Impact of Age on Takeover Behavior in Automated Driving in Complex Traffic Situations: A Case Study of Beijing, China

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Abstract: Research on the influence of age on various automated driving conditions will contribute to an understanding of driving behavior characteristics and the development of specific automated driving systems. This study aims to analyze the relationship between age and takeover behavior in automated driving, where 16 test conditions were taken into consideration, including two driving tasks, two warning times and four driving scenarios. Forty-two drivers in Beijing, China in 2020 were recruited to participate in a static driving simulator with Level 3 (L3) conditional automation to obtain detailed test information of the recorded takeover time, mean speed and mean lateral offset. An ANOVA test was proposed to examine the significance among different age groups and conditions. The results confirmed that reaction time increased significantly with age and the driving stability of the older group was worse than the young and middle groups. It was also indicated that the older group could not adapt to complex tasks well when driving due to their limited cognitive driving ability. Additionally, the higher urgency of a scenario explained the variance in the takeover quality. According to the obtained influencing mechanisms, policy implications for the development of vehicle automation, considering the various driving behaviors of drivers, were put forward, so as to correctly identify the high-risk driving conditions in different age groups. For further research, on-road validation will be necessary in order to check for driving simulation-related effects.

Keywords: automated driving; older driver; driving condition; takeover time; takeover quality

1. Introduction

Nowadays, China is witnessing a major change in the proportion of older drivers in road traffic. The number of drivers aged 60 and older has increased by 7.5 million in the past five years, and, by 2020, there were more than 15 million older drivers. It is controversially discussed whether the elderly have an increased involvement in accidents. In 2019, the accident rate of the elderly in China was three times higher compared to drivers aged between 21 and 25 and those between 36 and 50. Several studies have explored whether older drivers are more likely to make mistakes in driving and be at fault in a crash, using the method of statistical analysis. In addition, older drivers differ from younger drivers in the types of crashes they have [1,2] and show compensatory driving behavior. Therefore, the safety of older drivers has become a problem that must be addressed by society. The automation of driving tasks has become an important research field within the last few years, and, with automation, drivers can engage in secondary activities while traveling to their destination. It may also propose a new way to ensure the safety of older drivers. In Level 3 (L3) conditional automation, the driver is not required to monitor the driving environment or the automated system performance. Nevertheless, the driver still has to be available for taking over the vehicle’s controls in “situations that exceed the operational limits of the automated driving system”, detected and announced by the
automated system. Therefore, it is essential to analyze the behavior of older drivers in highly automated driving systems in varying conditions.

Aging is accompanied by a decline in cognitive functions, and since driving is a complex task, such impairments may also be relevant for safe road behavior. Abundant studies have explored whether the driving ability of older drivers decline as drivers grow older, based on simulated driving data in regular driving behavior scenarios without autonomous driving scenarios [3–6]. Older drivers experienced significantly slower reaction times, had more collisions, drove slower, deviated less in speed, and were less able to maintain a constant distance behind a pace car [7]. Depestele analyzed 22 studies and also concluded that older persons had a more variable, less consistent driving simulator performance, such as more variable speed adaptation or less consistent lane keeping behavior [8]. Nakano and Wood found that age sensitivity was significantly associated with the driver safety ratings of the AMD (Age-related Macular Degeneration) drivers [9,10]. Significant age differences in simulated driving performance were demonstrated [11–14]. Furthermore, driving tasks and scenarios were also analyzed to identify the age-related driving performance [15–17]. Bunce revealed that older drivers exhibited significantly greater performance inconsistency, particularly marked in the faster motorway condition [18]. On the dual carriageway, both young and older drivers drove at similar average speeds, while older drivers showed a 50% higher standard deviation (SD) in steering wheel angular velocity with regard to steering stability. On the mountain road, older drivers again demonstrated more difficulty in maintaining a correct lane position. Driving through the inner-city circuit, the SD of the steering wheel angular velocity was approximately 17% higher for older drivers, and the older participants drove significantly slower in this section [19,20]. Rumschlag found that texting skill level and driver age were significantly correlated with the percent of subjects exhibiting lane excursions, where the highly text-skilled drivers’ age was significantly correlated with the number of lane excursions, the percent of subjects exhibiting lane excursions and the percent of texting time in lane excursions [21].

With regard to the automated driving tasks, a large variety of takeover studies have been conducted within the past few years, giving insights into drivers’ behavior in takeover situations, although most of this research has not focused on the influence of age. Firstly, the training system for automated driving tasks was examined and Sportillo indicated that the light VR training is preferred with respect to other systems [22]. Then, dependent variables, including reaction time, maximum acceleration, average lane departure distance, number of collisions and so on, were collected and analyzed [23,24]. A shorter mean takeover time was associated with a higher urgency of the situation, not using a handheld device, not performing a visual non-driving task, having experienced another takeover scenario before in the experiment and receiving an auditory or vibratory takeover request, while the mean and standard deviation of the takeover time were highly correlated [25]. Gold investigated the effect of traffic in takeover situations and the 20-Questions task, and the report showed that the presence of traffic led to longer takeover times and worse takeover quality in the form of shorter times until a collision and more collisions, while the 20-Questions task did not influence takeover time but seemed to have minor effects on the takeover quality. Furthermore, a few researchers have investigated the influence of age on vehicle control while performing a takeover in a highly automated driving system. Körber found that older drivers reacted as fast as younger drivers, however, they differed in their modus operandi as they braked more often and more strongly and maintained a higher time-to-collision [26]. Gold revealed that, in particular, the time budget, traffic density and the repetition strongly influenced takeover performance, while non-driving-related tasks, the lane and drivers’ age explained a minor portion of the variance in the takeover performances [27].

Considering the significant increase in the number of older drivers and the development of automated driving technology, existing studies have only focused on identifying the differences in driving ability between younger and older drivers in terms of manual driving. However, the age effects existing in automated driving behavior have not been
fully considered or analyzed, including the older drivers’ takeover time, driving stability and so on. Based on the hypotheses that the driving behavior of older drivers differs to that of young drivers and varies under different automated driving tasks, this study records and calculates the data of takeover behavior in automated driving, including the takeover time, mean speed and mean lateral offset. In particular, 16 test conditions have been taken into consideration, including driving task, warning time and driving scenarios.

2. Methodology

2.1. Participants

Forty-two participants (Mean age = 42.53, SD = 15.85) were recruited to take part in this experiment and signed the informed consent form, including 10 females and 32 males. Based on the age classification standard in China, the participants were classified into three groups, where the young group (n = 15, M = 25.4 years) ranged from 18 to 30 years, the middle group (n = 14, M = 43.3 years) ranged from 31 to 60 years and the old group (n = 13, M = 64.7 years) ranged from 61 to 82 years. The possession of a driving license for at least one year was required for participation and participants held their license for a mean of 17.06 (SD = 12.17) years. (Table 1)

Table 1. Statistics of participants’ personal attributes.

| Variables          | Percentage |
|--------------------|------------|
| Age                |            |
| 18–30              | 35.7%      |
| 31–60              | 33.3%      |
| 61+                | 31.0%      |
| Sex                |            |
| Male               | 76.2%      |
| Female             | 23.8%      |
| Driving experience |            |
| <10 years          | 42.9%      |
| 10–20 years        | 33.3%      |
| >20 years          | 23.8%      |

2.2. Study Design and Measures

Each participant drove around the circuit under four different driving scenarios (Main-line, On-ramp, Fog-cluster and Accident driving scenarios) each for four times, once for each of the two driving tasks (working state and entertainment state driving task) and two warning time (5 s or 10 s). One participant needed to complete 16 tests in total and the order of tests was random. The relationship between age and driving task, warning time and driving scenarios was analyzed for this experiment.

Dependent variables were takeover time (TOT), control time (CT), mean speed (MS) and mean lateral offset (MLO). Taking over time was defined as the time between the warning signal and the takeover, which changed the automated driving mode into manual driving mode. The control time was defined as the time between the warning signal and the first input after takeover using brake pedal, steering wheel or accelerator. When the speed the vehicle reached varied within 1 km/h, it was regarded as a stable state. Takeover quality was measured in this study by mean speed and mean lateral offset. Table 2 summarizes the dependent variables.
Table 2. Description of dependent variables.

| Variable               | Unit | Variable Type            | Definition                                                                 |
|------------------------|------|--------------------------|---------------------------------------------------------------------------|
| Takeover time (TOT)    | (s)  | Time related to takeover | Time between warning signal and takeover                                  |
| Control time (CT)      | (s)  | Time related to takeover | Time between warning signal and the first input after takeover             |
| Mean speed (MS)        | (m/s)| Takeover quality         | Mean speed between warning signal and vehicle in stability                 |
| Mean lateral offset (MLO) | (m) | Takeover quality         | Mean lateral offset between warning signal and vehicle in stability        |

2.3. Apparatus

**Driving simulator:** The experiment was conducted in a static driving simulator with Level 3 (L3) conditional automation, composed of steering wheel, throttle, brake and dashboard. Data were recorded at a frequency of 20 Hz and transferred to central control platform. Participants drove highly automated at a speed of 100 km/h on average on a four-lane highway, where the free-flow speed was 120 km/h and the width of road cross section was 26 m (Lane width = 3.75 m, width of green belt = 2 m, width of road shoulder = 2 m). The length of the whole experimental section was 1000 m (the length in fog zone was 250 m), and the starting point was 200 m apart from the starting point of warning time, as shown in Figure 1.

![Figure 1. Takeover situation in Level 3 Conditional Automation.](image)

**Driving Task:** In conditionally automated vehicles, drivers can engage in secondary activities while traveling to their destination, so working state and entertainment state driving task were simulated in this study. In work state driving task, the participants were required to read the manuscript, text and send the content by their hand phones, where the number of the messages would be recorded. In the entertainment state driving task, the participants needed to watch the entertainment video and answer the questions about the video after the experiment.

**Warning time:** The visual and auditory warning signal was alerted before the Takeover Request (TOR). The visual warning signal provided information by the Human Machine Interface (HMI), while the voice warning signal was provided by human voice and alarm sound. We changed the length of warning signals from 5 s to 10 s to examine whether the length of warning signals influenced the takeover behavior in the different groups.

**Driving scenarios:** Four driving scenarios were simulated including Main-line, On-ramp, Fog-cluster and Accident driving scenarios. Main-line Driving scenario: participants
needed to take over vehicles on the highway with no incident in front of the automated car after the TOR. On-ramp driving scenario: participants needed to take over the vehicle and enter the ramp to the service area that existed on the right side of the highway. Fog-cluster driving scenario: participants would take over the vehicles and drive through the fog area whose visibility was 725 m. Accident driving scenario: participants needed to take over vehicles on the highway with an incident in front of the automated car after the TOR and utilize the emergency lane to bypass the accident area.

2.4. Procedure

Participants were asked to finish the questionnaire about personal information and the driving experience. The experiment and the automation was then introduced, where the automation would carry out longitudinal and lateral control and did not have to be monitored. Under the situations that the automation could not solve, the TOR warned the drivers to take over the vehicle. After participants indicated that they were familiar with driving operation, the experiment was started and the data were collected during the experiment.

3. Results

3.1. Result of Different Driving Tasks

A total of 672 pieces of takeover data were obtained in this test, where two participants failed to take over the vehicle. Finally, 670 valid pieces of data were obtained. We formally tested age difference through the 3 (young, middle, old) × 2 (driving task) Analyses of Variance (ANOVA). Table 3 shows that the main effects for age and driving task between the older drivers were significant in takeover time. The TOT and CT under the working state driving task suggested a high correlation with age (pTOT(Young × Old) = 0.000, pTOT(Middle × Old) = 0.006, pCT(Young × Old) = 0.072, pCT(Middle × Old) = 0.003). The older age group was associated with a higher reaction time in TOT and CT, where the older drivers reacted 0.6 s slower than the young and middle groups on average. Under the entertainment state driving task, the TOT of the older drivers was similar to the young group, where the TOTs were all equal to 3.73 s. Considering the takeover quality, the ANOVA indicated that age had no significant impact under the working task, except that the MLO of the old group was more than 0.04 m higher than the young and middle group on average. During the entertainment task, the middle and old groups showed a greater difference in takeover quality (pMS-E (Middle × Old) = 0.024, pMLO-W (Middle × Old) = 0.002), while the young and old group only showed a difference in MLO (pMLO-E (Young × Old) = 0.011).

During the driving task, a significant driving difference between the working and entertainment states was found in the older group (pTOT-Old = 0.000, pCT-Old = 0.000), while there was no difference in the young or middle groups. The TOT and CT under the working task were 0.9 s and 0.98 s higher than the entertainment task, respectively. Additionally, the MS and MLO varied in the range of 0.6 km/h and 0.2 m, respectively, without significant difference.
Table 3. Results obtained from ANOVA test in different tasks.

| Variables | Task         | Young   | Middle  | Old     | SIG (Young × Old) | SIG (Middle × Old) |
|-----------|--------------|---------|---------|---------|-------------------|--------------------|
|           | Working      | 3.89    | 4.11    | 4.63    | 0.000 ***         | 0.006 ***          |
|           | (SD)         | (1.00)  | (1.11)  | (1.92)  |                   |                    |
|           | Entertainment| 3.73    | 3.86    | 3.73    | 0.003 ***         | 0.119              |
|           | (SD)         | (0.99)  | (1.30)  | (1.11)  |                   |                    |
|           | SIG          | 0.229   | 0.125   | 0.000 ***|                   |                    |
| TOT (s)   | Working      | 3.89    | 4.11    | 4.63    | 0.000 ***         | 0.006 ***          |
|           | (SD)         | (1.00)  | (1.11)  | (1.92)  |                   |                    |
|           | Entertainment| 3.73    | 3.86    | 3.73    | 0.003 ***         | 0.119              |
|           | (SD)         | (0.99)  | (1.30)  | (1.11)  |                   |                    |
|           | SIG          | 0.229   | 0.125   | 0.000 ***|                   |                    |
| CT (s)    | Working      | 5.31    | 5.02    | 5.74    | 0.072 *           | 0.003 ***          |
|           | (SD)         | (1.96)  | (1.25)  | (2.02)  |                   |                    |
|           | Entertainment| 5.25    | 4.99    | 4.76    | 0.857             | 0.153              |
|           | (SD)         | (1.90)  | (1.84)  | (1.17)  |                   |                    |
|           | SIG          | 0.815   | 0.873   | 0.000 ***|                   |                    |
| MS (km/h) | Working      | 70.31   | 67      | 70.57   | 0.981             | 0.166              |
|           | (SD)         | (17.95) | (17.57) | (17.16) |                   |                    |
|           | Entertainment| 69.74   | 66.86   | 71.07   | 0.673             | 0.024 **           |
|           | (SD)         | (18.09) | (16.47) | (16.23) |                   |                    |
|           | SIG          | 0.807   | 0.951   | 0.764   |                   |                    |
| MLO (m)   | Working      | 0.48    | 0.45    | 0.52    | 0.205             | 0.023 **           |
|           | (SD)         | (0.22)  | (0.22)  | (0.21)  |                   |                    |
|           | Entertainment| 0.47    | 0.47    | 0.53    | 0.011 **          | 0.002 ***          |
|           | (SD)         | (0.19)  | (0.20)  | (0.20)  |                   |                    |
|           | SIG          | 0.612   | 0.454   | 0.675   |                   |                    |

Note: ***, **, * = significance at 1%, 5% and 10%.

3.2. Result of Different Warning Time

As shown in Table 4, age difference through the 3 (young, middle, old) × 2 (warning time) Analyses of Variance (ANOVA) was tested. The TOT suggested a high correlation between age and the 10 s warning time (pTOT-10 s (Young × Old) = 0.008), where older drivers spent 0.4 s more time than the younger drivers in TOT. The results showed that age had no impact on the CT and MS under different warning times, except for the older drivers driving 3.9 km/h faster than the middle group under the 10 s warning time (pMS-10 s (Middle × Old) = 0.089). Additionally, age was found to be the significant main effect for the MLO, (pMLO-5 s (Young × Old) = 0.071, pMLO-5 s (Middle × Old) = 0.048, pMLO-10 s (Young × Old) = 0.073, pMLO-10 s (Middle × Old) = 0.012), and the MLOs of the older drivers ranged from 0.5 m to 0.8 m higher than the other groups.

With regard to the warning time, a significant driving difference in CT was found in all age groups (pCT-Young = 0.055, pCT-Middle = 0.006, pCT-Old = 0.083), while there was no difference in TOT. The increased warning time decreased the CT by 0.49 s on average. We repeated the analysis for the takeover quality and found that warning time had no significant impact in the old and middle groups on takeover quality, while the longer warning time decreased the MS by 3.98 s and increased the MLO of the young group by 0.5 m (pMS-Young = 0.089, pMLO-Young = 0.073).
Table 4. Results obtained from ANOVA test in different warning time.

| Variables | Warning Time | Young | Middle | Old | SIG (Young × Old) | SIG (Middle × Old) |
|-----------|--------------|-------|--------|-----|-------------------|-------------------|
| TOT (s)   | 5 s          | 3.90  | 4.04   | 4.21| 0.100             | 0.363             |
|           | (SD)         | (1.04)| (1.32) | (1.80)|                  |                   |
|           | 10 s         | 3.73  | 3.93   | 4.14| 0.008 **          | 0.180             |
|           | (SD)         | (0.93)| (1.09) | (1.41)|                  |                   |
| SIG       |              | 0.195 | 0.532  | 0.769|                   |                   |
| CT (s)    | 5 s          | 5.52  | 5.30   | 5.45| 0.791             | 0.518             |
|           | (SD)         | (1.84)| (1.76) | (1.80)|                  |                   |
|           | 10 s         | 5.04  | 4.72   | 5.04| 0.998             | 0.159             |
|           | (SD)         | (1.97)| (1.27) | (1.59)|                  |                   |
| SIG       |              | 0.055 *| 0.006 **| 0.083 *|                  |                   |
| MS (km/h) | 5 s          | 72.02 | 68.82  | 72.48| 0.848             | 0.133             |
|           | (SD)         | (17.93)| (17.40)| (17.39)|                  |                   |
|           | 10 s         | 68.04 | 65.06  | 68.96| 0.684             | 0.089 *            |
|           | (SD)         | (17.75)| (16.28)| (15.16)|                  |                   |
| SIG       |              | 0.089 *| 0.100   | 0.132|                  |                   |
| MLO (m)   | 5 s          | 0.45  | 0.44   | 0.50| 0.071 *            | 0.048 **          |
|           | (SD)         | (0.20)| (0.21) | (0.20)|                  |                   |
|           | 10 s         | 0.50  | 0.47   | 0.55| 0.073 *            | 0.012 **          |
|           | (SD)         | (0.20)| (0.21) | (0.21)|                  |                   |
| SIG       |              | 0.073 *| 0.268  | 0.101|                  |                   |

Note: **, * = significance at 5% and 10%.

3.3. Result of Different Driving Scenarios

As shown in Table 5, the TOT of older drivers was 0.5 s longer than the young group under the Main-line and Fog-cluster driving scenarios (pTOT-Main (Young × Old) = 0.072, pTOT-Fog (Young × Old) = 0.033), while there was no significant difference in CT between the three groups. With regard to the driving stability, the MS of the old group was more than 8 km/h higher than the middle group under the Fog-cluster and Accident driving scenarios (pMS-Fog (Middle × Old) = 0.001, pMS-Accident (Middle × Old) = 0.007). At the same time, the MLO increased strongly in the old group (pMLO-Main (Young × Old) = 0.02 and pMLO-On-ramp (Middle × Old) = 0.001) in the scenario of Main-line driving. The dependent variables of the old group for the On-ramp driving scenario were all higher than the young and middle groups, although the difference was not significant, except the MLO between the middle and the old group (pMLO-On-ramp (Middle × Old) = 0.08).

With regard to the driving scenarios, they had no significant impact on the time related to takeover. The MS in the Main-line driving scenario was statistically higher than the other scenarios at a confidence level above 99% regardless of age, where the ranked speeds from low to high were observed during the On-ramp, Accident, Fog-cluster and Main-lane driving scenarios. The inconsistency of MLO revealed that the driving scenario had a significant influence on the young and middle groups, where all of the p-values were smaller than 0.01 (pMLO-Young = 0.057, pMLO-middle = 0.019). The MLO of the old group increased by 0.12 m, from 0.49 m to 0.61 m, due to the Fog-cluster.
### Table 5. Results obtained from ANOVA test in different driving scenario.

| Variables | Scenario | Young (SD) | Middle (SD) | Old (SD) | SIG (Young × Old) | SIG (Middle × Old) |
|-----------|----------|------------|-------------|----------|-------------------|-------------------|
| **TOT (s)** | Main-line | 3.89 (0.97) | 4.05 (1.20) | 4.34 (1.67) | 0.072 * | 0.256 |
|           | On-ramp (SD) | 3.80 (1.00) | 3.78 (0.88) | 4.01 (1.65) | 0.352 | 0.327 |
|           | Fog-cluster (SD) | 3.79 (1.03) | 4.06 (0.93) | 4.26 (1.43) | 0.033 * | 0.357 |
|           | Accident (SD) | 3.77 (0.98) | 4.04 (1.66) | 4.10 (1.72) | 0.248 | 0.835 |
|           | SIG | 0.572 | 0.728 | 0.529 | - | - |
| **CT (s)** | Main-line | 5.25 (1.59) | 4.99 (1.49) | 5.47 (1.83) | 0.478 | 0.133 |
|           | On-ramp (SD) | 4.78 (1.33) | 4.59 (1.11) | 4.98 (1.84) | 0.468 | 0.166 |
|           | Fog-cluster (SD) | 5.78 (2.36) | 5.16 (1.08) | 5.44 (1.37) | 0.303 | 0.415 |
|           | Accident (SD) | 5.30 (2.13) | 5.27 (2.22) | 5.10 (1.73) | 0.613 | 0.67 |
|           | SIG | 0.397 | 0.361 | 0.449 | - | - |
| **MS (km/h)** | Main-line | 90.13 (9.80) | 88.82 (8.34) | 87.52 (10.70) | 0.158 | 0.489 |
|           | On-ramp (SD) | 53.02 (10.62) | 51.67 (9.42) | 53.45 (7.55) | 0.809 | 0.331 |
|           | Fog-cluster (SD) | 71.90 (13.20) | 66.48 (9.49) | 74.55 (12.40) | 0.248 | 0.001 *** |
|           | Accident (SD) | 64.96 (13.84) | 60.49 (12.56) | 67.51 (13.44) | 0.32 | 0.007 *** |
|           | SIG | 0.000 *** | 0.000 *** | 0.000 *** | - | - |
| **MLO (m)** | Main-line | 0.39 (0.21) | 0.35 (0.21) | 0.49 (0.20) | 0.02 ** | 0.001 *** |
|           | On-ramp (SD) | 0.48 (0.14) | 0.45 (0.15) | 0.49 (0.12) | 0.614 | 0.08 * |
|           | Fog-cluster (SD) | 0.57 (0.23) | 0.57 (0.25) | 0.61 (0.26) | 0.376 | 0.411 |
|           | Accident (SD) | 0.44 (0.17) | 0.46 (0.16) | 0.50 (0.19) | 0.104 | 0.273 |
|           | SIG | 0.057 ** | 0.019 *** | 0.543 | - | - |

Note: ***, **, * = significance at 1%, 5% and 10%.

### 4. Discussion

In this study, we investigated the influence of age, driving task, warning time and driving scenario on the takeover time and takeover quality, where the takeover time was evaluated by the TOT and CT, and the takeover quality was evaluated by the MS and MLO.

**Age:** The TOT and CT appears to increase with age overall, while the MS and MLO of the older drivers are all higher than the other groups. It is confirmed that age had a negative influence on the takeover stability, agreeing with previous findings and indicting that older drivers differed in their modus operandi as they braked more often and more strongly and maintained a higher time-to-collision [26,27]. More precisely, older drivers had increased TOT particularly under the working state driving task, 5 s warning time, 10 s warning time, Main-line and Fog-cluster scenarios, increased CT in the entertainment state driving task, increased MS under the entertainment state driving task, 10 s warning time, Fog-cluster and Accident scenarios, and increased MLO under the working state driving task, entertainment state driving task, 5 s warning time, 10 s warning time and Main-line scenario. The increased MS revealed that the older group drove in emergencies as fast as possible to keep safe instead of reducing their driving speed.
Driving task: The confidence intervals of TOT and CT in the old group show a high overlap, while no significant differences in the young and middle groups were found. When the complexity of the driving task increased, the takeover time of the older group increased by nearly 1 s. It is indicated that the older drivers could not finish complex task, such as texting and sending messages, due to their decreased cognitive driving ability. This is consistent with a similar, previous study by Lu, where the longer the video length, the lower the absolute error of the number of placed cars, the total distance error and the geometric difference between the placed cars and the actual cars [23]. What is more, the dependent variable of takeover quality was not impacted by the driving task. However, contrary to our findings, Gold found the 20-Questions task did not influence takeover time but seemed to have minor effects on the takeover quality [28]. One possible explanation for the contradictory results could be that two driving tasks with different complexity were used in this study, while the previous study only took one driving task into consideration and compared the result between the task group and non-task group.

Warning time: Increased warning time significantly decreased the CT by about 0.5 s on average in all age groups, indicating that the longer warning time could prompt thinking time about the first input after the takeover. At the same time, the takeover quality of the young group was more sensitive to the warning time, where the MS decreased from 72.02 km/h to 68.04 km/h to guarantee safety and the MLO increased from 0.45 m to 0.50 m.

Driving scenario: The driving scenario had no influence on the TOT or the CT in all age groups but led to strong differences in takeover quality, where the ranked speeds from low to high were observed during the On-ramp, Accident, Fog-cluster and Main-lane driving scenarios. This is also consistent with Gold’s research that showed that the presence of traffic in takeover situations led to worse takeover quality [28]. Kim and Zhang also confirmed that the reaction times were significantly different between events, where shorter mean takeover times were associated with the higher urgency of a situation [24,25]. These research results used a different independent variable, traffic density, as the driving scenario, while this research used different driving environments such as Fog-cluster, On-ramp driving and Accident instead of changing the traffic density.

5. Conclusions

To investigate how older drivers performed using a highly automated system in China, a driving simulation test with L3 conditional automation was designed in this study, where 16 test conditions were taken into consideration, including two driving tasks, two warning times and four driving scenarios. An ANOVA test was used to examine the significance of driving behavior among three groups in 16 simulated conditions. The results clarified that age affects the driver’s driving stability and adaptability under different conditions, where reaction time increased significantly with age and the driving stability of the elderly was worse than the young and middle groups. What is more, the elderly cannot adapt to the complex task well due to their limited cognitive driving ability. Additionally, the higher urgency of scenarios explained the variance in takeover quality.

The results of this study have important policy implications for the development of vehicle automation considering the various driving behaviors of drivers. Measurements and modeling of driver states in this research may help disclose the underlying effects, which focused on assessing the influence of driving tasks on the takeover. The result is able to correctly identify the high-risk driving conditions in different groups, so as to avoid unsafe takeover performance. In particular, the first takeover situations that the older driver experiences should not include a short warning time combined with the working state task.

There are, nevertheless, two potentially important limitations in the present study. Firstly, on-road validation will be necessary in order to check for driving simulation-related effects. What is more, the traffic density under different test conditions were constant and
may not have been fully representative of the driving environment in realistic scenarios, thus the result may not reveal the detailed significance in specific conditions.

This study is an initial step in investigating the influence of age on behaviors during highly automated driving in varying conditions. However, further comprehensive research is necessary. The specific test environment, considering the interaction of the test conditions under a simulated test, was meant to evaluate and analyze the travel demands of the elderly. Consequently, future research could explore how to keep older drivers safe under highly automated driving conditions by appropriate task limitation or warning time, in order for them to stay on the road as safe drivers and enable their community mobility.

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