Driver takeover performance in conditionally automated driving: sudden system failure situation versus ODD exit situation

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ABSTRACT
Conditionally automated driving is expected to become available to the public in near future. However, the driver is expected to take over control from the system when a sudden system failure occurs or when the driving automation system is approaching its operational design domain (ODD) exit. The time budget for drivers to take over control is different: (1) in the sudden system failure situation, the system needs to be deactivated immediately with issuing a request to intervene (RTI); (2) in the ODD exit situation, the system could keep active for a while after the issue of RTI. In this paper, two hypotheses were put forward based on driver’s expected utility analysis: (1) the drivers respond faster to the RTI in the system failure situation; (2) the drivers perform smoother driving behaviour after takeover in the ODD exit situation. We recruited 32 participants to conduct a driving simulator experiment, in which the driver takeover performance in system failure situation was compared with that in the ODD exit condition. Results revealed that drivers responded significantly faster in the system failure situation. There was no significant difference of longitudinal takeover performance between the two types of limitations. However, the drivers generally performed smoother lateral takeover performance in the ODD exit situation, which supported our hypothesis.

1. Introduction
Nowadays, driving automation systems are getting into our real life based on the rapid development of intelligent technologies, which is attracting increasing attention of researchers, automotive manufacturers and even internet-related service companies. Adaptive cruise control (ACC), lane keeping system (LKS), blind spot assistance, lane change collision avoidance and automatic emergency braking system (AEBS) are examples of such automation systems that have been applied in the current transportation. However, fully automated driving is not yet available for public use although it has been investigated for about half a century [1]. We should reach the goal of fully automated driving step by step.

The Society for Automotive Engineers (SAE) has shown us a taxonomy and definition for levels of driving automation from level 0 to level 5 [2]. Among the six levels, the conditionally automated driving (level 3) is expected to allow drivers to engage in non-driving related tasks (NDRT) instead of concentrating on the driving tasks all the time. It is likely to penetrate the market within the next decade [3,4]. Nevertheless, there is still a great challenge as the driver is expected to take over control manually when the automated system encounters some limitations, which generally include two types: the sudden system failure and ODD exit [2]. No matter which limitation the system encounters, the drivers are expected to regain situation awareness, make decision and take over control timely when a request to intervene (RTI) is issued from the system. These two kinds of limitations are so crucial that should be discussed explicitly in conditionally automated driving. Yao et al. [5] has investigated how does driver takeover performance worsen in a system failure of conditionally automated driving. Nevertheless, takeover performance is derived from the drivers’ decision which is usually made based on their expected utility [6–8]. Inagaki and Sheridan [9] established mathematical model of expected utility to evaluate the design of RTI messages. The mathematical analysis of driver’s expected utility should be developed here as it helps to further explain the differences of takeover performance in the two types of limitations. In the following section, we analysed the driver’s expected utility, which was the additional original contribution to the SICE2020 conference paper (i.e. citation [5]).

In conditionally automated driving, system failure might occur suddenly with issuing an RTI. In a worse case, the automation could deactivate simultaneously (see Figure 1). Figure 1 shows that drivers have to respond instantly to take control from the system, otherwise the vehicle will be out of control. It is an extremely critical situation that should be discussed...
in driving automation. Zhou et al. [10] investigated the effect of a sudden system failure on the intervention behaviour of drivers in partially automated driving. Strand et al. [11] showed that drivers were worse at handling complete than partial automation failure. Some other researchers also conducted investigation on the influence of automation failure on driver behaviour in Adaptive Cruise Control (ACC) [12,13]. In an ODD exit situation, the automation will be deactivated once the driver resumes control or be disengaged automatically after T seconds (see Figure 2). Hence, drivers have T seconds to regain situation awareness and take control from the system when the RTI issues. However, it is still a challenge for drivers to perform well after taking over control. Vogelpohl et al. [14] showed that distracted drivers required additional time to acquire enough situation awareness comparing with manual drivers. It highlighted the challenge for getting the drivers back into the loop and maintain takeover performance even several seconds was provided to the drivers to do response. An integrated model approach of driver behaviour in emergency takeover situations was presented by Zeeb et al. [15]. It was reported that the takeover time was determined by the driver cognitive processes instead of the motor processes.

The motivation of this study is investigating the difference of takeover performance in the two types of limitations (the system failure situation and ODD exit situation). In conditionally automated driving, the comparative experiments of the two types of limitations have not been carried out, and the difference was still not clear. Furthermore, this paper aims at analysing the driver’s expected utility in the two types of limitations. This mathematical analysis can help us to put forward more reasonable and logical hypotheses. Then, the experiment becomes more significant as it can be used to verify the hypotheses derived from the mathematical analysis.

2. Expected utility analysis and hypotheses

In a sudden system failure situation, the time budget for drivers to resume control could be extremely limited. There would be two possible actions taken by the drivers. One is taking over control immediately, the other one is doing response calmly but with delay. Let

\[ P(\text{IR}|\text{System-failure}) \]

denote the probability of driver’s immediate resuming (IR) after the RTI is issued, and

\[ P(\text{CR}|\text{System-failure}) \]

be the probability of driver’s calm resuming (CR) after the RTI. Since the driver’s response to the RTI is either IR or CR in the system failure situation, we have:

\[ P(\text{IR}|\text{System-failure}) + P(\text{CR}|\text{System-failure}) = 1 \]  

(1)

Let \( a \) be the utility of driver’s immediate resuming (e.g. the driver resumes control immediately in the short time budget, he/she is satisfied. Utility is a variable to evaluate how satisfied he/she is), and \( b \) denote the utility of driver’s calm resuming. The expected utility \( U_{\text{system-failure}} \) can be given by

\[ U_{\text{system-failure}} = aP(\text{IR}|\text{System-failure}) + bP(\text{CR}|\text{System-failure}) \]  

(2)

In an ODD exit situation, drivers are given long enough time to do response. There are also two possible actions that would be taken by drivers (i.e. immediate resuming and calm resuming). Similarly, let \( P(\text{IR}|\text{ODD-exit}) \) denote the probability of driver’s immediate resuming (IR) in the ODD exit situation, and \( P(\text{CR}|\text{ODD-exit}) \) be the probability of driver’s calm resuming (CR). Since the driver’s response to the RTI is either IR or CR in the ODD exit situation, we have:

\[ P(\text{IR}|\text{ODD-exit}) + P(\text{CR}|\text{ODD-exit}) = 1 \]  

(3)

Here, let \( a^* \) be the utility of driver’s immediate resuming in the ODD exit situation, and \( b^* \) denote the utility of driver’s calm resuming. The expected utility \( U_{\text{ODD-exit}} \) can be given by

\[ U_{\text{ODD-exit}} = a^*P(\text{IR}|\text{ODD-exit}) + b^*P(\text{CR}|\text{ODD-exit}) \]  

(4)

Substitute (1) into (2), substitute (3) into (4), and calculate the difference between (2) and (4), we can get:

\[ U_{\text{ODD-exit}} - U_{\text{system-failure}} = (a^* - a) + (b^* - a^*)P(\text{CR}|\text{ODD-exit}) + (a - b)P(\text{CR}|\text{System-failure}) \]  

(5)

In the system failure situation, the automation disengages simultaneously when the RTI issues. In this case,
the takeover time given to the driver is extremely short. The driver would have lower satisfaction on CR because the response is too late as the automation has got disengaged for a period. Therefore, \(a > b\). In the ODD exit situation, the automation does not disengage immediately when the RTI issues. In this case, the takeover time given to the driver is relatively longer. The driver would have higher satisfaction on CR, because he/she has better preparation (e.g. more situation awareness) for resuming control. Hence, \(b^* > a^*\). The automation has just been disengaged for an extremely short time when the driver takes immediate resuming in the system failure situation. Therefore, the driver’s satisfaction on IR in the system failure situation could be the same with that in the ODD exit situation. Thereby, \(a = a^*\).

Accordingly, we can assume: \(b^* > a(a^*) > b\).

Thus, \(U_{ODD-exit} > U_{system-failure}\)

Here, it has been shown that the expected utility of ODD exit situation is higher than that of the system failure situation. The expected utility would affect their decision making which suggested by their takeover performance. For instance, the driver’s higher expected utility on ODD exit situation makes them more satisfied with the RTI system of ODD exit situation. Then, they would take soft braking or smooth steering after taking over control. Hence, we put forward the two following hypotheses:

1. the drivers respond faster to the RTI in the system failure situation as they have lower expected utility then are eager to resume control immediately.
2. the drivers perform more smoothly (both longitudinal behaviour and lateral behaviour) in the ODD exit situation as their expected utility is higher.

3. Experiment

This study was conducted under the approvement of the ethics committee of University of Tsukuba.

3.1. Apparatus

The experiment was conducted with a Mitsubishi Driving Simulator (Figure 3). The simulator was designed to accommodate a simple cab, which was static but provided the driver with immersive driving environment. Realistic road and engine sounds were played over a sound system. The visual environment was displayed on a 180-degree visual field which composed of five flat screens. The steering wheel and pedals mounted with the Moog Control Loading System could provide drivers with force feedback. The experimental data were recorded at the frequency of 120 Hz.

3.2. Participants

In order to conduct the driving simulation experiment, a total of 32 participants (17 males + 15 females) were recruited with the support of a professional human resource corporation. The range of their age was from 21 to 35 years old (\(M = 25.3\) years, \(SD = 4.6\) years). They all held a valid Japanese driving license for at least 1 year, drove at least several times a month.

3.3. Experimental design

In this experiment, a \(2 \times 3\) mixed design was utilized. One was a between-subjects factor which was the type of limitations (system failure, ODD exit), and the other was within-subjects factor which was the takeover scenarios. Three takeover scenarios: fog, route choosing, and lane closing were designed in this experiment as previous work claimed that road works, freeway exit ramps and fogs were complicated driving situations in which an RTI should be issued [16–18]. The three experimental takeover scenarios were shown in Figure 4. Each participant had to experience three trials (one for each fog, route choosing, lane closing) in the ODD exit condition. In the system failure condition, the participants also experienced the three events (one for each fog, route choosing, lane closing). It was used to ensure the same road environment after resuming control under the ODD exit condition. Every participant experienced each scenario once. The events occurred at different time points of the trials. It aimed at preventing the participants’ prediction to the event appearing. The RTI issued 7 s ahead of the events as the time budget was appropriate according to the previous research [18]. A beep emitted as an auditory signal when the RTI issued in both the system failure and ODD exit conditions. Each experimental trial lasted for varying duration (fog 230s, route choosing 50s, lane closing 160s). The sequence of the driving trials was randomized for every participant to counteract order effects. The speed was 80 km/h during automated driving.

3.4. Tasks for participants

Each experimental trial started with automated driving mode. Participants were asked to play Tetris as NDRT from the beginning of trials. An iPad used for Tetris
task was mounted on the right side of the steering wheel (see Figure 3). When RTI was issued, participants should stop playing Tetris and engage into driving task. They could deactivate the automation system by braking ($\geq 10\%$) or by applying torque on the steering wheel ($\geq 5\text{N.m}$). They had to take manual driving until the end of each trial.

3.5. Procedure

Each participant was firstly welcomed into the room to complete the demographic survey, a questionnaire measuring their driving experience and frequency, and the experimental consent. Afterwards, participants were given general instructions of the conditionally automated driving system and the experimental motivation through slides. After that, a three-steps-practice was administered for each participant from step one to step three. (1) step one: participants were provided with a manual driving practice, during which basic maneuver of the driving simulator were instructed; (2) step two: participants experienced conditionally automated driving and NDRT, during which some explanations were given to them; (3) step three: each participant was asked to experience the RTI and the resuming maneuver. During the three-steps-practice, it was possible for the participants to take practice of any step for more than once if they required. The three-steps-practice was taken to ensure that the participants were familiar enough with the maneuver of conditionally automated driving. The main experiment initiated after the driving practice. The participants received their rewards after completion of the experiment.

3.6. Dependent variables

In the current study, the following metrics were measured to assess the takeover performance of system failure and ODD exit conditions. All the measurements were recorded by the simulation system, and extracted from the data after the experiment.

- Reaction time: elapsed time from the time point of RTI issuing to the time point of driver resuming control. The reaction time to the RTI was measured to assess how quickly the participants responded in system failure and ODD exit situations. It has been assumed that the participants would react more quickly in the system failure situation. However, this assumption should be verified.
- Maximum driver brake input: brake pedal position ($\%$) implemented by the driver. The driver brake input is a metric that indicated by the brake pedal position implemented by the driver. Higher driver brake input might suggest drivers’ panic or expectation to get more situation awareness.
- Maximum longitudinal acceleration: Longitudinal acceleration was widely utilized to evaluate the longitudinal driving performance in a couple of prior investigations [19–21].
- Maximum steering wheel angle: The maximum steering wheel angle was measured in this experiment. It was a metric that used to show the lateral takeover performance after the transition from system to manual control. A greater maximum steering wheel angle was expected to indicate a worse lateral driving performance in the same scenario.
- Maximum lateral acceleration: The maximum lateral acceleration was also a widely used metric to assess the lateral driving performance in previous research [19–21].

4. Results

Data of the dependent variables were analysed through a two-way mixed ANOVA (analysis of variance) as the mixed-subject design. Data of one participant in the system failure were missed. SPSS was used to administer the data analysis.

4.1. Reaction time

A two-way mixed ANOVA revealed significant main effect of the type of limitations on the reaction time (see Table 1). No significant main effect of scenarios and the interaction were shown. Figure 5 depicts the data.

4.2. Maximum driver brake input

Although we hypothesized that drivers take more brake input in the system failure situation, the result showed
Table 1. Result of two-way mixed ANOVA for reaction time.

| Factors       | Df | F    | $\eta^2$ | p   |
|---------------|----|------|----------|-----|
| Scenarios     | 2  | .972 | .032     | .385|
| Limitations   | 1  | 80.650 | .736     | <.001**|
| Interaction   | 2  | 2.382 | .076     | .101|

**$p < .001$.

Table 2. Result of two-way mixed ANOVA for maximum driver brake input.

| Factors       | df | F    | $\eta^2$ | p   |
|---------------|----|------|----------|-----|
| Scenarios     | 2  | 1.933 | .063     | .154|
| Limitations   | 1  | .232 | .008     | .634|
| Interaction   | 2  | .971 | .032     | .385|

Table 3. Result of two-way mixed ANOVA for maximum longitudinal acceleration.

| Factors       | Df | F    | $\eta^2$ | p   |
|---------------|----|------|----------|-----|
| Scenarios     | 2  | 2.640 | .083     | .080|
| Limitations   | 1  | .013 | <.001    | .908|
| Interaction   | 2  | .528 | .018     | .592|

**$p < .001$ *$p < .05$.**

4.3. Maximum longitudinal acceleration

The result of ANOVA analysis revealed no significant main effect of the type of limitations on the maximum longitudinal acceleration. The main effect of scenarios and interactions were also not significant (see Table 3 and Figure 7).

4.4. Maximum steering wheel angle

The result of a two-way mixed ANOVA was reported in Table 4. It showed significant main effect of the type of limitations on the maximum steering wheel angle. The main effect of scenarios on this metric was also significant. Post hoc tests with the Bonferroni corrected method revealed that the route choosing scenario had much higher maximum steering wheel angle than the fog scenario and lane closing scenario ($p < .001$). Besides, the lane closing scenario had higher maximum steering wheel angle than the fog scenario ($p = .022$). No significant interaction effect of these two factors was shown. The data were also illustrated in Figure 8.

4.5. Maximum lateral acceleration

The result in Table 5 revealed significant main effect of the type of limitations on the maximum lateral acceleration. The main effect of the three scenarios was highly significant. Post hoc tests with Bonferroni adjustment revealed that the route choosing scenario had much higher maximum lateral acceleration than the fog scenario and lane closing scenario (post hoc: all $p$ values < .001). However, it showed no significant difference between the fog scenario and lane closing scenario ($p = .072$). The result comparison between system failure and ODD exit conditions was also shown in Figure 9.
5. Discussions

Based on the results of driving behaviour, the difference of takeover performance in system failure and ODD exit conditions was analysed. In this section, we mainly discussed how the experimental result supports the hypotheses. We discussed the maximum driver brake input and maximum longitudinal acceleration together as these two metrics belonged to longitudinal takeover performance. Similarly, we discussed the maximum steering wheel angle and maximum lateral acceleration together as they belonged to lateral takeover performance.

5.1. Reaction time

In the system failure situation, we observed participants performed significantly faster than the ODD exit situation. It appeared in Table 1 and Figure 5. This result supported our first hypothesis (drivers respond faster in the sudden system failure situation). However, we could not say that all the drivers responded faster in the system failure situation, as the slowest participant in system failure situation responded slower than the fastest one in the ODD exit situation (see Figure 5). Generally, we can further claim that drivers are inclined to resume control faster as they have less satisfaction on the system in the system failure situation. The satisfaction represents the expected utility in decision making. Thereby, the faster response also demonstrated the driver’s lower expected utility in the system failure situation. It supported our expected utility analysis ($U_{ODD\, exit} > U_{system\, failure}$). The assumption ($b^* > a(a^*) > b$) was also proved to be reasonable. Besides, the time budget of system failure situation was much shorter than that of ODD exit situation based on the definition of system failure and ODD exit situation. Radlmayr and Bengler [22] claimed that longer time budget usually led to longer takeover time. Hence, the participants in system failure situation responded much faster. Nevertheless, the ANOVA presented no significant effect of scenario on the reaction time. Radlmayr et al. [23] suggested that the complexity of takeover situation and the NDRT were two critical factors that influenced the reaction time significantly. Thereby, one possible explanation is that the complexity of the three scenarios in this experiment is generally the same.

5.2. Longitudinal takeover performance

The analysis of maximum driver brake input and maximum longitudinal acceleration suggested no significant difference between the system failure and ODD exit situations. It further indicated that the drivers did not take worse longitudinal takeover performance significantly in the system failure condition. Hence, the second hypothesis (drivers take smoother actions in the ODD exit situation) was not supported by the longitudinal takeover performance significantly. It was also hard to say that the expected utility in the ODD exit situation was higher than that in the system failure situation. Thereby, the mathematical relationship ($U_{ODD\, exit} > U_{system\, failure}$), as well as the assumption ($b^* > a(a^*) > b$), was not supported by the experimental results of longitudinal takeover performance.

However, Figures 6 and 7 reveal drivers’ slightly less brake input and longitudinal acceleration in the system failure situation of lane closing scenario. It further indicated that drivers were slightly inclined to take smoother longitudinal actions in the system failure situation of lane closing scenario, which was beyond our expectation. This result might be explained by the driver maneuver preference, on which Drivers preferred to firstly hold the steering wheel to stabilize the vehicle in the lane. Furthermore, Blommer et al. [24] claimed that drivers usually tended to use evasive steering rather than braking to avoid forward collision in manual control in a lane closing scenario. Hence, the longitudinal metrics were not sensitive to reflex the difference of the takeover performance in the two types of limitations.

5.3. Lateral takeover performance

For the lateral takeover performance, there was significant difference between the two types of limitations, as well as the varying scenarios. No factor interaction was revealed from the results. Figures 8 and 9 suggest these results graphically. These two figures indicated that the drivers performed smoother lateral takeover performance in the ODD exit situation of all the scenarios, which supported our second hypothesis (i.e. drivers
perform smoothly in the ODD exit situation). Namely, $U_{\text{ODD-exit}} > U_{\text{system-failure}}$. The assumption ($b' > a(a'') > b$) was also reasonable. The drivers had higher expected utility, which led to higher satisfaction on the system in the ODD exit situation. They would not maneuver too much or take actions excessively as they are more satisfied with the system in the ODD exit situation. Moreover, it was quite difficult for drivers to acquire enough situation awareness before resuming control in the system failure situation as the shorter time budget. Situation awareness contributes to the perception of elements, the comprehension of meaning, and the prediction of the status in the environment [25]. Thereby, the drivers could not take exact maneuver as the situation awareness was too limited. In the varying scenarios, the curve and lateral gradient of roads were quite different. Hence, the effect of scenario on lateral driving performance was significant. There were three different scenarios in the current study. Post hoc tests had to be conducted to exactly check the differences between any two scenarios. For the lateral acceleration, Post hoc tests showed no significant difference between the fog scenario and lane closing scenario ($p = .072$). The $p$ value was not low. It could be illustrated by the relatively small sample size of the experiment.

5.4. Limitations

In the current study, all the driving scenarios were designed with the same driving speed (80 km/h). Nevertheless, the driving speed is always changing during driving in the real world. Additionally, there were no other vehicles around the ego-vehicle during the control transition from system to human in this experiment. This design is a bit far from the real world in which the traffic environment is usually complicated. The driver might perform a little worse in the real world than that in the driving experiment. Furthermore, all the participants of this experiment are youngers. How aged driver takeover worsen in a sudden system failure of conditionally automated driving is still not clear.

6. Conclusion and future work

The present investigation offered insights into the issue: how does driver takeover worsen in a sudden system failure of conditionally automated driving. The experimental results revealed drivers’ faster reaction to the RTI under the system failure condition, which supported the first hypothesis. For the second hypothesis, there was no significant difference of longitudinal takeover performance between the two types of limitations. However, drivers generally performed smoother lateral takeover performance in the ODD exit situation. This would contribute to the conditionally automated driving system design with considering the characteristics of takeover performance in the two types of limitations (sudden system failure and ODD exit). In conditionally automated driving system, a sudden system failure occurred with extremely short time budge for driver takeover maneuver. Hence, the worse lateral takeover performance under system failure situation suggested that the shorter time budget could lead to worse lateral takeover performance.

Further research is necessary to improve driver lateral takeover performance under sudden system failure condition in conditionally automated driving. For instance, an automatic deceleration can be considered as a safety compensation to prolong the time budget in a sudden system failure.

Acknowledgements

The work was supported by JSPS KAKENHI Grant-in-Aid Scientific Research (S) of Japan. The authors thank Yoshihiro Noguchi for his help in this investigation.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work was supported by JSPS KAKENHI Grant-in-Aid Scientific Research (S) 15H05716.

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