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Investigation of older driver's take-over control performance in highly automated vehicles in adverse weather conditions.

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Abstract: Driving is important for older people to maintain mobility. In order to reduce age-related functional decline, older drivers may adjust their driving by avoiding difficult situations. One of these situations is driving in adverse weather conditions, such as in the rain, snow, and fog which reduce visual clarity of the road ahead. The upcoming highly automated vehicle (HAV) has the potential supporting older people. However, only limited work has been done to study older drivers' interaction with HAV, especially in adverse weather conditions. This study investigates the effect of age and weather on take-over control performance among drivers from HAV. A driving simulation study with 76 drivers has been implemented. The participants took over the vehicle control from HAV under four weather conditions-clear weather, rain, snow and fog where the time and quality of the take-over control are quantified and measured. Results show age did affect the take-over time and quality. Moreover, adverse weather conditions, especially snow and fog, lead to a longer take-over time and worse take-over quality. The results highlighted that a user-centred design of human-machine interaction would have the potential to facilitate a safe interaction with HAV under the adverse weather for older drivers.

1. Introduction

There is an ageing trend both in the world and in the UK [1]. To many older people, driving is an essential component to maintaining mobility and being independent. Moreover, it has been generally recognised that continuing mobility is strongly associated with their quality of life and wellbeing [2, 3, 4]. In the UK, travelling by car has become a dominant transport mode for many older people, and most of their trips in cars are as drivers. Older drivers are tending to drive more frequently and over longer distance [2, 5]. As opposed to the general belief older drivers do not pose a greater risk to the other road users, and they are less likely to be involved in risk-seeking driving behaviour than younger drivers [4, 6]. Nevertheless, driving is a complex task that requires a variety of physical, mental and cognitive functions and their interaction and coordination [7]. Age-related visual, cognitive and psychomotor functional impairments may result in making driving tasks more demanding and thus older drivers become a more vulnerable group to specific types of motoring offences, traffic accidents and collisions [3, 4, 6]. For example, older drivers are more likely to be seriously injured or killed in car crashes, largely due to their increased frailty [4, 6]. In addition, they have been found to have an increased propensity to being involved with collisions at intersections and failing to adhere to right of way rules [6, 8]. In order to compensate for age-related functional decline, older drivers may need to modify or regulate their driving behaviour by changing when, where and how they drive. One situation that older drivers are more likely to avoid is to driving in adverse weather conditions, such as driving in heavy rain, in heavy snow and thick fog conditions all of which reduce visibility [9, 10]. The positive side of this self-regulatory behaviour is that older people are less likely to be involved in crashes and accidents during adverse weather [6]. The final step in self-regulatory behaviour for the older driver is to cease driving altogether [3]. Nevertheless, the reduced moblity of older drivers due to the self-regulatory behaviour is highly linked with enhanced social isolation, depressive symptoms and declined self-value and identity [3, 11, 12]. Meanwhile, technologies for road transport are developing and the arrival of automated vehicle for public roads may have the potential to reduce traffic emission, congestion, and accidents. Additionally, it may potentially enhance older drivers' mobility, independence and wellbeing by offering new functionalities that will enable older people to drive safely for a longer time.

There are different levels of vehicle automation, as defined by many authorities and research organisations [13, 14, 15, 16]. These definitions have a similar hierarchical structure based on the system's capabilities and the expectations of the driver's tasks and the need for them to complement the automated functions. Among these automation systems, the highly automated vehicle (HAV), also known as the level 3 automation [15], is a system in which the drivers can be completely disengaged from driving but may be required to take-over manual control for some parts of the trip. It could possibly be a good way for older drivers who can be assisted in enhancing their mobility while still feeling some control over their lives through driving manually. The potential introduction of automated vehicles has generated a need to study older drivers' interaction with automated vehicles, since the automated vehicles will create a new type of driver-vehicle interaction that allows the driver to be completely disengaged from driving and as well as safely engaged in non-driving related secondary tasks. This paradigm creates a need to investigate what this may mean for older drivers in terms of how they may interact with the system, and to identify any age-related preferences and needs specific to this group and what types of human-machine interactions will be needed.

1.1. Take-over control from highly automated vehicle

Take-over is an important feature of HAV, occurring either: when the automation systems encounter a system limitation and require the driver to take over vehicle control; or when the drivers decides to drive the vehicle manually [16]. Lower levels of vehicle automation systems (Levels 1 and 2 and driver assistance systems) already allow drivers to be disengaged from the longitudinal or/and lateral driving of the vehicle; however, they must constantly monitoring the driving system. In HAVs, levels of permitted driving disengagement have been further enhanced, from monitoring driving to completely disengaging from driving, allowing the drivers to safely engage in other non-driving related secondary tasks. Therefore in system-initiated take-over situations, the HAV informs the driver by issuing a take-over control request (TOR) and providing a sufficient lead time to stop performing other non-driving tasks and to take over control of the vehicle [13, 14, 15, 16].

1.2. Effect of age on take-over control from HAV

Older driver's interaction with HAV has been investigated. Research by [17] explored the effect of age on take-over performance. Participants were asked to perform three non-driving related tasks: watching a film, reading a tablet, and monitoring driving. They did not find any significant effects of the age or type of non-driving related task on take-over performance. Research by [18] investigated the influence of age on take-over performance when drivers were engaged in a questioning task presented by a hands-free phone. They found age had no effect on take-over time, but older subjects braked more frequently and harder, and left greater time to collision. They reported that older drivers were more cautions during the taking over control from the HAV, which was because of their greater driving experience. In addition, research by [19] investigated age differences in the preferences of the non-driving related tasks as well as take-over control performance. They found that older and younger drivers preferred to engage in different non-driving related tasks during automated driving. Younger subjects were more likely use electronic devices, while older subjects were more likely to talk to other people. In addition, older drivers were more likely to become heavily engaged in non-driving related tasks and they had a more cautious approach to take-over. Research by [20] examined the age effect on the take-over control behaviour between automated and manual driving. They did not apply any non-driving tasks during automated driving, but drivers were allowed to choose when to activate the automated systems, and it was found that older subjects aged 65-75 years were similar in behaviour to the comparison younger group aged 25-45 years.

1.3. Purpose of This Research

Despite the efforts of previous research to build an understanding of how drivers interact with highly automated vehicles, there are still many gaps in knowledge in this field. To begin with, previous research has not elucidated the age differences in take-over performance [17, 18, 19, 20] and thus it is necessary to address whether the effect of age-related functional decline in a driver's safe manual driving ability [9] could be implicated in their ability to take over control from automated vehicle systems. In addition, previous research mainly focused on examining the take-over behaviour from HAV among the older drivers in clear weather conditions. How they interact with HAV in adverse weather conditions has not been well studied. Given the fact that older people's mobility in these bad weather conditions may be enhanced by HAV, it is important to investigate their take-over performance from HAV in adverse weather conditions.

Therefore, the purpose of this research is to investigate the effect of age and weather on driver's take-over control performance.

2. Method

2.1. Participants

In order to be eligible for the research, the participants were required to have valid UK driving licenses and to be active drivers at the time they participated in the test. Younger drivers were used as the control group to compare with the experimental aged group. The study recruited younger drivers from the students and staff at Newcastle University. Therefore, the higher proportion of students may have resulted in a much younger age range in the younger driver group. Older drivers (aged 60 and over) were recruited from the local community in Newcastle upon Tyne. A total of 76 subjects participated in the experiments, and aged between 20-81 years (mean=49.21years, SD= 23.32years; 33 female, 43 male). 37 subjects were younger drivers aged between 20 to 35 years (mean=26.05 years, SD=4.47 years; 17 female, 20 male), and 39 were older drivers aged between 60 to 81 years (mean=71.18 years, SD=6.06 years; 16 female, 23 male). Older drivers formed an experimental group while younger drivers formed a control group. Table 1 indicates their annual driving mileages by age group.

2.2. Apparatus

The ST Software Jentig50 driving simulator (see Fig.1) has been used in a number of studies and it has been found to be reliable and valid in investigating older people's interaction with in-vehicle technologies in previous research [21, 22]. It consists of an aluminium cabin equipped with five 50-inch LCD screens, with all of the controls of a real car, 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 the LCD screens. The system comes with a 5.1 surround sound system which provides drivers with an authentic 3D driving experience. All participants evaluated the driving on the simulator as 'good enough' compared with driving their own car.

Table 1 Participant's annual mileage

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

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

2.3. HAV Scenario

The highly automated vehicle implemented on the driving simulator was derived from the DfT's definitions of high automation [16] and SAE level 3 automation [15]. As Fig.2 indicates, the HAV scenario starts with automated driving for one minute. In the automated driving, the HAV system executes longitudinal and lateral vehicle control allowing the driver to be completely disengaged from driving and to safely perform other non-driving related tasks. After one minute, the system detects a stationary red car suddenly obstructing the driving lane, and then it warns the driver by a take-over control request (TOR) and provides the driver with a lead time of 20s to take over the control of the vehicle and to change lane in order to avoid the stationary car. After the driver has successfully passed the stationary car, they are asked to pull the car over and the scenario ends.

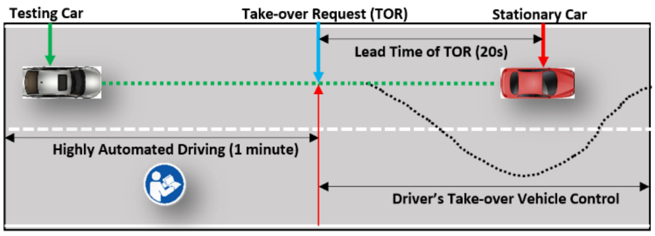

Fig. 2. Illustration of the HAV scenario

2.4. Testing Roads and Take-over Request (TOR) Modalities

The HAV scenario runs on two types of roads: a city road and a motorway (see Fig.3). Two most common UK national speed limits, 30mph and 60mph, have been applied in this research.

On the city road, the HAV system travels at 30mph (13.41m/s). It detects the stationary car with an advance distance of 268.2m and provides the drivers with 20s to respond. On the motorway, the HAV system travels at 60mph (26.82m/s). It detects the stationary car with an advance distance of 536.4m and provides the drivers with 20s to respond.

When the HAV system detects the stationary car ahead, it alarms the driver by a visual and audible take-over request consisting of a prominent red message on the screen reading "Please take-over" and a female voice saying "Attention! Please take over the vehicle control".

Fig. 3. City road (left) and motorway (right)

2.5. Non-Driving Related Task in HAV

When the HAV system is controlling the vehicle, in order to ensure that subjects are as completely disengaged from driving as possible, as shown in Fig. 4 they are asked to read aloud the material displayed on an iPad on the left-hand side of the steering wheel.

Fig. 4. Non-driving tasks in HAV

2.6. Weather Effects

As Fig.5 indicates, the clear weather and three adverse weather conditions were integrated into the HAV scenario. The adverse weather conditions consist by rain, heavy snow and thick fog. The clear weather condition has a visibility of approximate 1000 meters. The heavy rain condition has a visibility of approximate 400 meters. The heavy snow condition has a visibility of approximate 200 meters. And the thick fog condition has a visibility of approximate 100 meters.

In order to set up a controlled experiment to investigate the effect of the adverse weather condition on take-over performance. The driving speed of HAV before TOR was assumed same under different weather conditions. In addition, due to the limitation of the driving simulator used in this research, the effects of adverse weather on the road surface could not be considered.

Fig. 5. Weather conditions in the HAV scenario, clear weather, rain, snow and fog from the left to the right

2.7. Experimental Design

This research adopted a 2 × 2 × 4 between- and within-subjects mixed factor experimental design. The between-subjects independent variables are age (younger, older) and road type (city road, motorway). The within-subjects independent variables is weather (clear weather, rain, snow and fog). An overview of the experimental design is shown in Table 2.

Table 2 Experimental design overview

Between-subjects independent variable		***Within-subjects independent variables***
City Road	Younger drivers	C, R, S, F
City Road	Older drivers	C, R, S, F
Motorway	Younger drivers	C, R, S, F
Motorway	Older drivers	C, R, S, F

Note. C=clear weather, R=rain, S=snow, F=fog

The following dependent variables (see Table 3) have been adopted. Participants' take-over performance is measured by the time aspects of take-over and take-over quality. Firstly, the time aspects of take-over include reaction time, take-over time and indicator time. Reaction time refers to the time between the take-over control request (TOR) and the point when drivers change back to the manual driving position. The manual driving position is the position when subjects' eyes on the road, hands on the steering wheel and feet on the pedals. It measures how fast subjects respond to the TOR from conducting the reading task. Take-over time is the time between the TOR and the driver's conscious input to the vehicle. The latter has been previously defined as a manoeuvre of the steering wheel angle of 2 degrees and/or 10% movement of accelerator or brake pedal positions [23]. Indicator time refers to the time between the TOR and driver's input of indicator signal for lane change. It measures how fast subjects begin to change lane to avoid the stationary car.

Also, the minimum time to collision (TTC) is an effective measure in assessing the severity of potential collisions [24]. In the context of the current research, the minimum TTC refers to the time required for the test vehicle to collide with the stationary vehicle obstructing the driving lane if it continues at its speed at the time it changes to the next lane completely. The lane width is 3.6m. Both the testing car and stationary car has a width of 1.8m and they were located at the lane centre in default. Therefore, the point when the value of the lane position of the testing car is lower than 1.8m is defined as it has changed to the next lane completely. The minimum TTC is calculated as equation (1), the higher the minimum TTC, then the less critical the take-over performance is.

$$Min\ TTC = \frac{d_s - d_c}{v_c} \qquad (1)$$

$d_s = distance\ when\ stationary\ car\ appears$
$d_c = distance\ when\ testing\ car\ changes\ to\ next\ lane$
$v_c = speed\ when\ testing\ car\ changes\ to\ next\ lane$

In addition, the driver's resulting acceleration after the TOR is a useful measure of the take-over control quality, reflecting the force that the car tyre has to transfer to the ground. If this reaches the physical limit, where the maximum values of the braking manoeuvres centred on the car tyre are around 11m/s², the driving is considered to be unstable and dangerous [25]. The parameter is calculated as according to the maximum longitudinal acceleration and lateral acceleration, as equation (2) indicates.

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

Also, steering wheel angle (standard deviation in degree of central line of steering wheel) is also an effective measurement of take-over quality [23]. The higher the value the less stable the take-over performance is.

Moreover, the number of collisions and critical encounters (CCE) were used to assess the effectiveness of the take-over behaviour. The total number of collisions that a participant had in each test was recorded, including colliding to the stationary car as well as driving off the road. The critical encounter is defined as any take-over behaviour with the threshold value of a minimum TTC less than 1.5s [24].

Table 3 Overview of the dependent variables

Dependent variables	***Unit***
Reaction time	s
Take-over 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

2.8. Procedure of the study

When the participant arrived, their driving licence was checked, and they completed the ethical form and the demographic questionnaire. After that, the reason of the research was briefly explained to them as to investigate their take-over performance in HAV. All participants were provided with considerable practice time to become comfortable with the simulator until they confirmed verbally they were ready. Then, the HAV scenario was explained briefly. The participants were told that their performance of each driving session will be assessed; they need to take over control of the vehicle as soon as they received the TOR; after take-over control, they need to obey the speed limit, indicate when changing lanes and drive as they normally would in real life. After that, the experiment started and the sequence of the driving sections was random to avoid order effects.

The driving simulator collects data on the subject' driving performance at a frequency of 20 sample per second (every 0.05s). The data from the driving simulator is in binary form and can be converted into ASCII format. Then the ASCII format data were input to MS Excel. Values of all of the dependent variables were calculated in MS Excel and input into SPSS. The descriptive and statistical analyses were carried out by SPSS.

3. Results

3.1. Trajectories

Fig.6 shows the average take-over trajectories under different weather and thus visibility conditions. Drivers' average take-over trajectories in clear weather and in the rain were more smooth and gradual than those in the snow and fog. The average take-over trajectories in the snow and fog were sharper and much closer to the stationary car than those in clear weather and rain. In addition, older drivers' average trajectories in the snow and fog were more inconsistent than those of younger drivers.

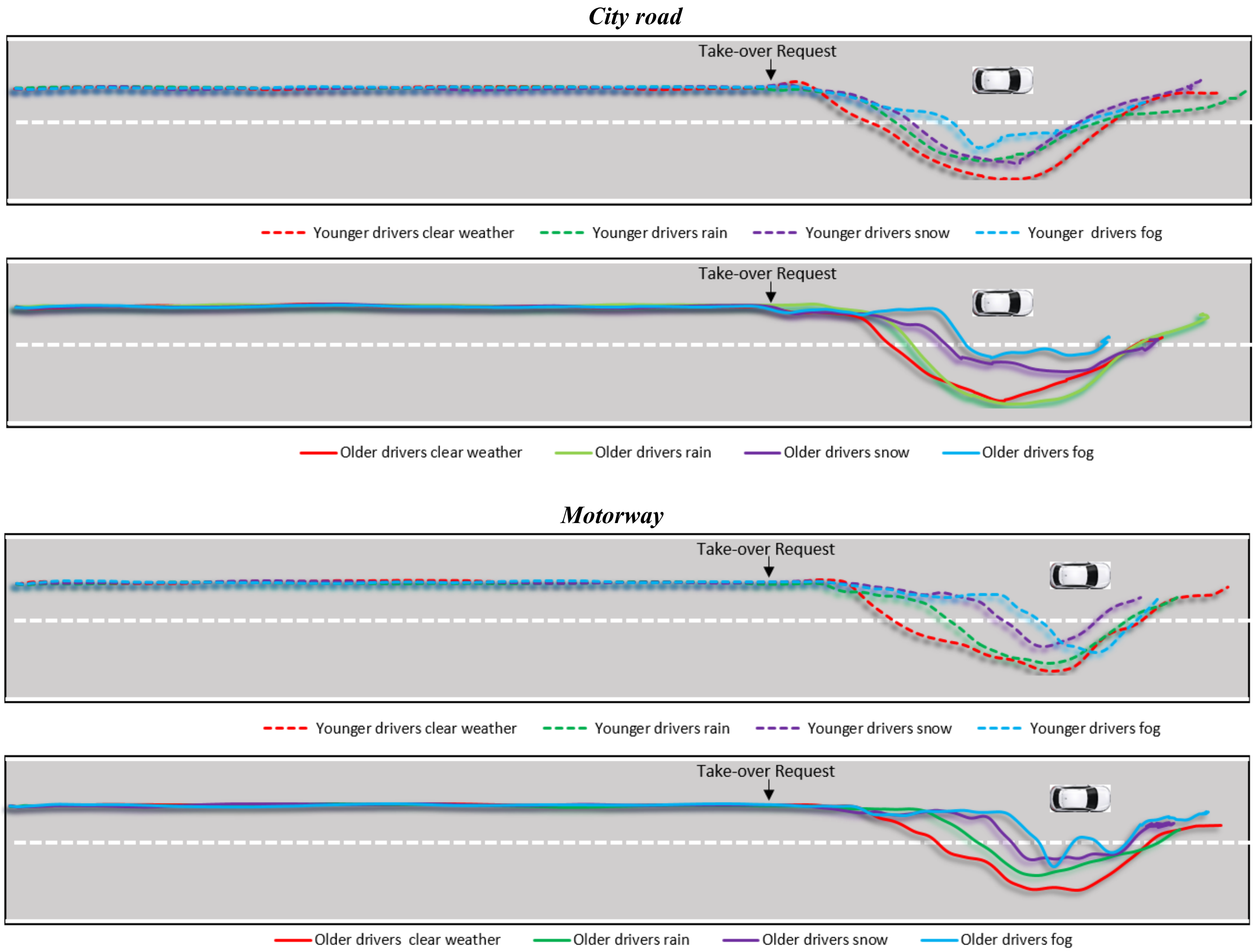

Fig.6. *Average trajectories when older and younger drivers took over control from the HAV on city road and motorway under different weather conditions.*

3.2 Collision or Critical Encounter (CCE)

Fig.7 shows the collisions and critical encounters that participants had when taking over control from HAV in different weather conditions. In general, the collisions or critical encounters (CCE) were mostly happened in the snow and fog. In clear weather and rain, there were 1 CCE among older drivers and 1 CCE among younger drivers on city road. In the snow, 2 CCEs were recorded among younger drivers and 7 CCE among older drivers on city road. Whereas there were 4 CCEs among younger drivers and 10 CCEs among older drivers on motorway. In the fog, there were 12 CCEs among older drivers and 9 CCEs among younger drivers on city road, and there were 14 CCEs among older drivers and 15 CCEs among younger drivers on the motorway.

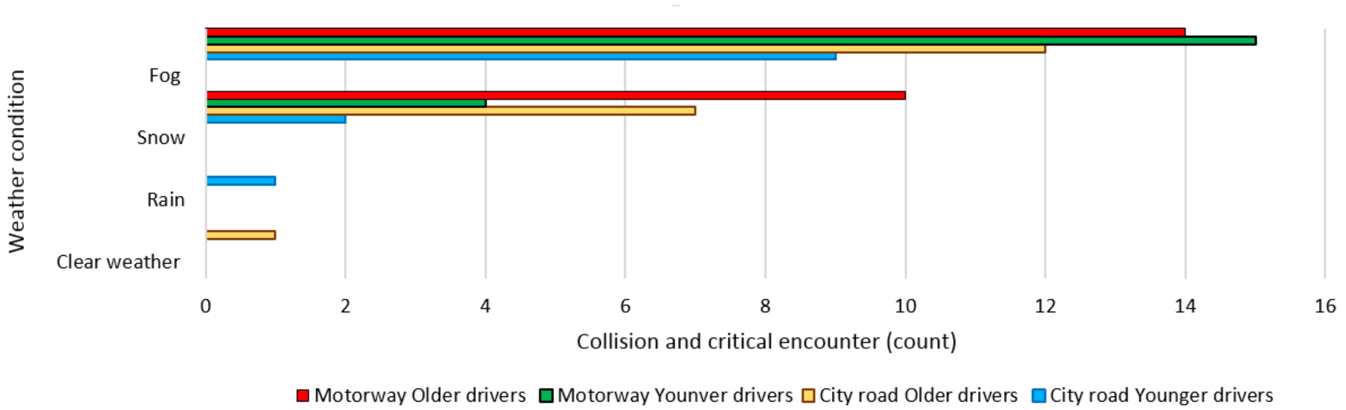

Fig.7. *Collisions and critical encounters of participants under different situations*

3.3. Reaction Time

The results of the mixed factorial ANOVA with Huynh-Feldt correction (Table 4 and Fig.8) indicate age showed a significant effect on the reaction time, with older drivers (M=2.88s,SD=0.76s) reacted slower to the take-over request (TOR) than the younger drivers (M=2.21s, SD=0.55s). Also, results show weather had a significant effect on the reaction time, post hoc test with Bonferroni correction ($p \leqslant 0.05$) indicated that driver's reaction time in clear weather (M=2.52s, SD=0.74s) is significantly faster than it in the fog (M=2.65s, SD=0.82s). In addition, road type yielded a significant effect on reaction time, with drivers had faster reaction on city road (M=2.35s, SD=0.67s) than on motorway (M=2.74s, SD=0.78s). Moreover, there is a significant interaction between age and weather on the reaction time. Older drivers' reaction time showed a relative steady trend across the clear weather (M=2.91s, SD=0.70s), in the rain (M=2.87s, SD=0.77s), in snow (M=2.75s, SD=0.73s), and in the fog (M=2.99s, SD=0.82s). However, younger drivers' reaction time showed a trend of consistent increasing in clear weather (M=2.12s, SD=0.52s), in the rain (M=2.15s, SD=0.47s), in the snow (M=2.26s, SD=0.52s) and in the fog (M=2.29s, SD=0.66s).

Finally, there is a significant interaction between weather and road type. 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.

Table 4 Results of a mixed ANOVA for reaction time

	df	*F*	*p*	ηp^2
A	1,72	26.903***	<0.001	0.272
W	2.927,23.930	3.168*	0.026	0.042
RT	1,72	8.852**	0.004	0.109
A×W	2.927,23.930	2.946*	0.035	0.039
A×RT	1,72	1.816	0.182	0.025
W×RT	2.927,23.930	2.773*	0.044	0.037
A×W×RT	2.927,23.930	0.719	0.538	0.010

*Note: A=age, W=weather, RT=road type, *= p ⩽ 0.05, **= p ⩽ 0.01, ***= p ⩽ 0.001*

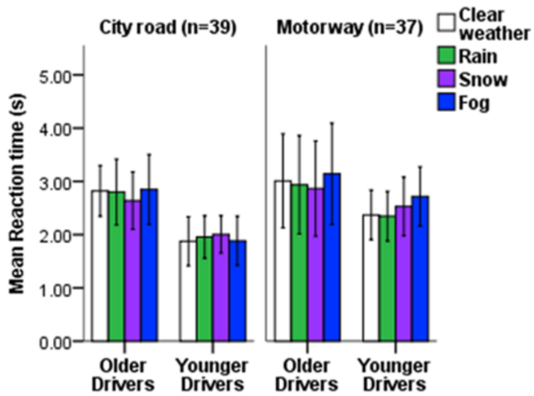

Fig. 8. *Reaction time for different driver groups in different situations (Error bars=±SD).*

3.4. Take-over time

As Table 5 and Fig.9 indicate, results of the mixed factorial ANOVA with Huynh-Feldt correction show age had a significant effect on driver's take-over time, with older drivers had longer take-over time (M=4.33s, SD=1.84s) than the younger drivers (M=3.61s, SD=1.79s).

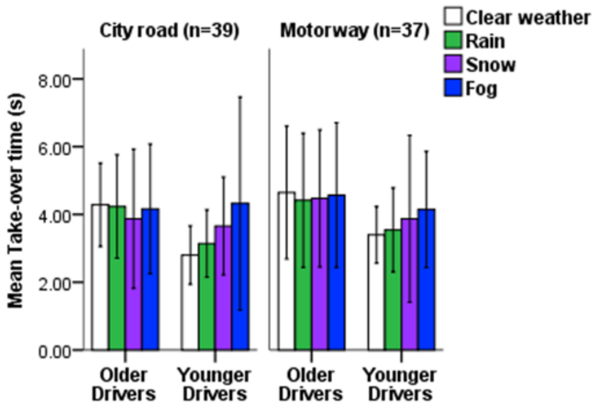

Fig. 9. *Take-over time for different driver groups in different situations (Error bars=±SD).*

In addition, there was a significant interaction between age and weather. In clear weather, older drivers' take-over time (M=4.46s, SD=1.61s) was much slower than it of younger drivers (M=3.09, SD=0.89s). In the rain, older drivers (M=4.32s, SD=1.74s) also had slower take-over time than younger drivers (M=3.34s, SD=1.12s), but the difference became less pronounced than in clear weather. Likewise, in the snow, older drivers' take-over time (M=4.16s, SD=2.04s) is longer than it of younger drivers (M=3.76s, SD=1.98s), and the difference is smaller than it in the rain. Finally, in the fog, older driver showed slower take-over time (M=4.36s, SD=2.01s) than it of younger drivers (M=4.24s, SD=2.52s), but the difference became quite small.

Table 5 Results of a mixed ANOVA for take-over time

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

*Note: A=age, W=weather, RT=road type, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001*

3.5. Indicator Time

Results of the mixed factorial ANOVA with Huynh-Feldt correction (Table 6 and Fig.10) show age had a significant effect on driver's indicator time, with older drivers had longer indicator time (M=15.68s, SD=6.50s) than the younger drivers (M=11.53s, SD=6.01s). In addition, results show weather had a significant effect on the indicator time, 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). 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. Lastly, the post hoc test (p<0.001) shows indicator time in the snow is faster than it in the fog. There is also a significant effect of road type on the indicator time, with drivers exhibiting longer indicator time on motorway (M=15.15s, SD=7.18s) than on city road (M=12.24s, SD=5.65s).

Lastly, there is a significant interaction between weather and road type on the indicator time. In clear weather, driver's indicator time on city road (M=8.75s, SD=3.23s) is quite close with it on the motorway (M=8.82s, SD=3.69s). However, in the other adverse weather conditions, drivers' indicator times on the motorway (rain: M=12.29s, SD=4.27s; snow: M=18.55s, SD=6.29s; fog: M=20.96s, SD=6.55s) are generally much longer than those on city road (rain: M=10.81s, SD=3.85s; snow: M=16.27s, SD=6.41s; fog: M=18.77s, SD=6.49s).

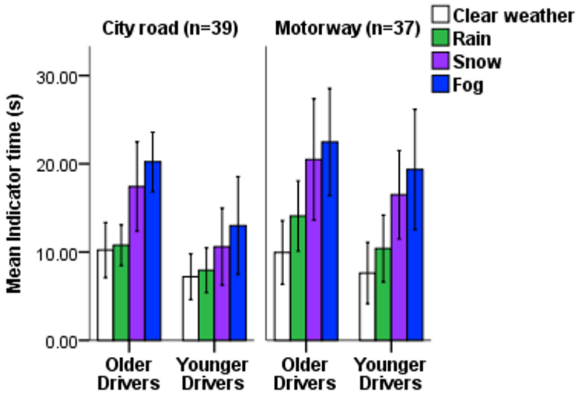

Fig. 10. *Indicator time for different driver groups in different situations (Error bars=±SD).*

Table 6 Results of a mixed ANOVA for indicator time

	df	*F*	*p*	*ηp²*
A	1,72	37.023***	<0.001	0.340
W	2.606,187.652	107.338***	<0.001	0.599
RT	1,72	18.731***	<0.001	0.206
A×W	2.606,187.652	2.287	0.089	0.031
A×RT	1,72	1.554	0.217	0.021
W×RT	2.606,187.652	5.118**	0.003	0.066
A×W×RT	2.606,187.652	1.495	0.222	0.020

*Note: A=age, W=weather, RT=road type, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001*

3.6. Time to Collision (TTC)

The results of the mixed factorial ANOVA with Huynh-Feldt correction (Table 7 and Fig.11) show that age has a significant effect on drivers' TTC, with older drivers having smaller TTC (M=5.13, SD=4.70s) than it of younger drivers (M=6.90s, SD=5.38s). Moreover, weather yielded a significant effect on the value of the driver's TTC. Post hoc test with Bonferroni correction (p<0.01) show 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). 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 fog (M=2.81s, SD=4.79s). Moreover, it (p<0.001) indicates the TTC in the rain is larger than it in the rain is larger than it in the snow and fog.

Table 7 Results of a mixed ANOVA for TTC

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

*Note: A=age, W=weather, RT=road type, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001*

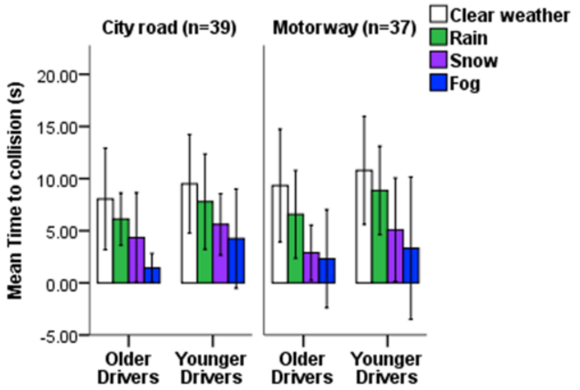

Fig. 11. *TTC for different driver groups in different situations (Error bars=±SD).*

3.7. Resulting Acceleration

The results of the mixed factorial ANOVA with Huynh-Feldt correction (Table 8 and Fig.12) show that age has a significant effect on drivers' resulting acceleration, with older drivers (M=4.14m/s², SD=2.46m/s²) exhibiting greater resulting acceleration than younger drivers (M=2.71m/s², SD=1.74m/s²). Weather also yielded a significant effect on the value of the driver's resulting acceleration. Post hoc with Bonferroni correction (p<0.001) shows that the driver's resulting acceleration in clear weather (M=2.72m/s², SD=1.86m/s²) is smaller than it in the snow (M=4.26m/s², SD=2.46m/s²). It (p=0.001) also shows that the resulting acceleration in clear weather is smaller than it is in the fog (M=4.04m/s², SD=2.36m/s²). In addition, it (p<0.001) indicates the resulting acceleration in the rain (M=2.77m/s², SD=1.72m/s²) is smaller than it in the snow and fog.

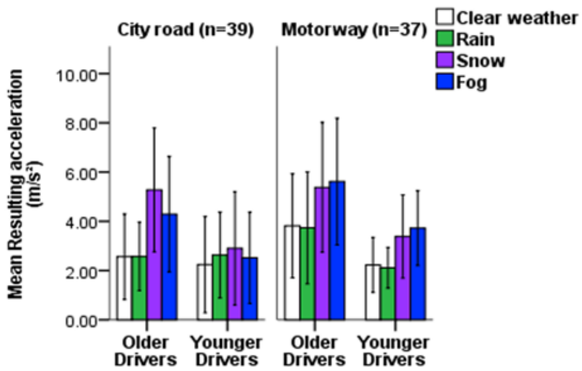

Fig. 12. *Resulting acceleration for different driver groups in different situations (Error bars=±SD).*

Table 8 Results of a mixed ANOVA for resulting acceleration

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

*Note: A=age, W=weather, RT=road type, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001*

3.8. Steering Wheel Angle

The results of the mixed factorial ANOVA with Huynh-Feldt correction (Table 9 and Fig.13) show that age has a significant effect on drivers 'steering wheel angle, with older drivers (M=10.73 degrees, SD=6.75 degrees) exhibiting greater steering wheel angle than younger drivers (M=7.04 degrees, SD=4.89 degrees). In addition, weather yielded a significant effect on drivers' resulting acceleration. 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). 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). 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. And it (p<0.001) indicates the steering wheel angel in the rain is smaller than it in the fog.

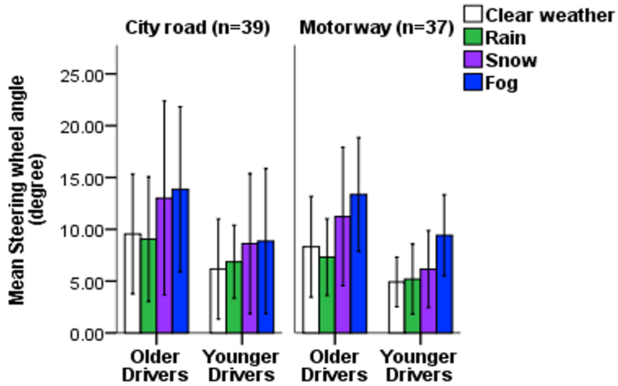

Fig. 13. *Steering wheel angle for different driver groups in different situations (Error bars=±SD).*

Table 9 Results of a mixed ANOVA for steering wheel angle

	df	*F*	*p*	*ηp²*
A	1,72	17.870***	<0.001	0.199
W	2.532,182.3	13.496***	<0.001	0.158
RT	1,72	2.081	0.153	0.028
A×W	2.532,182.3	1.098	0.345	0.015
A×RT	1,72	0.004	0.947	0.000
W×RT	2.532,182.3	0.683	0.539	0.009
A×W×RT	2.532,182.3	0.102	0.750	0.001

*Note: A=age, W=weather, RT=road type, *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001*

4. Discussion

This research investigates the take-over control performance among older and younger drivers in clear and adverse weather conditions which impacted on vision.

When comparing the take-over performance between older and younger drivers. The time aspects of take-over were used to reflect how quickly the participants reacted to the take-over 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 take-over than younger drivers. These findings could be explained in terms of the fact that the take-over control process in this research requires participants to first perceive and understand the system take-over 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 take-over process, including declines in age-related visual and hearing [26, 27] and cognitive abilities [28, 29], slower reaction times [30, 31], and reduced psychomotor abilities [32]. Also, age was shown to have significant effects on the measurements of take-over 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 [18, 19]. 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 CCEs (collisions and critical encounters) involving older drivers (44) was larger than for younger drivers (31). Taken together, these findings indicate that older drivers' take-over is less effective and more critical than that of younger drivers. However, these findings are contrary to those of another study [18] 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 [18] 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' take-over from HAVs in clear weather conditions [17, 18, 19, 20], the current research adopted clear weather condition together with a series of adverse weather conditions (rain, fog and snow) which may have made the take-over task more difficult, therefore resulting in worse take-over quality among the older drivers.

Another important area for investigation in this research is the effect of weather conditions on the driver's take-over performance. With regards to the time aspects of take-over, 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 [33], 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 take-over 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' take-over 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 take-over 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 take-over 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 take-over quality [34].

In addition, this research has found that there is a significant interaction effect between age and weather on the time aspects of take-over in terms of reaction time (RT) and take-over 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) which occurred for each group. In general, younger drivers' time aspects of take-over 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 take-over behaviours, with 1 CCE for each group. 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' take-over was more dangerous (17 CCEs) than that of the younger drivers (6 CCEs). In addition, in foggy conditions, the gap in the time aspects of take-over, and especially the take-over 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 take-over (26 CCEs) than the younger drivers (23 CCEs). These findings could be because the take-over 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 take-over request, to process information and to generate active input than the younger drivers, so that their take-over 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 [35]. 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 take-over 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. This could also be explained in terms of the enhanced levels of task difficulty resulting in slower and less accurate task performance [36]. However, in the same conditions, older drivers' time aspects did not show any increasing trend, but more CCEs 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 [37]. 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 [21, 38].

5. Conclusion

In summary, this research investigated the take-over control performance of younger and older drivers in HAV during clear weather, rain, snow, and fog. We found that age –related performance differences are marked in the task of taking over control from HAV under different weather conditions. Comparing to younger drivers, older drivers took longer time to react, generate active input to the vehicle and make the decision of lane change slower. Also, older drivers were recorded with harder braking and accelerating patterns than the younger drivers. And older drivers' take-over is more critical than it of the younger drivers. In addition, adverse weather conditions, particularly heavy snow and thick fog, led to slower reaction and decision making as well as a less effective and more dangerous take-over behaviour for both the younger and older drivers. Younger drivers and older drivers were affected differently by the adverse weather. Adverse weather resulted in slowed time aspects of take-over and worse take-over quality among younger drivers. For older drivers, their already slower time aspects of take-over were not slowed down even further by adverse weather, but their overall take-over became much more dangerous.

The findings of this research indicates that the HAV may not be simply seen as the solution to all older drivers' mobility issues and age differences are still pronounced in negatively influencing performance in the drivers' interaction with the HAV. Therefore, it is necessary to fully consider older people's requirements during the design process of HAVs. Several implications for the design of age-friendly human-machine interaction (HMI) in highly automated vehicles could be drown from our findings. Firstly, a supportive HMI in HAV should alarm the drivers who are disengaged from driving about the adverse weather to help them to be prepared in case any take-over control would be needed. During the take-over control period in adverse weather conditions, a supportive HMI could project driving environment to the head-up display to compensate drivers' reduced visibility. Also, more support mechanism should be provided to the drivers during the take-over process in adverse weather conditions, such as steering wheel stabilization systems.

Moreover, the results showed that both younger and older drivers performed poorly when assuming control from the HAV in adverse weather conditions. Given that the HAV in this research involves level 3 automation which relies on the human drivers to respond safely to TORs [15], this may suggest a need to promote the development of the level 4 automation which can automatically initiate and adopt the safe mode even if the human driver does not respond safely when driving in adverse weather conditions [15]. For example, if snow or fog was too heavy for the drivers to perform a safe take-over, the HAV could activate the 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 take-over for the driver.

While this research has provided useful findings, limitations still exist. To begin with, in order to set up a controlled experiment, the current research assumed that the traveling speed of the HAV is the same under different weather conditions. When interpreting the results, it should be noted that people adopt lower driving speeds in adverse weather in real life. Also, the sample size of the current research is still relatively small. Future research could repeated the current research with a larger sample size. The younger subjects in this research had smaller annual 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 cover those aged over 81 years. Therefore, future research should adopt a different sample that includes subjects aged 36-59 years and over 81 years to also study their take-over performance in HAVs. Additionally, this research focused on studying only the effect of age on take-over performance. There are other demographic factors affecting driving performance, such as gender. Thus, future research has been planned to test these variables and their effects on take-over performance. Moreover, the current research investigated drivers' take-over performance under adverse weather in the daytime, future research could examine drivers' take-over performance under the adverse weather conditions at night and explore the methods which may have potential to improve older drivers' take-over performance under adverse conditions.

Finally, due to the limitation of using the particular driving simulator, this research has only considered 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. Given that weather-related visibility reduction is a significant problem affecting manual driving performance [39, 40, 41], the current findings provide evidence indicating that these effects of adverse weather also affect the driver's performance of take-over control from the HAV. Nevertheless, future research could repeat the current research and validate the results in real-life situations with all of the effects of adverse weather being taken into account. Above all, this research emphasises the need for a user-centred design of the human-machine interaction tailored for the older drivers to ensure their safe usage of HAV in adverse weather conditions.

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