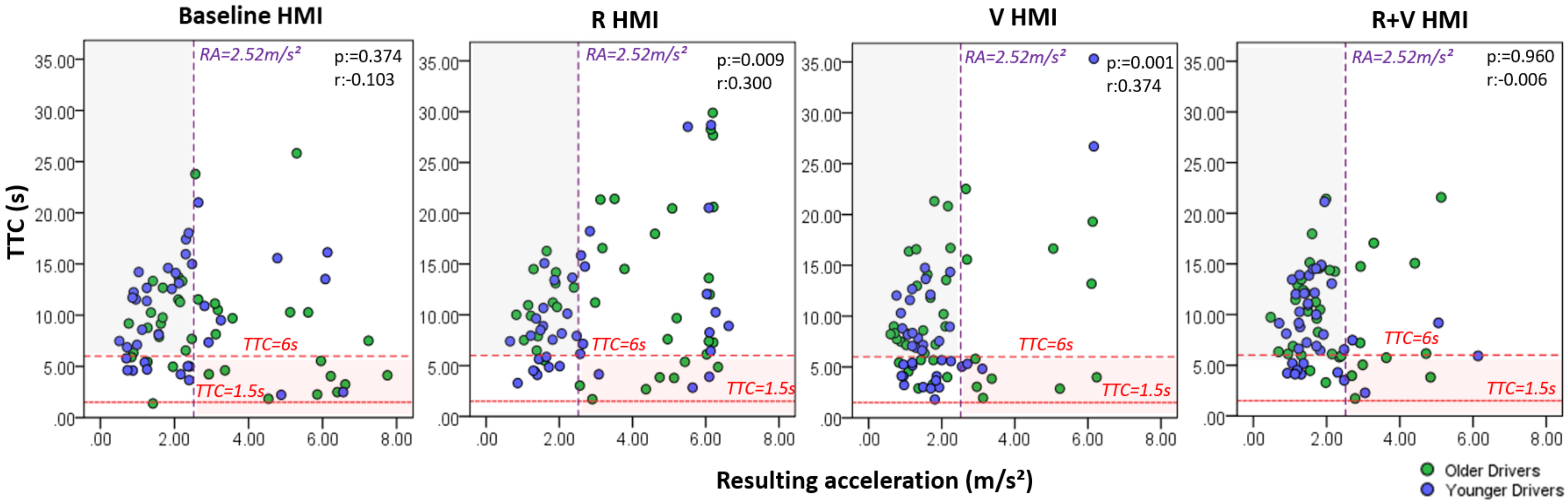


Figure 7.23 Scatter plot of the TTCs (s) relative to resulting acceleration (m/s²) for different age groups in the four HMI situations.

7.3.12 Correlation between TTC and steering wheel angle

To examine the relationship between participants' TTC and steering wheel angle, several Pearson's correlation tests were performed. The correlation coefficients are displayed in Table 7.13. The results show that R HMI resulted in a statistically significant moderate positive correlation between TTC and steering wheel angle. The other HMIs did not lead to any significant correlation between the two variables.

Table 7.13 Results of Pearson's correlation of TTC (s) and steering wheel angle (degree)

Correlation between TTC (s) and steering wheel angle (degree)	*Correlation coefficients*
Baseline HMI	r (76) = 0.031, p=0.793
R HMI	r (76) = 0.328, p=0.004
V HMI	r (76) = -0.087, p=0.454
R+V HMI	r (76) = 0.138, p=0.233

The scatterplots of the TTC correlates steering wheel angle in the four types of HMI situation are displayed in Figure 7.24. Similar to section 3.8.2, the purple dotted vertical lines represent the point when the steering wheel angle equals 7.17 degrees, which is the mean value of steering wheel angle in the four HMI situations. The upper red dotted horizontal lines represent the point when TTC equals 6s, which has been used as the threshold value for a safe headway time between the lead and following cars (Vogel, 2002; Vogel, 2003). Each scatterplot is divided into four segments by the vertical and horizontal lines. If a data point falls in the upper right segments (highlighted grey), this suggests that the driver has a safe TTC and the steering wheel angle was smaller than the overall mean value. Meanwhile, if a data point is shown in the lower right segments (highlighted red), this indicates that the driver has a critical TTC and the steering wheel angle was greater than the mean value. Table 7.14 shows the number of participants who fell into the upper left and lower right segments in different HMI situations.

Table 7.14 Number of participants falling into safe and critical segments of TTC correlates steering wheel angle

	Baseline HMI		*R HMI*		*V HMI*		*R+V HMI*	
	Safe	*Critical*	*Safe*	*Critical*	*Safe*	*Critical*	*Safe*	*Critical*
Older drivers	13	8	13	7	16	9	25	5
Younger drivers	22	2	17	2	11	2	17	1
Total	35	10	30	9	37	11	42	6

Note: Safe: upper left segment, Critical: lower right segment

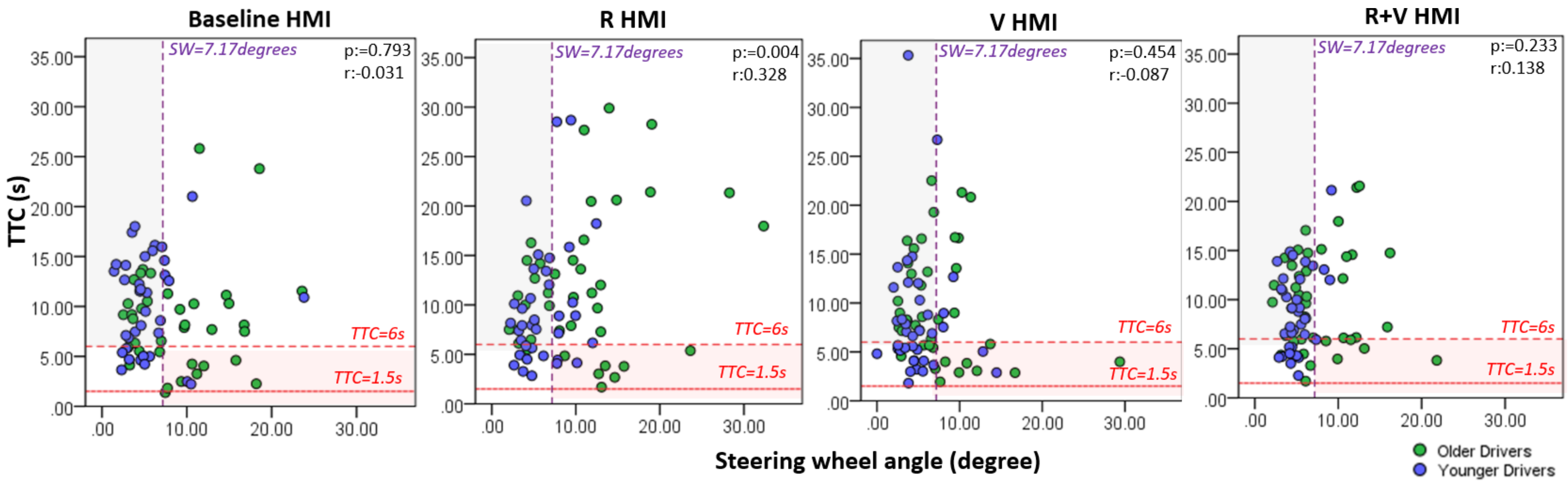


Figure 7.24 Scatter plot of the TTC (s) relative to steering wheel angle (degrees) for different age groups in the four HMI situations.

7.3.13 Workload

This section focuses on the workload that the participants perceived when taking over control from HAV when using the four types of HMI. Their overall workload was assessed using responses of the NASA-RTLX questionnaire. Figure 7.25 provides an overview of the participants' workloads when retaking the control from the HAV. It shows that, in general, older drivers perceived the workload to be higher than did the younger drivers.

In order to investigate whether or not there were significant differences in the perceived workloads of older and younger drivers when taking over control from the HAV in different HMI situations, a mixed factorial ANOVA was conducted. The results of ANOVA in Table 7.15 show that age had a statistically significant effect on the workload score, $F(1,74)= 4.614$, $p=0.035$, $\eta p^2=0.059$, with older drivers (M=29.02, SD=6.78) perceiving significantly higher workload than younger drivers (M=26.02, SD=7.75); a significant difference of 3.00 (95% CI, 0.22 to 5.79).

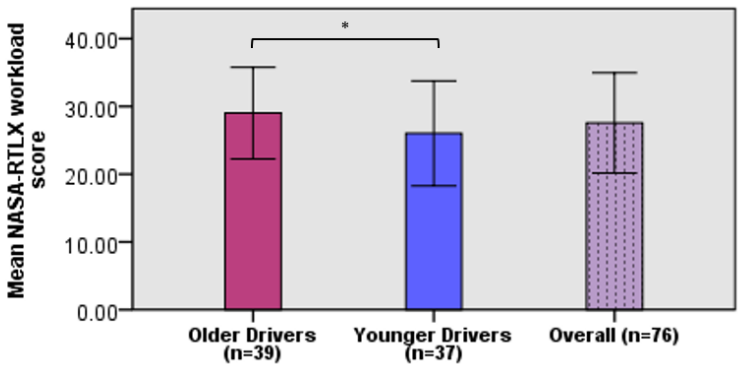


Figure 7.25 Mean NASA-RTLX workload scores for different driver groups (error bars=±1 SD, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$).

Figure 7.26 shows that overall workload was perceived to be highest when using R HMI. The lowest perceived workload was reported when using R+V HMI. In terms of the effect of HMI on the workload, the assumption of sphericity was violated, as assessed by Mauchly's test of Sphericity $X^2(5) =25.211$, $p<0.001$ and the Huynh-Feldt correction ($\varepsilon>0.75$) was applied. Results showed that HMI type had a statistically significant effect on the perceived workload, $F(2.515,186.125)= 23.391$, $p<0.001$, $\eta p^2=0.240$.

A post-hoc test using the Bonferroni correction revealed significant difference between:

- Baseline HMI (M=28.27, SD=9.53) to R HMI (M=30.24, SD=6.87), a significant increase of 2.05 (95% CI, 0.49 to 3.63), p=0.004.
- Baseline HMI to R+V HMI (M=25.14, SD=6.07), a significant decrease of 3.05 (95% CI, 1.14 to 4.96), p<0.001.
- R HMI to V HMI (M=26.59, SD=5.70); a significant decrease of 3.67 (95% CI, 2.04 to 5.29), p<0.001.
- R HMI to R+V HMI, a significant decrease of 5.10 (95% CI, 3.64 to 6.56), p<0.001.

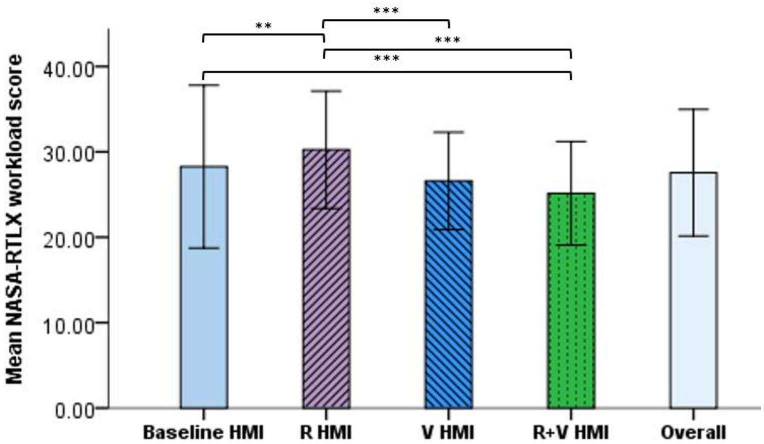


Figure 7.26 NASA-RTLX workload scores for different HMI conditions (error bars=±1 SD, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001).

Table 7.15 Results of mixed ANOVA for workload scores

	df	*F*	*p*	ηp^2
Age	1,74	4.614*	0.035	0.059
HMI Type	2.515,186.125	23.391***	<0.001	0.240
Age × HMI Type	2.515,186.125	8.682***	<0.001	0.105

Note:= p ⩽ 0.05, **= p ⩽ 0.01, ***= p ⩽ 0.001*

In addition, the mixed factorial ANOVA with Huynh-Feldt correction revealed a significant interaction effect between age and HMI type on the workload score, as show in Table 7.20. As figure 7.27 indicates, this interaction indicates that the four types of HMI influenced the workload scores of older and younger drivers differently. To future interpret it, several paired sample t-tests were applied.

For the older drivers, they perceived the highest workload when using the Baseline HMI, then their perceived workload showed a consistent decreasing trend from R HMI, V HMI and R+V HMI. The difference between HMIs were:

- Baseline HMI ($M=31.64$, $SD=8.83$) to R HMI ($M=30.87$, $SD=6.26$), there is no significant difference, $t(38)= 0.986$, $p=0.330$.
- Baseline HMI to V HMI ($M=27.79$, $SD=4.84$), a significant decrease of 3.84 (95% CI, 1.49 to 6.19), $t(38)= 3.310$, $p=0.002$.
- Baseline HMI, to R+V HMI ($M=30.87$, $SD=6.26$), a significant decrease of 5.85 (95% CI, 3.57 to 8.12), $t(38)= 5.205$, $p<0.001$.
- R HMI to V HMI, a significant decrease of 3.08 (95% CI, 1.52 to 4.64), $t(38)= 3.989$, $p<0.001$.
- R HMI to R+V HMI, a significant decrease of 5.08 (95% CI, 3.37 to 6.79), $t(38)= 6.010$, $p<0.001$.
- V HMI to R+V HMI, a significant decrease of 2.00 (95% CI, 0.79 to 3.22), $t(38)= 3.342$, $p=0.002$.

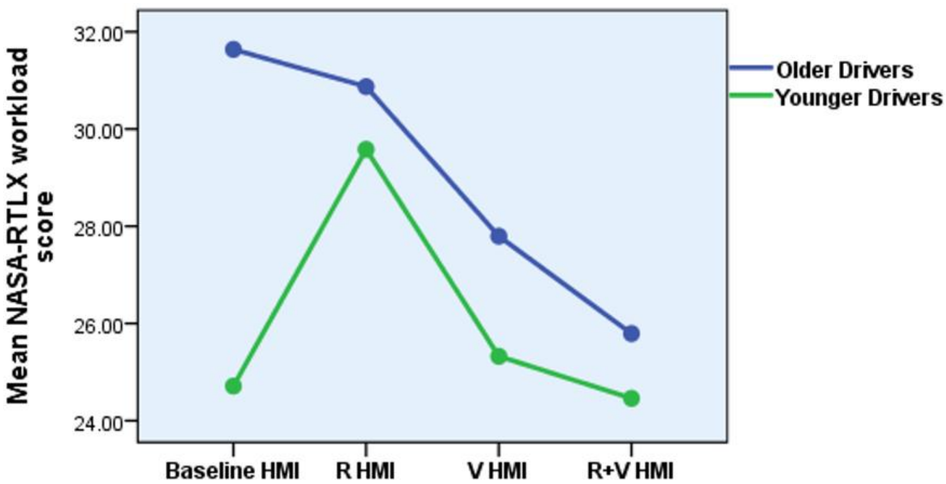


Figure 7.27 Illustration of the significant interaction effect between age and HMI on NASA – RTLX workload score.

For the younger drivers, their perceived workload exhibited a sharp increase from the Baseline HMI to the R HMI, and then it showed a trend of a consistent decline from R HMI to V HMI and R+V HMI. The difference between HMIs were:

- Baseline HMI (M= 24.71, SD=9.03) to R HMI (M=29.58, SD=7.48), a significant increase of 4.87 (95% CI, 3.11 to 6.63), $t(36)=-5.615$, $p<0.001$.
- Baseline HMI to V HMI (M=25.33, SD=6.31), there is no significant difference, $t(36)= -0.536$, $p=0.596$.
- Baseline HMI to R+V HMI (M=24.46, SD=7.10), there is no significant difference, $t(36)= 0.304$, $p=0.763$.
- R HMI to V HMI, a significant decrease of 4.26 (95% CI, 2.39 to 6.13), $t(36)= 4.616$, $p<0.001$.
- R HMI to R+V HMI, a significant decrease of 5.12 (95% CI, 3.79 to 6.45), $t(36)= 7.813$, $p<0.001$.
- V HMI to R+V HMI, there is no significant difference, $t(36)= 0.894$, $p=0.377$.

The above findings regarding participants' perceived workload were discussed in Section 7.4.4.

7.3.14 Attitude towards HMIs

Participants' attitudes and acceptance towards the four types of HMI were examined using a 7-Likert scale questionnaire. Table 7.16 provides a summary of the participants' responses. The figures in Table 7.16 refer to the medians and modes of participants' responses, as well as the percentages of positive attitudes, which refer to participants answering with the scores of 5, 6 or 7 on the Likert scale (7=strongly agree and 1=strongly disagree). For the Baseline HMI, 51.3% of the participants showed positive attitudes. This percentage becomes much larger for the R HMI (82.9%). Then it continues to increase to 93.4% for the V HMI and 98.7% for the R+V HMI.

Table 7.16 Summary of participants' attitudes towards different types of HMI in the HAV

"I would like to have the following HMI in my HAV"	*Median*	*Mode*	*% Positive Attitude*
Baseline HMI	5	5	51.3
R HMI	5	5	82.9
V HMI	6	6	93.4
R+V HMI	6.5	7	98.7

Note: Positive attitude refers to the drivers' answering 5, 6 or 7 on the scale

In order to examine whether or not there were significant differences in participants' attitudes towards the four types of HMI in the HAV, a Friedman test was applied. The results show that there was a statistically significant difference in participants' attitudes towards the different types of HMI, χ^2 (3) = 108.746, p<0.001. The post-hoc Wilcoxon signed-rank test with Bonferroni adjustment showed that participants' attitudes towards the R HMI (Mdn=5, p<0.001), V HMI (Mdn=6, p<0.001) and R+V HMI (Mdn=6.5, p<0.001) were statistically significantly different compared to the Baseline HMI (Mdn=5). Also, participants' attitudes toward the V HMI (Mdn=6, p<0.001) and R+V HMI (Mdn=6.5, p<0.001) were statistically significantly more positive compared to the R HMI (Mdn=5). Moreover, the attitudes towards R+V HMI (Mdn=6.5, p<0.001) were statistically significantly more positive than the attitudes towards V HMI (Mdn=6).

Moreover to investigate age differences in attitudes towards the four types of HMI, several Mann-Whitney U tests were administered. For the Baseline HMI, older drivers showed lower medians in their attitudes (Mdn=4) than the younger drivers (Mdn=5), but the difference was not significant, U=629.000, p=0.323. For the R HMI, older drivers had a higher median (Mdn=6) attitudes than younger drivers (Mdn=5); however, the difference was again not statistically significant, U=668.500, p=0.560. For the V HMI, younger and older drivers exhibited the same median (Mdn=6) attitude and so there was no significant age effect on attitudes, U=680.500, p=0.652.Similarly, for R+V HMI, despite older drivers having a higher median score (Mdn=7) in their attitudes than younger drivers (Mdn=6), the difference was not significant, U=640.000, p=0.354.

7.4 Discussion

This chapter has investigated the effects of four HMI types and age on drivers' performance, workload and attitudes when retaking driving control from a HAV operating in automated driving mode. This section discusses the results of the participants' takeover control performance including the time aspects of takeover and takeover quality and their perceived workload as well as their attitudes when using each of the four types of HMI.

7.4.1 Time aspects of takeover

7.4.1.1 Effect of HMI on the time aspects of takeover

The Time aspects of takeover consists of reaction time, takeover time and indicator time. These variables were used to measure how quickly the participants responded to the HAV system's takeover request, when they executed the first conscious input to the vehicle and made the decision to conduct the lane change to avoid the stationary vehicle ahead on the road during the process of taking over manual driving control from the HAV.

For the reaction time, the results in Section 7.3.2 show that participants reacted to the takeover request significantly faster when using the V HMI and R+V HMI compared to the Baseline HMI and R HMI. The reaction time of R HMI was also slightly faster than that of the Baseline HMI, but the difference was not statistically significantly. Regarding takeover time, the results in Section 7.3.3 reveal that the time that participants took to generate the first active input to the vehicle was significantly faster in the R+V HMI situation compared to the R HMI situation. Although there was no statistically significant differences between the takeover times for other HMI situations, the data seems to indicate some potential differences. For instance, participants generated the first active input to the vehicle much more quickly when using the V HMI (M=3.40s, SD=1.48s) and R+V HMI (M=3.26, SD=1.30s) compared to when using the Baseline HMI (M=3.79s, SD=1.47s) and R HMI (M=3.26s, SD=1.30s).

The results strongly suggest that, when using the V HMI and R+V HMI, disengaged drivers were more confident and reacted quicker. Both reaction time to the takeover request and time to execute the first active input to the vehicle were shortened. This benefit may be credited to the provision of information on the vehicle status prior to the HAV system's takeover request. This indicates that, when drivers were fully concentrating on the reading task rather than driving the HAV, such information could speed up the process of getting them back into the vehicle control loop. The issue of ‘out-of-the-loop’ performance decrement has been broadly recognized as a negative effect of automation systems (Endsley and Kiris, 1995; Kaber and Endsley, 1997). When human operators are kept out of the control loop of a system, little or no interaction between the operator and the system could significantly reduce the human’s situation awareness significantly. As an result of this, when the system requires the operators to reassume control, the time taken by the operators to shift their focus, understand what is going on, recognise the problems and be ready for execution can be much longer than when they are constantly involved in the system’s control loop (Endsley and Kiris, 1995; Kaber and Endsley, 1997). Therefore, in the current research, when the HAV system suddenly initiated a takeover request, participants who were fully concentrated on reading with little awareness of what was happening, required a longer time to proceed with the task of taking over control of the vehicle than if they were already engaged in the driving loop. Providing the indications of the current mode or status of the system is an understandable way of enhancing operators’ situation awareness (Endsley, 1995b). This has guided the design of the current study. Audible information on vehicle status, including automation mode followed by the speed prior to the takeover request, may have enhanced the participants’ perception of the relevant information and elements in the environment (Level 1 situation awareness) and made the understanding of the current situation easier (Level 2 situation awareness) and enabled a ‘projection’ of the likely consequence (Endsley, 1995b; Stanton *et al.*, 2001). The enhanced situation awareness may have compensated for the negative effect of the ‘out-of-the-loop’ issue to some extent and thus resulted in faster reaction times and takeover times among participants. The outcomes of the current research are in line with an earlier study by Seppelt and Lee (2007), who found that providing continuous information about the functionality of the in-vehicle system potentially enhanced the driver’s situation awareness.

In terms of indicator time, the results in Section 7.3.4 show that the time that the participants took to make the decision concerning lane change was statistically significantly faster in the R+V HMI situation than with R HMI and V HMI. Although no statistically significant difference was found between other HMI situations, the data suggest that participants’ indicator time was similar among the Baseline HMI, R HMI and V HMI situations. However, the indicator time when using R+V HMI was much faster than when using the Baseline HMI, and the difference showed a certain trend towards statistically significant ($p=0.087$). These results provide an indication that, when the information concerning vehicle status and reasons for takeover are presented to participants separately, such as in the R HMI and V HMI, their effects on speeding up indicator time are not obvious. However, when combining these two types of information together in the HMI of the HAV, such as in R+V HMI, this may have the potential to make the indicator time faster, which reflects a more rapid decision about the lane chance to overcome the stationary car ahead among the participants after taking back control from the HAV. Thus, it can be suggested that providing the information of the critical cues has the potential to enhance the operators' situation awareness during critical events (Endsley, 1995b). In the context of the transition control process in the HAV, the drivers need to firstly take back control of the vehicle and then respond to whatever critical events lie ahead of them. Thus, despite verbally informing them of the reasons for takeover may have some effect on helping them to better understand the critical event (stationary car ahead), they may have spent extra time while obtaining the vehicle control due to the 'out-of-the-loop' performance decrement in the HAV (Endsley and Kiris, 1995). When verbally informing the drivers of the vehicle status together with the reasons for being requested for intervention in the takeover request, this may have a more comprehensive effect on enhancing participants' perceptions and comprehension of the tasks of taking over control of the vehicle as well as overtaking the stationary car ahead, and therefore their enhanced situation awareness may have a substantial contribution in speeding up the time that participants take to make the decision to change lane to overtake the stationary vehicle.

7.4.1.2 Effect of Age on Time aspect of takeover

In terms of the influence of age on the time aspects of takeover, the results in Sections 7.3.2 and 7.3.4 reveal that older drivers exhibited significantly longer reaction times and indicator times compared to the younger drivers. These findings correspond to the findings of Chapters 4 and 5. Again, these findings could be possibly explained in terms of a number of age-related functional changes, involving impairments in visual and aural senses, cognitive abilities, and longer reaction times as well as deteriorating psychomotor abilities which may have resulted in delaying the time taken to switch to the manual driving position and generating the turn signal indicator for the lane change among the older drivers compared to the younger drivers when resuming control from the HAV (Stelmach and Goggin, 1988; Brouwer *et al.*, 1991; Attebo *et al.*, 1996; Helzner *et al.*, 2005; Myerson *et al.*, 2007; Pollatsek *et al.*, 2012; Ferreira *et al.*, 2013a).

In contrast to the findings in Chapter 4 and 5, the results in Section 7.3.3 show there were no significant differences in the takeover time of older and younger drivers. A possible explanation for this could be that the simulated HAV in this chapter incorporated four types of HMIs, whereas the simulated HAV in Chapters 4 and 5 only used the baseline HMI. The new types of HMIs may have compensated the age difference in the takeover time to some extent. This results could be explained by the significant interaction effect between age and HMI type on the takeover time, which is discussed in the next section.

7.4.1.3 HMI × Age interaction Effect on Time aspect of takeover

The results in Sections 7.3.2 and 7.3.3 show a significant interaction effect between age and HMI type on participants' reaction time and takeover time, which indicates that older and younger drivers were affected differently by different types of HMIs. For the older drivers, all three measurements showed a trend of consistent reduction from using the Baseline HMI, to the R HMI, V HMI and the R+V HMI. However, the three measurements for the younger drivers exhibited a trend of increasing time from the Baseline HMI to the R HMI, and then they showed a trend of progressive decline in time when using V HMI and R+V HMI. R HMI benefits older drivers but not younger drivers in terms of these three measurements. These findings indicate that providing different types of HMI in the HAV has different effects on older and younger drivers. These findings are further discussed together with the results for participants' perceived workload in Section 7.4.4.3.

7.4.2 Takeover quality

7.4.2.1 Effect of HMI on takeover quality

The quality of takeover consists of the variables TTC, resulting acceleration as well as steering wheel angle. In terms of the effect of different types of HMI on takeover quality, the results in Section 7.3.5 show that there was no statistically significant difference in TTC in the four types of HMI situation. However, the results in Section 7.3.6 reveal that the resulting acceleration in the V HMI and R+V HMI situations were statistically significantly lower than in the Baseline HMI and R HMI situations. Moreover, the steering wheel angle (see Section 7.3.7) in the V HMI and R+V HMI situations was statistically significantly smaller than in R HMI. Although there were no statistically significant differences in steering wheel angle between the V HMI and R+V HMI compared to the Baseline HMI, the data seems to indicate potential differences where the V HMI and R+V HMI led to smaller steering wheel angle, representing more stable takeover, than the Baseline HMI. Finally, the V HMI and R+V HMI led to similar levels of resulting acceleration and steering wheel angle, and no significant differences were found between them.

These results provide a clear indication that solely providing participants with the information about HAV status (V HMI) as well as providing information of HAV status together with the reasons for takeover (R+V HMI) yielded a smaller resulting acceleration and steering wheel angle among the participants compared to the Baseline HMI and R HMI. This reflects that both V and R+V HMIs have similarly positive effects on longitudinal and lateral input to the vehicle. These findings could be possibly explained as that tasks of operating the longitudinal and lateral control of the vehicle essentially require the perception and understanding of the driving environment (Matthews *et al.*, 2001). Providing information about the HAV status (automation mode and speed) before the takeover request may have enhanced drivers' perception (Level 1 situation awareness) and comprehension (Level 2 situation awareness) of the takeover task (Endsley, 1995b) and thus lead to more stable longitudinal and lateral input to the vehicle among the participants. In terms of aspects of the drivers' mental workload, this finding could be explained if we consider that providing information of HAV status about the drivers before a takeover request may have helped them to maintain their attention capacity close to the optimal levels (Young and Stanton, 2002b; Young and Stanton, 2002a), which would improve the performance of operators of the automation systems(Young and Stanton, 2002b).

In addition, the results show that the analysis did not yield any statistically significant differences in the measurements of takeover quality in the R HMI and the Baseline HMI situations. However, the data showed that R HMI gave rise to the strongest resulting acceleration and the largest steering wheel angle among the four types of HMI (see Section 7.3.6 and 7.3.7). This may provide an indication that solely providing the participants with the reasons for takeover in the request, such as in the R HMI, may result in sharper and less stable longitudinal and lateral input to the vehicle, and therefore worse takeover quality among the participants. A possible explanation for this could be that when solely providing the reasons for takeover in the takeover request, the drivers had to assemble and process more information within the limited time available for takeover (a maximum 20s in this research). This suddenly increased demand may have exceeded the drivers' attentional capacity and caused a mental overload which could lead to deteriorating driving performance (Young and Stanton, 2002a). In addition, when drivers were suddenly informed about the stationary vehicle ahead of them in the takeover request, they may have become stressed, which may worsen the negative effect of mental overload on performance (Matthews and Desmond, 1995).

7.4.2.2 Effect of age on takeover quality

With regard to the effect of age on takeover quality, the results in Section 7.3.5 show that there was no significant difference in TTC between the younger and older drivers. This finding is in accordance with the findings of Chapter 4 (see Section 4.3.7). However, results of Chapter 5 (see Section 5.3.5) reveal that older drivers had significantly smaller TTCs than younger drivers. This could be due to that the HAV scenarios were all in clear weather conditions in Chapters 4 and 7, but they involved adverse weather in Chapter 5. This provides an indication that the age difference in terms of the TTC may not be noticeable when drivers were reassuming control from the HAV in clear weather, but it may have become more pronounced in adverse weather conditions.

In terms of the effect of age on the resulting acceleration and steering wheel angle, the results in Sections 7.3.6 and 7.3.7 show that older drivers generated significantly greater resulting acceleration and steering wheel angles than the younger drivers. This indicates that older drivers’ takeover is more abrupt and less stable than that of younger drivers, which is in accordance with the findings of Chapters 4 and 5.

7.4.3 Correlation analysis of takeover performance

7.4.3.1 Correlation between reaction time and takeover time

The results in Section 7.3.8.1 showed that for the R HMI there was no significant correlation between reaction time and takeover time. However, there were significant positive correlations between participants’ reaction time and takeover time when using the Baseline HMI, V HMI and R+V HMI. This indicates that in these three HMI situations participants who switched back to the manual position more rapidly also generated their first active input to the vehicle sooner. In addition, when taking over control of the vehicle from the HAV, if drivers’ takeover time is smaller than their reaction time, this indicates that they have executed the active input to the vehicle before they have completely switched to the ‘ready to drive’ position from and initial stage of engaging in the non-driving tasks, thus indicating relatively risky takeover behaviour. By qualitatively inspecting the scatterplots in Section

7.3.8.1 as shown in Figure 7.21, it is clear that the quantity of this type of risky participant are highest (13) when using the R HMI compared to the other HMI options. Also, V HMI resulted in the detection of 8 risky participants, and the Baseline HMI and R+V HMI led to 2 risky participants each. These findings provide an indication that the interface of the HAV should provide the information on vehicle status and reasons for takeover to participants together, as is done in the R+V HMI case. Providing these two pieces of information separately to participants, such as in R HMI and V HMI, is shown to potentially cause risky takeover behaviour among some participants.

7.4.3.2 Correlation between TTC and resulting acceleration

The results in Section 7.3.8.2 revealed that there was no significant correlation between TTC and resulting acceleration when the participants were using the Baseline HMI and R+V HMI. However, there was a significant moderate positive correlation between TTC and resulting acceleration when they were using the R HMI and V HMI. This finding may suggest that providing the reasons for takeover and vehicle status separately to the drivers may have resulted in sudden collision avoidance behaviour, where they braked and steered harder that resulted in a longer TTC in order to avoid the stationary car. In addition, the findings of qualitative inspection of the scatterplots in Figure 7.22, which showed that the R+V HMI resulted in the highest number of safe drivers (49), while the R HMI led to the smallest number of safe drivers (30). Also, the R+V HMI resulted in the smallest number of potentially unsafe drivers (7), while the Baseline HMI resulted in the highest number (11). The majority of critical drivers under all HMI situations were older drivers. These findings provide an indication of which HMI design concept is most beneficial to drivers of the HAV.

7.4.3.3 Correlation between TTC and steering wheel angle

The results in Section 7.3.8.3 show that there was no significant correlation between TTC and steering wheel angle when the participants were using the Baseline HMI, V HMI and R+V HMI. However, the R HMI led to a significant moderate positive correlation between TTC and steering wheel angle. This may indicate that when the HMI verbally informing the drivers the reasons for takeover during the takeover request, drivers who had larger deviations in their steering wheel input left a longer TTC to the stationary vehicle, which may also suggest sudden collision avoidance behaviour. In addition, Table 7.19 shows the results of a qualitative inspection of the scatterplots in Figure 7.23, where the R+V HMI resulted in the highest number of safe drivers, while the R HMI resulted in the lowest number. Also, R+V HMI led to the smallest number of critical drivers, while V HMI led to the highest number. The majority of critical drivers in all HMI situations were older drivers. The findings of this section correspond to those of Section 7.4.3.2, indicating that the R+V HMI is beneficial to HAV drivers.

7.4.4 Workload and attitudes

7.4.4.1 Effect of HMI on workload and attitudes

According to responses to the NASA-RTLX scale (see Section 7.3.8), participants rated their workload to be lowest when using R+V HMI, and it was significantly lower than when using the Baseline HMI. In addition, participants' highest perceived workload was when using the R HMI, which was significantly higher than when using the other three types of HMI. In terms of participants' attitudes towards the four types of HMI, according to responses to the 7-Likert scale questionnaire, the results in Section 7.3.9 show that the percentage of positive attitudes towards the R HMI, V HMI and R+V HMI were higher than for the Baseline HMI. The R+V HMI received the highest percentage of positive attitudes among the four types of HMI. In addition, the Baseline HMI received the same median attitude scores (Mdn=5) as the R HMI. The attitude scores for the V HMI and R+V HMI were significantly higher than those for the Baseline HMI and R HMI. Moreover, the attitude score for R+V HMI were significantly higher than those for V HMI.

The above results for participants' perceived workload and subjective attitudes suggest that the R+V HMI approach of providing information about HAV status before the TOR together with the reason for takeover during the TOR leads to the lowest workload and highest acceptance. Considering this result together with the findings of sections 7.4.1.1 and 7.4.1.2, a clear indication is provided that the R+V HMI design concept is beneficial to drivers of the HAV. The R+V HMI concept may have helped to maintain drivers' workload demand to an optimizing level and therefore improved their performance in reassuming control of the vehicle (Stanton and Young, 1998). Moreover, this finding corresponds with previous findings which suggest that inadequate feedback about the status of an automation system causes difficulties among human operators (Norman, 1990) and drivers of automated vehicles should be informed about the current mode of the system in order to avoid confusion (Debernard *et al.*, 2016). In addition, results show the R HMI concept which solely informs drivers about the stationary car ahead in the TOR increases participants' perceived workload. When considering this finding along with the findings in Section 7.4.2.1, there is clear evidence that the R HMI concept resulted in significant issues in the participants' takeover quality as well as in their perceived workload.

7.4.4.2 Effect of age on workload and attitudes

In terms of age differences in perceived workload, the results in Section 7.3.8 show that older drivers (M=29.02, SD=6.78) perceived a significantly greater workload than younger drivers (M=26.02, SD= 7.75) when reassuming control from the HAV. This finding corresponds with those of previous studies that older drivers perceived significantly higher workload than younger drivers when interacting with advance driver-assistance systems (ADAS) as well as automated vehicles (Kim and Son, 2011; Molnar *et al.*, 2017).

Regarding the effect of age on subjective attitudes towards the HMIs of the HAV, the results in Section 7.3.9 show that older and younger drivers had similar attitudes towards the HMIs of the HAV, and no significant age differences were found. Considering that the three HMIs tested in this study-R HMI, V HMI and R+V HMI were designed based on older drivers' requirements derived from the findings of Chapter 6, this provides an important evidence supporting the idea of designing in-vehicle technologies for older drivers which may also benefit drivers of all ages (Czaja *et al.*, 2009).

7.4.4.3 HMI × Age interaction

In addition, the results in Section 7.3.8 reveal a significant interaction between age and HMI type in influencing the participants' workload scores. This shows that the perceived workload of older and younger drivers were affected differently by the four types of HMI. Their workload scores of older drivers showed a trend of consistently sharp decreases from using the Baseline HMI, to the R HMI, V HMI and the R+V HMI. However, the workload scores for younger drivers exhibited a trend of sharply increasing from the Baseline HMI to the R HMI, and then showed a sharp reduction from the R HMI to V HMI. Then they declined slightly from the V HMI to the R+V HMI.

When considering the above results together with the results in Sections 7.3.2 and 7.3.3, there is a clear indication that the R HMI where only the information about the HAV status (automation mode and speed) is provided before the takeover request affected older and younger drivers in opposite ways. This finding could be possibly explained by that the fact in this research, after the HAV system initiated a takeover request, drivers have to stop the reading task they were performing and then to perceive and comprehend the situation in order to effectively take over control of the vehicle. However, age-related visual and cognitive functional impairments may negatively affect older drivers' ability of perceiving and understanding the takeover situation. Providing them with information that there is a vehicle ahead in the takeover request may have compensated for any such age-related visual and cognitive impairments, and thus resulted in slightly faster reaction times and takeover times as well as a lower perceived workload. However, for the younger drivers, this same information about the HAV status may just represent an additional distraction and add to the workload, which may have resulted in delayed responses to the takeover request as well as a higher perceived workload.

Generally, these findings provide new evidence to support the hypothesis that older drivers react to HMIs in HAVs in different ways compared to the younger drivers. Moreover, their needs and requirements of both sets of drivers should be carefully considered during the design process of new technologies (Emmerson *et al.*, 2013; Guo *et al.*, 2013a; Edwards *et al.*, 2016).

7.5 Conclusion

This investigation aimed to study two areas; firstly, to investigate the effect of different types of HMI with different levels of information which results in a request for the driver to retake over manual control of a HAV that is currently operating in automatic mode, on the driver's takeover performance, and perceived workload as well as attitudes; and secondly to further examine age differences in terms of takeover performance, workload and attitudes.

Firstly, in regard to the effect of different HMIs, the four types of HMI used in this investigation included one baseline HMI and three other types (R HMI, V HMI, R+V HMI) which were developed based on two of the older drivers' stated requirements for the human-machine interface of HAV that were identified in Chapter 6. This investigation has found that the HMI informing drivers of vehicle status together with the reasons for takeover (R+V HMI) resulted in good takeover performance, lower perceived workload and highly positive attitudes, and it is clearly the most beneficial and optimal HMI approach to the drivers of

HAVs. This conclusion was drawn through the analysis of the parameters measured and observed below, where the R+V HMI resulted in:

- the fastest reaction time among the four HMIs and significantly faster reaction time compared to the R HMI and the Baseline HMI.
- the fastest takeover time among the four HMIs and significantly faster takeover time compared to the R HMI.
- the fastest indicator time among the four HMIs, and significantly faster indicator times compared to the R HMI, and faster indicator times compared to the Baseline HMI, and where the difference showed a certain trend towards significance (p=0.087).
- the smallest resulting acceleration among the four HMIs and significantly smaller resulting acceleration compared to the R HMI and the Baseline HMI.
- the smaller steering wheel angles compared to the Baseline HMI and significantly smaller steering wheel angles compared to the R HMI.
- less risky takeover than the R HMI and V HMI, and the highest number of safe drivers and smallest number of critical drivers among the four HMIs.
- lowest workload scores and significantly lower workload scores than for the Baseline HMI and R HMI
- the most positive attitudes among the four HMIs which were significantly more positive than for the Baseline HMI, R HMI and V HMI.

Furthermore, this investigation has found that verbally informing the drivers about the vehicle status, including automation mode and speed, before the takeover request (V HMI) also had a positive effect on takeover performance, workload and attitudes. Specifically, it had a similar positive effect to that of the R+V HMI in terms of reaction time, takeover time, resulting acceleration and steering wheel angle. It led to lower perceived workload than the Baseline HMI and significantly lower workload than the R HMI. Moreover, it resulted in significantly higher positive attitudes compared to the Baseline HMI and R HMI.

Moreover, this investigation has found that the R HMI affected the older and younger drivers in different ways in terms of reaction time, takeover time and the workload score. Although it reduced reaction time, takeover time and workload compared to the Baseline HMI among the older drivers, it resulted in a rise in all the three parameters among the younger drivers. In addition, for the participants overall, it resulted in the highest resulting acceleration, and steering wheel angle and the largest number of risky takeovers among the four HMIs. Therefore, the R HMI approach could not be deemed as a suitable design.

The second aim of this research was to examine age differences when drivers were interacting with the HAV. This investigation has found significant age differences in drivers' takeover performance and perceived workload through the analysis of the parameters of reaction time, indicator time, resulting acceleration, steering wheel angle and workload score. The findings of this investigation suggest that compared to younger drivers, older drivers took longer to switch back to the manual driving positon after receiving the takeover request. They were also slower to take the decision to change lane to overtake the stationary car ahead. Moreover, older drivers were recorded to have harder braking and accelerating patterns, less stable steering control, and more critical and risky takeover than among the younger drivers. One can conclude that, older drivers perceived the workloads to be higher compared to the younger drivers.

In summary, the findings of this investigation emphasize the importance of fully considering the needs and requirements of older people when designing the HMIs of automated driving systems, and this would have potential to facilitate safer and more effective performance when interacting with the HAV for both younger and older drivers. The implications and recommendations of the findings are discussed in the next chapter.

Chapter 8. Recommendations for Facilitating Safe and Comfortable Human-Machine Interaction in HAVs for Older Drivers

8.1 Implications and recommendations

The findings described in Chapters 4 to 7 provided several implications and recommendations for policy makers as well as the original equipment manufacturers (OEMs) in terms of designing and facilitating safe and comfortable human-machine interactions in HAVs for older drivers. In order to present these implications and recommendations in a logical structure, they were grouped into five categories based on the different scenarios involving older drivers interacting with the HAV, as shown in Table 8.1. Furthermore, some of the recommendation made in this study may create the need for future research to determine their effectiveness and safety, and this is discussed in greater detail in Section 9.2.

Table 8.1 Overview of recommendations

Implications and recommendations for the design of human-machine interaction in the HAV	
Pre-usage of the HAV	• Appropriate strategies for introducing the HAV to the older drivers • Hands-on opportunities in the HAV for older drivers • A test of takeover performance in the HAV • Training process of the takeover of control in the HAV
During automated driving in the HAV	• Specially design car interiors to support older drivers' preferred tasks • Driver monitoring system in the HAV • Information systems in the HAV • Adaptive modalities of system feedback
During the takeover of control in HAV	• Providing sufficient lead time for takeover in the HAV • Providing a longer lead time for takeover in snowy and foggy weather • Adjustable and hierarchical takeover request • Explanatory takeover request • Specially designed car interiors taking into consideration of takeover request • Additional support mechanisms during takeover
Driving styles of the HAV	• Imitative and corrective driving styles of the HAV • Multiple-user mode of driving style.
Beyond the HAV	• Close cooperation between the HAV and connected ITS • Promoting level 4 automation (SAE) • Differentiating older drivers' requirements towards the HAV and FAV.

8.2 Recommendations for Pre-usage of the HAV

This section presents the recommendations focusing on the measures that could be implemented before using the HAV to potentially help older drivers to develop a better understanding of the HAV and to be better prepared to use it, including the following:

- ***Appropriate introduction strategies of HAV to older drivers.***

The findings of this study indicate that it is very important for older drivers to be able to maintain the ability to manually drive the HAV and they need to perceive the potential control of the HAV this entails knowing that they could intervene to control the vehicle at any time even though they are not at present exercising manual control in the HAV (see Section 6.3.3 for further detail). A recommendation could follow from this finding indicating a suitable way to introduce and explain the HAV to older drivers. The introduction strategies or instructions describing the HAV and its functionality should have a section that clearly explains to the user or potential purchaser that the driver can retake manual driving control at any time they wish and may be requested by the HAV to take over driving control from the automated driving state. Instead of overemphasizing the 'self-driving' or 'autonomous driving' features of the HAV, which may result in the misapprehension by some older drivers that their driving abilities could potentially be taken away from them by the HAV and thus causing anxiety about losing control over their lives, an appropriate standpoint to introduce the HAV to older drivers could be, for example, that the 'HAV is a new type of vehicle that drivers can drive exactly as with a conventional vehicle; however, under circumstances where the driver does not feel like driving in, such as when driving on a motorway, or they feel it is difficult to drive, such as when driving long journeys, they can give control over the vehicle to the HAV and can then safely do other activities such as reading, although the driver can take back control of driving at any time they want'.

- ***Hands-on opportunities in the HAV for older drivers.***

This study found that first-hand experience with the HAV on the driving simulator helped older drivers to develop a realistic understanding of HAVs and to improve their trust and confidence in the HAV (see Section 6.3.2 for further details). Therefore, it is necessary to provide more hands-on opportunities for older drivers to enable them to gain first-hand experience of the HAV. Here there are analogies to the early days of the introduction of electric vehicles, where until people experienced them their perception of the technology was generally negative. This research provides evidence indicating that hands-on experience on the driving simulator is beneficial for older drivers to gain a better understanding of the HAV, and further research could examine the effect of experience HAV on real roads on the attitudes and performance of older drivers.

- ***A test of takeover performance in the HAV.***

This study found statistically significant age differences in the performance of the interaction with the HAV, and considerable individual variability in takeover performance among the older drivers (see Section 4.3, 5.3 and 7.3 for further details). Before starting driving with an HAV, a test of takeover performance could be suggested to the potential users of HAVs. Such a test should include takeover scenarios under various types of weather conditions if possible. The results of the test would help the older drivers to build an understanding of their capability and performance of interacting with the HAV. Although this study only included HAV system-initiated takeover situation (see Sections 3.3.3.1 for further details), such a test could include both HAV system-initiated takeover and driver-initiated takeover situations.

- ***Training process of takeover control.***

Based on the results of the testing suggested above, a corresponding training process of taking over control in the HAV could be implemented for the drivers. Such a training process may help the older drivers to be better prepared to use the HAV, as training has been found to be able to improve driving performance of older people on the trained tasks (Cuenen *et al.*, 2016).

8.3 Recommendations concerning the human-machine interaction during the automated driving in the HAV

This section presents the recommendations drawn from this study focusing on the design of the human-machine interaction functions during the period when the HAV is performing the automated driving and allowing drivers to be disengaged from driving, including the following:

- ***Specially designed car interiors to support older drivers' preferred tasks.***

In the qualitative part of this study, it was found that the older drivers preferred to perform a variety of non-driving related tasks when disengaging from driving in the HAV, including reading, talking with passengers in the car, listening to the radio, looking at the scenery and monitoring the system driving, using a mobile phone, watching TV or movies, doing exercises, thinking, meditation and breathing, working, doing crosswords, monitoring the HAV driving, and eating and drinking tea or coffee (see Section 6.3.4 for further details). The interior of the HAV should be designed to support these preferences of older drivers so as to enhance the comfort of their experience in the HAV. For example, a compact bookshelf and a tablet dock could be provided for the convenience of those who would like to read; and adjustable and rotatable driver's seats could provide more space for those older drivers who want to do exercises and also to allow older drivers to better enjoying their conversations with other people sitting in the back of the vehicle without constantly having to turn their head. A mobile phone holder would benefit those who want to use their phone; a large in-vehicle screen would allow them to better enjoying TV and film; a panoramic windscreen could also enhance their experience while monitoring driving or looking at the scenery, a foldable table would benefit those who preferred to work or do crosswords and would enable them to better enjoy their food and drink during automated driving; a water boiler could be provided to help them make coffee and tea and a cup holder may prevent the drink from spilling. Future research should examine the effects of these aspects of interior design on drivers' performance and the usability of HAVs.

- ***Driver monitoring system in the HAV.***

During automated driving in the HAV, previous research found that older drivers were more involved or engrossed in the non-driving related tasks compared to younger drivers (Clark and Feng, 2017)and in the present quantitative part of this study, it was found that older drivers' takeover performance was more affected than younger drivers by their complete disengagement from driving than younger drivers' (see Sections 4.3 further details). These findings may suggest that it is necessary for the HAV system to keep an eye on older drivers' status when they are not driving in the HAV. This implication was supported by the findings of the qualitative research part of this study which showed that older drivers expressed a desire that the HAV should be able to monitor their status and react accordingly (see Section 6.3.5 for further details). Combining the findings above, there is a need for the HAV to incorporate a driver monitoring system. Given that the benefits and effectiveness of the driver monitoring systems in conventional vehicles have already been widely recognized.(Dong et al., 2011; Gesser-Edelsburg and Guttman, 2013), the findings of this study indicate that such a system could also be useful and could potentially enhance the safety of older drivers when interacting with the HAV. For example, if the driver monitoring system detects that drivers were too involved in non-driving tasks in the HAV or had fallen asleep and may not respond to a takeover request safely and effectively, the driver could be warned by an additional alert, a higher-volume audio alert or a haptic vibration alert. Such a system could also occasionally remind older drivers who were doing other tasks to re-engage with driving for a period of time, such as reminding them to manually drive or monitor the system driving, so as to reduce the influence of complete disengagement from driving on their take-over performance. Future research could thus explore the detailed design of such a system in the HAV and also evaluate its effectiveness and safety.

- ***Information systems in the HAV.***

The quantitative part of this study found that adverse weather, especially fog and snow, led to significant deterioration in drivers' takeover performance in the HAV and older drivers were affected more seriously than younger drivers (see Section 5.3 for further details). Therefore it could be useful to provide advance notice of adverse weather to alert older drivers who are disengaged from driving, to help them to be prepared in case any takeover of control was needed. Corresponding to this, the qualitative part of this study found that older drivers would like to receive feedback from the HAV to keep them updated with information about the journey, vehicle status and traffic when the HAV is performing automated driving (see Section 6.3.5 for more details). Furthermore, this requirement was tested quantitatively in this study (see Section 7.3), and the results showed that feedback about vehicle status, including automation mode and speed, before the takeover request was beneficial to drivers' takeover performance. Combining all these findings, it might be necessary for the HAV to include an information system to inform the drivers, especially when they were disengaged from driving, about important aspects of the journey. Before travelling with the HAV, the information system should issue warnings of adverse weather, particularly snow and fog, to drivers in case they had not been aware of it when planning their trip. If the HAV system receives a weather forecast about forthcoming adverse weather during the trip, the information system should alert drivers who are disengaged from driving about the adverse weather in advance in order to help them to be prepared in case any takeover of control was needed. It could also provide feedback about vehicle status and give journey information to disengaged drivers to facilitate safe and effective interaction with the HAV. The significance of information systems for older drivers' safety in manual driving has been pointed out by previous research (Merat et al., 2005; Guo et al., 2010a). This study shows that it could also be useful in the field of the HAV. Future research should further assess the effectiveness and safety of such a system and what information is the most critical to be provided.

- ***Adaptive modalities of system feedback.***

This study found that older drivers require the system feedback of the monitoring and information systems to differentiate between routine and urgent information (see Section 6.3.5). This indicates that of the actions of monitoring and feedback systems should adapt to the urgency of information. For advisory information, such as concerning the journey, vehicle status, traffic conditions and road conditions, information could be presented in a visual modality, or visual combined with a voice modality. The voice could be a soft voice. For urgent and safety critical information, such as concerning fuel status or takeover requests, a visual combined with a voice modality could be used. The voice should be loud and clear enough to interrupt the non-driving related tasks drivers were performing and to attract their attention quickly and effectively.

8.4 Recommendations concerning the human-machine interaction during the takeover control in HAV

This section focuses on the implications and recommendations concerning the human-machine interaction of the HAV during the process of taking control, including the following:

- ***Providing sufficient lead time for takeover in the HAV.***

In the HAV scenario in this study, a lead time of 20 seconds was provided to drivers to take over control of the vehicle (see Section 3.3.3.5 for details). In the qualitative part of the study it was found that this lead time is generally an adequate period for the older drivers to comfortably reassume control of the HAV in clear weather (see Section 6.3.6). This finding was also validated in the quantitative part of this study, where this lead time resulted in no collisions involving either the younger or older drivers when taking over control in clear and rainy weather (see Section 5.3.3). These findings concerning the lead time for takeover focus on the variables and conditions of this study and generate a need for providing sufficient time for takeover in HAVs.

- ***Providing a longer lead time for takeover in snow and fog conditions.***

In the qualitative part of this study it was found that older drivers indicated that a longer lead time was needed when taking over control from the HAV in foggy weather (see Section 6.3.6). This finding was supported by quantitative results in this study showing that considerable numbers of collisions and critical encounters were recorded in snow and fog (see Section 5.3.3 for details). Therefore a longer lead time should be provided if any takeover has to be conducted in adverse weather conditions such as snow or fog, although this may be an issue for the HAV if visual cameras are used by the vehicle to detect a stationary vehicle ahead as its range and accuracy may be compromised due to the snow or fog.

- ***Adjustable and hierarchical takeover request.***

The findings of this study (see Section 6.3.6 for details) indicated that older drivers expressed a need to be able to adjust situations in which they would receive a takeover request from the HAV, such as on familiar roads or when driving conditions are evaluated to be suitable for them to wish to drive manually. In addition, they would like a hierarchical structure of takeover requests that would differentiate between safety critical and non-urgent takeover situations. For an urgent takeover request, such as when encountering a system limitation, the visual message could be in red, and the voice message should be clear, serious and straightforward. For non-urgent takeover requests, such as a user's predefined takeover request on familiar routes, the visual message could be in green and the voice message could be relaxed and soft.

- ***Explanatory takeover request.***

This study found that some older drivers wanted the HAV to inform them about what is happening when they are disengaged from driving (see Section 6.3.5), and also they would like takeover requests to include descriptions of the reasons for takeover to manual driving request (see Section 6.3.6). Based on these two requirements of older drivers, this study has designed an explanatory takeover request (see Section 7.2.1 for details) which gives information about vehicle status together with providing the reasons for the takeover. This was found to have statistically significant benefits for both younger and older drivers. Therefore, the explanatory takeover request (R+V HMI in Section 7.2.1.3) is recommended for the design of the HAV.

- ***Specially designed car interiors coordinating with takeover request.***

As discussed above in Section 8.3, the findings of this study suggested several specially designed car interior features to facilitate non-driving related tasks so as to enhance older drivers' driving experience in the HAV. However, for an urgent takeover request, some non-driving related tasks may pose a threat to the safe and effective takeover of control; for example, if drivers are too involved in the film they are watching or book they are reading, or both their hands are fully occupied due to holding a tea cup in one hand and a book in the other. In this case, there is a need for specially designed car interior features to be suitable for the system takeover request in order to ensure the safety and efficiency of takeover and to enable drivers to be able to rapidly disengage from the non-driving related tasks. For example, following an urgent takeover request, the tablet should be turned off or moved away from the driver automatically; or the rotatable seat should turn back to the driving direction if the driver was facing the back talking to other people in the car. Also the cup holder or bookshelf should be close enough for the drivers to put down their cup or book promptly so as to switch back to the driving position and to take over control of the vehicle.

- ***Additional support mechanisms during takeover.***

This study found significant age difference in terms of operating the steering wheel and pedals when taking over control from the HAV (See Sections 4.3.8, 4.3.9, 5.3.6 and 5.3.7). This suggests that additional support mechanisms could be provided for older drivers such as a steering assistance system (SAS) and intelligent speed adaption (ISA) for use during the process of reassuming control process of the HAV. In addition, this study found worse take-over performance among both older and younger drivers in the snow and fog (see Section 5.3). In this study, the simulated adverse weather conditions mainly focused on reduced visual clarity, and therefore there is a need for additional HMI functionality in the HAV, for example, projecting an image of the driving environment and road conditions to the head-up display (HUD) to compensate for drivers' reduced visibility. Moreover, other support mechanisms could be provided to the driver during these adverse weather situations, such as a collision avoidance system (CAS).

8.5 Recommendations concerning the driving styles of the HAV

This section discusses the implications and recommendations drawn from this study in terms of the style of driving the HAV.

- ***Imitative and corrective driving style.***

This study found that older drivers had a specific requirement in terms of the driving style of the HAV (see Section 6.3.7 for more detail). The HAV could thus be designed to be able to analyse the drivers' driving style when the driver is manually driving the vehicle. And then then it could adjust itself to drive like their owner when it is performing automated driving. However, it should only adapt to the good driving styles of their owner, but to correct all the bad aspects of driving style. If the HAV system detects any potentially dangerous driving habits when drivers are driving manually, it could also send a reminder to help the driver to correct them and drive more safely. The significance of such driving style analysis functions on driving safety have already been recognized in research into manual driving (Constantinescu et al., 2010; Meiring and Myburgh, 2015), and the findings of this study indicate that it may also potentially enhance the safety and comfort of drivers when interacting with the HAV.

- ***Multiple-user mode of driving style.***

Given that people's preferences and driving styles vary, the HAV could be designed to have multiple-user modes in terms the driving style, so that every time it detects that a different driver is using it, it could automatically switch to the corresponding user mode to fit individual requirements.

8.6 Recommendations beyond the HAV

This section focus on recommendations beyond the boundaries of the HAV.

- ***Close cooperation between the HAV and connected ITS.***

The findings of this study lead to an emphasis on the need for automated vehicles to be in communication with an intelligent infrastructure to enable them to have a better understanding and recognition of the driving environment, so that they can effectively update drivers with information concerning road and traffic conditions to compensate for the reduced visual clarity of the road ahead caused, for example, by adverse weather conditions. This highlights the importance of the collaboration between automated vehicle research community and the Connected ITS research community. However, the present research used a lead time for takeover of 20s for a vehicle driving at 60mph, gives a physical distance between the point when the driver is asked to take over control of the vehicle and the (obstacle) stationary car of just over 500m. In reality there would be many situations where the vehicle may not have 500m of 'electronic vision' to the obstacle due to traffic conditions or the curvature of the road. This suggests that vehicles will need to be in communication with intelligent infrastructure so that obstacles can be detected and relevant information conveyed to on-coming automated vehicles so that they can initiate evasive measures automatically or, as in the case of the trials tested here, make a request to the driver to take over control of the vehicle. This adds additional complexity to road vehicle automation with the requirement for vehicle-to-vehicle and vehicle-to-infrastructure communication. It is thus imperative that the automated vehicle research community and those that are undertaking the development and proving of Connected ITS (Edwards et al., 2018) work closely together to solve these safety-critical issues.

- ***Prompting Level 4 automation (SAE).***

In the quantitative part of this study, the findings of Chapter 5 indicate that, despite 20 seconds of lead time being provided, both younger and older drivers performed poorly when taking over control of the vehicle from the HAV in adverse weather conditions, especially in snow and fog. Given that the HAV in this research involves level 3 automation (SAE, 2014) which relies on human drivers to respond safely to takeover requests initiated by the system, one implication is that the usage of level 3 automated vehicles may need to be limited in adverse weather. In addition, there may also be a need to promote the development of level 4 automation which can automatically initiate and adopt a safe driving mode even if the human driver does not respond safely to a takeover request when driving in adverse weather conditions (SAE, 2014). For example, if the snow or fog was too heavy for the drivers to perform a safe takeover, the HAV could activate a safe mode which would pull the vehicle over to a safe place until the weather conditions had been evaluated as being within the safety range of a safe and smooth takeover for the driver. In addition, in terms of the driver-initiated takeover where drivers want to manually control the vehicle during adverse weather, the HMI of the HAV should also inform the drivers about the potential negative impact of the adverse weather on their takeover performance and advise them to takeover control and drive cautiously. After the drivers have successfully taken over control of the vehicle, the HAV system may need to continue monitoring drivers' driving performance to take into account the potential negative influence of adverse weather.

- ***Differentiating between older drivers' different requirements towards HAV and FAV.***

The findings of the qualitative part of this study showed that older drivers would like a HAV in automated mode to help them keep driving safely and for longer distances for now, and they would like a completely driverless car (Level 5 automation SAE (2014) to help them to stay mobile when they become too old to drive safely (see Section 6.3.2 for further details). This shows the importance for OEMs and policy makers to distinguish between the different requirements of those older people who are still active drivers and those who have already given up driving. For example, Level 3 or 4 HAVs with good manoeuvrability would still allow drivers to enjoy the pleasure of manually driving, and this may be more easily adopted by some older active drivers. Meanwhile, for those who have ceased driving, they may be more interested in the Level 5 automated vehicles (SAE, 2014) which are able to help them to fulfil their daily travel demands and to maintain mobility and independence. And those older active drivers who prefer to use Level 3 or 4 HAVs may be more likely to use a Level 5 fully automated vehicle when they give up driving.

Finally, the recommendations arising from the findings of this research are coloured and highlighted in three categories in Figure 8.1 based on their priority in supporting older drivers in HAV. The first category (the green box in Figure 8.1) summarises the recommendations could have the greatest potential impact on enhancing the safety of older drivers when interacting with the HAV, therefore they were proposed as the top priority. The second category (the yellow box in Figure 8.1) summarises the recommendations that could potentially have a positive impact mainly on acceptance of the HAV and comfort for older drivers, thus they were proposed as medium-priority recommendations. Finally, the third category summarises the recommendations which generally require the popularization of HAVs or advanced developments in vehicle automation technologies, therefore, they were proposed as long term recommendations.

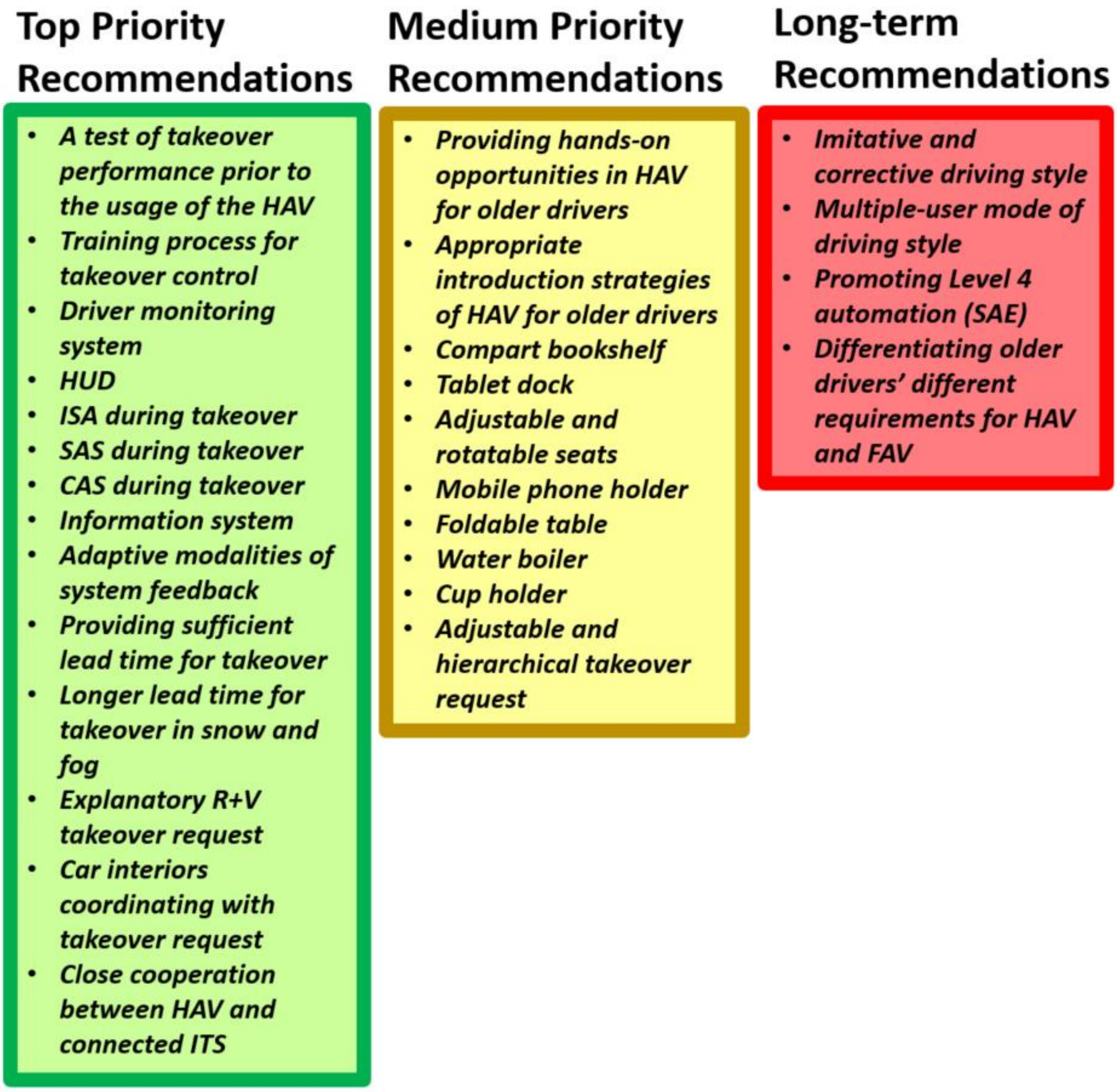


Figure 8.1 Implications and recommendations for the development of age-friendly human-machine interaction in the HAV.

Chapter 9. Conclusions

9.1 Introduction

The development of highly automated vehicle (HAV) has the potential to enhance road safety, improve social inclusion, and reduce emissions and congestion (DfT, 2015e). It also has the potential to deliver benefits for the mobility and wellbeing of older drivers by enabling them to continue to drive safely and for longer distance. This has created the need to involve older drivers in research into HAV. In this context, the aim of this study was to investigate older drivers' takeover performance in the HAV as well as to explore and test their requirements concerning the HAV in order to develop knowledge to facilitate safe and comfortable human-machine interaction in the HAV. To achieve this aim, seven objectives were set.

The research conducted in this thesis has met the aim and objectives set in Section 1.6. Specifically, the previous chapters in this thesis included a literature review (Chapter 2); an overview of the methodology used in this study (Chapter 3); and descriptions of the first driving simulator investigation which examined older drivers' takeover performance when they were completely disengaged from driving in the HAV (Chapter 4), the second driving simulator investigation which considered older drivers' takeover performance in the HAV in adverse weather conditions (Chapter 5), followed by an interview investigation which explored older drivers' requirements concerning the HAVs (Chapter 6); Some key requirements were then tested in the third driving simulator investigation which evaluated the effectiveness of several HAV human-machine interface concepts which were designed based on older drivers' requirements (Chapter 7); and subsequently a summary of recommendations for the design of safe and comfortable human-machine interaction in the HAV for older drivers was provided (Chapter 8).

This chapter details the conclusions and key implications as well as the overall contributions of this thesis, and proposes recommendations for future work.

9.2 Conclusions

In accordance with the aim of this thesis, the conclusions of this thesis will be divided into three parts. The first details the major findings associated with older drivers' takeover performance in the HAV. The second part highlights the findings related to older drivers' requirements concerning HAVs. Finally the third part focuses on the key findings from testing older drivers' requirements of HAVs.

9.2.1 Major findings on older drivers' takeover performance in the HAV

To address the first research question listed in Section 1.5, this study examined the takeover performance among the older and younger drivers when reassuming control of the vehicle from the HAV through three waves of driving simulator investigations (Chapters 4, 5 and 7). The major finding was:

- **There were significant age differences in drivers' takeover performance in the HAV, where older drivers exhibited worse takeover performance compared to younger drivers.**

This study has found that, after the HAV system initiated a takeover request to the driver, older drivers took significantly longer than younger drivers to switch back to the manual driving position so as to react to the takeover request. Furthermore they needed significantly longer to execute the first active input to the vehicle. They were also found to be significantly slower in making the decision to change lane to avoid the stationary car which was blocking the lane ahead. In addition, older drivers were recorded to have significantly stronger braking and acceleration patterns, and significantly less stable steering control of the vehicle than younger drivers. Moreover, when taking over control of the vehicle in adverse weather conditions, older drivers also exhibited significantly shorter value of TTC as well as being more involved more collisions and critical encounters compared to younger drivers. Although this study did not directly focus on investigating the influence of age-related functional impairments on takeover performance in the HAV, elements of age-related deterioration in reaction time, and cognitive functions as well as psychomotor abilities were evidenced by the findings of this study. Even though the effects of age on drivers' performance in driving conventional vehicles have been widely recognized in previous research (Ball *et al.*, 1998; Hakamies-Blomqvist and Wahlström., 1998; Guo *et al.*, 2013a; Edwards *et al.*, 2016; Karthaus and Falkenstein, 2016), research attempting to explore the interaction of elderly drivers and HAV (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017) has not fully addressed whether or not and how age would influence performance of interacting with the HAV. Therefore the findings of the present study have represent new knowledge, emphasizing that age plays a non-negligible role in drivers' performance when interacting with an HAV. Overall, the implication of this conclusion is that it is important for policy makers, OEMs and academics to fully consider the roles and capabilities of older drivers during the process of researching, testing, designing and manufacturing HAVs.

To address the second research question listed in Section 1.5, this study studied the effects of the state of complete disengagement from driving in HAV on drivers' performance during the takeover process and found that:

- **The state of complete disengagement from driving in the HAV has a significantly negative impact on drivers' takeover performance compared to the state of being engaged in driving, and this affected older drivers more seriously than younger drivers.**

Enabling drivers to be completely disengaged from driving and safely performing other non-driving related activities is an important feature of the HAV (SAE, 2014; DfT, 2015c), which could potentially provide a revolutionary driving experience for users. This study has explored the influence of this key feature of the HAV, the state of complete disengagement from driving, on drivers' takeover performance. It is revealed that, compared to being engaged in driving, when drivers were completely disengaged from driving they took significantly longer time to switch back to the manual driving position after receiving a takeover request from the HAV system. The state of complete disengagement from driving also led to a significantly longer time for the drivers to generate their first active input to the vehicle and a significantly longer time for the drivers to make the decision to change lane so as to overcome stationary car. In addition, drivers exhibited significantly shorter TTCs when they were disengaged from driving compared to when being engaged in driving. Moreover, the state of complete disengagement from driving resulted in stronger breaking and accelerating behaviour and less stable steering of the vehicle among participants. These findings are generally in line with those of previous studies (Radlmayr et al., 2014; Zeeb et al., 2016; Eriksson and Stanton, 2017; Zeeb et al., 2017), but nevertheless do provide additional knowledge supporting the idea that the state of complete disengagement from driving in HAVs could potentially negatively affect the takeover performance of drivers if they were suddenly required to by the HAV system to take back control of the vehicle due to a safety issue. In addition, this study has found that the state of complete disengagement affected older drivers more seriously than younger drivers. It increased the time taken for older drivers to switch back to the manual driving position, and the time before the first active input to the vehicle, as well as to make the decision to change lane to a greater extent compared to the younger drivers. Furthermore the findings of this research showed that it reduced older drivers' TTC more profoundly than among younger drivers. Existing literature has not fully investigated the effects of the state of complete disengagement from driving in the HAV specifically on the performance of older driver coherent (Körber et al., 2016; Miller et al., 2016; Clark and Feng, 2017; Molnar et al., 2017), and therefore the findings of the present study provide new knowledge suggesting that older drivers could be more vulnerable than younger drivers when under the influence of complete disengagement from driving when interacting with the HAV. The implication arising from this conclusion is that while the convenience and pleasure that the complete disengagement from driving in the HAV could deliver to users and society can be acknowledged, the risks associated with this feature should not be neglected and it is important for policy makers, OEMs and academics to pay considerable attention to exploring and evaluating solutions that could potentially compensate for the negative effects of this feature, such as the in recommendations proposed in Sections 8.2, 8.3 and 8.5. In addition, the findings have provided evidence which further strengthens the significance for policy makers, OEMs and academics of careful consideration of the competency and capability of older drivers in research into and demonstration of HAVs, rather than only focusing on general drivers.

To address the third research question listed in Section 1.5, this study investigated the effects of adverse weather conditions on drivers' takeover performance in HAVs and found that:

- **Adverse weather conditions, and particularly snow and fog, had a significantly negative effect on drivers' takeover performance and led to less effective and more dangerous takeover in the HAV, and these conditions affected older and younger drivers' takeover performance in different ways.**

The second driving simulator investigation (Chapter 5) in this study revealed that, compared to taking over control of the vehicle in clear weather, snowy and foggy weather resulted in a significantly longer time for drivers to switch back to the manual driving position, a significantly longer time for the drivers to generate their first conscious input to the vehicle and a significantly longer time for the drivers to make the decision to change lane to avoid the stationary car. In addition, drivers exhibited significantly shorter TTC, significantly more collisions and critical encounters as well as significantly more hasty takeovers when they were reassuming control of the HAV in snowy and foggy conditions compared to clear weather. In addition, this study also found that younger drivers and older drivers were affected differently by adverse weather conditions. Adverse weather resulted in significantly slower time aspects of takeover and worse takeover quality among the younger drivers. For older drivers, their already slower time aspects of takeover was not significantly slowed down further by adverse weather conditions, but their takeover became less effective overall and much more dangerous. Due to the capabilities of the particular driving simulator used in this study, this research has only considered the visual impact of adverse weather, such as visual distractions and reduced visibility. Some other influences of adverse weather which may also make driving more dangerous, such as, slippery road surfaces, extended braking distances, accumulative snow, or car windows steaming up, could not be considered in the current research as the functionalities was not available with the simulator used. Although the weather-related reductions in visibility have been widely recognized as a significant problem affecting the driving performance when operating a conventional vehicle (Mueller and Trick, 2012; NeelimaChakrabartya, 2013; Ashley et al., 2015; Bellet et al., 2018), the impact of adverse weather on drivers' interaction with HAVs has tended to be neglected in the existing HAV literature (Gold et al., 2013a; Radlmayr et al., 2014; Gold et al., 2015; Melcher et al., 2015; Körber et al., 2016; Miller et al., 2016; Zeeb et al., 2016; Clark and Feng, 2017; Eriksson and Stanton, 2017). Thus, the findings of this study have generated new knowledge and insight to understand how these visual effects of adverse weather could negatively affect drivers' performance when interacting and operating a HAV. The implication raised from this conclusion is that it is important for policymakers, OEMs and academics to take weather factors into consideration, and to clearly distinguish between the difference impacts that weather could have on older and younger drivers' performance when testing and researching HAVs. This also suggests that a connected environment of vehicles and infrastructure could be required to mitigate the negative impact of adverse weather. Testing of the usability of HAVs should be conducted in various weather conditions before introducing them to the market. In addition, it should be noted that the HAV in this study was based on the Level 3 automation (SAE, 2014) and the adverse weather lead to deteriorations in both the younger and older drivers' takeover performance. Thus another implication of this study could be that, as proposed in Section 8.6, it would be necessary for policymakers and OEMs to encourage the development higher levels of automated vehicles, and digital connectivity with other vehicles and infrastructure, which could still guarantee safety regardless of whether or not drivers are able to accomplish an effective takeover in conditions such as adverse weather.

9.2.2 Major findings from studying older drivers' requirements concerning HAVs

To address the fourth research question listed in Section 1.5, after enabling the older drivers to experience the HAV on the driving simulator, their requirements concerning HAVs were investigated in a series of qualitative interviews (Chapter 6). The major findings were as follows:

- **Older drivers believed that the first-hand experience with the HAV is important to help them to develop a realistic understanding of the HAVs, and to enhance their trust and confidence.**

This study has found that older drivers welcomed the first-hand experience with the HAV and indicated that it was important for them to better understand the HAV and helped them build their trust and confidence in the HAV. This finding is in line with previous studies and adds the knowledge in supporting the idea that first-hand experience could deepen participants' understanding towards a subjects and this was especially helpful to allow older adults to understand the technology more clearly (Eisma et al., 2003; Davies and Lam, 2009). This finding highlights the importance of providing sufficient hands-on opportunities with HAVs for older drivers. This could be in the form of a testing or training before a driver starts to use the HAV.

- **Older drivers exhibited positive opinions towards the HAV and perceived a variety of potential benefits of HAV in enhancing their mobility.**

This study has found that older drivers had positive attitudes towards the HAV and believed their mobility could be enhanced by it, especially when driving on long journeys, in adverse weather conditions and on unfamiliar roads. The benefits of HAV that they perceived mainly linked to enhancing their mobility. The situations in which they perceived that HAV could be helpful are generally in line with those difficult driving situations that older drivers always adjust to or avoid when driving conventional vehicles in real life (Hakamies-Blomqvist and Wahlström., 1998; Rimmö and Hakamies-Blomqvist, 2002; Charlton et al., 2006). Therefore, this finding provides evidence showing that one important area of significance of the adoption the forthcoming HAVs among older drivers is the potential for maintaining and improving their mobility which is strongly linked with the quality of life of older people (Charlton et al., 2006; Guo et al., 2010a; Edwards et al., 2016).

- **Older drivers strongly desired to retain physical control and potential control of the HAV.**

This study has found that older drivers expressed a strong need to remain active drivers and to retain physical control of the HAV. In the meantime, they showed a requirement to perceive that they have potential control in HAV, which means knowing that they would be able to intervene in automated driving and take over control back at any time when the HAV is being driven automatically. This finding provides new evidence supporting the idea of the importance of retaining independence and control over one's life to older adults' wellbeing (Gabriel and Bowling, 2004). An important indication of this finding is that the baseline in the design and introduction of HAVs to older drivers should allow them to maintain mobility for longer and safer without compromising their self-mastery and independence.

- **Older drivers expressed the requirements to perform a variety of non-driving-related tasks when completely disengaged from driving in the HAV.**

The study has revealed that older drivers preferred to perform a variety of non-driving related activities when completely disengaged from driving in the HAV, including relaxing tasks such as listening to the radio, reading, looking at the scenery, talking with others, using a mobile phone, watching the TV and films, doing exercises, thinking, and meditation and breathing; along with other tasks including working, doing crosswords, monitoring the HAV driving, and eating and drinking. This finding is in line with the observations of Clark and Feng (2017) that older drivers preferred to have conversations with others when not driving the HAV. Considering that few studies in the existing literature have focused on exploring older drivers' preferred activities in HAVs, the finding of the present study provide a fundamental understanding on how the revolutionary driving experience delivered by HAVs could potentially make older drivers' driving more enjoyable and productive. This has also generated a need for future research to explore the impact of performing such activities on drivers' performance.

- **Older drivers required an information system and a driver monitoring system to assist them when they are completely disengaged from driving in the HAV.**

This study has found that, during automated driving in the HAV, older drivers required the HAV systems to keep them updated about what is happening and to inform them about the journey, vehicle status and road conditions. Essentially, they expressed a desire for the HAV to inform them that it is adapting its driving to suit the conditions it is driving in. Moreover, older drivers needed the HAV system to monitor the driver's status and to take action accordingly. The modalities of system feedback should differentiate between normal and urgent information. As proposed in Chapter 8, this finding has generated an important indication for the design of the human-machine interaction in the HAV.

- **Older drivers required a takeover request in the HAV with adjustable, explanatory and hierarchical characteristics.**

This study has found that, in terms of the taking over of control in the HAV, older drivers required to be able to adjust when and where to receive takeover requests. The takeover request should include a description of the reasons for takeover. In addition, the modality of the takeover request should be hierarchical, based on how urgent the takeover situation is. In addition, car interiors should be coordinates with the nature of takeover requests in order to ensure safe and effective takeover. These findings lead to recommendations for the design of takeover requests in HAVs for older drivers, as proposed in Chapter 8.

- **Older drivers needed a sufficient and adaptive lead time for taking over control of driving in the HAV.**

This study found that older drivers believed that twenty seconds would be considered a long enough lead time for them to take over control of the HAV, but this should be adapted to weather conditions and the driver's status. This finding was confirmed in the quantitative driving simulator investigations where a lead time of twenty seconds lead time resulted in successful takeover among all the participants in clear and rainy conditions.

- **Older drivers required the driving style of HAV to be imitative and corrective.**

This study found that older drivers exhibited a requirement towards the driving style of HAVs that it should be able to adapt to their owners' driving style, but it should only to safe aspects of style and it should correct dangerous aspects. Furthermore they would like the HAV to allow them to choose routes and to remember the purpose of a trip. Given that little research has been conducted into exploring the driving styles in HAVs. This finding provides a fundamental understanding of the driving style of age-friendly HAVs. Future research is required to evaluate the usability of this design and assess how it would actually affect users' preference towards HAVs.

9.2.3 Major findings on testing older drivers' requirements concerning HAVs

To address the last research question listed in Section 1.5, after investigating older drivers' takeover performance and requirements concerning the HAV, the third driving simulator investigation (Chapter 7) tested older drivers' requirements by evaluating the effectiveness of three HMIs designed based on two key requirements that older drivers had identified in the interview investigation: The first was providing information on the reasons for takeover in the takeover request, and the second one was informing drivers about what is happening when drivers are completely disengaged from driving. The major findings were as follows:

- **The 'R' HMI (solely informing drivers about the reasons for takeover as part of the takeover request) affected older and younger drivers differently, and resulted in deteriorations in performance and more risky takeover for both older and younger drivers compared to the baseline HMI.**

This research has found that the R HMI influenced older and younger drivers differently. Although it shortened reaction time, takeover time and reduced the workload compared to the Baseline HMI among the older drivers, it led to a rise in all three parameters among the younger drivers. Moreover, for the both older and younger drivers, it resulted in the strongest resulting acceleration and steering wheel angle, and the largest number of risky takeovers among the four HMIs. This highlights that solely providing a description of reasons for takeover in the takeover request could pose safety risks for drivers when reassuming control from the HAV.

- **The ‘V’ HMI (verbally informing the drivers about vehicle status, including automation mode and speed, before the takeover request) had a positive effect on drivers’ takeover performance, perceived workload and attitudes.**

This study found that the V-HMI resulted in significantly faster reaction time, faster takeover time and indicator time, significantly lower resulting acceleration and smaller steering wheel angle, lower perceived workload, and significantly better attitudes compared to the baseline HMI. Additionally, it led to significantly faster reaction time, faster takeover time, faster indicator time, significantly smaller resulting acceleration and steering wheel angle, significantly lower perceived workload, and significantly better attitude compared to the R HMI. Therefore, the concept of V HMI was proven to be beneficial to participants.

- **The ‘R+V’HMI (informing drivers of vehicle status together with providing reasons for takeover) led to better takeover performance, lower perceived workload and highly positive attitudes, and is the most beneficial and effective HMI.**

Finally, this study found that the R+V HMI resulted in the fastest takeover time among the four HMIs and significantly faster take-over time compared to the R HMI. It also lead to the fastest indicator time among the four HMIs, and significantly faster indicator times compared to the R HMI and Baseline HMI; the smallest resulting acceleration among the four HMIs and significantly smaller resulting acceleration compared to the R HMI and the Baseline HMI; the smaller steering wheel angles compared to the Baseline HMI and significantly smaller steering wheel angles compared to the R HMI; less risky takeover than with the R HMI and V HMI, and the highest number of safe drivers and smallest number of critical drivers among the four HMIs; the lowest workload scores and significantly lower workload scores than for the Baseline HMI and R HMI; it was also the most preferred HMI among the four HMIs and significantly more preferred than either the Baseline HMI, R HMI or V HMI. This highlights and confirms that the R+V HMI that informing drivers of vehicle status together with the reasons for takeover was found to be the most beneficial and effective HMI in the HAV to facilitate a safe and comfortable takeover in the HAV.

Overall, in terms of the existing literature regarding drivers’ interaction with HAV, the findings of this study represent new knowledge indicating that drivers’ performance in interacting with the HAV could potentially be enhanced through a carefully designed HMI.

Moreover, given that existing research concerning vehicle automation and older drivers has not focused on exploring and evaluating age-friendly HMI in the HAV (Yang and Coughlin, 2014; Körber et al., 2016; Miller et al., 2016; Zeeb et al., 2016; Clark and Feng, 2017; Molnar et al., 2017), the findings of this study also provide a basic understanding on how to design of the HMI of HAV based on the specific requirements of older driver coherent with clear evidence underpinning this knowledge. Furthermore, the finding of this study provide additional evidence in supporting the importance and necessity of involving older drivers and fully considering their attitudes, capabilities and requirements during the design of human-machine interaction for in-vehicle assistance and vehicle automation systems, and supporting the idea that designing for the older people can benefit people at all ages (Musselwhite and Haddad, 2007; Guo *et al.*, 2010a; Emmerson *et al.*, 2013; Guo *et al.*, 2013a; Edwards *et al.*, 2016; Young *et al.*, 2017).

9.3 Limitations and Future work

This thesis has provided important knowledge with regard to HAVs and older drivers. This section discusses the limitations of this study and proposes a number of directions so that the findings of this study could be developed and extended in the future.

Firstly, the HAV scenario used in the driving simulator investigations in this study exposed the participants to automated driving for a short period of time (one minute of each driving session) before asking them to take over control of the vehicle. Future research could explore older drivers' takeover performance after a longer duration of automated driving and could also explore the change in their performance after long-term use of the HAV. Secondly, the roads adopted for the HAV scenario in the three driving simulator investigations were straight roads, and therefore future research could examine older drivers' takeover performance in HAVs using simulated environments representing other scenarios, such as urban scene clutter, intersections and roundabouts where accidents involving elderly people typically occur (McGwin Jr and Brown, 1999; Braitman et al., 2007). Finally, the takeover task in the HAV scenario in this study was to overcome a stationary vehicle suddenly blocking the driving lane, whereas future research could introduce more complex manoeuvres required after takeover to study older drivers' takeover performance, such as avoiding potential collisions to a slow moving vehicle or interacting with moving pedestrians and cyclists.

When setting up a controlled experiment, the current research assumed that the traveling speed of the HAV is the same in different weather conditions that were simulated. When interpreting the findings, it should be noted that people adopt lower driving speeds in adverse weather in real life. Moreover, the current research investigated drivers' takeover performance in three adverse weather conditions (rain, snow and fog) in the daytime, and future research could examine drivers' takeover performance under more severely adverse weather conditions, for example, rainy, snowy and foggy weather combined with windy conditions, or adverse weather at night. Measures which may have the potential to improve older drivers' takeover performance under adverse conditions could also be explored.

This thesis studied older drivers' requirements towards the HAV through a qualitative semi-structured interview investigation which did not focus on making generalizations but attempted to yield a rich, contextualized understanding of human experience (Polit and Beck, 2010). It has yielded information on a variety of older drivers' requirements towards HAVs. Due to the limitation of this study, only two key requirements of older drivers were subsequently tested and evaluated in a quantitative driving simulator investigation, which yielded important implications for the design of age-friendly HMIs in HAVs. However, the potential impact of many other of the older drivers' requirements, on the design of HAVs still remains unclear. Therefore, here is a strong need for future research to test and evaluate the other requirements that older drivers' may desire when using the HAV yielded by the interview investigation of this study in order to broadly generalize the current qualitative findings.

In addition, considering one of the major findings of this study is that the negative impact of the state of complete disengagement from driving which was facilitated by engaging the driver in a reading task on the takeover performance. The study also found that older drivers preferred to perform a variety of non-driving related tasks in the HAV and they showed strong concerns that in some circumstances the drivers could fall asleep they may not be able to safety respond to a system takeover request. Importantly, this has created a strong need for the future research to fully investigate the impact of engaging in other different types of activities, such as sleep and sleep deprivation, on drivers' takeover time and quality, which could have important implication to determine which activities should be allowed and which should be prohibited in the HAV. With more evidence policy makers will have clearer data on which to consider regulation and guideline on HAV use and operation.

Moreover, this study incorporated only a small sample size (n=24) in the qualitative investigation to identify older drivers' requirements of HAVs and larger sample sizes (n=76) in the quantitative driving simulator investigations to examine their takeover performance and test their requirements of the HAV. However, the sample sizes used in the current research are still relatively small. Future research could repeat the current research with larger samples. The younger subjects in this research had smaller annual driving mileages than the older drivers and they had a relatively young age range (20-35 years). Also the older subjects in this research did not include those aged over 81 years old. Therefore, future research could adopt a larger sample that includes subjects aged 36-59 years and over 81 years to also study their takeover performance in HAVs. Additional cohorts in the age range 36 to 59 would enhance the knowledge of HAV interactions across the whole age-range of UK drivers. The older drivers who participated in this study were active drivers, and future research could explore what vehicle automation means for those have already ceased driving. Moreover, future research could explore the takeover performance in HAVs of different age brackets within the older driver category, for example, comparing the performance of older drivers aged 60-74 years and those aged 75 years old and over.

Finally, the important findings yielded from this study are based on investigations and experiments conducted on a driving simulator, as this is an effective and appropriate method to use to study driving behaviour and evaluate in-vehicle technologies (Reed and Green, 1999; De Winter et al., 2012; Gold et al., 2015; Gold et al., 2016; Körber et al., 2016). The specific driving simulator used in this study has been found in previous research to be reliable and valid in investigating older people's interaction with in-vehicle technologies (Guo *et al.*, 2013a; Edwards *et al.*, 2016). However, with the trend for on-road trial of automated vehicles, the findings of this thesis could be studied on a full scale highly automated vehicle in real road situations. Such on-road tests could potentially compensate for the limitations of the quantitative and qualitative methods used in this thesis and further develop the findings of this study. For example, this study only considered the visual effects of adverse weather, while future research could repeat the current study and validate the results in real-life situations with all of the effects of adverse weather being taken into account. In addition, future research could investigate the opinions and requirements of older people after experiencing an authentic HAV in real life. Lastly, this thesis has proposed a wide range of recommendations concerning the design of human-machine interaction in the HAV, and further research could apply those recommendations on a full-scale HAV and fully evaluate their potential and effectiveness in assisting drivers in HAVs.

9.4 Closing Statement

This thesis represents a comprehensive study using mixed quantitative and qualitative methods approach to investigate older drivers' interaction with the forthcoming highly automated vehicles. Firstly, older drivers' takeover performance in the HAV was studied using a quantitative approach in a simulated highly automated driving environment, and significant age differences were found in performance in interacting with the HAV. Following on from this, older drivers' requirements towards the HAV were studied using a qualitative approach, which revealed a range of needs and requirements concerning HAVs among older drivers. After that, three HMIs were designed based on some of the key requirements of older drivers and they were evaluated using another quantitative approach in a simulated HAV environment. From these findings, a series of recommendations promoting the better interaction of older drivers and the HAV were proposed. The development and extension of the major findings of this thesis through future work could potentially facilitate a safe and comfortable human-machine interaction in HAVs for older drivers, allowing them to drive more safely and to be happier for longer, ultimately benefiting their mobility, independence and wellbeing. With the emerging global trends in ageing in society together with the forthcoming roll-out of automated vehicles, ensuring that HAV design takes into account the roles, capabilities and requirements of older driver coherent to enable them to remain mobile and healthy could deliver substantial benefits to the whole of society. With the UK's Government recognising that the Future of Mobility and the Ageing Society being two of the four Grand Challenges that the Industrial Strategy are underpinned by – illustrates that the research is addressing important current challenges in the UK to make HAVs useable by the whole population and in particular the growing number of older drivers who aspire to remain mobile for longer.

References

2025AD (2015) *DEFINITION: LEVELS OF AD*. Available at: https://www.2025ad.com/latest/the-levels-of-automation/.

Albert, M., Lange, A., Schmidt, A., Wimmer, M. and Bengler, K. (2015) 'Automated driving–Assessment of interaction concepts under real driving conditions', *Procedia Manufacturing*, 3, pp. 2832-2839.

Alshenqeeti, H. (2014) 'Interviewing as a data collection method: A critical review', *English Linguistics Research*, 3(1), p. 39.

Anderson, R.W.G., McLean, A.J., Farmer, M.J.B., Lee, B.H. and Brooks, C.G. (1997) 'Vehicle travel speeds and the incidence of fatal pedestrian crashes', *Accident Analysis & Prevention*, 29(5), pp. 667-674.

Anderson, S.W., Rizzo, M., Shi, Q., Uc, E.Y. and Dawson, J.D. (2005) 'Cognitive abilities related to driving performance in a simulator and crashing on the road' *the 3rd International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*. Rockport Maine,United States.

Aronson, J. (1995) 'A pragmatic view of thematic analysis', *The qualitative report*, 2(1), pp. 1-3.

Ashley, W.S., Strader, S., Dziubla, D.C. and Haberlie, A. (2015) 'Driving blind: Weather-related vision hazards and fatal motor vehicle crashes', *Bulletin of the American Meteorological Society*, 96(5), pp. 755-778.

Attebo, K., Mitchell, P. and Smith, W. (1996) 'Visual acuity and the causes of visual loss in Australia: the Blue Mountains Eye Study', *Ophthalmology*, 103(3), pp. 357-364.

Ball, K., Owsley, C., Stalvey, B., Roenker, D.L., Sloane, M.E. and Graves, M. (1998) 'Driving avoidance and functional impairment in older drivers', *Accident Analysis & Prevention*, 30(3), pp. 313-322.

Ball, K.K., Clay, O.J., Wadley, V.G., Roth, D.L., Edwards, J.D. and Roenker, D.L. (2005) 'Predicting driving performance in older adults with the useful field of view test: A meta-analysis' *the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design* Rockport, Maine.

Banks, V.A., Eriksson, A., O'Donoghue, J. and Stanton, N.A. (2018) 'Is partially automated driving a bad idea? Observations from an on-road study', *Applied ergonomics*, 68, pp. 138-145.

Bazilinskyy, P. and de Winter, J. (2015) 'Auditory interfaces in automated driving: an international survey', *PeerJ Computer Science*, 1, p. e13.

Bellet, T., Paris, J.C. and Marin-Lamellet, C. (2018) 'Difficulties experienced by older drivers during their regular driving and their expectations towards Advanced Driving Aid Systems and vehicle automation', *Transportation Research Part F: Traffic Psychology and Behaviour*, 52, pp. 138-163.

Bird, D.K. (2009) 'The use of questionnaires for acquiring information on public perception of natural hazards and risk mitigation–a review of current knowledge and practice', *Natural Hazards and Earth System Sciences*, 9(4), pp. 1307-1325.

Blough, P.M. and Slavin, L.K. (1987) 'Reaction time assessments of gender differences in visual-spatial performance', *Perception & Psychophysics*, 41(3), pp. 276-281.

Botwinick, J. (1966) 'Cautiousness in advanced age', *Journal of Gerontology*, 21(3), pp. 347-353.

Boyatzis, R.E. (1998) *Transforming qualitative information: Thematic analysis and code development*. Sage.

Braitman, K.A., Kirley, B.B., Ferguson, S. and Chaudhary, N.K. (2007) 'Factors leading to older drivers' intersection crashes', *Traffic injury prevention*, 8(3), pp. 267-274.

Braitman, K.A. and McCartt, A.T. (2008) 'Characteristics of older drivers who self-limit their driving' *Annals of Advances in Automotive Medicine/Annual Scientific Conference*. Association for the Advancement of Automotive Medicine.

Braun, V. and Clarke, V. (2006) 'Using thematic analysis in psychology', *Qualitative Research in Psychology*, 3(2), pp. 77-101.

Braver, E.R. and Trempel, R.E. (2004) 'Are older drivers actually at higher risk of involvement in collisions resulting in deaths or non-fatal injuries among their passengers and other road users?', *Injury Prevention*, 10(1), pp. 27-32.

Brayne, C., Dufouil, C., Ahmed, A., Dening, T.R., Chi, L.Y., McGee, M. and Huppert, F.A. (2000) 'Very old drivers: findings from a population cohort of people aged 84 and over', *International Journal of Epidemiology*, 29(4), pp. 704-707.

Brébion, G. (2003) 'Working memory, language comprehension, and aging: four experiments to understand the deficit', *Experimental Aging Research*, 29(3), pp. 269-301

Broberg, T. and Willstrand, T.D. (2014) 'Safe mobility for elderly drivers—Considerations based on expert and self-assessment', *Accident Analysis & Prevention*, 66, pp. 104-113.

Brookhuis, K.A. and de Waard, D. (2010) 'Monitoring drivers' mental workload in driving simulators using physiological measures', *Accident Analysis & Prevention*, 42(3), pp. 898-903.

Brooks, J.O., Goodenough, R.R., Crisler, M.C., Klein, N.D., Alley, R.L., Koon, B.L., Logan Jr, W.C., Ogle, J.H., Tyrrell, R.A. and Wills, R.F. (2010) 'Simulator sickness during driving simulation studies', *Accident Analysis & Prevention*, 42(3), pp. 788-796.

Brouwer, W.H., Waterink, W., Van Wolffelaar, P.C. and Rothengatter, T. (1991) 'Divided attention in experienced young and older drivers: lane tracking and visual analysis in a dynamic driving simulator', *Human factors*, 33(5), pp. 573-582.

Buckley, L., Kaye, S.A. and Pradhan, A.K. (2018) 'A qualitative examination of drivers' responses to partially automated vehicles', *Transportation Research Part F: Traffic Psychology and Behaviour*, 56(167-175).

Burton, J. (2012) *Personalisation for social workers: opportunities and challenges for frontline practice*. McGraw-Hill Education (UK).

Byers, J.C., Bittner, A.C. and Hill, S.G. (1989) 'Traditional and raw task load index (TLX) correlations: Are paired comparisons necessary', in Mital, A. (ed.) *Advances in Industrial Ergonomics and Safety* Taylor & Francis, pp. 481-485.

Cain, B. (2007) *A review of the mental workload literature*.

Campbell, J.L., Carney, C. and Kantowitz, B.H. (1998) *Human factors design guidelines for advanced traveler information systems (ATIS) and commercial vehicle operations (CVO)*. Washington, DC.

Campbell, J.L., Richard, C.M., Brown, J.L. and McCallum, M. (2007) *Crash warning system interfaces: Human factors insights and lessons learned*. Washington, DC.

Cassell, C. and Symon, G. (1994) *Qualitative methods in organizational research: a practical guide*. Sage.

Castleberry, A. and Nolen, A. (2018) 'Thematic analysis of qualitative research data: Is it as easy as it sounds?', *Currents in Pharmacy Teaching and Learning*.

Catapult, T.S. (2017) *Future Proofing Infrastructure for Connected and Automated Vehicles*. [Online]. Available at: https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2017/04/25115313/ATS40-Future-Proofing-Infrastructure-for-CAVs.pdf.

Chan, C.Y. (2017) 'Advancements, prospects, and impacts of automated driving systems', *International Journal of Transportation Science and Technology*, 6(3), pp. 208-216.

Charlton, J.L., Oxley, J., Fildes, B., Oxley, P., Newstead, S., Koppel, S. and O'Hare, M., 2006. (2006) 'Characteristics of older drivers who adopt self-regulatory driving behaviours', *Transportation Research Part F: Traffic Psychology and Behaviour*, 9(5), pp. 363-373.

Charness, G., Gneezy, U. and Kuhn, M.A. (2012) 'Experimental methods: Between-subject and within-subject design', *Journal of Economic Behavior & Organization*, 81(1), pp. 1-8.

Clark, H. and Feng, J. (2017) 'Age differences in the takeover of vehicle control and engagement in non-driving-related activities in simulated driving with conditional automation', *Accident Analysis & Prevention*, 106, pp. 468-479.

Cohen, L., Manion, L. and Morrison, K. (2000) *Research methods in education (5th ed.)*. London: Routledge Falmer.

Cohen, M., L. and Morrison, K. (2011) *Research Methods in Education*. 7th edn. Routledge.

Constantinescu, Z., Marinoiu, C. and Vladoiu, M. (2010) 'Driving style analysis using data mining techniques', *International Journal of Computers Communications & Control*, 5(5), pp. 654-663.

Creswell, J. (1998) 'Qualitative inquiry and research design: Choosing among five traditions'. Thousand Oaks, CA: Sage.

Crizzle, A.M., Classen, S., Lanford, D., Malaty, I.A., Okun, M.S., Shukla, A.W. and McFarland, N.R. (2013) 'Driving performance and behaviors: a comparison of gender differences in Parkinson's disease', *Traffic injury prevention*, 14(4), pp. 340-345.

Croasmun, J.T. and Ostrom, L. (2011) 'Using Likert-Type Scales in the Social Sciences', *Journal of Adult Education*, 40(1), pp. 19-22.

Croson, R. and Gneezy, U. (2009) 'Gender differences in preferences', *Journal of Economic literature*, 47(2), pp. 448-74.

Cuenen, A., Jongen, E.M., Brijs, T., Brijs, K., Houben, K. and Wets., G. (2016) 'Effect of a working memory training on aspects of cognitive ability and driving ability of older drivers: merits of an adaptive training over a non-adaptive training', *Transportation Research Part F: Traffic Psychology and Behaviour*, 42, pp. 15-27.

Czaja, S.J., Rogers, W.A., Fisk, A.D., Charness, N. and Sharit, J. (2009) *Designing for older adults: Principles and creative human factors approaches*. CRC press.

Daigneault, G., Joly, P. and Frigon, J.Y. (2002) 'Executive functions in the evaluation of accident risk of older drivers', *Journal of Clinical and Experimental Neuropsychology*, 24(2), pp. 221-238.

Damiani, S., Deregibus, E. and Andreone, L. (2009) 'Driver-vehicle interfaces and interaction: where are they going?', *European Transport Research Review*, 1(2), pp. 87-96.

Davidse, R.J. (2006) 'Older drivers and ADAS: Which systems improve road safety?', *IATSS Research*, 30(1), pp. 6-20.

Davies, A.D.M. and Davies, D.R. (1975) 'The effects of noise and time of day upon age differences in performance at two checking task', *Ergonomics*, 18(3), pp. 321–336.

Davies, D. and Lam, E. (2009) 'The role of first-hand experience in the development education of university students', *International Journal of Development Education and Global Learning*, 2(2), pp. 35-52.

De Winter, J., Van Leuween, P. and Happee, P. (2012) ' Advantages and disadvantages of driving simulators: a discussion' *In Proceedings of Measuring Behavior 2012* Utrecht, The Netherlands.

De Winter, J.C.F., Wieringa, P.A., Dankelman, J., Mulder, M., Van Paassen, M.M. and De Groot, S. (2007) 'Driving simulator fidelity and training effectiveness' *Proceedings of the 26th European annual conference on human decision making and manual control*. Lyngby, Denmark.

Debernard, S., Chauvin, C., Pokam, R. and Langlois, S. (2016) 'Designing human-machine interface for autonomous vehicles', *IFAC-PapersOnLine*, 49(19), pp. 609-614.

DfT (2014) *Driverless cars: 4 cities get green light for everyday trials*. Available at: https://www.gov.uk/government/news/driverless-cars-4-cities-get-green-light-for-everyday-trials (Accessed: October 2016).

DfT (2015a) *The Highway Code*. [Online]. Available at: https://www.gov.uk/guidance/the-highway-code/driving-in-adverse-weather-conditions-226-to-237.

DfT (2015b) *National Travel Survey:England 2015*. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/551437/national-travel-survey-2015.pdf.

DfT (2015c) *The Pathway to Driverless Car: A Code of Practice for Testing*. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/446316/pathway-driverless-cars.pdf

DfT (2015d) *The Pathway to Driverless Cars: detailed review of regulations for automated vehicle technologies*. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/401565/pathway-driverless-cars-main.pdf (Accessed: October 2016).

DfT (2015e) *The Pathway to Driverless Cars: Summary report and action plan*. [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/401562/pathway-driverless-cars-summary.pdf.

DfT (2016) *Road use statistics: 2016*. [Online]. Available at: https://www.gov.uk/government/statistics/road-use-statistics-2016.

DfT (2017) *Transport Statistics Great Britain: 2017*. [Online]. Available at: https://www.gov.uk/government/statistics/transport-statistics-great-britain-2017.

DiCicco-Bloom, B. and Crabtree, B.F. (2006) 'The qualitative research interview', *Medical Education*, 40(4), pp. 314-321.

Dilshad, R.M. and Latif, M.I. (2013) 'Focus Group Interview as a Tool for Qualitative Research: An Analysis', *Pakistan Journal of Social Sciences (PJSS)*, 33(1), pp. 191-198.

Dong, Y., Hu, Z., Uchimura, K. and Murayama, N. (2011) 'Driver inattention monitoring system for intelligent vehicles: A review', *IEEE transactions on intelligent transportation systems*, 12(2), pp. 596-614.

Donorfio, L.K., Mohyde, M., Coughlin, J. and D'Ambrosio, L. (2008) 'A qualitative exploration of self-regulation behaviors among older drivers', *Journal of aging & social policy*, 20(3), pp. 323-339.

Dykiert, D., G. Der, J.M.S. and Deary, I.J. (2012) 'Age differences in intra-individual variability in simple and choice reaction time: systematic review and meta-analysis', *PLOS one* 7(10), p. e45759.

Earles, J.L., Kersten, A.W., Mas, B.B. and Miccio., D.M. (2004) 'Aging and memory for self-performed tasks: Effects of task difficulty and time pressure', *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 59(6), pp. 285-293.

Eberhard, J. (1996) 'Safe mobility of senior citizens', *Journal of the International Association of Traffic and Safety Sciences*, 20(1), pp. 29–37.

Eby, D.W. and Molnar, L.J. (2012) *Has the time come for an older driver vehicle?* [Online]. Available at: https://deepblue.lib.umich.edu/handle/2027.42/89960.

Edwards, J.B. (1998) 'The relationship between road accident severity and recorded weather', *Journal of Safety Research*, 29(4), pp. 249-262.

Edwards, S.J., Emmerson, C., Namdeo, A., Blythe, P.T. and Guo, W. (2016) 'Optimising landmark-based route guidance for older drivers', *Transportation Research Part F: Traffic Psychology and Behaviour*, 43, pp. 225-237.

Eisma, R., Dickinson, A., Goodman, J., Mival, O., Syme, A. and Tiwari, L. (2003) 'March. Mutual inspiration in the development of new technology for older people', *Proceedings of Include*, 7, pp. 252-259.

Elliott, A.C. and Woodward, W.A. (2007) *Statistical analysis quick reference guidebook: With SPSS examples*. London: Sage.

Emmerson, C., Guo, W., Blythe, P., Namdeo, A. and Edwards, S. (2013) 'Fork in the road: In-vehicle navigation systems and older drivers', *Transportation Research Part F: Traffic Psychology and Behaviour*, 21, pp. 173-180.

Endsley, M.R. (1995a) 'Measurement of situation awareness in dynamic systems', *Human factors*, 37(1), pp. 65-84.

Endsley, M.R. (1995b) 'Toward a theory of situation awareness in dynamic systems', *Human factors*, 37(1), pp. 32-64.

Endsley, M.R. and Kiris, E.O. (1995) 'The out-of-the-loop performance problem and level of control in automation', *Human factors*, 37(2), pp. 381-394.

Eriksson, A., Banks, V.A. and Stanton, N.A. (2017) 'Transition to manual: Comparing simulator with on-road control transitions', *Accident Analysis & Prevention*, 102, pp. 227-234.

Eriksson, A. and Stanton, N.A. (2017) 'Takeover time in highly automated vehicles: noncritical transitions to and from manual control', *Human Factors*, 59(4), pp. 689-705.

EuropeanCommission (2016) *Research and Innovation funding 2014-2020*. Available at: https://ec.europa.eu/research/fp7/index_en.cfm (Accessed: March 2017).

Fereday, J. and Muir-Cochrane, E. (2006) 'Demonstrating rigor using thematic analysis: A hybrid approach of inductive and deductive coding and theme development', *International journal of qualitative methods*, 5(1), pp. 80-92.

Ferreira, I.S., Simões, M.R. and Marôco, J. (2013a) 'Cognitive and psychomotor tests as predictors of on-road driving ability in older primary care patients', *Transportation research part F: traffic psychology and behaviour*, 21, pp. 146-158.

Ferreira, I.S., Simões, M.R. and Marôco., J. (2013b) 'Cognitive and psychomotor tests as predictors of on-road driving ability in older primary care patients', *Transportation Research Part F: Traffic Psychology and Behaviour* 21, pp. 146-158.

Field, A. (2013) *Discovering statistics using IBM SPSS*. 4th edn. London, UK: Sage.

Flemisch, F., Kelsch, J., Löper, C., Schieben, A. and Schindler, J. (2008) 'Automation Spectrum, Inner/Outer Compatibility and Other Potentially Useful Human Factors Concepts for Assistance and Automation', in Waard, D.d., Flemisch, F., Lorenz, B., H. Oberheid and Brookhuis, K. (eds.) *Human Factors for Assistance and Automation*. Maastricht: Shaker, pp. 1 – 16.

Fofanova, J. and Vollrath, M. (2012) 'Distraction in older drivers: a face-to-face interview study', *Safety Science*, 50(3), pp. 502-509.

Forster, Y., Naujoks, F., Neukum, A. and Huestegge, L. (2017) 'Driver compliance to take-over requests with different auditory outputs in conditional automation', *Accident Analysis & Prevention*, 109, pp. 18-28.

Fotios, S., Cheal, C., Fox, S. and Uttley, J. (2017) 'The transition between lit and unlit sections of road and detection of driving hazards after dark', *Lighting Research & Technology*, 0, pp. 1-19.

Gabriel, Z. and Bowling, A. (2004) 'Quality of life from the perspectives of older people', *Ageing & Society*, 24(5), pp. 675-691.

Gasser, T.M. and Westhoff, D. (2012) 'BASt-study: definitions of automation and legal issues in Germany', *the TRB Workshop on Road Vehicle Automation*,. Irvine, CA

GATEway (2017a) *GATEway demonstrates how teleoperation and autonomy can improve mobility for disabled drivers*. Available at: https://gateway-project.org.uk/gateway-demonstrates-how-teleoperation-and-autonomy-can-improve-mobility-for-disabled-drivers/ (Accessed: March 2017).

GATEway (2017b) *GATEway demonstrates how teleoperation and autonomy can improve mobility for disabled drivers'*. Available at: https://gateway-project.org.uk/gateway-demonstrates-how-teleoperation-and-autonomy-can-improve-mobility-for-disabled-drivers/ (Accessed: March 2017).

Gesser-Edelsburg, A. and Guttman, N. (2013) '"Virtual" versus "actual" parental accompaniment of teen drivers: A qualitative study of teens' views of in-vehicle driver monitoring technologies', *Transportation Research Part F: Traffic Psychology and Behaviour*, 17, pp. 114-124.

Ghasemi, A. and Zahediasl, S. (2012) 'Normality tests for statistical analysis: a guide for non-statisticians', *International journal of endocrinology and metabolism*, 10(2).

Gibbs, A. (1997) 'Focus groups', *Social Research Update*, 19(8), pp. 1-8.

Gill, P., Stewart, K., Treasure, E. and Chadwick, B. (2008) 'Methods of data collection in qualitative research: interviews and focus groups', *British Dental Journal*, 204(6), p. 291.

Gish, J., Vrkljan, B., Grenier, A. and Van Miltenburg, B. (2017) 'Driving with advanced vehicle technology: a qualitative investigation of older drivers' perceptions and motivations for use', *Accident Analysis & Prevention*, 106, pp. 498-504.

Gitelman, V., Pesahov, F., Carmel, R. and Chen, S. (2017) 'Exploring the characteristics of potential and current users of mobility scooters, among older people in Israel', *Transportation Research Part F: Traffic Psychology and Behaviour*, 46, pp. 373-389.

Godley, S.T., Triggs, T.J. and Fildes, B.N. (2002) 'Driving simulator validation for speed research', *Accident Analysis and Prevention*, 34, pp. 589-600.

Gold, C. and Bengler, K. (2014) 'Taking Over Control from Highly Automated Vehicles', in Stanton, N., Landry, S., Bucchianico, G. and Vallicelli, A. (eds.) *Advances in Human Aspects of Transportation: Part II*. AHFE Conference.

Gold, C., Damböck, D., Lorenz, L. and Bengler, K. (2013a) '"Take over!" How long does it take to get the driver back into the loop?' *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Los Angeles: SAGE

Gold, C., Körber, M., Hohenberger, C., Lechner, D. and Bengler, K. (2015) 'Trust in automation–Before and after the experience of take-over scenarios in a highly automated vehicle', *Procedia Manufacturing*, 3, pp. 3025-3032.

Gold, C., Körber, M., Lechner, D. and Bengler, K. (2016) 'Taking over control from highly automated vehicles in complex traffic situations: the role of traffic density', *Human Factors*, 58(4), pp. 642-652.

Gold, C., Lorenz, L., Damböck, D. and Bengler, K. (2013b) 'Partially Automated Driving as a Fallback Level of High Automation', *6. Tagung Fahrerassistenzsysteme*. Munich, Germany.

Gorman, G.E. and Clayton, P. (2005) *Qualitative research for the information professionals: A practical handbook*. London: Facet Publishing.

Gouy, M., Wiedemann, K., Stevens, A., Brunett, G. and Reed, N. (2014) 'Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control?', *Transportation Research Part F: Traffic Psychology and Behaviour*, 27, pp. 264-273.

GOV.UK (2018) *Speed limits*. Available at: https://www.gov.uk/speed-limits (Accessed: September 2018).

Guest, G., Bunce, A. and Johnson, L. (2006) 'How many interviews are enough? An experiment with data saturation and variability', *Field Methods*, 18(1), pp. 59-82.

Guest, G., MacQueen, K.M. and Namey, E.E. (2011) *Applied thematic analysis*. London: Sage.

Guest, G., Namey, E., Taylor, J., Eley, N. and McKenna, K. (2017) 'Comparing focus groups and individual interviews: findings from a randomized study', *International Journal of Social Research Methodology*, 20(6), pp. 693-708.

Gugerty, L.J. (1997) 'Situation awareness during driving: Explicit and implicit knowledge in dynamic spatial memory', *Journal of Experimental Psychology: Applied*, 3(1), p. 42.

Gulian, E., Glendon, A.I., Matthews, G., Davies, D.R. and Debney, L.M. (1990) 'The stress of driving: A diary study', *Work & Stress*, 4(1), pp. 7-16.

Guo, A.W., Brake, J.F., Edwards, S.J., Blythe, P.T. and Fairchild, R.G. (2010a) 'The application of in-vehicle systems for elderly drivers', *European Transport Research Review*, 2(3), pp. 165-174.

Guo, F., Klauer, S.G., Hankey, J.M. and Dingus, T.A. (2010b) 'Near crashes as crash surrogate for naturalistic driving studies', *Transportation Research Record*, 2147(1), pp. 66-74.

Guo, W., Blythe, P.T., Edwards, S., Pavkova, K. and Brennan, D. (2013a) 'Effect of intelligent speed adaptation technology on older drivers' driving performance', *IET intelligent transport systems*, 9(3), pp. 343-350.

Guo, W., Brennan, D. and Blythe, P.T. (2013b) 'Detecting older driver's stress level during real-world driving tasks', *International conference on applied psychology and behavioral sciences*. Paris, France. World Academy of Science, Engineering and Technology.

Haegerstrom-Portnoy, G., Schneck, M.E. and Brabyn, J.A. (1999) 'Seeing into old age: vision function beyond acuity', *Optometry & Vision Science*, 76(3), pp. 141-158.

Hakamies-Blomqvist, L. and Wahlström., B. (1998) 'Why do older drivers give up driving?', *Accident Analysis & Prevention* 30(3), pp. 305-312.

Harrell, M.C. and Bradley, M.A. (2009) *Data collection methods. Semi-structured interviews and focus groups*. [Online]. Available at: http://www.dtic.mil/docs/citations/ADA512853.

Hart, S.G. and Staveland, L.E. (1988) 'Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research', *Advances in Psychology*, 52, pp. 139-183.

Hautiere, N., Dumont, E., Bremond, R. and Ledoux, V. (2009) 'Review of the mechanisms of visibility reduction by rain and wet road' *International Symposium on Automotive Lighting (ISAL'09)*. Darmstadt, Germany.

Hays, W.L. (1988) *Statistics (4th ed.)*. Fort Worth, Texas: Holt, Reinhart, & Winston, Inc.

Heinrich, C. (2012) 'Automotive HMI International Standards' *4th International Conference on Applied Human Factors and Ergonomics (AHFE'12)*. San Francisco Union Square, California.

Helzner, E.P., Cauley, J.A., Pratt, S.R., Wisniewski, S.R., Zmuda, J.M., Talbott, E.O., De Rekeneire, N., Harris, T.B., Rubin, S.M., Simonsick, E.M. and Tylavsky, F.A. (2005) 'Race and sex differences in age‐related hearing loss: The Health, Aging and Body Composition Study', *Journal of the American Geriatrics Society*, 53(12), pp. 2119-2127.

Hennessy, D.E. (1995) *Vision Testing of Renewal Applicants: Crashes Predicted when Compensation for Impairment is Inadequate*. Sacramento, CA.

Herriotts, P. (2005) 'Identification of vehicle design requirements for older drivers', *Applied ergonomics*, 36(3), pp. 255-262.

Hill, S.G., Iavecchia, H.P., Byers, J.C., Bittner, A.C., Zaklade, A.L. and Christ, R.E. (1992) 'Comparison of four subjective workload rating scales', *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 34(4), pp. 429-439.

Hoffman, J., Lee, J., Brown, T. and McGehee, D. (2002) 'Comparison of driver braking responses in a high-fidelity simulator and on a test track', *Transportation Research Record: Journal of the Transportation Research Board 1803*, pp. 59-65.

Houx, P.J. and Jolles, J. (1993) 'Age-related decline of psychomotor speed: effects of age, brain health, sex, and education', *Perceptual and Motor skills*, 76(1), pp. 195-211.

Huisingh, C., McGwin, G., Wood, J. and Owsley, C. (2015) 'The driving visual field and a history of motor vehicle collision involvement in older drivers: a population-based examination', *Investigative ophthalmology & visual science*, 56(1), pp. 132-138.

Illmer, A. (2016) *China's push for driverless cars accelerates*. Available at: http://www.bbc.co.uk/news/business-36136590 (Accessed: March 2017).

Insel, K., Morrow, D., Brewer, B. and Figueredo, A. (2006) 'Executive function, working memory, and medication adherence among older adults', *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 61(2), pp. P102-P107.

Jaeger, R.G. and Halliday, T.R. (1998) 'On confirmatory versus exploratory research', *Herpetologica*, 54, pp. S64-S66.

Jenness, J.W., Lerner, N.D., Mazor, S., Osberg, J.S. and Tefft, B.C. (2008) *Use of advanced in-vehicle technology by young and older early adopters Survey Results on Adaptive Cruise Control Systems.*

Report No. DOT HS 810 828. [Online]. Available at: www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/.../DOT-HS-810-828rev.pdf.

Jette, A.M. and Branch, L.G. (1992) 'A ten-year follow-up of driving patterns among the community-dwelling elderly', *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 34(1), pp. 25-31.

Johnson, R.B. and Onwuegbuzie, A.J. (2004) 'Mixed methods research: A research paradigm whose time has come', *Educational researcher*, 33(7), pp. 14-26.

Jones, R.E., Connors, E.S., Mossey, M.E., Hyatt, J.R., Hansen, N.J. and Endsley, M.R. (2011) 'Using fuzzy cognitive mapping techniques to model situation awareness for army infantry platoon leaders', *Computational and Mathematical Organization Theory*, 17(3), pp. 272-295.

Kaber, D.B. and Endsley, M.R. (1997) 'Out‐of‐the‐loop performance problems and the use of intermediate levels of automation for improved control system functioning and safety', *Process Safety Progress*, 16(3), pp. 126-131.

Kallman, D.A., Plato, C.C. and Tobin, J.D. (1990) 'The role of muscle loss in the age-related decline of grip strength: cross-sectional and longitudinal perspectives', *Journal of gerontology*, 45(3), pp. M82-M88.

Karthaus, M. and Falkenstein, M. (2016) 'Functional changes and driving performance in older drivers: assessment and interventions', *Geriatrics*, 1(2), p. 12.

Kawulich, B.B. (2005) 'Participant observation as a data collection method. Forum Qualitative', *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research*, 6(2), p. Art. 43.

Kelley, K., Clark, B., Brown, V. and Sitzia, J. (2003) 'Good practice in the conduct and reporting of survey research', *International Journal for Quality in Health Care*, 15(3), pp. 261-266.

Kelso, S. (1982) *Human Motor Behavior: An Introduction*. Hillsadale, New Jersey: Lawrence Erlbaum Assoc.

Kennedy, R.S., K.M. Stanney and Dunlap, W.P. (2000) 'Duration and exposure to virtual environments: sickness curves during and across sessions', *Presence: Teleoperators & Virtual Environments*, 9(5), pp. 463-472.

Kent, R., Trowbridge, M., Lopez-Valdes, F.J., Ordoyo, R.H. and Segui-Gomez, M. (2009) 'How many people are injured and killed as a result of aging? Frailty, fragility, and the elderly risk-exposure tradeoff assessed via a risk saturation model', *Ann Adv Automot Med*, 53(41), p. e50.

Keshavarz, B., Ramkhalawansingh, R., Haycock, B., S. Shahab and Campos, J.L. (2018) 'Comparing simulator sickness in younger and older adults during simulated driving under different multisensory conditions', *Transportation Research Part F: Traffic Psychology and Behaviour*, 54, pp. 47-62.

Kiefer, R.J., Cassar, M.T., Flannagan, C.A., LeBlanc, D.J., Palmer, M.D., Deering, R.K. and Shulman, M.A. (2003) *Forward Collision Warning Requirements Project: Refining the CAMP Crash Alert Timing Approach by Examining "Last-Second" Braking and Lane Change Maneuvers Under Various Kinematic Conditions*.

Kim, M.H. and Son, J. (2011) 'On-road assessment of in-vehicle driving workload for older drivers: Design guidelines for intelligent vehicles', *International Journal of Automotive Technology*, 12(2), pp. 265-272.

Kline, D.W., Kline, T.J., Fozard, J.L., Kosnik, W., Schieber, F. and Sekuler, R. (1992) 'Vision, aging, and driving: The problems of older drivers', *Journal of gerontology*, 47(1), pp. P27-P34.

Körber, M., Gold, C., Lechner, D. and Bengler, K. (2016) 'The influence of age on the take-over of vehicle control in highly automated driving', *Transportation Research Part F: Traffic Psychology and Behaviour*, 39, pp. 19-32.

Kostyniuk, L. and Shope, J. (1998) *Reduction and cessation of driving among older drivers: Focus Groups. (Report UMTRI-98-26)*

Kostyniuk, L.P. and Molnar, L.J. (2008) 'Self-regulatory driving practices among older adults: Health, age and sex effects', *Accident Analysis & Prevention*, 40(4), pp. 1576-1580.

Kramer, A.F., Cassavaugh, N., Horrey, W.J., Becic, E. and Mayhugh, J.L. (2007) 'Influence of age and proximity warning devices on collision avoidance in simulated driving', *Human Factors*, 49(5), pp. 935-949.

Kyriakidis, M., Happee, R. and de Winter, J.C. (2015) 'Public opinion on automated driving: Results of an international questionnaire among 5000 respondents', *Transportation Research Part F: Traffic Psychology and Behaviour*, 32, pp. 127-140.

legislation.gov.uk (2018) *Automated and Electric Vehicles Act 2018*. Available at: http://www.legislation.gov.uk/ukpga/2018/18/contents.

Levasseur, M., Coallier, J.C., Gabaude, C., Beaudry, M., Bedard, M., Langlais, M.È. and St-Pierre, C. (2016) 'Facilitators, barriers and needs in the use of adaptive driving strategies to enhance older drivers' mobility: Importance of openness, perceptions, knowledge and support', *Transportation Research Part F: Traffic Psychology and Behaviour*, 43, pp. 56-66.

Lewis, J.R. (1989) 'Pairs of latin squares to counterbalance sequential effects and pairing of conditions and stimuli' *In Proceedings of the Human Factors Society Annual Meeting*. Los Angeles, CA. SAGE Publications.

Li, G., Braver, E.R. and Chen, L.H. (2003) 'Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers', *Accident Analysis & Prevention*, 35(2), pp. 227-235.

Liljamo, T., Liimatainen, H. and Pöllänen, M. (2018) 'Attitudes and concerns on automated vehicles', *Transportation Research Part F: Traffic Psychology and Behaviour*, 59, pp. 24-44.

Lin, R., Ma, L. and Zhang, W. (2018) 'An interview study exploring Tesla drivers' behavioural adaptation', *Applied ergonomics*, 72, pp. 37-47.

Litman, T. (2017) *Autonomous vehicle implementation predictions*. Victoria, Canada: Victoria Transport Policy Institute.

Liu, Y.C. (2001) 'Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveller information systems', *Ergonomics*, 44(4), pp. 425-442.

Llaneras, R.E., Salinger, J. and Green, C.A. (2013) 'Human factors issues associated withlimited ability autonomous driving systems: drivers' allocation of visualattention to the forward roadway' *the 7th International Driving Symposium on Human Factors in Driver Assessment,Training and Vehicle Design*. Bolton Landing, New York.

Lorenz, L., Kerschbaum, P. and Schumann, J. (2014) 'Designing take over scenarios for automated driving: How does augmented reality support the driver to get back into the loop?' *the Human Factors and Ergonomics Society Annual Meeting*. Los Angeles, CA. SAGE Publications.

Louw, T., Merat, N. and Jamson, H. (2015) 'Engaging with Highly Automated Driving: To be or Not to be in the Loop?' *the Eighth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. Salt Lake City, Utah. Iowa City, IA. Public Policy Center, University of Iowa.

Lowhorn, G.L. (2007) 'Qualitative and Quantitative Research: How to Choose the Best Design', *Academic Business World International Conference* Nashville, Tennessee, USA. Available at: http://abwic.org/Proceedings/2007/ABW07-238.doc.

Lu, Z., Happee, R., Cabrall, C.D., Kyriakidis, M. and de Winter, J.C. (2016) 'Human factors of transitions in automated driving: A general framework and literature survey', *Transportation research part F: Traffic Psychology and Behaviour*, 43, pp. 183-198.

Luborsky, M.R. and Rubinstein, R.L. (1995) 'Sampling in qualitative research: Rationale, issues, and methods', *Research on Aging*, 17(1), pp. 89-113.

Lyman, J.M., McGwin, G. and Sims, R.V. (2001) 'Factors related to driving difficulty and habits in older drivers', *Accident Analysis & Prevention*, 33(3), pp. 413-421.

Maguire, M. and Bevan, N. (2002) 'User requirements analysis' *IFIP 17th World Computer Congress*. Montreal, Canada,. Kluwer Academic Publishers.

Mani, T.M., Bedwell, J.S. and Miller, L.S. (2005) 'Age-related decrements in performance on a brief continuous performance test', *Archives of Clinical Neuropsychology*, 20(5), pp. 575–586.

Mårdh, S. (2016) 'Identifying factors for traffic safety support in older drivers', *Transportation Research Part F: Traffic Psychology and Behaviour*, 38, pp. 118-126.

Marmeleira, J.F., Godinho, M.B. and Fernandes, O.M. (2009) 'The effects of an exercise program on several abilities associated with driving performance in older adults', *Accident Analysis & Prevention*, 41(1), pp. 90-97.

Marottoli, R.A., Leon, C.F.M., Glass, T.A., Williams, C.S., Cooney, L.M., Berkman, L.F. and Tinetti, M.E. (1997) 'Driving cessation and increased depressive symptoms: Prospective evidence from the New Haven EPESE', *Journal of the American Geriatrics Society*, 45(2), pp. 202-206.

Marottoli, R.A., Ostfeld, A.M., Merrill, S.S., Perlman, G.D., Foley, D.J. and Cooney Jr, L.M. (1993) 'Driving cessation and changes in mileage driven among elderly individuals', *Journal of gerontology*, 48(5), pp. S255-S260.

Marshall, B., Cardon, P., Poddar, A. and Fontenot, R. (2013) 'Does sample size matter in qualitative research?: A review of qualitative interviews in IS research', *Journal of Computer Information Systems*, 54(1), pp. 11-22.

Mason, M. (2010) *Sample size and saturation in PhD studies using qualitative interviews.* [Online]. Available at: http://www.qualitative-research.net/index.php/fqs/article/view/1428/3028.

Mathers, N., Fox, N. and Hunn, A. (2007) *Surveys and questionnaires*. [Online]. Available at: https://www.rds-yh.nihr.ac.uk/wp-content/uploads/2013/05/12_Surveys_and_Questionnaires_Revision_2009.pdf.

Matthews, G. and Desmond, P.A. (1995) 'Stress as a factor in the design of in-car driving enhancement systems', *Le Travail Humain*, 58(2), p. 109.

Matthews, M., Bryant, D., Webb, R. and Harbluk, J. (2001) 'Model for situation awareness and driving: Application to analysis and research for intelligent transportation systems', *Transportation Research Record: Journal of the Transportation Research Board*, (1779), pp. 26-32.

McCrum-Gardner, E. (2008) 'Which is the correct statistical test to use?', *British Journal of Oral and Maxillofacial Surgery*, 46(1), pp. 38-41.

McDowd, J.M. and Birren, J.E. (1990) 'Aging and attentional processes. Handbook of the psychology of aging', in Birren, J.E. and Warnar Schaie, K. (eds.) *Handbook of The Psychology of Aging*. 3rd edn. ELSEVIER.

McGwin Jr, G. and Brown, D.B. (1999) 'Characteristics of traffic crashes among young, middle-aged, and older drivers', *Accident Analysis & Prevention*, 31(3), pp. 181-198.

McLaughlin, S., Hankey, J. and Dingus, T. (2009) 'Driver measurement: methods and applications', in Harris, D. (ed.) *Engineering Psychology and Cognitive Ergonomics: HCII 2009, LNAI 5639*. Berlin, Heidelberg: Springer-Verlag, pp. 404-413.

McLaughlin, S.B., Hankey, J.M. and Dingus, T.A. (2008) 'A method for evaluating collision avoidance systems using naturalistic driving data', *Accident Analysis & Prevention*, 40(1), pp. 8-16.

Meiring, G.A.M. and Myburgh, H.C. (2015) 'A review of intelligent driving style analysis systems and related artificial intelligence algorithms', *Sensors*, 15(12), pp. pp.30653-30682.

Melcher, V., Rauh, S., Diederichs, F., Widlroither, H. and Bauer, W. (2015) 'Take-over requests for automated driving', *Procedia Manufacturing*, 3, pp. 2867-2873.

Meng, A., Siren, A. and Teasdale, T.W. (2013) 'Older drivers with cognitive impairment: Perceived changes in driving skills, driving-related discomfort and self-regulation of driving', *European Geriatric Medicine*, 4(3), pp. 154-160.

Merat, N., Anttila, V. and Luoma, J. (2005) 'Comparing the driving performance of average and older drivers: The effect of surrogate in-vehicle information systems', *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2), pp. 147-166.

Merat, N. and Jamson, A.H. (2009) 'Is Drivers' Situation Awareness Influenced by a Fully Automated Driving Scenario?', *Human Factors, Security and Safety. Human Factors and Ergonomics Society Europe Chapter Conference*. Soesterberg, the Netherlands. Shaker Publishing.

Merat, N., Jamson, A.H., Lai, F.C. and Carsten, O. (2012) 'Highly automated driving, secondary task performance, and driver state', *Human factors*, 54(5), pp. 762-771.

Merat, N., Jamson, A.H., Lai, F.C., Daly, M. and Carsten, O.M. (2014) 'Transition to manual: Driver behaviour when resuming control from a highly automated vehicle', *Transportation Research Part F: Traffic Psychology and Behaviour*, 27, pp. 274-282.

MetOffice (2018a) *Blizzards and snow drifts*. Available at: https://www.metoffice.gov.uk/learning/precipitation/snow/blizzard (Accessed: September).

MetOffice (2018b) *What is fog?* Available at: https://www.metoffice.gov.uk/learning/clouds/fog (Accessed: September).

Metz, D.H. (2000) 'Mobility of older people and their quality of life', *Transport Policy*, 7(2), pp. 149-152.

Miller, D., Johns, M., Ive, H.P., Gowda, N., Sirkin, D., Sibi, S., Mok, B., Aich, S. and Ju, W. (2016) *Exploring Transitional Automation with New and Old Drivers* (No. 2016-01-1442). SAE Technical Paper.

Mitchell, C.G.B. and Suen, S.L. (1997) 'ITS impact on elderly drivers', *the 13th International Road Federation IRF World Meeting*. Toronto, Ontario, Canada.

Mok, B., Johns, M., Lee, K.J., Miller, D., Sirkin, D., Ive, P. and Ju, W. (2015a) 'Emergency, automation off: unstructured transition timing for distracted drivers of automated vehicles', *2015 IEEE 18th International Conference on Intelligent Transportation Systems*. Canary Islands, Spain. IEEE.

Mok, B.K.J., Johns, M., Lee, K.J., Ive, H.P., Miller, D. and Ju, W. (2015b) 'Timing of unstructured transitions of control in automated driving' *Intelligent Vehicles Symposium (IV), 2015 IEEE*. IEEE.

Molnar, L.J., Pradhan, A.K., Eby, D.W., Ryan, L.H., St. Louis, R.M., Zakrajsek, J., Ross, B., Lin, B.T., Liang, C., Zalewski, B. and Zhang, L. (2017) *Age-Related Differences in Driver Behavior Associated with Automated Vehicles and the Transfer of Control between Automated and Manual Control: A Simulator Evaluation*. Ann Arbor.

Morgan, D.L. (1996) 'Focus groups', *Annual Review of Sociology*, 22(1), pp. 129-152.

Mueller, A.S., Sangrar, R. and Vrkljan, B. (2017) 'Rearview camera system use among older drivers: A naturalistic observation study', *Transportation Research Part F: Traffic Psychology and Behaviour*.

Mueller, A.S. and Trick, L.M. (2012) 'Driving in fog: The effects of driving experience and visibility on speed compensation and hazard avoidance', *Accident Analysis & Prevention*, 48, pp. 472-479.

Musselwhite, C. (2011) 'The importance of driving for older people and how the pain of driving cessation can be reduced', *Journal of Dementia and Mental Health*, 15(3), pp. 22-26.

Musselwhite, C. and Haddad, H. (2010) 'Exploring older drivers' perceptions of driving', *European Journal of Ageing*, 7(3), pp. 181-188.

Musselwhite, C.B. and Haddad, H. (2007) *Prolonging the safe driving of older people through technology*. England, U.o.t.W.o.

Musselwhite, C.B. and Shergold, I. (2013) 'Examining the process of driving cessation in later life', *European Journal of Ageing*, 10(2), pp. 89-100.

Myers, A.M., Paradis, J.A. and Blanchard, R.A. (2008) 'Conceptualizing and measuring confidence in older drivers: Development of the day and night driving comfort scales', *Archives of physical medicine and rehabilitation*, 89(4), pp. 630-640.

Myerson, J., Robertson, S. and Hale, S. (2007) 'Aging and intraindividual variability in performance: Analyses of response time distributions', *Journal of the Experimental Analysis of Behavior*, 88(3), pp. 319-337.

Naujoks, F., Mai, C. and Nekum, A. (2014a) 'The effect of urgency of take-over requests during highly automated driving under distracted conditions', *the 5th International Conference on Applied Human Factors and Ergonomics*. Krakow, Poland.

Naujoks, F., Mai, C. and Neukum, A. (2014b) 'The effect of urgency of take-over requests during highly automated driving under distraction conditions', *Advances in Human Aspects of Transportation*, 7(Part I), p. 431.

NeelimaChakrabartya, K. (2013) 'Analysis of Driver Behaviour and Crash Characteristics during Adverse Weather Conditions', *Procedia-Social and Behavioral Sciences, 2nd Conference of Transportation Research Group of India (2nd CTRG)*, 104, pp. 1048-1057.

NHTSA (2013) *National Highway Traffic Safety Administration Preliminary Statement of Policy Concerning Automated Vehicles*. [Online]. Available at: https://www.nhtsa.gov/staticfiles/rulemaking/pdf/Automated_Vehicles_Policy.pdf.

Norman, D.A. (1984) 'Stages and levels in human-machine interaction', *International journal of man-machine studies*, 21(4), pp. 365-375.

Norman, D.A. (1990) 'The 'problem'with automation: inappropriate feedback and interaction, not 'over-automation'', *Phil. Trans. R. Soc. Lond. B*, 327(1241), pp. 585-593.

Norman, G. (2010) 'Likert scales, levels of measurement and the "laws" of statistics', *Advances in Health Sciences Education*, 15(5), pp. 625-632.

Nowell, L.S., Norris, J.M., White, D.E. and Moules, N.J. (2017) 'Thematic analysis: Striving to meet the trustworthiness criteria', *International Journal of Qualitative Methods*, 16(1), p. 1609406917733847.

O'Keeffe, J., Buytaert, W., Mijic, A., Brozović, N. and Sinha, R. (2016) 'The use of semi-structured interviews for the characterisation of farmer irrigation practices', *Hydrology and Earth System Sciences*, 20(5), pp. 1911-1924.

O'reilly, M. and Parker, N. (2013) 'Unsatisfactory Saturation': a critical exploration of the notion of saturated sample sizes in qualitative research', *Qualitative Research*, 13(2), pp. 190-197.

Obst, P., Armstrong, K., Smith, S. and Banks, T. (2011) 'Age and gender comparisons of driving while sleepy: Behaviours and risk perceptions', *Transportation Research Part F: Traffic Psychology and Behaviour*, 14(6), pp. 539-542.

ONS (2012) *Population Ageing in the United Kingdom, its Constituent Countries and the European Union*. [Online]. Available at: http://webarchive.nationalarchives.gov.uk/20160105160709/http://www.ons.gov.uk/ons/rel/mortality-ageing/focus-on-older-people/population-ageing-in-the-united-kingdom-and-europe/rpt-age-uk-eu.html.

ONS (2014) *National Population Projections: 2014-based Statistical Bulletin*. [Online]. Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2015-10-29.

ONS (2017) *Overview of the UK population: July 2017. Office for National Statistics*. [Online]. Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/july2017.

Opdenakker, R. (2006) *Advantages and disadvantages of four interview techniques in qualitative research*. [Online]. Available at: http://www.qualitative-research.net/index.php/fqs/article/view/175/391.

Owsley, C., Stalvey, B., Wells, J. and Sloane, M.E. (1999) 'Older drivers and cataract: driving habits and crash risk', *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences*, 54(4), pp. M203-M211.

Panek, P.E., Barrett, G.V., Sterns, H.L. and Alexander, R.A. (1977) 'A review of age changes in perceptual information processing ability with regard to driving', *Experimental Aging Research*, 3(4-6), pp. 387-449.

Pangbourne, K., Aditjandra, P.T. and Nelson, J.D. (2010) 'New technology and quality of life for older people: Exploring health and transport dimensions in the UK context', *IET Intelligent Transport Systems*, 4(4), pp. 318-327

Persson, D. (1993) 'The elderly driver: deciding when to stop', *The Gerontologist*, 33(1), pp. 88-91.

Petermeijer, S., Bazilinskyy, P., Bengler, K. and de Winter, J. (2017) 'Take-over again: Investigating multimodal and directional TORs to get the driver back into the loop', *Applied Ergonomics*, 62, pp. 204-215.

Piao, J., McDonald, M., Hounsell, N., Graindorge, M., Graindorge, T. and Malhene, N. (2016) 'Public views towards implementation of automated vehicles in urban areas', *Transportation Research Procedia*, 14, pp. 2168-2177.

Pichora-Fuller, M.K. (2003) 'Processing speed and timing in aging adults: psychoacoustics, speech perception, and comprehension', *International Journal of Audiology*, 42(sup1), pp. 59-67.

Polit, D.F. and Beck, C.T. (2010) 'Generalization in quantitative and qualitative research: Myths and strategies', *International journal of nursing studies*, 47(11), pp. 1451-1458.

Pollatsek, A., Romoser, M.R. and Fisher, D.L. (2012) 'Identifying and remediating failures of selective attention in older drivers', *Current directions in psychological science*, 21(1), pp. 3-7.

Prat, F., Gras, M.E., Planes, M., Font-Mayolas, S. and Sullman, M.J.M. (2017) 'Driving distractions: an insight gained from roadside interviews on their prevalence and factors associated with driver distraction', *Transportation research part F: traffic psychology and behaviour*, 45, pp. 194-207.

Purchase, H.C. (2012) *Experimental human-computer interaction: a practical guide with visual examples*. Cambridge University Press.

Quigley, J.T. (2013) *Japanese Prime Minister "Test Drives" Autonomous Vehicles*. Available at: http://thediplomat.com/2013/11/japanese-prime-minister-test-drives-autonomous-vehicles/ (Accessed: March 2017).

Rabiee, F. (2004) 'Focus-group interview and data analysis. Proceedings of the nutrition society', *Proceedings of the nutrition society*, 63(4), pp. 655-660.

Radlmayr, J., Gold, C., Lorenz, L., Farid, M. and Bengler, K. (2014) 'How traffic situations and non-driving related tasks affect the take-over quality in highly automated driving', *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 58, pp. 2063-2067.

Ranney, T.A., Harbluk, J.L. and Noy, Y.I. (2005) 'Effects of voice technology on test track driving performance: Implications for driver distraction', *Human factors*, 47(2), pp. 439-454.

Ranney, T.A., Mazzae, E., Garrott, R. and Goodman, M.J. (2000) *NHTSA driver distraction research: Past, present, and future*. [Online]. Available at: www-nrd.nhtsa.dot.gov/departments/nrd-13/driver-distraction/Welcome.htm.

Reason, J., Manstead, A., Stradling, S., Baxter, J. and Campbell, K. (1990) 'Errors and violations on the roads: a real distinction?', *Ergonomics*, 33(10-11), pp. 1315-1332.

Reed, M.P. and Green, P.A. (1999) 'Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task', *Ergonomics*, 42(8), pp. 1015-1037.

Rice, S., Winter, S.R., Doherty, S. and Milner, M. (2017) 'Advantages and disadvantages of using internet-based survey methods in aviation-related research', *Journal of Aviation Technology and Engineering*, 7(1), p. 5.

Richards, T.J. and Richards, L. (1994) 'Using computers in qualitative research', *Handbook of qualitative research*, 2, pp. 445-62.

Rimmö, P.A. and Hakamies-Blomqvist, L. (2002) 'Older drivers' aberrant driving behaviour, impaired activity, and health as reasons for self-imposed driving limitations', *Transportation Research Part F: Traffic Psychology and Behaviour*, 5(1), pp. 47-62.

Rodríguez-Aranda, C., Waterloo, K., Sparr, S. and Sundet, K. (2006) 'Age-related psychomotor slowing as an important component of verbal fluency', *Journal of neurology*, 253(11), p. 1414.

Rogers, W.A., Meyer, B., Walker, N. and Fisk, A.D. (1998) 'Functional limitations to daily living tasks in the aged: A focus group analysis', *Human factors*, 40(1), pp. 111-125.

Rosenbloom, T. (2006) 'Driving performance while using cell phones: an observational study', *Journal of Safety Research*, 37(2), pp. 207-212.

SAE (2014) *SAE Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems*. [Online]. Available at: https://saemobilus.sae.org/content/j3016_201609 (Accessed: August 2018).

Salmon, P., Stanton, N., Walker, G. and Green, D. (2006) 'Situation awareness measurement: A review of applicability for C4i environments', *Applied ergonomics*, 37(2), pp. 225-238.

Salthouse, T.A. (1996) 'The processing-speed theory of adult age differences in cognition', *Psychological Review* 103(3), p. 403.

Sandelowski, M. and Leeman, J. (2012) 'Writing usable qualitative health research findings', *Qualitative health research*, 22(10), pp. 1404-1413.

Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., Bartlam, B., Burroughs, H. and Jinks, C. (2018) 'Saturation in qualitative research: exploring its conceptualization and operationalization', *Quality & Quantity*, 52(4), pp. 1893-1907.

Schieber, F. (1994) 'Age and glare recovery time for low-contrast stimuli' *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. SAGE Publications.

Schmitz, F. and Voss., A. (2014) 'Components of task switching: A closer look at task switching and cue switching', *Acta psychologica*, 151, pp. 184-196.

Seddon, C. (2011) 'Lifestyles and social participation', *Social Trends*, 41(1), pp. 146-180.

Sekuler, B., Bennett, P. and Mortimer, A. (2000) 'Effects of aging on the useful field of view', *Experimental Aging Research*, 26(2), pp. 103-120.

Seltman, H.J. (2009) *Experimental Design and Analysis*.

Seppelt, B.D. and Lee, J.D. (2007) 'Making adaptive cruise control (ACC) limits visible', *International journal of human-computer studies*, 65(3), pp. 192-205.

Shanmugaratnam, S., Kass, S.J. and Arruda, J.E. (2010) 'Age differences in cognitive and psychomotor abilities and simulated driving', *Accident Analysis & Prevention*, 42(3), pp. 802-808.

Shinar, D. and Compton, R. (2004) 'Aggressive driving: an observational study of driver, vehicle, and situational variables', *Accident Analysis & Prevention*, 36(3), pp. 429-437.

Shumway-Cook, A. and Woollacott, M. (2000) 'Attentional demands and postural control: the effect of sensory context', *Journals of Gerontology Series A: Biological and Medical Sciences*, 55(1), p. 10.

Siren, A. and Hakamies-Blomqvist, L. (2005) 'Sense and sensibility. A narrative study of older women’s car driving', *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(3), pp. 213-228.

Siren, A., Hakamies-Blomqvist, L. and Lindeman, M. (2004) 'Driving cessation and health in older women', *Journal of Applied Gerontology*, 23(1), pp. 58-69.

Sodnik, J., Dicke, C., Tomažič, S. and Billinghurst, M. (2008) 'A user study of auditory versus visual interfaces for use while driving', *International journal of human-computer studies*, 66(5), pp. 318-332.

Stanton, N.A., Chambers, P.R. and Piggott, J. (2001) 'Situational awareness and safety', *Safety science*, 39(3), pp. 189-204.

Stanton, N.A., Dunoyer, A. and Leatherland, A. (2011) 'Detection of new in-path targets by drivers using Stop & Go Adaptive Cruise Control', *Applied ergonomics*, 42(4), pp. 592-601.

Stanton, N.A. and Young, M.S. (1998) 'Vehicle automation and driving performance', *Ergonomics*, 41(7), pp. 1014-1028.

Staplin, L.K., Lococo, K., Stewart, J., Decina, L.E. and TransAnalytics., L.L.C. (1999) *Safe mobility for older people notebook*. [Online]. Available at: http://ntl.bts.gov/DOCS/Safe_Ntbk/tech-doc.htm.

Steinberger, F., Moeller, A. and Schroeter, R. (2016) 'The antecedents, experience, and coping strategies of driver boredom in young adult males', *Journal of Safety Research*, 59, pp. 69-82.

Stelmach, G.E. and Goggin, N.L. (1988) 'Psychomotor decline with age', *choice*, 247(307), p. 24.

Stevens, A. (2000) 'Safety of driver interaction with in-vehicle information systems', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 214(6), pp. 639-644.

Stevens, A., Quimby, A., Board, A., Kersloot, T. and Burns, P. (2002) *Design guidelines for safety of in-vehicle information systems. Project report PA3721/01*.

Sullivan, J.M. (2004) *Driver Performance and Workload Using a Night Vision System (UMTRI-2004-8)*

Ann Arbor, MI 48109-2150 U.S.A.

Symonds, P.M. (1924) 'On the Loss of Reliability in Ratings Due to Coarseness of the Scale', *Journal of Experimental Psychology*, 7(6), p. 456.

Trick, G.L. and Silverman, S.E. (1991) 'Visual sensitivity to motion Age - related changes and deficits in senile dementia of the Alzheimer type', *Neurology*, 41(9), pp. 1437-1437.

TRL (2017) *Published GATEway Project Report PPR807 Driver responses to encountering automated vehicles in an urban environment*. [Online]. Available at: file:///H:/Stage2%20Take%20Over%20Simualtor%20Trail/5.%20Development%20of%20Vehicle%20Automation/Driver-responses-to-encountering-automated-vehicles-in-an-urban-environment-1.pdf.

Trübswetter, N. and Bengler, K. (2013) 'Why should i use ADAS? Advanced driver assistance systems and the elderly: knowledge, experience and usage barriers' *the 7th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*. Bolton Landing New York, United States.

UKAutodrive (2016a) *Lords get latest on UK trials*. Available at: http://www.ukautodrive.com/lords-get-latest-on-uk-trials/ (Accessed: March 2017).

UKAutodrive (2016b) *UK Autodrive completes first trials*. Available at: http://www.ukautodrive.com/uk-autodrive-completes-first-vehicle-trials/.

UN (2015) *World Population Prospects*. [Online]. Available at: https://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf.

Underwood, G., Crundall, D. and Chapman, P. (2011) 'Driving simulator validation with hazard perception', *Transportation Research Part F: Traffic Psychology and Behaviour*, 14, pp. 435-446.

Vaezipour, A., Rakotonirainy, A., Haworth, N. and Delhomme, P. (2017) 'Enhancing eco-safe driving behaviour through the use of in-vehicle human-machine interface: A qualitative study', *Transportation Research Part A: Policy and Practice*, 100, pp. 247-263.

Vaismoradi, M., Jones, J., Turunen, H. and Snelgrove, S. (2016) 'Theme development in qualitative content analysis and thematic analysis', *Journal of Nursing Education and Practice*, 6(5), p. 100.

van den Beukel, A.P. and van der Voort, M.C. (2013) 'The influence of time-criticality on Situation Awareness when retrieving human control after automated driving', *16th International IEEE Conference on Intelligent Transportation Systems IEEE*. The Hague, The Netherlands.

van der Horst, R. and Hogema, J. (1993) 'Time-to-collision and Collision Avoidance Systems' *The 6th ICTCT Workshop: Safety Evaluation of Traffic Systems: Traffic Conflicts and Other Measures*. Salzburg, Austrian. University of Lund.

Van Driel, C. and van Arem, B. (2005) 'Investigation of user needs for driver assistance: results of an Internet questionnaire', *European Journal of Transport and Infrastructure Research*, 5(4), pp. 297-316.

Vaportzis, E., Georgiou-Karistianis, N. and Stout, J.C. (2013) 'Dual task performance in normal aging: a comparison of choice reaction time tasks', *PLOS one*, 8(3), p. e60265

VENTURER (2017) *Trial 1: Planned Handover Technical Report*. [Online]. Available at: https://www.venturer-cars.com/wp-content/uploads/2017/05/VENTURER-Trial-1-Planned-Handover-Technical-Report.pdf.

VENTURER (2018) *Final Report Providing insight on human responses to, and perceptions of, connected and autonomous vehicles and helping unlock their potential benefits*. [Online]. Available at: https://www.venturer-cars.com/wp-content/uploads/2018/09/VENTURER-Final-Report.pdf.

Vlassenroot, S., Brookhuis, K., Marchau, V. and Witlox, F. (2010) 'Towards defining a unified concept for the acceptability of Intelligent Transport Systems (ITS): A conceptual analysis based on the case of Intelligent Speed Adaptation (ISA)', *Transportation Research Part F: Traffic Psychology and Behaviour*, 13(3), pp. 164-178.

Vogel, K. (2002) 'What characterizes a “free vehicle” in an urban area?', *Transportation research part F: traffic psychology and behaviour*, 5(1), pp. 15-29.

Vogel, K. (2003) 'A comparison of headway and time to collision as safety indicators', *Accident analysis & prevention*, 35(3), pp. 427-433.

Vrkljan, B.H. and Polgar, J.M. (2007) 'Linking occupational participation and occupational identity: An exploratory study of the transition from driving to driving cessation in older adulthood', *Journal of Occupational Science*, 14(1), pp. 30-39.

WAARD, D.D., Jessurun, M., Steyvers, F.J., Reggatt, P.T. and Brookhuis, K.A. (1995) 'Effect of road layout and road environment on driving performance, drivers' physiology and road appreciation', *Ergonomics*, 38(7), pp. 1395-1407.

WHO (2016) *Definition of an older or elderly person*. Available at: http://www.who.int/healthinfo/survey/ageingdefnolder/en/ (Accessed: October 2016).

Wood, E., Willoughby, T., Rushing, A., Bechtel, L. and Gilbert, J. (2005) 'Use of computer input devices by older adults', *Journal of Applied Gerontology*, 24(5), pp. 419-438.

Wooldridge, M.D., Bauer, K., Green, P. and Fitzpatrick, K. (2000) 'Comparison of driver visual demand in test track, simulator, on-road environments' *the 79th Annual Meeting of the Transportation Research Board, National Research Council*. Washington, D.C. National Academy Press.

Yang, J. and Coughlin, J.F. (2014) 'In-vehicle technology for self-driving cars: Advantages and challenges for aging drivers', *International Journal of Automotive Technology*, 15(2), pp. 333-340.

Young, K.L., Koppel, S. and Charlton, J.L. (2017) 'Driver Assistance Systems and the Transition to Automated Vehicles: A Path to Increase Older

Adult Safety and Mobility?', *Accident Analysis & Prevention*, 106, pp. 460-467.

Young, M.S. and Stanton, N.A. (2002a) 'Attention and automation: new perspectives on mental underload and performance', *Theoretical Issues in Ergonomics Science*, 3(2), pp. 178-194.

Young, M.S. and Stanton, N.A. (2002b) 'Malleable attentional resources theory: a new explanation for the effects of mental underload on performance', *Human factors*, 44(3), pp. 365-375.

Zachariou, P., James, J., Hammond, C., Naveen, B. and Mayson, R. (2011) *Speeding Effects on hazard perception and reaction time*. [Online]. Available at: http://images.thetruthaboutcars.com/2011/02/HRAR_REPORT243.pdf

Zamawe, F.C. (2015) 'The implication of using NVivo software in qualitative data analysis: Evidence-based reflections', *Malawi Medical Journal*, 27(1), pp. 13-5.

Zeeb, K., Buchner, A. and Schrauf, M. (2016) 'Is take-over time all that matters? The impact of visual-cognitive load on driver take-over quality after conditionally automated driving', *Accident Analysis & Prevention*, 92, pp. 230-239.

Zeeb, K., Härtel, M., Buchner, A. and Schrauf, M. (2017) 'Why is steering not the same as braking? The impact of non-driving related tasks on lateral and longitudinal driver interventions during conditionally automated driving', *Transportation Research Part F: Traffic Psychology and Behaviour*, 50, pp. 65-79.

Appendices

Appendix A: Participant Recruitment Information

Dear Sir/Madam

My name is Shuo Li. I'm a PhD student in the School of Civil Engineering and Geosciences at Newcastle University. My doctoral research is to investigate older drivers' interaction with the highly automated vehicles (HAVs).

An HAV can offer an automated driving which allows the driver to be "completely disengaged" from the driving and undertake other tasks, such as reading, watching a film and using the mobile phone. However, there are situations that manual driving from you may be required, it will then inform you to take over the control and provide you with enough time to do it.

I would like to invite you to participate in a driving simulator investigation which you would experience an HAV on the Newcastle University's driving simulator. This investigation will help me to understand your performance of interacting with an HAV.

This investigation will begin in the following weeks. Please circle all possible time slots that suit your timetable in the table below or you can propose another time. I will confirm your time slot upon receiving your reply.

Time	**Dates in March 2017**										Parking
	Mon	Tue	Wed	Thu	Fri	Mon	Tue	Wed	Thu	Fri	
10:00-12:00	13	14	15	16	17	20	21	22	23	24	
	27	28	29	30	31						
											Parking
14:00-16:00	13	14	15	16	17	20	21	22	23	24	
	27	28	29	30	31						

The investigation will take place in our driving simulator lab. We will meet you at the reception of the Devonshire Building (No. 48 on the attached Campus Map) Newcastle University and take you to our driving simulator lab. As a THANK YOU, you will be given a gift voucher worth £10 to compensate for your time and travel cost. Please also note that you are free to withdraw from the study at any time.

If you need any further information, please contact me at s.li7@newcastle.ac.uk (email) or 07596****** (telephone).

Look forward to hearing from you!

Best regards
Shuo Li

August 2011 Edition

Appendix B: Driving Simulator Investigation Participant Consent Form

Dear Participants

Thank you for agreeing to participate in a driving simulator test for Mr Shuo Li's doctoral thesis study. All the data and information collected from you, will be held anonymously and securely. No personal data are asked for or retained. Access to your data is limited to the people involved in this research. If published, they will not be identifiable by your name. If a photograph or video clip is used for presentation, your name will not be mentioned. If you do not want your likeness to be used in any of the material, your image can be blanked from view. Your participation of this study is entirely voluntary.

If you have questions about the study, you are welcome to contact me at: s.li7@newcastle.ac.uk (email) or 07596****** (telephone number).

Thank you very much.
Shuo Li

Please indicate your agreement with the following statements by circling "YES" or "NO"

I agree to participate in this driving simulator test. I understand that I can withdraw from it at any time for any reasons. **YES/NO**

I agree for the driving simulator test to be recorded (video). **YES/NO**

I agree for my likeness to be used (e.g., images and video clips). **YES/NO**

Printed Name: ______________________________

Signature: ______________________________

Date: ______________________________

Appendix C: Interview Investigation Participant Consent Form

Dear Participants

Thank you for agreeing to participate in an interview for Mr Shuo Li's doctoral thesis study. All the information that you provide, and the recordings of interviews, will be held anonymously and securely. No personal data are asked for or retained. Access to your data is limited to the people involved in this research. If published, they will not be identifiable by your name. If a photograph or video clip is used for presentation, your name will not be mentioned. If you do not want your likeness to be used in any of the material, your image can be blanked from view.

If you have questions about the study, you are welcome to contact me at: s.li7@newcastle.ac.uk (email) or 07596****** (telephone number).

Thank you very much.
Shuo Li

Please indicate your agreement with the following statements by circling "YES" or "NO"

I agree to participate in this interview. I understand that I can withdraw from it at any time for any reasons. **YES/NO**

I understand that I can leave any questions that I do not want to answer. **YES/NO**

I agree for the interview conversation to be recorded (audio). **YES/NO**

I agree for my likeness to be used (e.g., images and video clips). **YES/NO**

Printed Name: ______________________________

Signature: ______________________________

Date: ______________________________

Appendix D: Semi-structured Interview Questions

- Could you please briefly describe your driving behaviour in daily life and then tell me your opinions about automated vehicles?
- If you are travelling with an HAV, when you are not driving, what would you do?
- While you are performing other tasks, what would you expect from the HAV system in terms of interacting with you?
- Now we are in a situation where your manual control will be required, how would you like the HAV to inform you? How long do you need?
- If you could give one piece of advice to car manufacturers who are designing highly automated vehicles, what would that be?

Appendix E: Participant Demographic Questionnaire

We would like to know some basic background information about you, all information will remain anonymous and no individual will ever be identified by name. Accessing your data is limited to the people involved in this research.

Q1.What is your gender

- ☐ **Female**
- ☐ **Male**

Q2.What is your age?

____

Q3.What is your current work status? (Please select one only)

- ☐ **Employed full-time (30+ hours per week)**
- ☐ **Employed part-time (<30 hours per week)**
- ☐ **Self-employed**
- ☐ **Student**
- ☐ **Retired and not doing volunteer work**
- ☐ **Retired but still doing volunteer work**

Q4.What is your highest level of education? (Please select one only)

- ☐ **Less than GCSE**
- ☐ **GCSE or equivalent**
- ☐ **A level or equivalent**
- ☐ **Bachelor degree**
- ☐ **Master degree**
- ☐ **Doctorate degree**

Q5.How often do you drive? (Please select one only)

- ☐ **Less than 1 day a week**
- ☐ **1-2 days a week**
- ☐ **3-4 days a week**
- ☐ **5-7 days a week**

Q6.Approximately what is your annual mileage? (Please select one only)

- ☐ **0-3000 miles**
- ☐ **3000-6000 miles**
- ☐ **6000-10000 miles**
- ☐ **10000-15000 miles**
- ☐ **15000 miles and more**

Thank you very much!

Appendix F: NASA-RTLX

Six themes that contributes to the difficulty of the interactions and experience with highly automated vehicles.

1. ***Mental Demand***

This refers to any mental and perceptual activity placed on you when you are interacting with the highly automated vehicle (e.g., thinking, deciding, calculating, remembering, looking and searching).

2. ***Physical Demand***

This refers to any physical activity you have just experienced when you are interacting with the highly automated vehicle (e.g., taking over and operating the vehicle control).

3. ***Time Pressure***

This refers to how much time pressure did you feel when you are interacting with the highly automated vehicle (e.g. due to the limited time available for taking over vehicle control).

4. ***Performance***

This refers to how successful did you think you were in interacting with the highly automated vehicle.

5. ***Effort***

This refers to how much concentration and physically effort it took to complete the driving.

6. ***Stress Level***

This refers to how relaxed, complacent versus stressed you felt when interacting with the highly automated vehicle (e.g., annoyed, frustrated, worried and irritated).

Please place a line along each scale at the point that best represents how you feel for each factor

Mental Demand

Low High

Physical Demand

Low High

Time Pressure

Low High

Performance

Good Poor

Effort

Low High

Stress level

Low High

Thank you very much!

Appendix G: HMI Attitude Questionnaire

The human-machine interface (HMI) in HAVs refers to the interface that allows you to interact with HAVs, including any information and feedback you receive during automated driving, as well as the takeover request.

Please indicate how much do you agree with the following statement, please put a tick (✓) on the line.

I would like to have this HMI in my HAV.

	1	2	3	4	5	6	7	
Strongly Disagree	____	____	____	____	____	____	____	**Strongly Agree**

Thank you very much!

Appendix H: Ethical Approval

15-LI-70

Applicant Name:	Shuo Li
Applicant email:	s.li7@newcastle.ac.uk
Academic Unit	School of Civil Engineering and Geosciences
Supervisor email (if available)	phil.blythe@newcastle.ac.uk
Category	Student Project (PGT)
Project Title:	Investigating the Requirements of Older Drivers to Inform the Future Design of the Automated Driving Systems
Start / End Date	05/01/2015 – 31/12/2017
MyProjects Reference (if available)	N/A
Reviewer 1 Name: Date sent: Date comments received:	 Tom Joyce (MSE) 14/05/2015 02/06/2015
Reviewer 2 Name: Date sent: Date comments received:	
Date comments provided to researcher:	04/06/2015
Date researcher confirmed amendments made:	04/06/2015
Faculty final approval date:	10/06/2015
Notes	Use of Human Participants (non-clinical) Satisfactory amends received. Informal approval provided by email 4/6/15

Approved / ~~Not Approved~~ by the SAgE Faculty Ethics Committee

Prof. Werner Hofer (Chair)

....

Date:

10/06/2015

Appendix I: HAV Scenario maps of city road (top) and motorway (bottom)

Appendix J: Newcastle University Driving Simulator Laboratory

Appendix K: Coding strategy proposed by Vaismoradi et al. (2016)

This strategy has summarized five typical types of codes in thematic analysis based on different type of semantic features of the comments presented by the participants as follows:

- "Conceptual code" describes the important elements, domains and dimensions of the phenomenon of the research.
- "Relationship code" focuses on identifying the relationships, links and connections among different elements, domains and dimensions of the research phenomenon.
- "Participant perspective code" describes the research subjects' attitudes, feedback and comments towards an issue.
- "Participant characteristic code" focuses on the characteristics of the participants of the research.
- "Setting and situation code" identifies the location, environment or situations in which an issue has happened.

For example:

Types of code	**Example participant quotes**	**Extracted code**
Conceptual code	*"I would still like to have some control, just for mental, to make sure that you still have some reason for being in the car." (No.10, male, age 75)*	Psychological control of the HAV
Relationship code	*"And the car should be able to observe me, it should know if I am going to sleep or I am too involved in a film or something." (NO.15, female, age 65)*	HAV keeps an eye on the driver
Participant perspective code	*"I felt more confident by the end than I did in the first couple, I could see in a day, I would be better." (No. 20, male, age 77)*	Developing trust over time
Participant characteristic code	*"I think I'm a very good driver if everybody drives like me that would be brilliant."(No.22, female, age 60)*	I am a good driver
Sitting and situation code	*"If I am going to be driving a long way, I may turn on the automated driving, long drives would be so much easier if you can just sit there and read a book." (No.1, female, age 66)*	HAV is good for long journeys

Appendix L: Summary of thematic analysis

Key themes and sub themes	*Codes and frequency of codes*
1. Self-reported driving behaviour of older drivers	
	a. I drive cautiously and slowly (n=13, 7F, 6M) b. I am a good driver (n=8, 4F,4M) c. I like driving (n=8, 4F, 4M)
2. Older drivers' opinions towards the automated vehicles	
2.1 First-hand experience of interaction with the HAV	a. First-hand experience is useful (n=10, 6F, 4M) b. Developing trust over time (n=9, 5F, 4M)
2.2 Perceived benefits of the HAV	a. HAV is good for long journeys (n=16, 11F, 5M) b. HAV is good for motorway driving (n=5, 2F, 3M) c. HAV is suitable for adverse weathers (n=2, 2F) d. HAV is good for unfamiliar roads (n=3, 2F, 1M) e. HAV increases work efficiency (n=2, 2M)
2.3 HAV vs FAV	a. HAV vs FAV (n=17, 11F, 6M)
2.4 Expectations and Concerns of the HAV	a. Making it simple (n=4, 2F, 2M) b. Making it safe (n=5, 3F, 2M) c. Appearance of HAV (n=2, 1F, 1M) d. Eligibility to use HAV (n=1, 1M) e. Liability insurance of HAV (n=1, 1F)
3. Physical and potential control of the HAV	
3.1 Physical control of the HAV	a. Physical control of the HAV (n=15, 9F, 6M)
3.2 Potential control of the HAV	a. Potential control of the HAV (n=11, 6F, 5M)
4.Non-driving-related tasks in HAV	
4.1Relaxing tasks	a. Relaxing not demanding tasks (n=10, 5F, 5M) b. Listening to radio (n=8, 4F, 4M) c. Reading (n=16, 10F, 6M) d. Looking at scenery (n=7, 5F, 2M) e. Taking to others (n=4, 3F, 1M) f. Using mobile phone (n=3, 1F, 2M) g. Watching TV and films (n=2, 1F,1M) h. Doing exercise (n=1, 1F) i. Thinking (n=2, 1F, 1M) j. Meditation and breathing (n=1, 1F) k. Doing crosswords (n=2, 1F, 1M)
4.2Working	a. Working (n=2, 2M)
4.3Monitoring driving	a. Monitoring HAV system driving (n=12, 5F, 7M)
4.4Eating and drinking in the HAV	a. Eating and drinking (n=8, 5F, 3M) b. Meal table in HAV (n=1, 1F)
5.Human-machine interaction during automated driving in HAV	
5.1Information system in the HAV	a. Informing what's happening (n=21, 12F, 9M) b. Informing journey time (n=7, 3F, 4M) c. Informing vehicle status (n=7, 2F, 5M) d. Informing traffic conditions (n=4, 1F, 3M) e. Informing drivers being in a HAV (n=3, 2F, 1M) f. Informing HAV adapts to driving conditions (n=16, 10F, 6M)
5.2Monitoring system in the HAV	a. HAV monitors driver status (n=7, 4F, 3M)
5.3Form and modality of the feedback	a. Differentiating normal and urgent information (n=12, 4F, 8M) b. Helpful but not annoying information (n=3, 3M) c. Customizing the voice (n=9, 2F, 7M)
6.Human-machine interaction during taking over control in HAV	
6.1Takeover request in the HAV	a. Adjusting when and where to receive takeover request (n=5, 3F, 2M) b. I am happy with the existing takeover request (n=14, 9F, 6M) c. Only visual modality is not enough (n=4, 2F, 2M) d. Louder takeover request for drivers with hearing impairment (n=3, 1F, 2M)

	e. Loud clear but not panicking takeover request (n=1, 1M) f. Reasons for takeover (n=19, 11F, 8M) g. Takeover first then give reasons (n=3, 2F, 1M) h. Hierarchical takeover request (n=3, 1F, 2M) i. Car interior corresponds with takeover request (n=1, Female) j. Concerns of sleeping before takeover request (n=13, 7F, 6M) k. Concerns of drinking before takeover request (n=2, 2F) l. Fail safe mode (n=2, 1F, 1M)
6.2Lead time for takeover control in HAV	a. 20s is enough to take over (n=15, 8F, 7M) b. Lead time corresponds non-driving related tasks (n=5, 2F, 3M)
7.Driving style of HAV	
7.1Imitative and corrective driving style of HAV	a. Adapting to my drive style (n=11, 4F, 7M) b. Correct bad driving style (n=9, 5F, 4M)
7.2Multiple user mode	a. Multiple user mode (n=2, 2M)
7.3.Remembering journey purpose	a. HAV remembers the trip purpose (n=1, 1F)
7.4Optional journey routes of HAV	a. Allowing me to choose the route (n=1, 1F)

Note, F=female, M=male