Transportation Planning and Technology

ISSN: 0308-1060 (Print) 1029-0354 (Online) Journal homepage: https://www.tandfonline.com/loi/gtpt20

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To cite this article: Shuo Li, Phil Blythe, Weihong Guo & Anil Namdeo (2019) Investigating the effects of age and disengagement in driving on driver's takeover control performance in highly automated vehicles, Transportation Planning and Technology, 42:5, 470-497, DOI: 10.1080/03081060.2019.1609221

To link to this article: https://doi.org/10.1080/03081060.2019.1609221

Published online: 02 May 2019.

TRANSPORTATION PLANNING AND TECHNOLOGY
2019, VOL. 42, NO. 5, 470–497
https://doi.org/10.1080/03081060.2019.1609221

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Investigating the effects of age and disengagement in driving on driver's takeover control performance in highly automated vehicles

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ABSTRACT

Driving is closely linked to older people's mobility and independence. However, age-related functional decline reduces their safe driving abilities and thereby their wellbeing may decline. The rapid development of vehicle automation has the potential to enhance the mobility of older drivers by enabling them to continue driving safer for longer. So far only limited work has been carried out to study older drivers' interaction with highly automated vehicles (HAV). This study investigates the effect of age and level of driving disengagement on the takeover control performance in HAV. A driving simulation study with 76 drivers has been conducted. Results showed that 20 s was sufficient for drivers to take over control from HAV. Older drivers take longer to respond and make decisions than younger drivers. The age effect on some aspects of takeover quality, in terms of operating steering wheel and pedals, is still pronounced. In addition, complete disengagement in driving in HAV leads to a longer takeover time and worse takeover quality, and it affects older drivers more seriously than younger drivers. The results highlight that an age-friendly design of human-machine interaction is important for enhancing the safety and comfort of older drivers when interacting with HAVs.

ARTICLE HISTORY
Received 23 March 2018
Accepted 21 March 2019

KEYWORDS
Older drivers; vehicle automation; highly automated vehicles; age; human-machine interaction; takeover control

1. Introduction

The population in the UK is becoming older. In 1976, the percentage of people aged 65 and over accounted for 14.2% of the population in the UK; this figure increased to 18.0% in 2016 and is predicted to grow to 23.9% in 2036 (ONS 2017). To many older adults, accessing to a car is equivalent to maintaining mobility and being independent, and it has been generally recognised that continuing mobility is strongly linked to their quality of life and wellbeing (Guo et al. 2010; Musselwhite and Haddad 2010; Li et al. 2019). One of the important transport modes for older adults in the UK is travelling by cars, and a great proportion of their journeys in cars are as drivers (DfT 2015a). In order to perform the driving task safely, a variety of the drivers' physical, mental and

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cognitive functions and their interactions are required (Guo et al. 2013; Edwards et al. 2016; Karthaus and Falkenstein 2016; Li et al. 2018, 2019). However, age-related loss in the sensory, cognitive and psychomotor functional abilities may negatively affect the driving performance and safety of older drivers and potentially increase the risk of driving offences and traffic collisions among older drivers (Ball et al. 1998; Rimmö and Hakamies-Blomqvist 2002; Karthaus and Falkenstein 2016). In order to reduce the impact of age-related loss of functional abilities, some older drivers may change and regulate their driving behaviour, such as avoiding speeding, driving alone, driving at night, in heavy traffic, or adverse weather conditions, over unfamiliar routes, undertaking driving longer journeys, and reducing difficult parking and reversing exercises (Ball et al. 1998; Charlton et al. 2006; Karthaus and Falkenstein 2016). Finally, the ultimate self-regulation in driving that older drivers may adopt is to cease driving (Hakamies-Blomqvist and Wahlström 1998; Emmerson et al. 2013). Nevertheless, self-regulatory behaviours may substantially decrease older people's mobility and negatively affect their independence, freedom and well-being (Ball et al. 1998; Hakamies-Blomqvist and Wahlström 1998; Charlton et al. 2006). Meanwhile, the potential emergence of highly automated vehicles may have the potential to benefit the older drivers by introducing revolutionary human-machine interactions and offering new driving experience (SAE 2014; DfT 2015b; Li et al. 2019).

The existing advanced driver-assistance systems (ADAS) provide drivers with different types of assistance, some of them have provided drivers with the support of operating the longitudinal or/and lateral controls of the vehicle, for example, Adaptive Cruise Control (ACC), Lane Keeping Assist (LKA), Intelligent Speed Adaption (ISA) and Tesla Autopilot (Guo et al. 2010, 2013; Lin, Ma, and Zhang 2018). Although these systems enable drivers to be physically disengaged from driving occasionally, they are not allowed to take their eyes off the road and must be constantly monitoring the system driving (SAE 2014; DfT 2015b; Li et al. 2019). The potentially forthcoming roll-out of the highly automated vehicles (HAV), referred to Level 3 automation (SAE 2014), in which the level of vehicle autonomy has been further increased, allowing the drivers to be completely disengaged from driving, they can now take their eyes off the road and safely perform other non-driving related tasks during automated driving, such as reading, watching a movie, using mobile phones, while the drivers are expected to take over the vehicle control in some situations (SAE 2014; DfT 2015b; Li et al. 2019).

1.1. Takeover control from HAV

Takeover represents an important human-machine interaction of HAV, happening when a manual control of the vehicle replaces the automated driving (Gold et al. 2013; SAE 2014; Li et al. 2018, 2019). Takeovers in HAVs could be broadly grouped into two main categories: driver-initiated and HAV system-initiated takeovers (Lu et al. 2016; Li et al. 2019). A driver-initiated takeover refers to situations when the driver makes the decision to deactivate automated driving and to manually drive the vehicle by themselves, which generally happens in ordinary situations of low urgency (Lu et al. 2016). The second category is the HAV system-initiated takeover, which could be more critical and demanding for the drivers compared to a driver-initiated takeover (Lu et al. 2016). 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, it then informs to take over control of the vehicle and provide them with a sufficient lead time to do that (DfT 2015b; Gold et al. 2016; Lu et al. 2016; Li et al. 2019). When the HAV system encounters a situation that requires drivers to intervene, it issues a takeover control request (TOR) to drivers and allows them to take back the control of the vehicle within a sufficient lead time. Following the TOR, drivers switch their attention from the non-driving tasks to the road and start to conduct cognitive processing of the takeover situations, which includes perceiving and comprehension of the current situation as well as projection of the future status, and then, a decision was made and the action was executed (Endsley and Kiris 1995; Gold et al. 2013; Melcher et al. 2015). The significance of the system-initiated takeover in HAV has been recognised, and there have numerous research studies conducted to explore this process.

1.2. Effects of driving disengagement on the takeover performance

A key feature of the HAV is to enable the driver to be completely disengaged from driving and safety conduct non-driving related tasks. The effect of driving disengagement on takeover performance has been studied. For example, Eriksson and Stanton (2017) studied the effect of complete disengagement from driving caused by a task which involved reading a newspaper on takeover performance. They found that compared to when monitoring driving, participants exhibited greater variance and significantly slower takeover behaviour when they were completely disengaged from driving. Radlmayr et al. (2014) implemented a driving simulator investigation to examine the effects of complete disengagement from driving on takeover performance achieved by performing two standard tasks; a cognitively distracting performance task (N-Back task) and a visually distracting surrogate reference task (SuRT). They found 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. In addition, Zeeb, Buchner, and Schrauf (2016) investigated the impact of complete disengagement from driving on takeover performance caused by performing three naturalistic tasks of writing an email, reading the news and watching a video. 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. In addition, Zeeb et al. (2017) have 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).

1.3. Effects of the lead time on the takeover performance

In addition to exploring the effects of complete disengagement in driving on the takeover performance. Previous research has also investigated different lengths of lead time that the HAV system provides to drivers to takeover control. The lead-time is the time that HAV provides to the driver to take over the vehicle control. It is the time between the moment when the HAV informs the driver to reassume control and the moment when the vehicle reaches the system limitation if it continues at its current driving speed (Gold et al. 2013; Li et al. 2018).

van den Beukel and van der Voort (2013) implemented a driving simulator study to study the effect of three relatively short lead time (1.5, 2.2 and 2.8 s) 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. Gold et al. (2013) They found that the average response times for braking input were 2.06 s (5 s lead time) and 3.10 s (7 s lead time), and average response times for steering input were 2.27 s (5 s lead time) and 3.65 s (7 s 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 7 s could not be treated as a sufficient lead time due to the poor takeover performance it resulted in among participants. In contrast, Mok et al. (2015) investigated the effects of lead time of 2, 5 and 8 s on takeover control performance and indicated that a sufficient lead time is between 2 and 5 s. Similarly, Clark and Feng (2017) implemented driving simulator study to investigate the effect of age, engagement in secondary tasks and two time buffers of 4.5 and 7.5 s on takeover performance. They found that in general 4.5 s 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 7.5 s time buffers. Additionally, Melcher et al. (2015) found that a lead time of 10 s resulted in a median takeover time of 3.5 s for participants, and that this was a sufficient time for drivers to take over control of the vehicle from the HAV.

1.4. Effect of age on the takeover

Apart from factors such as driving disengagement and the length of the lead time, previous research also considered the effects of driver's demographic factors, such as age, on their takeover performance from HAV. For example, Miller et al. (2016) implemented a driving simulator investigation to study the effect of age on the takeover performance. During the automated driving, three types of non-driving related tasks were performed by the participants: watching a movie, reading a story from a tablet in their hands, and monitoring system driving. No significant effects were found of the age and type of secondary task on takeover performance. Also, Molnar (2017) conducted a driving simulator study to explore the influence of age on drivers' takeover performance in the HAV. Participants were not assigned to perform any non-driving related tasks, but they were given the power to choose when to activate the automated systems. It was found that older drivers aged 65–75 were similar in behaviour to the younger drivers aged 25–45. Additionally, Körber et al. (2016) studied the effect of age on takeover performance in the HAV on a driving simulator when drivers were distracted by a 'questions and answers' task on a hands-free mobile phone. Although age was not found to have any significant effect on takeover time, but older drivers were found to be safer and more cautions when taking over control from the HAV. In addition, Clark and Feng (2017) explored the impact of age on drivers' takeover performance and preferences of the types of non-driving related tasks in HAV. They found age difference in terms of the preference in non-driving related tasks during automated driving. Younger drivers preferred to use electronic devices, while older drivers were more interested in having conversations with others in the vehicle. And older drivers were more likely to become heavily engaged in the non-driving related tasks. Despite that, older drivers showed a more cautious and stable take-over than the younger drivers. In addition, they also found that older drivers, but not younger drivers, responded faster to the longer lead time.

1.5. Research gap

Considerable efforts have been made to understand how drivers interact with HAV, however, only limited work 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 (Yang and Coughlin 2014; Chan 2017; Young, Koppel, and Charlton 2017; Li et al. 2018, 2019), the effect of age on drivers' performance in interacting with HAVs during the process of taking over control needs to be further investigated. In addition, the potentially negative impact of a state of complete disengagement from driving in the HAV on drivers' takeover performance has been recognised. 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. For example, Molnar (2017) did not apply any non-driving related tasks to disengage older drivers from driving before taking over control; whilst Clark and Feng (2017) offered the older drivers the freedom to choose what tasks they would like to perform and how much they would like to be involved in these tasks. Although Körber et al. (2016) and Miller et al. (2016) adopted mandatory non-driving related tasks, however, the tasks could be interrupted by the participants at any time before they were asked to take over the control of the vehicle. Therefore, it is still not clear how the state of complete disengagement from driving would affect the takeover performance among older drivers.

1.6. Purpose of this research

In older to fill the research gap, the aim of this study is to investigate the effects of age and driving disengagement on drivers' takeover performance when taking over the control from the HAV.

2. Method

2.1. Participants

In order to participate this study, the participants were required to have valid UK driving licenses and to be active drivers. Older drivers aged 60 years and over were used as the experimental group for this study. They were recruited through the VOICE North older driver user group as well as personal approaches at the local community in Newcastle upon Tyne. Younger drivers were the control group and they were mainly recruited by personal approaches at Newcastle University. A total of 76 drivers were participated in the study and were aged between 20 and 81 years (mean = 49.21 years, SD = 23.32

years; 33 female, 43 male). Thirty-seven 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). Their annual driving mileages by age group are shown in Table 1.

2.2. Apparatus

This study used the Newcastle University fixed-based ST Software Jentig50 driving simulator (see Figure 1). It is composed of a metal framework fitted with five 50-inch LCD screens, which enables drivers with a high-resolution and wide angle vision view. It has 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, rear-view mirror and side mirrors are simulated by the driving simulator and are displayed on the LCD screens. The 5.1 surround sound system of the driving simulator provides drivers with a realistic driving experience. This specific driving simulator has been used in several research studies and has been proven to be valid and effective in studying older adults' driving behaviour and their interaction with in-vehicle systems (Emmerson et al. 2013; Guo et al. 2013; Edwards et al. 2016; Li et al. 2018, 2019).

2.3. HAV scenario

2.3.1. Duration of automated driving

In regard to the selection of the duration of the automated driving for the HAV scenario, there are several 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 2015b), 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 (1995) pointed out that if the system operators were disengaged from the task for 30 to 60 s, 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, Stanney, and Dunlap (2000) argued, task duration is positively related to simulator sickness and discomfort. 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, Van Leuween, and Happee 2012; Keshavarz et al. 2018). In addition, adopting short task durations could prevent the participants from potentially getting motion sickness, losing attention and becoming too tired (Purchase 2012). Therefore, according to the above considerations, a duration of one minute was selected for the HAV scenario in this study (Li et al. 2018, 2019).

Table 1. Annual mileage driven by participants.

Annual mileage (miles)	0–3000	3000–6000	6000–10,000	10,000-15,000	15,000+	Total
Younger drivers	15	13	5	2	2	37
Older drivers	6	10	12	10	1	39
Total	21	23	17	12	3	76

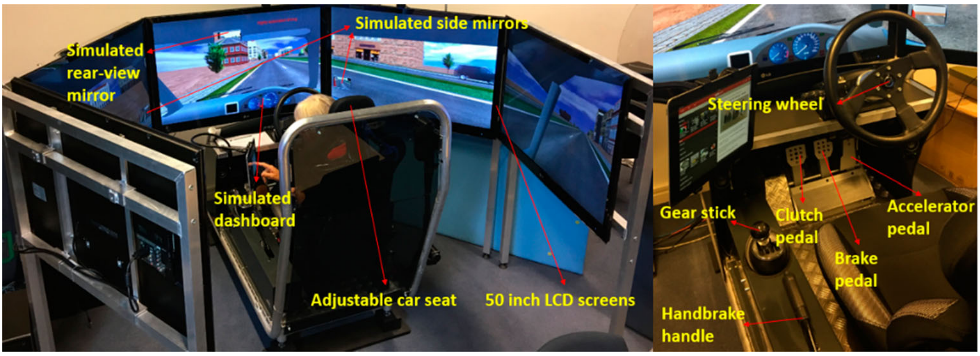

Figure 1. Fixed-based ST Software Jentig50 driving simulator.

2.3.2. The lead-time for takeover

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 4.5 to 7.5 s (Körber et al. 2016; Miller et al. 2016; Clark and Feng 2017; Molnar 2017). Although, some studies suggested that between 7.5 and 10 s 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. Considering 20 s was found to be enough for disengaged drivers to redirect their attention back to the centre of the road when being required by the automation system to take back the vehicle control (Merat et al. 2014). Although their study is not strictly comparable to the current investigation, 20 s may have the potential to initiate a less time-critical take-over of control from the HAV for the older drivers and has been selected as the lead-time for the HAV scenario in this study (Li et al. 2018, 2019).

2.3.3. HAV scenario

The HAV scenario (see Figure 2) starts with automated driving for a duration of one minute. During this period the HAV performs the longitudinal and lateral vehicle control and enables drivers to be completely disengaged from driving. After a minute, the HAV senses a stationary car suddenly blocking the road ahead, and then it

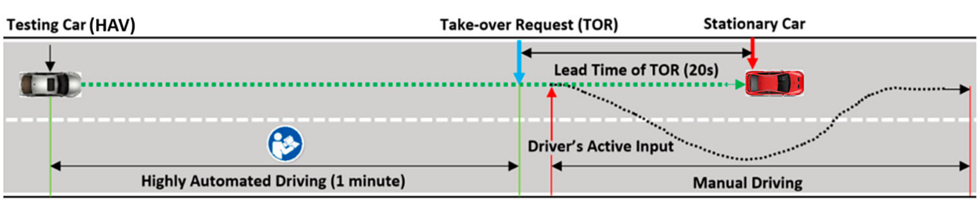

Figure 2. Illustration of HAV scenario.

informs the driver of this using a takeover control request (TOR). Meanwhile, the HAV continues to drive at its speed and provides a lead time of 20 s to the driver to reassume the vehicle control before it reaches the stationary car. As long as the HAV system detects the active input (2 degrees of steering wheel input or/and 10% pedal input) from the driver, it transfers the vehicle control to the driver (Gold et al. 2013, 2016; Radlmayr et al. 2014; Li et al. 2018). Then, the driver needs to avoid the stationary car by conducting a lane change. After the driver has avoided the stationary car, they are asked to pull over and the scenario ends.

2.4. Testing roads and takeover request (TOR)

As Figure 3 illustrates, two types of roads were applied to the HAV scenario, a city road and a motorway (Li et al. 2018, 2019). In order to set up a controlled experiment, there was no other traffic except the red stationary car on the two roads.

On the city road, the HAV drives at an even speed of 30 mph (13.41 m/s). It senses the stationary car with an advance range of 268.20 m and provides the drivers with a lead time of 20 s. On the motorway, the HAV drives at 60 mph (26.82 m/s). It senses the stationary car ahead with an advance range of 536.4 m and provides the drivers with a lead time of 20 s.

The TOR has a visual and sound modality consisting of a bold red writing on the screen reading ‘Please takeover’ and a computer-generated female voice speaking ‘Attention! Please take over the vehicle control’ (Li et al. 2018, 2019).

2.5. Non-driving related tasks

Previous research has adopted standardised tasks such as the cognitive N-Back task as well as naturalistic tasks in HAV research. Both of them were found to be able to completely disengage drivers from driving in the HAV, resulting in deteriorated takeover performance (Radlmayr et al. 2014; Zeeb, Buchner, and Schrauf 2016; Eriksson and Stanton 2017; Zeeb et al. 2017). Comparing to standardised tasks, some research indicated the importance of using naturalistic tasks in HAV research to ensure ecological validity (Körber et al. 2016; Zeeb, Buchner, and Schrauf 2016). In this study, naturalistic tasks would enable this test to be closer to the authentic use case of HAV for the older

Figure 3. City road (left) and motorway (right) for the HAV scenario.

people. The top three activities that elderly people perform most frequently in free time are watching television, spending time with friends and family and reading (Seddon 2011). Among them, watching television and reading could be possible for this study 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 that by asking participants to read aloud the material their disengagement in driving could be controlled. The reading material was presented by a tablet (Figure 4). To further guarantee subjects' disengagement in driving, the tablet was located on the 45 degree left to the central line of the steering wheel to ensure subjects' face was not towards the vehicle driving direction (Li et al. 2018). In addition, apart from the reading task, a task of monitoring HAV driving was adopted as a baseline condition for investigating the effect of complete disengagement in driving on takeover performance (Li et al. 2018).

2.6. Experimental design

This research adopted a $2 \times 2 \times 2$ between- and within-subjects mixed factorial design. Mixed factorial experimental design incorporates the benefits of within-subjects and between-subjects factors (Field 2013). The between-subjects independent variables are age (younger, older) and road type (city road, motorway). The within-subjects independent variables are driving disengagement level (DDL) consisting of monitoring driving, or being disengaged from driving. An overview of the experimental design is shown in Table 2.

2.6.1. Dependent variables

The dependent variables (see Table 3) adopted in this research to measure participants' takeover performance are broadly grouped into two categories-time aspects of takeover and takeover quality (Li et al. 2018; McDonald et al. 2019).

As Figure 5 illustrates, the time aspects of takeover consists of reaction time, takeover time and indicator time (Li et al. 2018). Reaction time is defined as the time between the point when the HAV sends the takeover control request (TOR) and the point that drivers switch back to the manual driving position which refers to the position when participants' eyes on the road, hands on the steering wheel and feet on the pedals (Li et al. 2018). It reflects how quickly participants react to the TOR. Takeover time describes the time

Figure 4. Non-driving related tasks in HAV.

Table 2. 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

Table 3. 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	s
Takeover quality	Resulting acceleration	m/s^2
Takeover quality	Steering wheel angle	degree
Takeover quality	Collisions	Count
Takeover quality	Critical encounters	Count

between the TOR and the driver's first active input to controls of the vehicle, and active input refers to an input of the steering wheel angle of 2 degrees and/or 10% movement of accelerator or brake pedal positions (Gold et al. 2013, 2016; Radlmayr et al. 2014; Mok et al. 2015; Li et al. 2018). Indicator time is defined as the time between the point that the TOR is issued and the point that driver initiates an indicator light signal warning fellow road users that the driver intends to change to avoid the stationary car ahead. It measures how quickly the participants make the decision of conducting a lane change (Li et al. 2018; McDonald et al. 2019).

The following variables are used to measure takeover quality. Firstly, the minimum time to collision (TTC) has been recognised as an useful parameter in quantifying the severity of potential crashes (van der horst and Hogema 1993). In this study, the TTC is defined as the time that the HAV needs to reach the stationary car ahead if it continues to drive at the speed at the point it avoids to the stationary car successfully (Li et al. 2018). The lane has a width of 3.6 m. The width of the HAV and stationary car is 1.8 m. Both cars drive at the centre of the lane as a default. Therefore, the point when the value of the lane position (distance between the car centre to the lane centre) of the HAV is smaller than 1.8

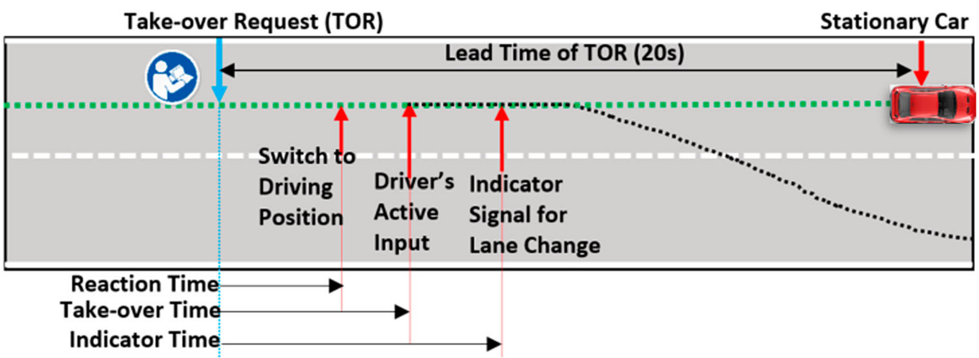

Figure 5. Time aspects of takeover.

m is defined as it has successfully avoided the stationary car. The minimum TTC is calculated as equation (1), the higher the minimum TTC, then the less critical the takeover performance is.

$$\text{Min TTC} = (d_s - d_c)/v_c \tag{1}$$

Where d_s – distance when the stationary car is visually detected; d_c– distance when HAV avoids the stationary car; v_c – speed when HAV avoids the stationary car;

In addition, as Equation (2) indicates, the resulting acceleration during the takeover process has been proven to be an effective indicator of the quality of takeover control, it measures the max resulting force that a vehicle sends to the ground, the greater the value, the less stable and more critical the takeover is (Gold et al. 2013; Radlmayr et al. 2014; Li et al. 2018; McDonald et al. 2019).

$$\text{Resulting Acc} = \sqrt{\text{Max Longitudinal Acc}^2 + \text{Max Lateral Acc}^2} \tag{2}$$

Steering wheel angle is the standard deviation in degree from the centre line of the steer wheel, and it has been a well-used measurement to quantify takeover quality in HAVs, greater steering wheel angle reflects more unstable and more critical takeover quality (Mok et al. 2015; Clark and Feng 2017; Eriksson and Stanton 2017; Li et al. 2018; McDonald et al. 2019).

Finally, the number of collisions and critical encounters recorded during takeover process is an effective measurement to evaluate the success of the takeover (Li et al. 2018; McDonald et al. 2019). The number of collision involves all the crashes happened during the takeover. The critical encounter considers any takeover resulted in a critical TTC (less than 1.5 s) reflecting potentially dangerous takeover behaviour (van den Beukel and van der Voort 2013).

2.7. Experimental procedure and data analysis

All participants' driving licence were checked when they arrived the lab, they were then requested to complete an ethical form and the demographic questionnaire, following this, then they were given a brief safety induction. After that, the participants were guided to the driving simulator and the research purpose and procedure was explained verbally. The participants were provided with time to practice in the driving simulator until they confirmed verbally that they were comfortable. They were informed that they are required to reassume the vehicle control promptly as soon as they perceive the TOR from the HAV; they should not break the speed limit, use the indicator light when conducting the lane change. Then the test started and the order of the driving sessions is randomised to prevent order effect.

The data collection frequency of the driving simulator is 20 Hz (every 0.05 s). The data was in binary form and converted into ASCII format. Then, values of all of the dependent variables were calculated according to their definitions in Section 2.6.1. To analyse the effects of age, driving disengagement level (DDL) and road type on the dependent variables, the three-way mixed ANOVA was adopted. It corresponds to the experimental design in Section 2.6. In addition, Pearson's correlation was used to examine the relationship between takeover time and quality.

3. Results

3.1. Takeover trajectories

Figure 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 phases exhibited very similar characteristics. However, there are apparent gaps between older drivers' average takeover trajectories in monitoring driving and disengaged from driving conditions, with those in monitoring driving conditions indicate an earlier intervention and a little further away to the stationary car than in disengaged from driving condition.

In addition, there were no collisions recorded for both younger and older drivers under all the situations. There was only one critical encounter recorded (TTC = 1.38 s). 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.

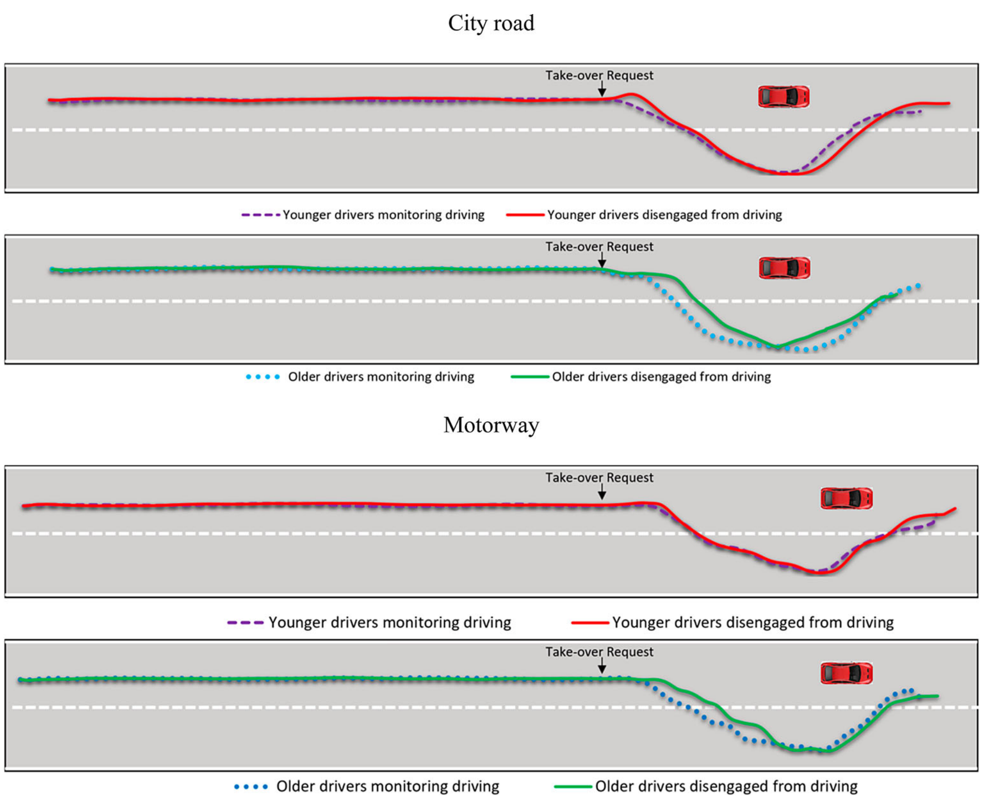

Figure 6. Average trajectories of participants' takeover control from the HAV on city road (top) and on motorway (bottom).

3.2. Time aspects of takeover control

3.2.1. Reaction time

The results of the mixed ANOVA (Table 4 and Figure 7) indicate that age showed a significant effect on driver's reaction time, with older drivers ($M = 2.14$ s, SD = 0.96 s) reacted slower to the takeover request (TOR) than the younger drivers (mean = 1.70 s, SD = 0.59 s). In addition, DDL had a significant effect on reaction time, with drivers took longer time to react to TOR when monitoring driving ($M = 1.33$ s, SD = 0.34 s) than being disengaged from driving ($M = 2.53$ s, SD = 0.73 s). In addition, road type had a significant effect on reaction time, with drivers took longer time to react to TOR on the motorway ($M = 2.11$ s, SD = 0.82 s) than on the city road (mean = 1.75 s, SD = 0.80 s). Moreover, there was a significant interaction between age and DDL on reaction time, with older drivers' mean reaction time slowing down more greatly (1.37 s of monitoring driving and 2.92 s when disengaged from driving) than younger drivers (1.30 s of monitoring driving and 2.12 s when disengaged from driving).

3.2.2. Takeover time

As Table 5 and Figure 8 indicates, the results of the mixed ANOVA show that age had a significant effect on the driver's takeover time, with older drivers recording longer times ($M = 3.38$ s, SD = 1.71 s) than younger drivers ($M = 2.84$ s, SD = 0.86 s). Also, DDL yielded a significant effect on the driver's takeover time, with drivers requiring longer to takeover vehicle control when they were disengaged ($M = 3.79$ s, SD = 1.47 s) compared to driving when monitoring driving ($M = 2.46$ s, SD = 0.87 s). Additionally, road type was found to have a significant effect on takeover time, with drivers showing longer takeover times on the motorway ($M = 3.41$ s, SD = 1.45 s) than on the city road ($M = 2.85$ s, SD = 1.27 s).

Moreover, there was a significant interaction between age and DDL, with older drivers' mean takeover time slowing down more sharply (2.35 s of monitoring driving and 4.47 s when disengaged from driving) compared to younger drivers (2.60 s when monitoring driving and 3.10 s when disengaged from driving).

3.2.3. Indicator time

As Table 6 and Figure 9 indicate, the results of the mixed ANOVA show that age had a significant effect on the driver's indicator time, with the older drivers cohort taking longer to initiated the indicator light signal of lane change ($M = 8.32$ s, SD = 3.48 s) compared to the time for the younger drivers cohort ($M = 6.99$ s, SD = 3.18 s). Also, DDL yielded a significant effect on the driver's indicator time, with drivers needing longer to

Table 4. Results of a mixed ANOVA for reaction time.

	df	*F*	*p*	ηp^2
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:*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

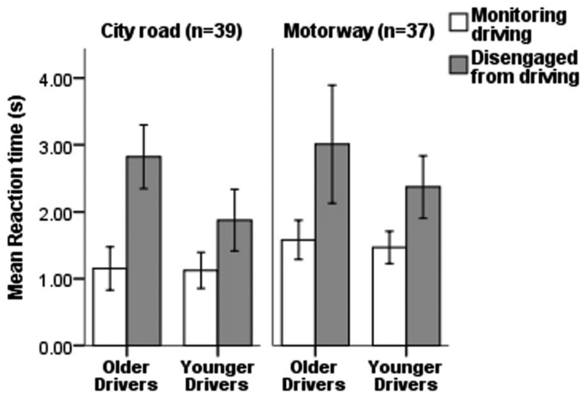

Figure 7. Reaction time for different driver groups in different situations (error bars represent ±1 standard deviation of the mean).

Table 5. Results of a mixed ANOVA for takeover time.

	df	*F*	*p*	ηp^2
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:$^*p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$.

generate indicator signal of lane change when they were disengaged ($M = 8.79$ s, SD = 3.44 s) compared to it when monitoring driving ($M = 6.56$ s, SD = 2.98 s). Additionally, the road type did not have significant effect on indicator time, with drivers measured taking longer to initiate the manoeuvre indicator light on the motorway ($M = 7.83$ s, SD = 3.54 s) than on the city road scenario ($M = 7.52$ s, SD = 3.27 s).

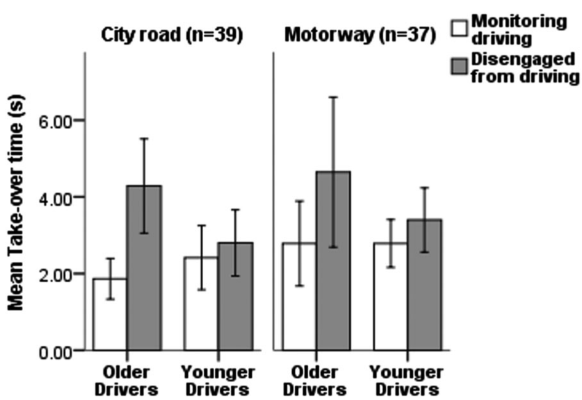

Figure 8. Takeover time for different driver groups in different situations (error bars represent ±1 standard deviation of the mean).

Table 6. Results of a mixed ANOVA for indicator time.

	df	*F*	*p*	ηp^2
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:*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

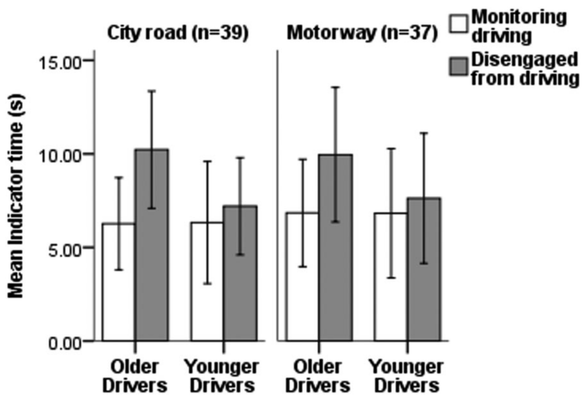

Figure 9. Indicator time for different driver groups in different situations (error bars represent ±1 standard deviation of the mean).

Moreover, there was a significant interaction between age and DDL, with time taken for older drivers' to initiate the indicator light being much greater (6.56 s of monitoring driving and 10.09 s when disengaged from driving) than the times measured for the younger drivers cohort (6.58 s when monitoring driving and 7.41 s when disengaged from driving).

3.3. Takeover quality

3.3.1. Time to collision (TTC)

Table 7 shows the results of the mixed ANOVA for TTC. Age and road type have no significant effect on drivers' TTC. However, DDL yielded a significant effect on the value of

Table 7. Results of a mixed ANOVA on TTC.

	df	*F*	*p*	ηp^2
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:*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

the driver's TTC, which was longer when they were monitoring driving ($M = 11.26$ s, SD $= 5.73$ s) than when disengaged from driving ($M = 9.37$ s, SD $= 5.05$ s). Also, there was a significant interaction between age and DDL, in that older drivers' TTC was reduced more seriously (11.96 s when monitoring driving and 8.68 s when disengaged from driving) compare to younger drivers (10.53 s when monitoring driving and 10.14 s when disengaged from driving). These results are visualised in Figure 10.

3.3.2. Resulting acceleration

Table 8 shows the results of the mixed ANOVA for resulting acceleration. Age had a significant effect on resulting acceleration, with older drivers showing significantly higher acceleration ($M = 2.95$ m/s^2, SD $= 1.78$ m/s^2) than younger drivers ($M = 2.26$ m/s^2, SD $= 1.58$ m/s^2). Figure 11 visualises these results.

3.3.3. Steering wheel angle

Table 9 shows the results of the mixed ANOVA for steering wheel angle. Age had a significant effect. Older drivers showed larger steering wheel deviation ($M = 8.46$ degrees, SD $= 4.71$ degrees) than the younger drivers ($M = 5.20$ degrees, SD $= 3.54$ degrees). Figure 12 visualises these results.

3.4. Correlation analysis

Pearson correlation analyses of reaction time and takeover time is listed in Table 10. There is positive correlation between reaction time and takeover time when subjects were monitoring driving and disengaged from driving (Figure 13). This suggests that the subjects who react faster to the TOR also generate active input of vehicle control quicker.

As Table 10 indicates, there is positive correlation between the indicator time and takeover time when subjects were monitoring driving. That suggests that subjects who execute conscious input of the vehicle more quickly also use indicator signal for lane change faster (Figure 14).

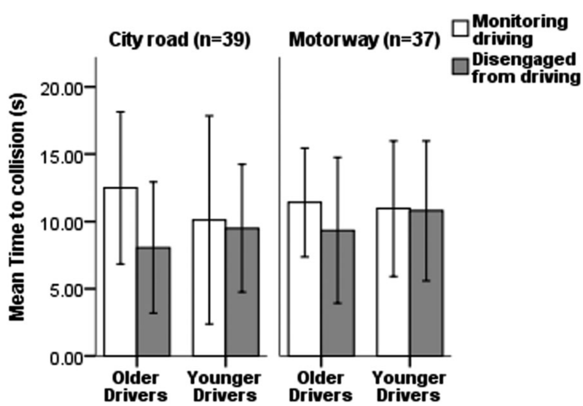

Figure 10. Minimum TTC for different age groups under different situations (error bars represent ±1 standard deviation of the mean).

Table 8. Results of a mixed ANOVA on resulting acceleration.

	df	F	p	ηp^2
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:*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

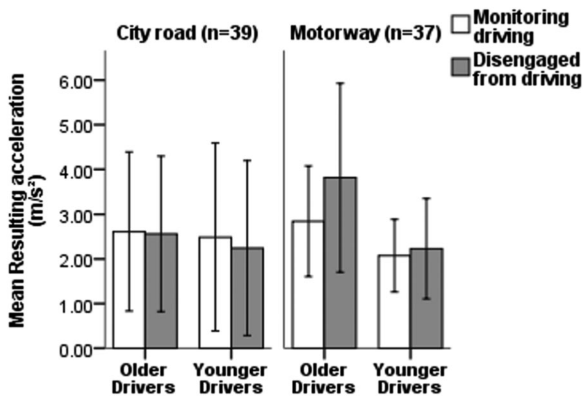

Figure 11. Resulting acceleration during takeover control process for different driver groups in different situations (error bars represent ±1 standard deviation of the mean).

Table 9. Results of a mixed ANOVA on steering wheel angle.

	df	F	p	ηp^2
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:*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

Person correlation analyses were implemented to examine the relationship between the takeover time and quality. Table 10 and Figure 15 show that there was no significant correlation between the takeover time and takeover quality when participants were monitoring driving.

Table 10. Results of Pearson's correlation coefficients of takeover time and quality.

	Correlation coefficient	
Correlation between takeover time and the following items	Monitoring	Disengaged
Reaction time (s)	r (76) = 0.564***, $p < 0.001$	r (76) = 0.710***, $p < 0.001$
Indicator time (s)	r (76) = 0.245*, $p = 0.033$	r (76) = 0.062, $p = 0.597$
Time to collision (s)	r (76) = −0.179, $p = 0.121$	r (76) = −0.245*, $p = 0.033$
Resulting acceleration (m/s^2)	r (76) = −0.089, $p = 0.446$	r (76) = −0.125, $p = 0.282$
Steering wheel angle (°)	r (76) = −0.066, $p = 0.573$	r (76) = 0.254*, $p = 0.027$

Note: *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

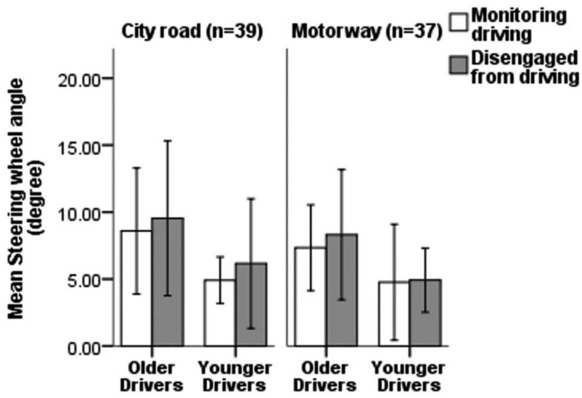

Figure 12. Steering wheel angle for different age groups under different situations (error bars represent ±1 standard deviation of the mean).

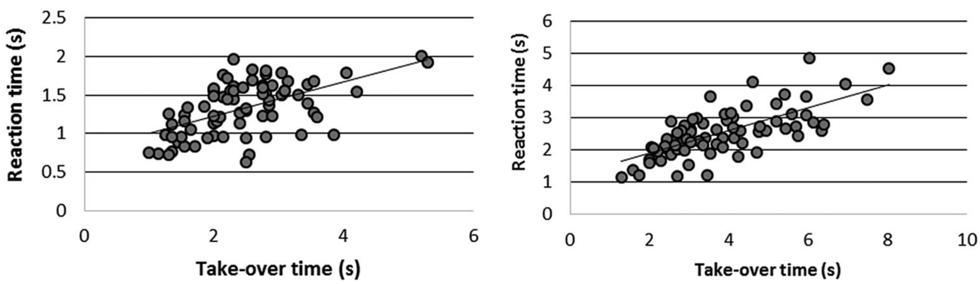

Figure 13. Correlation between the reaction time and takeover time of drivers when monitoring driving (left) and disengaged from driving (right).

However, when participants were disengaged from driving, as Table 10 and Figure 16 indicate, there was a significant negative correlation between the value of takeover time and TTC. In addition, there was a significant positive correlation between the value of takeover time and steering wheel deviation. This suggests that when being disengaged from driving, participants who have longer takeover time also have smaller TTC and greater steering wheel deviation.

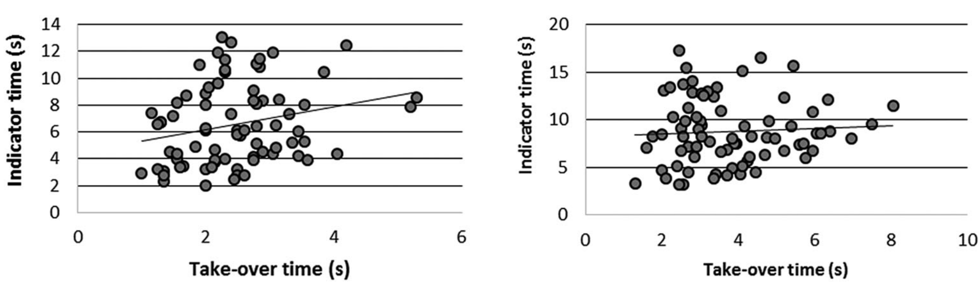

Figure 14. Correlation between the indicator time and takeover time of drivers when monitoring driving (left) and disengaged from driving (right).

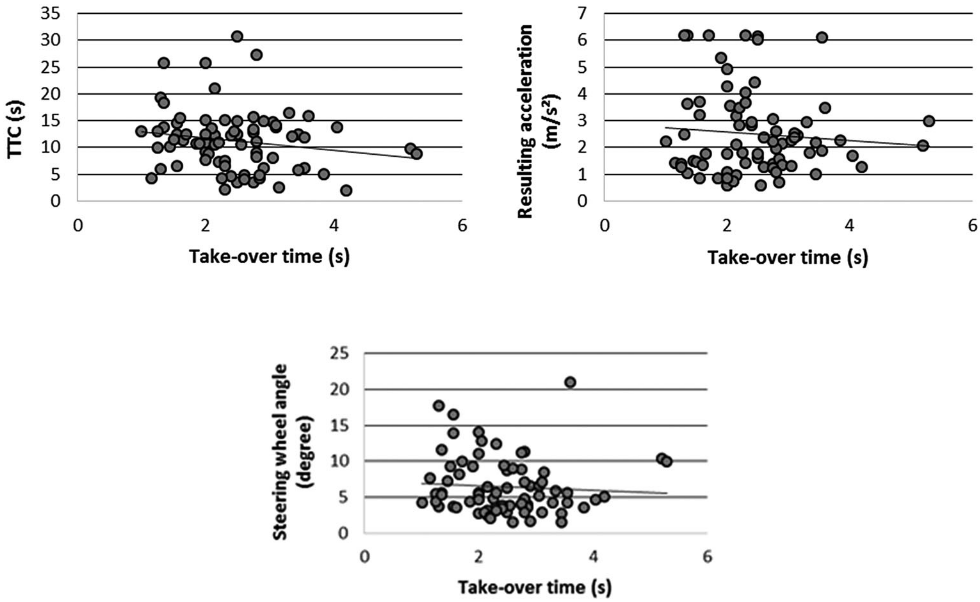

Figure 15. Correlation between the takeover time and takeover quality of drivers when monitoring driving.

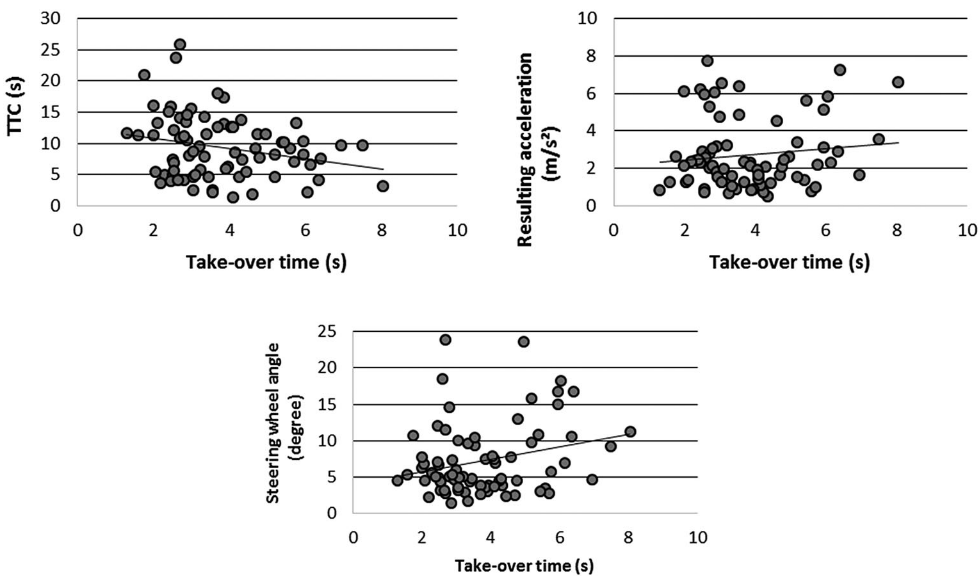

Figure 16. Correlation between the takeover time and takeover quality of drivers when disengaged from driving.

4. Discussion

This research investigated the influence of age, driving disengagement level (DDL) and road type on the time aspects of takeover and takeover quality. All participants were able to take over control of the vehicle effectively and successfully responded to the stationary car, so that no collisions occurred.

4.1. Effect of age on takeover performance

This research adopted 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 participants' takeover behaviour. They reflect the time that subjects took to switch to manual driving position, generate conscious input to the car and start to conduct lane change, respectively, after the HAV system has sent the TOR 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, Simões, and Marôco 2013), cognitive impairments, including information processing speed, attention switch, memory and problem solving (Brouwer et al. 1991; Salthouse 1996; Pollatsek, Romoser, and Fisher 2012) as well as declining psychomotor abilities (Staplin et al. 1999).

However, although the effect of age on driving has been well recognised, 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 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 20 s to take over control of the vehicle, which is much larger than the lead time (4.5 to 7.5 s) used in previous studies (Körber et al. 2016; Miller et al. 2016; Clark and Feng 2017; Molnar 2017). A longer lead time may have reduced 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, Georgiou-Karistianis, and Stout (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 present study which provided the participants with a lead time of 20 s to take over the control of the vehicle and where the mean takeover time for disengaged participants was 3.79 s, previous studies adopted lead time between 2 and 8 s leading to smaller mean takeover times between 1.7 and 3.66 s (Gold et al. 2013; Melcher et al. 2015; Körber et al. 2016; Zeeb, Buchner, and Schrauf 2016; Clark and Feng 2017; Molnar 2017; Zeeb et al. 2017). However, research by Eriksson and Stanton (2017) yielded a larger mean takeover time (4.46–6.06 s) when the participants were provided with an unlimited lead time to reassume the control of the vehicle. This may suggests that when shorter lead time is available for drivers to reassume the control of the vehicle, the faster their resulting mean takeover time is. This is in line with the research by Gold et al. (2013) who found that shorter lead time results in faster takeover times. The possible explanation for this finding could be that when the HAV informs drivers to take back the control with a shorter lead time, their perceived urgency of the takeover request (TOR) is relatively higher, which could lead to faster response among them (Edworthy et al. 2000).

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 20 s 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, Georgiou-Karistianis, and Stout 2013). In addition, this finding could be a negative demonstration of the finding by Gold et al. (2013) indicates that an inadequate lead time resulted in quicker decisions and responses, but worse takeover quality. Therefore, it may suggests 20 s 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.

4.2. Effect of driving disengagement level 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 disengaged from driving compared to when monitoring driving. Some previous research found similar results (Radlmayr et al. 2014; Eriksson and Stanton 2017). However, Zeeb, Buchner, and Schrauf (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, standardised 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 takeover control ability for automation system operators (Endsley and Kiris 1995).

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 takeover 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 takeover performance and implies importance of considering the takeover time and quality as a cohort when designing HMI of HAV.

4.3. Interaction effect between age and DDL

The results found a significant interaction between the independent variables of age and DDL on the time aspects of takeover and takeover quality. This significant interaction suggests 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. 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 is 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 takeover performance from the HAV.

5. Conclusion

The present driving simulator study found that age differences are pronounced enough to be noticeable in an applied task such as taking over from the HAV. Twenty seconds seemed to be sufficient for both younger and older drivers to take over control safely and effectively. After the HAV initiated a TOR, comparing to younger drivers, older drivers took longer to be ready to manual driving position. Also, they took over the control of the vehicle more slowly. In addition, they took longer time to make decision of lane change for avoiding the stationary car. However, the extra time they took seemed to compensate for the age effects in influencing some aspects of the takeover quality, such as TTC and collision rate, thus making their takeover as successful and efficient as those of younger drivers. However, the effect of age on some aspects of takeover quality, in terms of operating steering wheel and accelerate and brake pedals, is still pronounced. Older drivers had a greater variability in their takeover performance than younger drivers when disengaged from driving in HAV. The negative effect of complete disengagement in driving on the takeover performance was observed among both the younger and older drivers. The complete disengagement in driving leads to a slower reaction and decision making and worse takeover quality than monitoring driving for both age groups. In addition, it affected older drivers more seriously than younger drivers. When disengaged from driving, drivers who had slower takeover time also had worse takeover quality. 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.

Taken into account all the findings, our results have several implications on the development of the human-machine interaction (HMI) of HAV for older drivers. Firstly, because of the great individual variability in the takeover performance among older drivers, before starting driving with an HAV, a test of takeover time and quality could be implemented to help the older drivers to build an understanding of their capability of interacting with the HAV. Then, a corresponding training of taking over control in HAV could be implemented for the older drivers based on their testing results, as training has been found to be able to improve driving performance of older people on the trained tasks (Cuenen et al. 2016). In the automated driving mode of HAV, in consider of older drivers were found to be more involved in the secondary tasks (Clark and Feng 2017) and the current research found they were more affected by the complete disengagement in driving than younger drivers, the HMI of HAV could occasionally remind the older drivers who were doing other tasks to come back to the driving loop for some time, such as remind them to manually driving or monitor system driving, to reduce the influence of completely disengagement in driving on their takeover performance. In addition, in the transition period of the control of automated vehicle, a supportive HMI should provide older drivers with a sufficient lead time. In spite of the individual variability in the sufficient time that different people require, the 20 s lead time used in this research could be a suitable one. In addition, the visual and sound TOR modality used in this research seems to be an effect way to inform both older and younger drivers of a takeover request. After the HAV initiates a TOR, there should be additional support for the older drivers to help them to be back to the driving position and generate conscious input quickly. For example, a verbal or visual message of 'Eyes on the road, hands on the steering wheel, foot on the pedal, and drive smoothly please'. After drivers have taken back the vehicle control, a smart HMI should support older drivers to process information, and make decision safely, quickly and effectively, for example by providing information about vehicle status, traffic conditions and the driving environment together with other additional support mechanisms such as steering assistance system (SAS), intelligent speed adaption (ISA) and collision avoidance system (CAS). Lastly, a smart human-machine interaction in the HAV could adopt a hierarchical support strategy based on different road types, such as providing drivers with a longer time buffer and additional information when reassuming the control over the vehicle on motorways.

While the study has yielded useful findings, there are still some limitations of this research. 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. Also, the roads of the HAV scenarios were straight roads, and future research should consider more complex road layouts, such intersections where accidents involving elderly people typically occur. In addition, the takeover task in the current research was to pass a stationary vehicle, whereas future research could again introduce more complicated tasks, such as taking over control in heavy traffic situation during peak hours, responding to a moving vehicle or interacting with pedestrians and cyclists. Moreover, the sample in this research did not include the oldest drivers aged over 85 years, and future research could investigate their takeover performance. Furthermore, this research used a reading task to completely disengage driver from attention to driving; however, this task is easily interrupted by the system's takeover request (TOR) allowing the drivers to start to prepare to reassume control of the vehicle. Future research could use other non-driving tasks that require much stronger stimuli in order to be interrupted, such as sleeping, so as to explore driver's takeover performance in such situations.

Finally, the research used a lead time of 20 s which for a vehicle driving at 60 mph 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 500 m. In reality there would be many situations where the vehicle may not have 500 m of 'electronic vision' to the obstacle due to traffic or curvature of road. This suggests that vehicles will need to be in communication with intelligent infrastructure so that obstacles can be detected and the information conveyed to on-coming automated vehicles so they can take evasive measures automatically or, as in the case of the trials tested here, request 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 communications. It is thus imperative that the automated vehicle research community and those that are undertaking the development and proving of Connected ITS work closely together to solve this safety-critical issue (Edwards et al. 2018).

Acknowledgements

The authors appreciate the time and effort of all the participants of this study, this research would not be possible without them.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research is part of a PhD at Newcastle University and the on-going support of the UK's Engineering and Physical Sciences Research Council (EPSRC) through the following funding wards: LC Transform (EP/N010612/1) (https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N010612/1); Helping Older Drivers continue driving safer for longer (EP/K037579/1) (https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/K037579/1); and the Centre for Energy Systems Integration (EP/P001173/1) (https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P001173/1).

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