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Developing Takeover Request Warning System to Improve Takeover Time and Post-takeover Performance in Level 3 Automated Drivin

Niloy Talukder
University of Windsor

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Developing Takeover Request Warning System to Improve Takeover Time and Post-takeover Performance in Level 3 Automated Driving

by

Niloy Talukder

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Developing Takeover Request Warning System to Improve Takeover Time and Post-takeover Performance in Level 3 Automated Driving

by

Niloy Talukder

APPROVED BY

E. Kim
Department of Mechanical, Automotive and Materials Engineering

---

B. Balasingam
Department of Electrical and Computer Engineering

H. Maoh
Department of Civil and Environmental Engineering

C. Lee, Co-Advisor
Department of Civil and Environmental Engineering

Y. H. Kim, Co-Advisor
Department of Civil and Environmental Engineering

January 20, 2022

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ABSTRACT

The automotive industry is shifting towards partial (level 3) or fully automated vehicles. An important research question in level 3 automated driving is how quickly drivers can take over the vehicle control in response to a critical event. In this regard, this study develops an integrated takeover request (TOR) system which provides visual and auditorial TOR warning in both vehicle interface and personal portable device (e.g., tablet). The study also evaluated the effectiveness of the integrated TOR system in reducing the takeover time and improving post-takeover performance. For these purposes, 44 drivers participated in the driving simulator experiment where they were involved in secondary task (watching video on a tablet) in automated driving and they were requested to manually drive after the integrated TOR or the conventional TOR (which provides visual and auditorial TOR warning in vehicle interface only) was provided. Results from the statistical analysis suggest that the integrated TOR significantly reduced the takeover time and improved post-takeover performance as indicated by longer minimum TTC, shorter lane change duration, lower standard deviation of steering wheel angle and lower maximum acceleration during lane changing. The result also suggests that the integrated TOR can reduce the takeover time more effectively with the use of headphone. As more people are likely to use headphone in automated driving for better sound quality, understanding the effect of the use of headphone is critical for improving the effectiveness of the integrated TOR in reducing the takeover time. The results of subjective questionnaire show that the participants generally perceived higher subjective comfort and safety level with the integrated TOR system. Therefore, it is recommended to apply the proposed integrated TOR system for safe transition from automated to manual driving.

DEDICATION

I would like to dedicate my thesis to my family and closest friends, who have supported me unconditionally during this journey.

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First and foremost, I would like to express my profound gratitude to my co-supervisors Dr. Chris Lee and Dr. Yoon Hoon Kim for their constant support, encouragement and exemplary guidance throughout my research. They have helped me grow academically and provided me with invaluable opportunities that I am eternally grateful for.

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1 Introduction

The number of deaths by traffic accidents reached 1.35 million annually according to the Global status report on road safety (World Health Organization, 2019). In this regard, Autonomous vehicles (AV) and advance driver assistance systems (ADAS) can potentially decrease traffic deaths by 90 percent and save millions of lives and billions of dollars every year in health care costs (McKinsey & Company, 2015). Not long ago, fully AVs for the masses were thought to be almost to the edge. But the final leap towards fully automated driving on any road at any time remains tantalizingly beyond the reach of engineers and safety regulators. (Meier, 2021).

Moreover, the rising health concerns because of the pandemic situation and the change of commuting patterns have accelerated the interest of personal vehicle globally particularly the city dwellers. AV's can be an attractive option for this increased number of city users. By eliminating the search of parking spaces, it can be a convenient option during rush hours. According to Euromonitor's Mobility survey (2020), 23% of the respondents indicated they would feel comfortable with driving an AV and 14% would prefer AV over traditional vehicle. Because of the increased demand, the leading car manufacturers are leaning towards partial or level 3 AVs. Partial AVs will allow drivers to be free from the primary task of driving and allow them to be engaged in secondary tasks while travelling.

Although technological features of AVs spread rapidly in mainstream vehicles (adaptative cruise control, lane assist system, etc.), these level 2 AVs require drivers to constantly monitor the driving environment. Unlike level 2 AVs, level 3 AVs allow drivers to be engaged in secondary task while the vehicle continues monitoring by itself. But level

3 AVs generate a takeover request (TOR) when they cannot perform the driving task and operate safely. When TOR is generated, drivers are required to take over the driving task and manually drive the vehicle.

However, since the driver cannot take control immediately after TOR, the time for transition from automated to manual driving or takeover time is important to ensure driver safety. Takeover is defined as the combination of physical, visual, and cognitive readiness after TOR is initiated (Zeeb et al., 2015). In most recent studies, the start time of takeover is considered as the time of 10% depression of brake pedal or more than 2º rotation of steering wheel by the driver (Zhang et al., 2019; Gold et al., 2017; Louw et al., 2017; Zeeb et al., 2015). Quality of post takeover performance is related to the smooth transition to manual driving after the takeover. This transition is evaluated from minimum time to crash, minimum and maximum lateral and longitudinal acceleration, lane change duration, minimum time headway to lead vehicle etc. Thus, short takeover time and reliable post-takeover performance are the most critical elements for the successful deployment of level 3 automation.

According to McDonald et al. (2019), secondary tasks and modality of TOR significantly affect takeover time and post-takeover control. Among a wide range of secondary tasks, handheld tasks involving personal portable devices (PPD) such as cell phones and tablets will be the most popular secondary task during autonomous driving. However, any handheld secondary task has higher adverse effect on both takeover time (Wan and Wu, 2018; Wandtner et al., 2018a) and post-takeover performance (Zeeb et al., 2017; Wandtner et al., 2018a) than non-handheld secondary tasks. This can be because of longer required time for physical and visual readiness. For instance, the meta-analysis of

Zhang et al. (2019) suggested that any handheld secondary tasks strongly affect takeover time and require an average additional 1.33 seconds for the takeover process.

Furthermore, more cognitively demanding tasks will impede the takeover (Radlmayr et al., 2014). For instance, Wan and Wu (2018) found that watching videos and reading using the cellphones resulted in the longest average reaction time and the shortest average minimum time to collision (TTC) among different secondary tasks - reading, typing, playing video games, watching videos and monitoring the driving environment. These secondary tasks were selected from the most frequently used by the passengers in various modes of public transportation (Gamberini et al. 2013; Guo et al. 2015) and from a large-scale opinion survey on what people would do instead of driving in an AV (Sivak and Scholettle, 2015). Sleeping was excluded from the secondary task. In level 3 AVs sleep inertia can affect the reaction time and the performance of the user. Adjusting the seat, regaining control and recovering safely within a few seconds is not safe (Hirsch et al., 2020). (Wandtner et al., 2018a) also found that handheld tasks using a tablet required both visual and cognitive attention, delayed break of the secondary task, and resulted in high mean and standard deviation of takeover time. Similarly, Zeeb et al. (2017) found the standard deviation of takeover time for both lateral and longitudinal maneuvers was higher when the participants watched videos and read an article using a tablet held at their hands.

To reduce takeover time in level 3 automated vehicles, many modalities of TOR warning have been studied. Audio, visual, vibrotactile and combination of these warning modalities are conventional TOR warning modalities. Petermeijer et al. (2017) found that a multimodal warning system resulted in an average of 0.2 seconds shorter takeover time than a unimodal warning system. Multimodal warnings also reduced physical readiness time and improved post-takeover performance (Naujoks et al., 2014). Physical readiness time is measured using feet-on reaction time, hands-on reaction time, automation deactivation time, etc. In level 3 AVs, most TOR is provided using the vehicle interface while the user is engaged in the secondary tasks.

To reduce takeover time when drivers use PPD for secondary tasks, TOR warning can also be provided in PPD instead of vehicle interface only. In this study, the combination of TOR from PPD and any of the vehicle interfaces (dashboard, windshield or infotainment system) is called an integrated TOR system. TOR in PPD can display the visual warning to drivers while facilitating their takeover time since the gaze of the driver is already on the PPD screen during the secondary task. In addition to the reduced gaze redirection time from visual warning, audio warning using PPD can also reduce the delay caused by the secondary task even if they are using a headphone with a high volume. Also, overtaking the secondary task with a warning can reduce the takeover time by reducing the distraction.

However, there is a lack of studies on TOR warning systems that restricts secondary task after TOR is generated. If the secondary task from the PPD is restricted after the TOR is generated, the driver cannot continue the secondary task. As a result, the driver can respond to the TOR faster and this will result in a relatively safer evasive maneuver. Melcher et al. (2015) considered providing TOR warning using mobile phones. However, the warning did not generate the audio warning and did not examine the effects of TOR warning on post-takeover performance. Although both Miller et al. (2015) and Yoon et al. (2018) considered a handoff message presented on a tablet to break the participant's attention, they did not compare results with TOR generated from the vehicle interface.

Thus, more studies are needed to test visual and auditory TOR warning from PPD and evaluate the effects of the warning on driver safety. The objectives of this study are:

1. To develop an effective TOR warning system that utilizes PPD that is being used by the drivers,
2. To investigate the effects of the integrated TOR warning system using both PPD and vehicle interface on takeover time and post-takeover performance, and
3. To evaluate the effectiveness of the integrated TOR warning system in reducing takeover time and improving post-takeover performance compared to the conventional TOR warning system which only uses vehicle interface.

This thesis is organized into the following chapters. The second chapter provides an outline of the previous studies regarding the takeover process, how secondary task and takeover request modalities affect the takeover time and post-takeover performance. The third chapter consists of details of the methodology and experiment design. The fourth chapter presents and discusses the results followed by the conclusion and recommendation chapter.

2 Literature Review

2.1 Automated Vehicle Takeover

Driver distraction significantly impacts road safety during manual driving (Dingus et al. 2006, Greenberg et al. 2003). During manual driving, doing both primary task driving and secondary tasks at the same time will exceed the driver's limited cognitive capacity, which will decrease the performance of both tasks. (Wickens, 1984). However, since SAE level 3 automated driving relieves all driving responsibilities, the transition between automated and manual driving is more critical than executing the primary and secondary tasks together. The switching between tasks is associated with a switch cost, as reactions are more error-prone and longer after a task switch (Mouncell, 2003). The reconfiguration of cognitive processing modules to continue the switched task delays takeover. Shifting attention, recuperating task-specific goals and rules, suppressing, and clearing away a previous task set are examples of the restructuring (Monsell 2003, Salvucci et al. 2009). The transition from automated driving is a complex process, and a successful transition ensures the safety of the users.

The transition of vehicle control from automated to manual driving is the takeover process. After this transition, the driver again becomes responsible for controlling movements of the vehicle and monitoring surrounding environment (Banks and Stanton, 2016; Banks et al., 2014). Resuming control from an automated driving condition requires returning visual attention to the road from the secondary task, scanning the driving scene to cognitively analyze and evaluate the traffic situation and make an appropriate decision, transferring hand to the steering wheel and leg to the pedals for control input, and executing the right action via the control input.

Takeover can be requested in both an emergency situation when the driver is required to respond with a self-paced resumption of manual control (Eriksson & Stanton 2017a) and an urgent situation that may or may not be accompanied by a TOR. In an urgent takeover situation, the extent to which the driver is engaged in monitoring the road environment and automation (Banks & Stanton. 2019) and physical readiness (Zeeb et al. 2015) determines the ability of the driver to safely takeover, which is SAE level 2 condition. So, any SAE level 3 automated vehicle should ensure that there will be no urgent takeover situation because of the system limitation or unexpected events.

Level 3 automated vehicles must allow sufficiently comfortable transition time after the TOR is provided (SAE International, 2018). However, the minimum time required for the safe transition is still not precise. Eriksson and Stanton (2017a) found a median of 2.5 seconds takeover time with a maximum value of up to 15 seconds to resume control. The study also suggested that considering only the average takeover time of drivers is insufficient because of the long tail distribution of takeover time. Physical takeover (grabbing the steering wheel, stepping on the brake pedal, or looking straight to the road) does not always imply that drivers are completely prepared to takeover. After the physical takeover, it is possible that the drivers' cognition is not ready for driving. It may happen because of the additional time required to switch between tasks or also known as resumption lag. As a result, drivers' cognitive readiness for takeover should also be considered.

The cognitive readiness depends mainly on the driver's engagement in the previous task. If the level of focus of the secondary task is high, then the resumption lag will also be higher. De Winter et al. (2014) also found that situational awareness is impaired if drivers have been out of the control loop for an extended period.

Although it is hard to observe the latencies caused by cognitive processes, the time of drivers’ eyes on the road and the time of drivers’ hands-on steering wheel after a take-over request has been initiated can be measured. It has been found that it took about 0.7–1 s for eyes-on-the-road and about 1.2–1.8 s for the first manual contact with the steering wheel after TOR (Gold et al., 2013; Zeeb et al., 2016; Zeeb et al., 2015).

The takeover process depicted in Figure 2-1 is adapted from Zeeb et al. (2015) but extended to include action evaluation and scanning (McDonald et al., 2019). After initiating the TOR, visual, motor, and cognitive readiness process starts. The physical process comprises motor readiness (time to put whatever is in the hand of the user if any, time to put hand on steering wheel and feet to the pedals) and action execution (steering or braking input). The visual process includes gaze redirection (redirection to identify the warning) and scanning of the road environment for decision making. The cognitive process includes cognitive readiness, action selection and evaluation. In Figure 2-1, cognitive readiness and action selection are the maximum latency readiness component but higher motor readiness time than cognitive load is also possible. So, both motor and cognitive readiness is required for takeover. Past studies that considered motor readiness time for takeover time – gaze reaction time (Eriksson et al., 2019), feet on reaction time (Petermeijer et al., 2017), and automation deactivation time (Dogan et al., 2017). Some studies considered the visual, motor, and cognitive readiness for takeover as a whole (Zhang et al., 2019). However, if these components are considered separately, it would be easier to understand how a takeover is affected by a particular design intended to improve the takeover process.

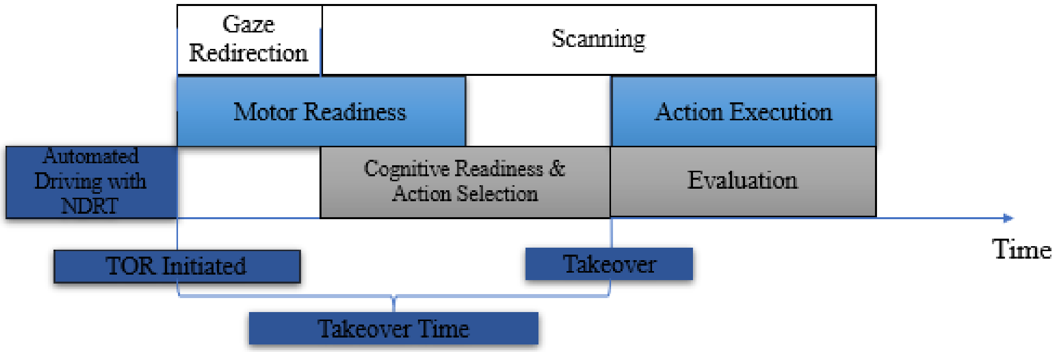


Figure 2-1. Conceptual Model of physical, visual, and cognitive components of takeover process
(Source: McDonald et al., 2019)

2.2 Effects of Secondary Task on Takeover Time and Post-takeover Performance

Any task in addition to driving or monitoring automated driving is considered a secondary task or secondary task. The ability of the drivers to re-engage in the driving task depends on the secondary task they perform during autonomous driving. The visual, auditory, physical, and cognitive demands of secondary task affect the preference, efficiency, and safety during the vehicle's transition of control (Zeeb et al., 2016; Marberger et al., 2017). In general, secondary task significantly increases the driver's takeover time (Wandtner et al., 2018b; Zeeb et al., 2017; Zhang et al., 2019) and negatively affects post-takeover performance.

When drivers are involved in a secondary task, it adversely affects the longitudinal post-takeover control and increases chances of crash in higher traffic density (Radlmayr et al., 2014) and decreases minimum TTC (Gold et al., 2016; Korber et al., 2016). Louw et al.

(2015) suggested that drivers involved in secondary tasks usually complete takeover with a braking action rather than steering in response. Secondary tasks also affect lateral post-takeover control which results in higher lateral acceleration (Louw et al. 2015), average and standard deviation of lane position, lane exceedance (Wandtner et al., 2018b; Zeeb et al., 2016), and the time required to change lanes and maximum steering wheel angle (Bueno et al., 2016).

In particular, the handheld secondary task using PPD (e.g., phone conversation or trivia game) significantly increases the takeover time (Wan and Wu, 2018). This is mainly because when switching from the task using handheld PPD to take over, the driver takes extra time to decide where to put down the device (Wandtner et al., 2018a; Zeeb et al., 2017). Wan and Wu (2018) showed that watching a video and reading using PPD results in longer reaction time and lower TTC relative to other tasks during automated driving. Also, the standard deviation of reaction time was relatively higher for watching videos and playing video games. Merat et al. (2012) found that involvement in the task using PPD reduced driver fatigue but decreased effectiveness to adapt speed in a critical incident with no influence on reaction time. While Zeeb et al. (2016) found deteriorated post-takeover performance with a small negative impact on reaction time.

On the other hand, Neubauer et al. (2012) found shorter braking reaction time while using a cellphone compared to drivers without any task, which was assumed to be the effect of reduced fatigue resulting from secondary task. Schomig et al. (2015) measured drivers' drowsiness during automated driving based on their eyelid closure and also found similar results. The drowsiness level was dropped because of the improved alertness because of secondary task. This inconsistent effect of the task using PPD on takeover time is due to the partially different conditionality of level 3 automated vehicles (SAE International, 2018). Neubauer et al. (2012) did not consider providing TOR whereas Gold et al. (2013) and Merat et al. (2014) did not provide any TOR and instructed the participants to monitor the driving environment periodically.

The secondary task using PPD also has negative impacts on post-takeover control. Delayed visual and manual reaction due to the task using PPD causes the driver’s urgent evasive maneuvers instead of a controlled action (Zeeb et al., 2017). Zeeb et al. (2017) also suggested that when PPD was held in hand instead of being mounted, post-takeover performance was degraded. With the ongoing trend of increased use of PPD like a tablet, cellphone and other devices, the effect of task using PPD on takeover time and post-takeover performance requires further investigation.

2.3 Modalities of Takeover Request

Different modalities of TOR provided to the drivers greatly influence the takeover time, performance, and quality of the takeover (Naujoks et al., 2014; Petermeijer et al., 2017). Several studies have investigated different alert methods, information provided for successful takeover and types of modality (auditory, visual, vibrotactile and combination of these modalities). The most common type of modality was the combination of visual and auditory warning (Eriksson et al., 2017; Gold et al., 2015; Miller et al., 2015; Melcher et al., 2015). Auditory TOR only was the second most common type of modality in the previous studies. (Gold et al., 2016; Korber et al., 2016).

Most of the studies compared multimodal and unimodal alerts to inform drivers to take over. For instance, Naujoks et al. (2014) and Politis et al. (2015) found that multimodal cues are more efficient. Petermeijer et al. (2017) showed that multimodal warning resulted in faster steer-touch time and better usefulness rating and satisfaction among the users. Bazilinskyy et al. (2018) also reported that participants preferred multimodal TOR warning compared to unimodal TOR warning. Politis et al. (2017) found that unimodal visual or vibrotactile TOR warning took longer takeover time than multimodal or auditory TOR warning.

Different interfaces of the visual warnings were examined in the previous studies - mounted screen or vehicle display (Zeeb et al., 2017; Kaye et al., 2021), dashboard (Yun and Yang, 2020; Wu et al., 2019; Melcher et al., 2015), tablet (Yoon et al., 2018; Miller et al., 2015; Politis et al., 2017), and cell phone (Melcher et al., 2015). In addition, some studies used generic warnings like icons (Zeeb et al., 2017; Miller et al., 2015; Naujoks et al., 2014) or ecological visual alert with instructions to the driver (Eriksson et al., 2019) instead of text message for the visual warning as shown in Figure 2-2.

In general, audio alerts were generated from the vehicle speakers in the previous studies (Eriksson et al., 2019; Korber et al., 2016; Melcher et al., 2015; Gold et al., 2015; Gold et al., 2016). However, if the driver is involved in a secondary task using PPD and uses a headphone, they may not be able to hear the audio alert from the vehicle speaker. These drivers generally exhibit slower response to resume control (Eriksson and Stanton, 2017b).

(a) lane change recommendation TOR
(b) brake condition due to the stopped vehicle
(c) generic visual on screen

Figure 2-2. Ecological visual TOR using carpet condition

Some studies compared different modalities of TOR. Naujoks et al. (2014) compared visual-auditory warning with a visual warning for emergency and non-emergency situations. They found that visual-auditory warning resulted in lower hands-on wheel time and better lateral vehicle control than visual warning. According to Eriksson et al. (2019), compared to auditory warning only, ecological visual warning with auditory alert reduced the time for braking decisions. Even though the combination did not improve the reaction time.

2.4 Integrated Takeover Request Warning using Personal Portable Device

During the secondary task using PPD, the audio alert from PPD can help reduce the drivers' takeover time because they can see the warning more quickly and better comprehend the warning message while the secondary task is stopped. For instance, Melcher et al. (2015) integrated TOR into a cellphone and compared the results without the integration using a driving simulator. Participants were asked to perform an artificial secondary task (quiz game) using the cellphone and multimodal (audio and visual) TOR warning was provided for the driving simulator experiment. In this integrated TOR warning, cellphone only provided the visual alert while the simulator provided the auditory alert. The study suggested that providing 10 seconds to take over the driving task was sufficient and the integrated TOR warning with cellphone reduced the mean takeover time.

Politis et al. (2017) also conducted a similar study by integrating the TOR using a tablet and playing games as a secondary task. The study provided visual warning from the tablet but auditory alert using an external speaker. The study found that this integrated TOR warning reduced the takeover time and lateral deviation.

Figure 2-3 illustrates different components of the physical and visual readiness time during the takeover process. These time components are determined based on the sequence of events after the TOR is generated.

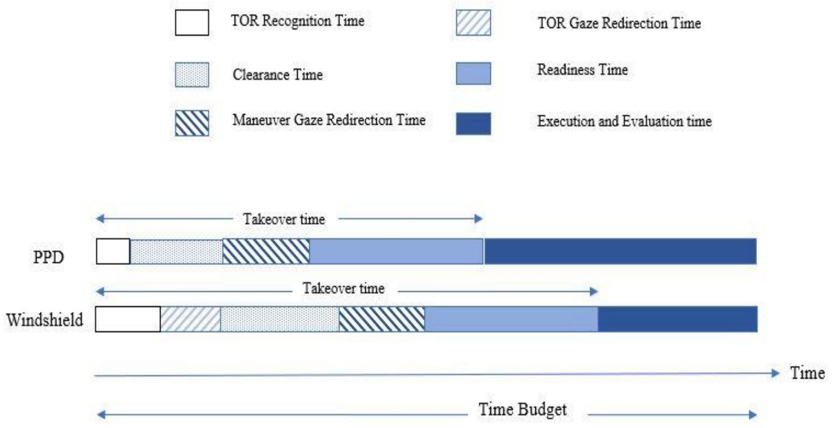


Figure 2-3. Components of visual and physical readiness time during takeover

First, the TOR recognition time is the time required to understand that the TOR warning is generated and start reacting. This recognition time will not be significant unless the user misses the TOR completely or there is a delay to understand the TOR. For similar takeover situation, the TOR recognition time is expected to be longer for conventional TOR compared to integrated system.

Second, the TOR gaze redirection time is the time required to redirect their gaze to the screen (either dashboard, windshield or vehicle interface) for conventional TOR only. TOR gaze redirection is not required in integrated TOR.

Third, the time from TOR gaze redirection to clearance of PPD from hand is the clearance time for conventional TOR. For integrated TOR, the clearance time is the time from TOR recognition to clearance of PPD.

Fourth, the maneuver gaze redirection time is the time required to shift gaze to the traffic environment so that the user can decide the required evasive maneuver. Finally, the time from maneuver gaze redirection to grabbing the steering wheel or stepping on the brake pedal (whichever comes first) is the readiness time.

This classification of time components helps understand how providing the integrated TOR with PPD will affect the takeover time. Since the integrated TOR can eliminate the TOR gaze redirection time, it will reduce the takeover time. The integrated TOR will also increase the execution and evaluation time, which results in better post-takeover performance.

The past studies demonstrated that the integrated TOR warning using PPD can effectively reduce takeover time and improve post-takeover performance, particularly when people are engaged in secondary task using PPD. However, more studies are needed to investigate the effectiveness of multimodal (visual and auditory) TOR warning using PPD in reducing takeover time and improving post-takeover performance and evaluate the reliability of the effectiveness.

3 Methodology

3.1 Apparatus

To investigate the effects of the integrated TOR warning system using PPD on takeover time and post-takeover performance, driver behavior was observed using a fixed-base NADS MiniSim™ driving simulator at the University of Windsor as shown in Figure 3-1. The simulator consists of three LCD monitors placed within a horizontal field-of-view with two side-view mirrors and a rear-view mirror on the plasma monitor. Surrounding sound from the speakers and vibration from the driver seat enhance the sense of reality.

Figure 3-1. NADS MiniSim driving simulator

The auto-drive feature of the MiniSim simulator is capable of longitudinal and lateral vehicle control when the automated driving is activated using the automation button. Automated driving is also capable of overtaking other vehicles and changing lanes. Once the driver moves the steering wheel or presses the brake pedal, the automated driving will stop. Automated driving can also be turned off using the automation button. The status of automated driving is displayed on the screen left to the steering wheel. A Samsung Galaxy S6 lite tablet with a 10.4-inch display was provided to participants during the experiment. The tablet was used for the secondary task and the display of TOR warning in the scenarios with integrated TOR.

The scenarios for the experiment were designed using Interactive Scenario Authoring tool (ISAT). This software can be used to create and test scenarios and verify them (review by play back option) to check debug or display errors. An Android application was developed for the TOR to be provided from the tablet.

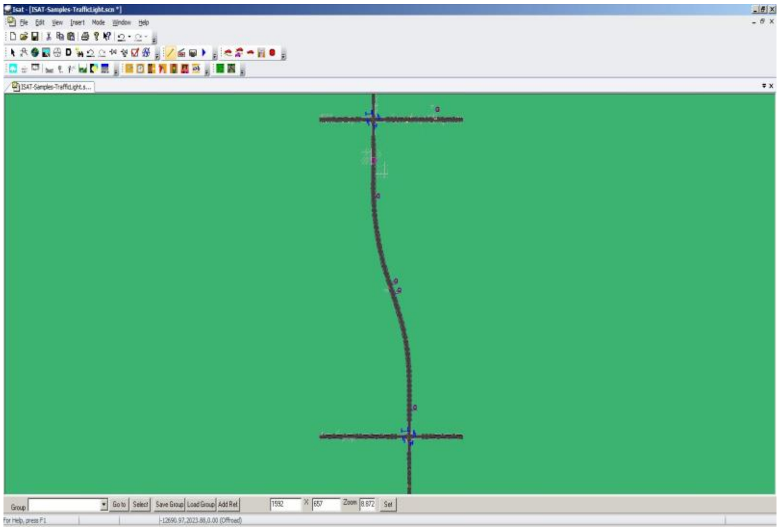


Figure 3-2. Interactive Scenario Authoring Tool (ISAT) interface

3.2 Participants

A total of 44 participants (30 males, 14 females) participated in the experiment in September and October 2021. Their ages varied from 21 to 50 years old (mean (M) = 27.5, standard deviation (SD) = 4.85). All participants were graduate and undergraduate students at the University of Windsor. A valid driving license with a minimum of 1 year of driving experience was required to participate. The participant’s driving experience was also recorded (M = 5.14, SD = 3.9). None of the participants had prior experience with automated driving. Participation in the experiment was voluntary and the participants were compensated $20 for the participation. The letter of consent to participate in the research is attached in Appendix A. The simulator experiment was cleared by the University of Windsor Research Ethics Board (REB). The experiment was also evaluated and approved by Research Safety Committee (RSC) because of the Covid-19 pandemic. The approval letters from REB and RSC are attached in Appendix B and C, respectively.

3.3 Driving Scenarios and Design of TOR

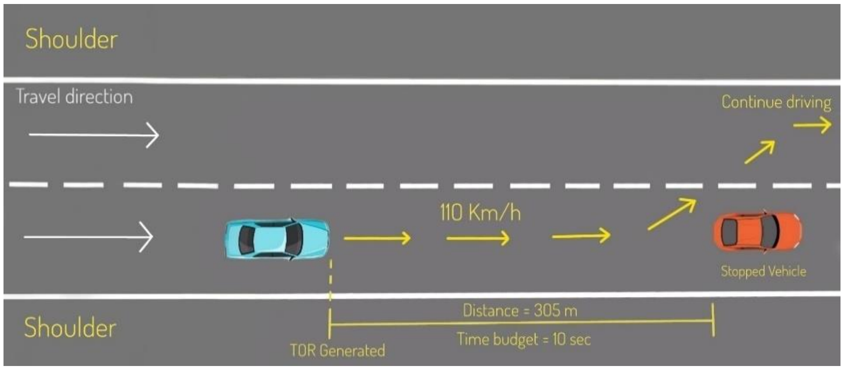
In the driving simulator experiment, the vehicle drove on a four-lane freeway (two lanes in each direction) which was a combination of straight and curved road in normal weather condition. Initially, participants will activate automated driving by pressing the automation button. The preset design speed for the experiment was 110 km/hr and the vehicle drove in the right lane. During the automated driving, participants were engaged in secondary task (i.e., watch video on a tablet) as shown in Figure 3-3.

Figure 3-3. Participant involved in secondary task during automated driving

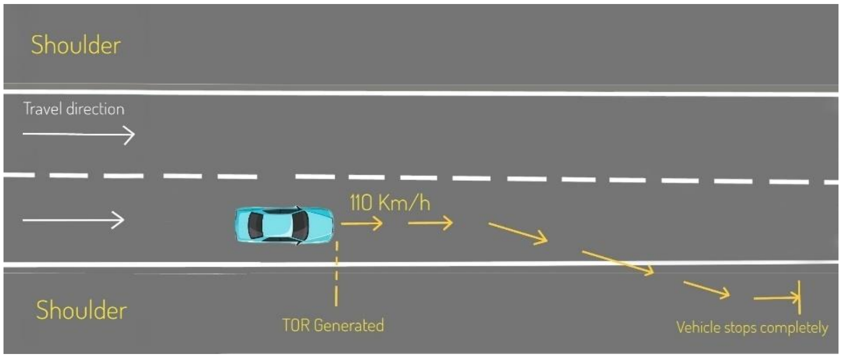
Before the experiment, participants were provided with a tablet with subscribed account of YouTube and Prime Video from which they selected their preferred video to watch. The minimum duration of the video selected by participants was 15 minutes and 22 out of the 44 participants used headphones while watching the video. Participants were informed that they are not required to monitor the driving environment during automated driving. Before the takeover situation, other vehicles simultaneously drove in the same direction as the subject vehicle. During automated driving, there were several situations because of the surrounding vehicles (slow or crashed vehicles). The subject vehicle completed the required evasive maneuver like changing lanes or slowing down by itself to safely continue driving.

During the automated driving, visual and audio TOR warning was generated in the following two circumstances – 1) Lane change scenario and 2) Pullover scenario – as shown in Figure 3-4. In both circumstances, the TOR was provided in a straight section of the highway and the weather condition was sunny with a clear sky. First, in the Lane change scenario, there is a stopped vehicle in the right lane and the participant received the TOR warning message to change to the left lane to avoid a crash with a time budget of 10 seconds (i.e., 305 m from the stopped vehicle) and continued driving manually. Two types of TOR warning system were tested for each participant – 1) Conventional warning system: Visual warning message "Change Lane" was displayed in the windshield (i.e., the middle simulator screen) with auditory warning from the driving simulator and 2) Integrated warning system: The same visual warning message was displayed in both windshield and tablet as shown in Figure 3-5 with auditory warning from both driving simulator and tablet. In case of the integrated warning system, the participants could press "STOP" button on the tablet to turn off the warning although they were not required to do so. During takeover situation, there was no surrounding vehicle except the lead stopped vehicle.

Second, in the Pullover scenario, participants were required to pull over to the right shoulder when TOR was generated. Similar to the Lane change scenario, both conventional and integrated TOR warning systems were tested for each participant. In this scenario, visual warning message "Pull Over to Right" was displayed in windshield and tablet. There was no surrounding vehicle during the takeover situation.



(a) Lane change scenario



(b) Pullover scenario

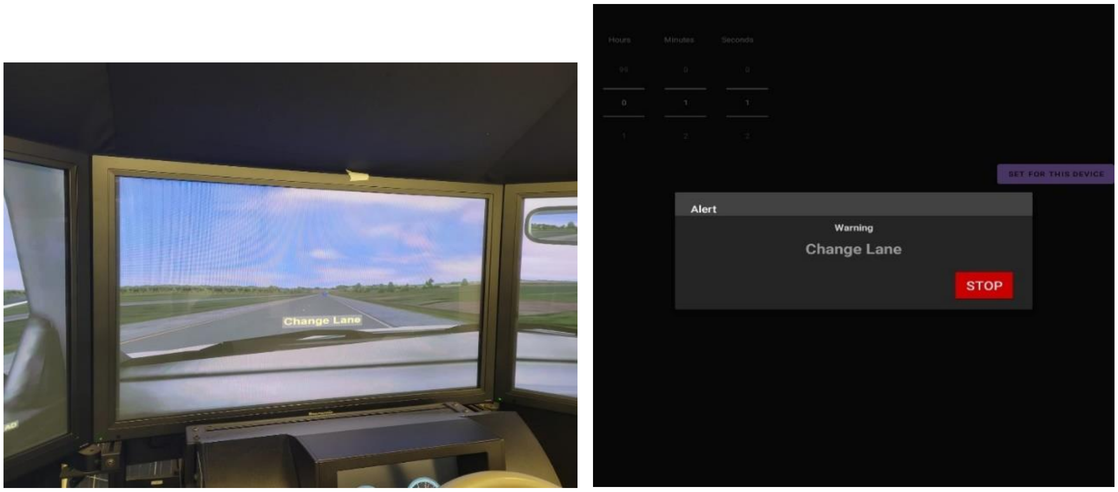
Figure 3-4. Takeover scenarios for driving simulator experiment

The decision-making procedure after TOR during the two scenarios was different. During the Lane change scenario, once the TOR was generated, the participants were required to analyze the driving environment. They need to make sure that they do not crash with the lead vehicle and there are no vehicles in the target lane to safely change the lane. But during the Pullover scenario, since the participants were only required to pull over the vehicle to the right shoulder, they only need to check that there is no risk of rear-end collision with any following vehicle. Due to additional tasks, the participants need longer takeover time during the Lane change scenario compared to the Pullover scenario.

Use of headphone during conventional TOR is more likely to distract the participants who did not use headphone. But with integrated TOR, the difference in distraction between use and non-use of headphone is likely to be small. This is because when the TOR is provided from the PPD, the TOR recognition time is likely to be shorter compared to conventional TOR if the participants are involved in a secondary task using PPD.

The participants were informed where to put the tablet before their manual control when the TOR was initiated. In the Lane change scenario after taking over, the participants were instructed to continue driving and after about 500 m of manual driving, the scenario ended.

Each participant conducted four driving scenarios as shown in Table 3-1 (either wearing headphone or not wearing headphone). The participants were informed that they would test these four scenarios, but they were not informed of the order of the scenarios. The order of the scenarios was randomly assigned to each participant to reduce the learning effect. The duration of each scenario was approximately 8-12 minutes.



(a) windshield (b) tablet

Figure 3-5. Visual TOR warning in Lane change scenario

Table 3-1. Experiment Scenarios

Scenario	Type of TOR warning (source of visual and auditory warning)	Warning message	Wearing Headphone	Type
1	Conventional (simulator only)	Change Lane	Yes	CH
			No	CNH
2	Integrated (both simulator and tablet)	Change Lane	Yes	IH
			No	INH
3	Conventional (simulator only)	Pullover to Right	Yes	CH
			No	CNH
4	Integrated (both simulator and tablet)	Pullover to Right	Yes	IH
			No	INH

3.4 Experiment Procedure

First, participants were requested to sign the consent form and complete the demographic questionnaire. After that, they were provided with a brief description about purpose of the study and were introduced to the driving simulator. Once they learned basic operation of the simulator and its automation feature, they were requested to start the experiment.

In the beginning, they tested two trial scenarios with a takeover situation using each TOR warning system (integrated and conventional). Once the participant felt comfortable with the automated driving and takeover procedure, the main experiment started.

Following each scenario, the participants were asked to answer the National Aeronautics and Space Administration Task Load Index (NASA TLX) questionnaire to assess their mental workload after the TOR warning was provided. At the end of the experiment, the participants answered a questionnaire related to preference and experience of automated driving and TOR.

3.5 Experiment Design

The research adopted a 2 × 2 × 2 between and within-subjects mixed factor experimental design. In between-subject design is when each participant is assigned to a different condition whereas within-subject design is when each participant is assigned to all conditions. The within-subject independent variables were TOR (conventional and integrated) and scenario type (Lane change and Pullover). The between-subject independent variable was the use of headphones (wearing or not wearing headphones). A mixed design can reduce the vulnerabilities by increasing the advantages of both within-subject factors (greater statistical power) and between-subject factors (less risk of subjects discovering the hypothesis). An overview of the experimental design is shown in Table 3.2.

Table 3-2. Experimental design

Within-subjects independent variables	Between-subjects independent variables
Lane Change Scenario/Conventional TOR (C)	H, NH
Lane Change Scenario/Integrated TOR (I)	H, NH
Pullover Scenario/Conventional TOR (C)	H, NH
Pullover Scenario/Integrated TOR (I)	H, NH

Note: H = wearing headphone NH = not wearing headphone

The dependent variables are described in Table 3-3. After the TOR warning was generated, the takeover time was measured and the post-take performance was also evaluated based on various driving parameters extracted from the driving simulator. These driving parameters include minimum time to collision (TTC), the standard deviation of steering wheel angle, lane change duration, and maximum resultant acceleration.

Table 3-3. Dependent Variables

Dependent Variables	Unit
Takeover Time	s
Time to Crash (TTC)	s
Lane change duration	s
Standard deviation of steering wheel angle	degree
Maximum acceleration and deceleration	m/s^2
Subjective mental workload measured by NASA TLX	1-100 (range)

In this study, the takeover time is defined as the difference between the time when TOR is generated and the time when automated driving is cancelled by pressing either brake pedal or accelerator. TTC has been used as a measure of rear-end collision risk between the lead and following vehicles. TTC was calculated using the following equation:

$$TTC(t) = \frac{S(t)}{V_{i+1}(t) - V_i(t)} \qquad V_{i+1}(t) > V_i(t)$$

where $S(t)$ = spacing between lead and following vehicles at time t and $V_i(t), V_{i+1}(t)$ = speed of lead and following vehicle at time t, respectively. The speed of the lead vehicle was zero in this study since the vehicle was stopped.

Lane change duration represents the difference between the time when automation is cancelled and the time when the center of the vehicle reaches the center of the left lane (the target lane). This was observed only in the Lane change scenario. A shorter lane change duration helps the driver avoid a collision with the stopped vehicle more quickly.

Standard deviation of steering wheel angle represents the variation in steering wheel angle during the takeover process. A smaller standard deviation of steering wheel angle suggests that the participants had better control of the vehicle during the post-takeover situation, which will result in a safer transition from automated to manual driving.

The maximum acceleration in the Lane change scenario (since the participants are required to accelerate to change lane) and the maximum deceleration in the Pullover scenario (since the participants are required to decelerate to pull over and stop) were calculated using the following equations:

$$\text{Maximum Acceleration} = \sqrt{(\text{max lateral acceleration}^2 + \text{ max longitudinal acceleration}^2)}$$

$$\text{Maximum Deceleration} = \sqrt{(\text{max lateral deceleration}^2 + \text{ max longitudinal deceleration}^2)}$$

Since higher maximum acceleration and deceleration represent a more abrupt change in speed over time, it indicates an unstable transition from automated to manual driving.

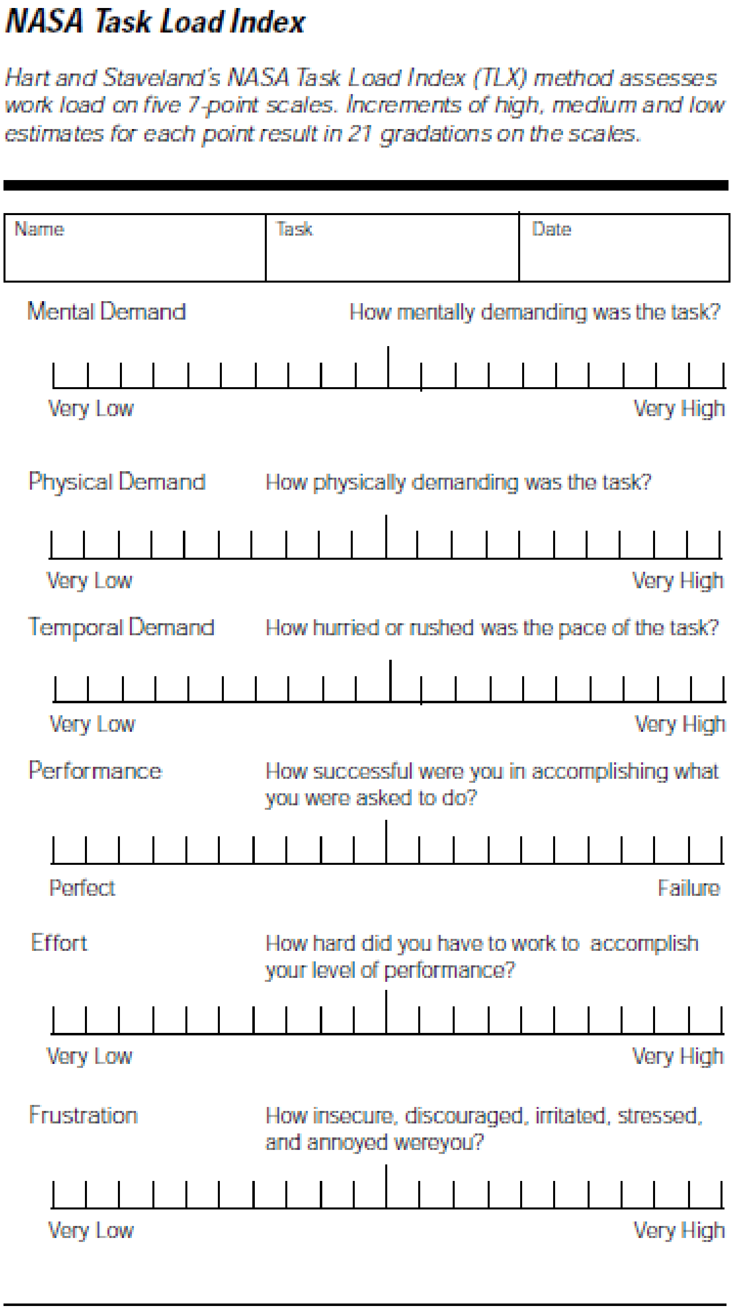
3.6 Subjective Measurement of Mental Workload

Mental workload and decision-making have a complex relationship. Decision-making tends to be better for moderate workload whereas both overload and underload can deteriorate the quality of decision making (Soria-Oliver et al., 2017). After the TOR is generated, taking over the vehicle control is a task that requires a high amplitude of workload. Thus, a reduced mental workload will have a positive effect on post-takeover performance.

In this regard, the NASA TLX was used to provide a reference of the subjective mental workload from different tasks. It is a widely used tool for various research projects involving human-machine interfaces (NASA, 2020). Mental workload is divided into two components, which are stress and strain (Young et al., 2005). Stress is measured by the demand the task requires, whereas strain is the impact of the task on the individual (Schlegel, 1993).

The six different subscales are used to measure subjective mental workload. The first three subscales relate to the demand of task which is mental, physical, and temporal demands; the rest of the three subscales relates to impact from the task which is performance, effort, and frustration. It asks the user to provide a separate subjective rating based on these subscales. Each subscale consists of a 21-tick Likert scale that ranges from “very low” to “very high” except for the Performance subscale which ranges from “perfect” to “failure” (Figure 3-6). This Likert scale is converted to a 1-100 scale. Fifteen comparisons between the subscales are made to select the weight of each subscale. The participants were asked to select the most relevant subscale while two were presented. Then each subscale value from the Likert scale was multiplied by their weight to calculate the overall subjective mental workload within the range of 1-100. Participants completed the NASA TLX questionnaire using the tablet.

It is expected that subjective mental workload will be different between the conventional and integrated TOR warning systems. A lower value of the mental workload indicates the participants' better decision-making ability and higher comfort during the takeover process after the TOR is generated.



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure 3-6. NASA Task Load Index
(Source: NASA, 2021)

3.7 Preference and Experience for Automated Driving and TOR Warning

Additional questions were asked to the participants to find their experience and preference for automated driving and TOR warning as shown in Figure 3-7.

1. Were you able to read the warning from the tablet? (Yes/No)
2. Were you able to read the warning from the windshield? (Yes/No)
3. Which warning system would you prefer in your vehicle? (Conventional/PPD Integrated)
4. How comfortable did you feel during the conventional warning system? (From 1-5 scale)
5. How comfortable did you feel during the PPD integrated warning system? (From 1-5 scale)
6. Do you think higher time budget is required for safer takeover process? (Yes/No)
7. How safe did you feel during the conventional warning system? (From 1-5 scale)
8. How safe did you feel during the PPD integrated warning system? (From 1-5 scale)
9. Are you likely to use headphone in automated driving? (Yes/No)

Figure 3-7. Questions related to participants' experience and preference for automated driving and TOR warning

3.8 Data Analysis

Various driving performance parameters during the post-takeover situation were extracted from the driving simulator using Python and R programming language. The data from the participants who crashed or missed the TOR warning were excluded from the analysis.

Statistical analysis was performed using Statistical Analysis Software (SAS) version 9.4. Generalized linear models (GLM) were developed to identify the relationship between dependent variable (takeover time, TTC, lane change duration, standard deviation of steering wheel angle and subjective mental workload value from NASA TLX) and independent variables (TOR warning system, scenario type, use of headphone, age, gender and driving experience).

GLM was used because the model allows to build a linear relationship between the independent and dependent variables and it can fit to any distribution of the dependent variable, not only normal distribution. The model can also analyze effects of continuous and categorical variables on a discrete or continuous dependent variable.

In particular, the functional form of GLM ensures that the dependent variable is a non-negative value as follows:

$$\ln(y) = a + b_i x_i$$

where y = dependent variable, x_i = independent variable i, a = constant, and b_i = coefficient for independent variable i. Since the takeover time, post-takeover performance parameters, and subject mental workload are non-negative values, GLM is suitable for predicting these as dependent variables.

3.9 Hypotheses

The following four hypotheses were tested based on the results of the experiment:

- H_1 (Reduced takeover time): Integrated TOR reduces takeover time.
- H_2 (Improved post-takeover performance): Integrated TOR improves takeover performance.
- H_3 (Reduced subjective mental workload): Integrated TOR reduces subjective mental workload.
- H_4 (Safer, comfortable and reliable automated driving): Integrated TOR makes the user feel safer, comfortable and more reliable on the level 3 automation.

4 Results and Discussion

4.1 Takeover Time

Table 4-1 and Figure 4-1 compare the takeover time between the conventional and integrated TOR warning systems for Lane change and Pullover scenarios. The integrated TOR warning resulted in shorter mean takeover time with or without the headphone in both scenario types. Reduced takeover time will provide more time for execution and evaluation in the post-takeover situation. The standard deviation of takeover time was mostly shorter for integrated TOR. The combination of shorter takeover time with low standard deviation strongly provides evidence of an improved TOR warning system.

Table 4-1. Takeover time (second) for conventional and integrated TOR

(a) Lane Change Scenario

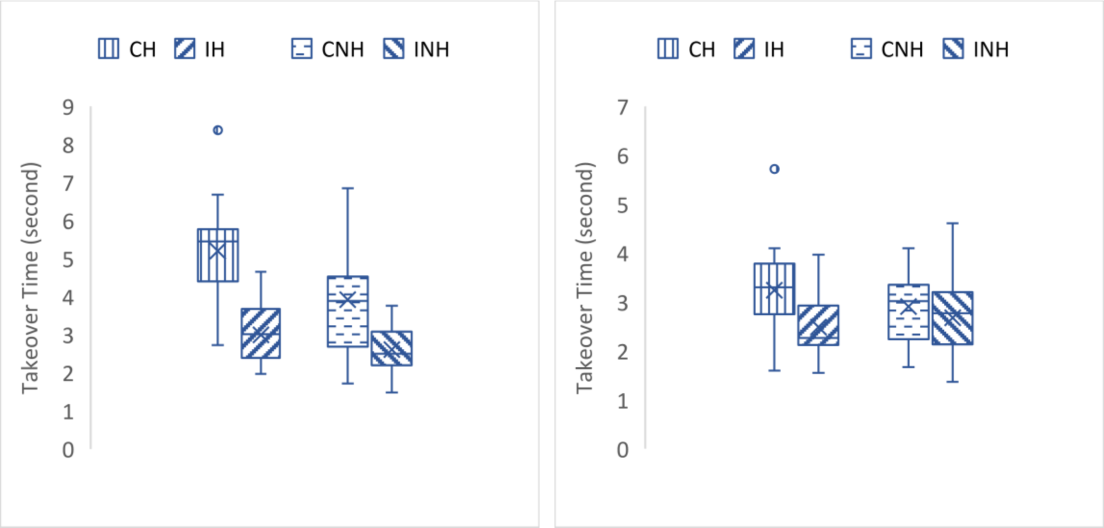
	Mean	Std	Min	Max
CH	5.24	1.45	2.73	8.37
IH	3	0.73	1.97	4.65
CNH	3.92	1.44	1.72	6.85
INH	2.61	0.59	1.48	3.67

Note: CH = Conventional with headphone IH = Integrated with headphone CNH = Conventional without headphone INH = Integrated without headphone

(b) Pullover Scenario

	Mean	Std	Min	Max
CH	3.24	0.93	1.6	5.72
IH	2.49	0.67	1.55	3.97
CNH	2.91	0.68	1.67	4.1
INH	2.68	0.75	1.37	4.61

In particular, the reduction in takeover time between the integrated and conventional TOR was greater when headphone was used compared to when headphone was not used in both scenario types. This indicates that while using headphone the effectiveness of the integrated TOR in reducing the takeover time increases.



(a) Lane Change Scenario (b) Pullover Scenario

Figure 4-1. Takeover time for conventional and integrated TOR

Generalized linear models were developed to identify the relationship between the takeover time and independent variables. For the model development, 75 observations during the Lane change scenario and 82 observations during the Pullover scenario were obtained from the repetition of the same scenario with different TOR (integrated and conventional TOR) for each participant. The scenarios when the participants crashed (Lane change scenario) or missed the TOR completely (Pullover scenario) were excluded.

Table 4-2 shows that in the Lane change scenario, the effects of the integrated TOR, use of headphone, gender and driving experience on the takeover time were statistically significant at a 95% confidence interval. The model fit was good ($R^2 = 0.5728$) – refer to the calculation of R^2 in Appendix D. A negative coefficient for the integrated TOR (1 = integrated TOR, 0 = conventional TOR) indicates that the integrated TOR significantly reduced the takeover time compared to conventional TOR. However, the use of headphone significantly increased the takeover time. There was no significant interaction effect of integrated TOR and the use of headphone.

The takeover time was relatively shorter for male participants than female participants. This result is consistent with Lipps et al. (2011) which found that male drivers generally showed shorter reaction time than female drivers.

Also, the takeover time was shorter for the participants with longer driving experience. This result aligns with the fact that the drivers with longer driving experience have quicker driving-related reflexes. For instance, Wright et al. (2016) found that more experienced middle-aged drivers visually identified hazardous situations quicker compared to less experienced drivers. But the drivers in older age group (60-81 years old) showed a longer takeover time compared to the drivers in younger age group (Li et al., 2018).

Table 4-2. Estimated parameters of generalized linear model for takeover time in Lane change scenario

Variable	Parameter	Standard error	t-statistics	p-value
Constant	0.68481	0.03048	22.5	<.0001
Integrated TOR	-0.17649	0.02596	-6.8	<.0001
Headphone	0.07716	0.02574	3.0	0.0038
Male	-0.10022	0.02648	-3.8	0.0003
Driving Experience	-0.00812	0.00282	-2.9	0.0053
$R^2 = 0.5728$				

In the Pullover scenario, only integrated TOR showed significant negative effect on the takeover time as shown in Table 4-3. There were no outliers of the takeover time for the Pullover scenario. The R^2 value of the model (= 0.0886) was low because of significant effects of unobserved variables that could not be considered in this study. Low R^2 value for the Pullover scenario is also because the impact of the TOR warning system on takeover time was relatively less significant when the drivers were not required to urgently react to avoid a crash and the takeover situation was relatively safer.

The integrated TOR has significant negative effect on the takeover time in both scenarios, hence the first hypothesis (H_1: Reduced takeover time) was accepted.

Table 4-3. Estimated parameters of generalized linear model for takeover time in Pullover scenario

Variable	Parameter	Standard error	t-statistics	p-value
Constant	1.08384	0.04397	24.65	<.0001
Integrated TOR	-0.16932	0.06072	-2.79	0.0066
$R^2 = .0866$				

4.2 Post-takeover Performance

4.2.1 Minimum Time to Crash (TTC)

Since there was no lead vehicle in the Pullover scenario, TTC was only compared between the conventional and integrated TOR for the Lane change scenario as shown in Table 4-4 and Figure 4-2. The result shows that the average value of minimum TTC was longer for the integrated TOR than the conventional TOR. This indicates that the integrated TOR can reduce the risk of collision. Wearing headphones increased the minimum TTC for both integrated and conventional TOR.

Table 4-4. Minimum TTC (second) for conventional and PPD integrated TOR during lane change scenario

	Mean	Std	Min	Max
CH	2.13	1.35	0.65	5.23
IH	4.5	1.02	2.49	6.31
CNH	3.28	1.56	0.71	5.89
INH	5.05	0.78	3.51	6.69

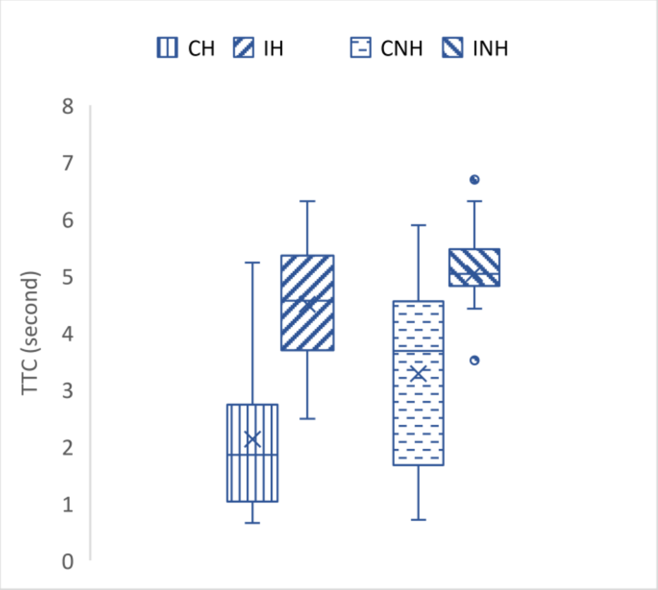


Figure 4-2. Minimum TTC for conventional and integrated TOR

In addition to the minimum TTC, the number of cases when the minimum TTC is shorter than the safety threshold (e.g., 2 s) is an important indicator of driver safety. A total of 15 participants (9 participants with headphone and 6 participants without headphone) showed TTC shorter than 2 s in the conventional TOR, but no participant showed TTC shorter than 2 s in the integrated TOR.

Table 4-5 shows the parameter values of the generalized linear model for TTC. The table shows that the integrated TOR increased TTC but the use of headphone decreased

TTC. Also, no significant interaction effect of integrated TOR and the use of headphone was found.

Table 4-5. Estimated parameters of generalized linear model for TTC in Lane change scenario

Variable	Parameter	Standard error	t-statistics	p-value
Constant	0.94031	0.09373	10.03	<.0001
Integrated TOR	0.73459	0.10752	6.83	<.0001
Headphone	-0.2712	0.10659	-2.54	0.0131
$R^2 = 0.4171$				

4.2.2 Standard Deviation of Steering Wheel Angle

Table 4-6 and Figure 4.3 compare the standard deviation of steering wheel angle between the conventional and integrated TOR. The integrated TOR showed smaller mean standard deviation of steering wheel angle than the conventional TOR. This indicates that the integrated TOR warning helped drivers take over the vehicle control more safely. In the Lane change scenario, the difference in mean standard deviation of steering wheel angle between the integrated and conventional TOR was greater for the use of headphone than the non-use of headphone. However, in the Pullover scenario, the differences in mean standard deviation of steering wheel angle between the integrated and conventional TOR were similar regardless of the use of headphone.

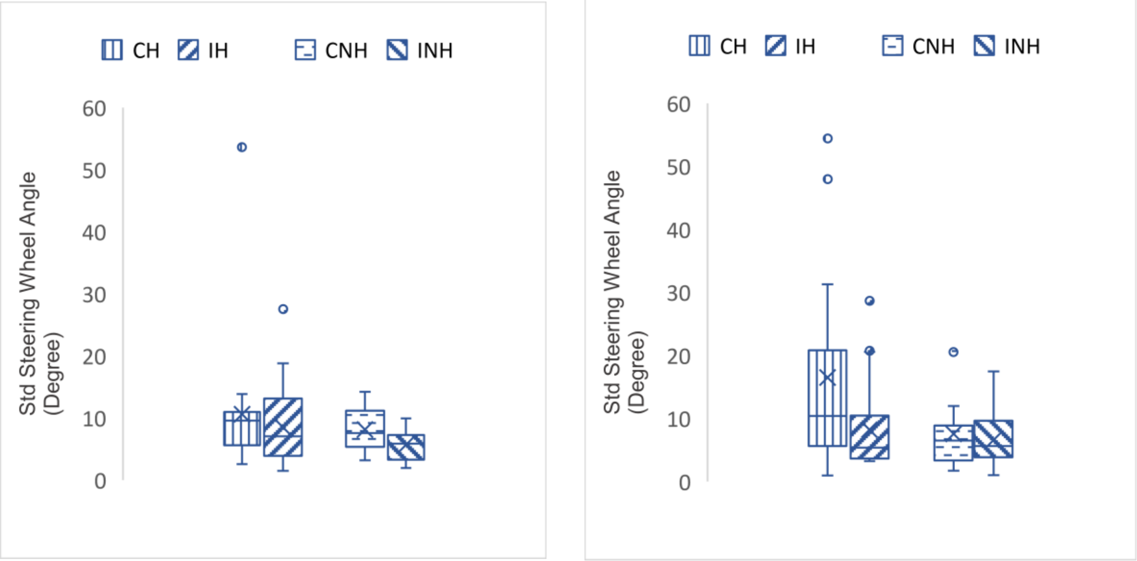
Table 4-6. Standard deviation of steering wheel angle (degree) for conventional and integrated TOR

(a) Lane Change Scenario

	Mean	Std	Min	Max
CH	16.52	16.63	0.97	54.44
IH	8.24	6.99	3.22	28.68
CNH	7.55	5.49	1.7	20.58
INH	6.61	3.92	1.02	17.48

(b) Pullover Scenario

	Mean	Std	Min	Max
CH	10.62	11.23	2.59	53.6
IH	8.51	6.70	1.47	27.52
CNH	8.16	3.27	3.2	14.24
INH	5.64	2.52	1.94	9.95



(a) Lane change scenario (b) Pullover scenario

Figure 4-3. Standard deviation of steering wheel angle for conventional and integrated TOR

Table 4-7 shows the parameter values of the generalized linear model for the Pullover scenario. No independent variable was significant in the generalized linear model for the Lane change scenario. In the Pullover scenario, the integrated TOR was significant and it reduced the standard deviation of steering wheel angle. The R^2 value of the model was 0.0648 for 82 observations. This indicates that the integrated TOR allowed a smoother transition from automated to manual driving.

After excluding the outliers, the R^2 value slightly increased to 0.0921 but the value was still low. This suggests that the unobserved variables had significant effects on the drivers' control of steering wheel angle in the Pullover scenario.

Table 4-7. Estimated parameters of generalized linear model for standard deviation of steering wheel angle in Pullover scenario

Variable	Parameter	Standard error	t-statistics	p-value
Constant	2.05028	0.09743	21.04	<.0001
Integrated TOR	-0.31671	0.13454	-2.35	0.021
$R^2 = 0.0648$				

4.2.3 Lane Change Duration

Table 4-8 and Figure 4-4 compare the lane change duration between the conventional and integrated TOR in the Lane change scenario. The integrated TOR showed shorter mean lane change duration than the conventional TOR. Use of headphones showed greater difference in the lane change duration between the conventional and integrated TOR than the non-use of headphone. Thus, the integrated TOR can more effectively reduce the lane change duration while wearing headphone. This is potentially because the integrated TOR facilitated the participants' evaluation of the situation and decision-making when TOR warning was generated.

Table 4-8. Lane change duration (seconds) for conventional and integrated TOR in Lane change scenario

	Mean	Std	Min	Max
CH	7.44	1.34	4.87	9.43
IH	4.79	0.92	3.28	6.47
CNH	5.86	1.64	3.23	9.33
INH	4.45	1.18	1.93	7.2

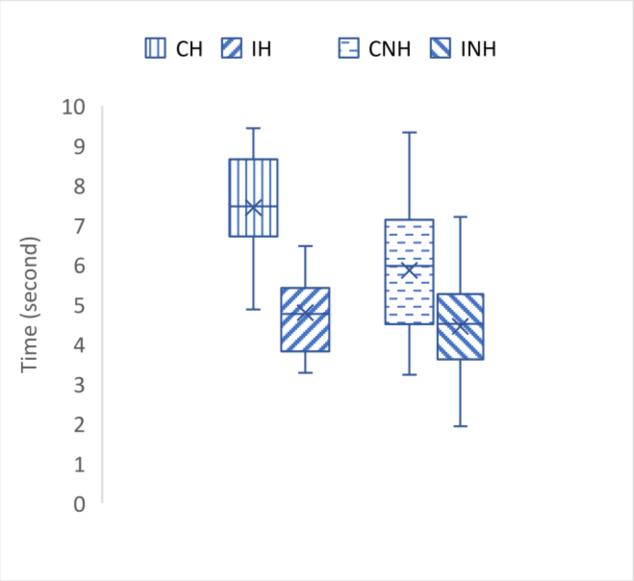


Figure 4-4. Lane change duration for conventional and integrated TOR

Table 4-9 shows the parameter values of the generalized linear model for lane change duration. The result shows that the integrated TOR reduced the lane change duration whereas the use of headphone increased the lane change duration. Interaction effect of integrated TOR and use of headphone was not significant.

Table 4-9. Estimated parameters of generalized linear model for lane change duration in Lane change scenario

Variable	Parameter	Standard error	t-statistics	p-value
Constant	1.7703	0.0513	34.51	<.0001
Integrated TOR	-0.34952	0.05884	-5.94	<.0001
Headphone	0.1652	0.05834	2.83	0.006
$R^2 = 0.3492$				

4.2.4 Maximum Acceleration and Deceleration

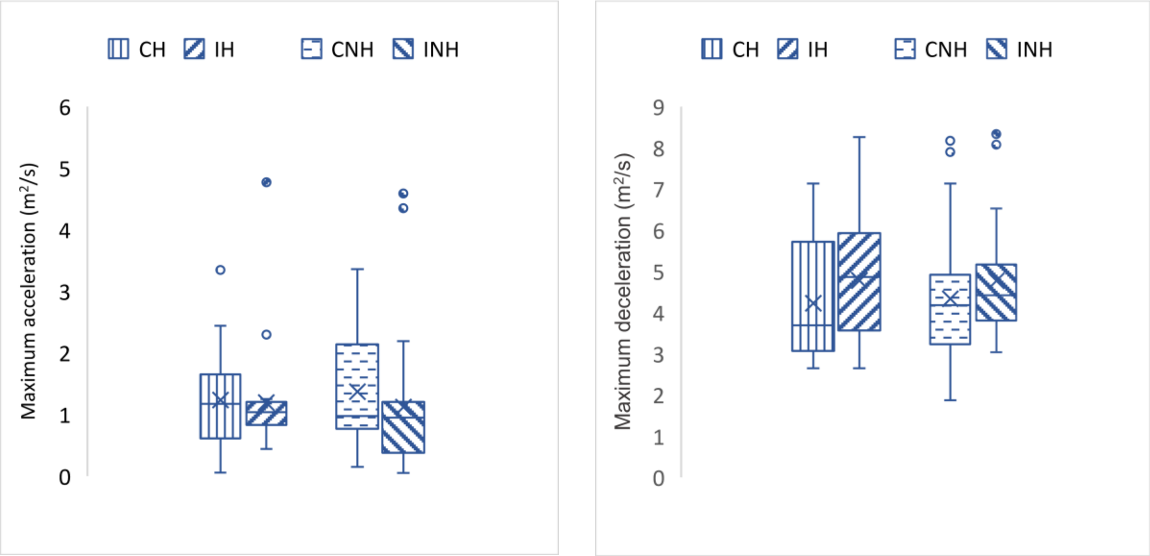
Tables 4-10 and 4-11 and Figure 4-5 compare the maximum acceleration during the Lane change scenario and the maximum deceleration during the Pullover scenario. Maximum acceleration was consistently lower for the integrated TOR than the conventional TOR. This result suggests that the integrated TOR helped the participants change speed more safely to complete the required lane change.

Table 4-10. Maximum Acceleration (m/s^2) for conventional and integrated TOR in Lane change scenario

	Mean	Std	Min	Max
CH	1.24	0.91	0.06	3.35
IH	1.19	0.91	0.44	4.77
CNH	1.37	0.97	0.15	3.36
INH	1.12	1.20	0.05	4.59

Table 4-11. Maximum deceleration (m/s^2) for conventional and integrated TOR in Pullover scenario

	Mean	Std	Min	Max
CH	4.23	1.48	2.65	7.13
IH	4.78	1.51	2.65	8.26
CNH	4.34	1.70	1.87	8.17
INH	4.77	1.34	3.04	8.33



(a) Lane Change Scenario (b) Pullover Scenario

Figure 4-5. Maximum acceleration (lane change scenario) and maximum deceleration (pullover scenario) for conventional and integrated TOR

On the other hand, the maximum deceleration was relatively higher for integrated TOR than the conventional TOR in the Pullover scenario. This is opposite to the result in the Lane change scenario. Although higher maximum deceleration represents unstable transition during the takeover process similar to higher maximum acceleration, it also represents faster participants' response to take over the vehicle control with the integrated TOR than the conventional TOR. In this sense, the integrated TOR provided better post-takeover performance than the conventional TOR.

No variable was significant in the generalized linear model for maximum acceleration in the Lane change scenario. The parameter values of the generalized linear model for maximum deceleration in the Pullover scenario is shown in Table 4-12. The result shows that the integrated TOR and younger participants had positive effect on the maximum deceleration.

After excluding the outliers, the R^2 value slightly increased to 0.1203 but the model fit was still low. Thus, similar to standard deviation of steering angle, the effect of unobserved variables on maximum deceleration was significant in the Pullover scenario.

Although most participants were in young age group but there were also a few participants in middle age group. Negative effect of age on maximum deceleration indicates that middle-aged drivers tend to be more careful while driving and applied lower maximum deceleration than young drivers. Similar results were found in Gold et al. (2018). In summary, there was no significant effect of age on the takeover time but young drivers showed relatively poor post-takeover performance than middle-aged drivers.

Table 4-12. Estimated parameters of generalized linear model for maximum deceleration in Pullover scenario

Variable	Parameter	Standard error	t-statistics	p-value
Constant	1.92	0.20413	9.4	<.0001
Integrated TOR	0.13826	0.06813	2.03	0.0458
Age	-0.01987	0.00748	-2.66	0.0095
R^2 = 0.1196				

4.2.5 Crash or Missed TOR Rate

The crash or missed TOR rate (i.e., percentage of participants who crashed or missed TOR warning) can also depict the post-takeover performance as shown in Table 4-13. No participants crashed during the scenarios with the integrated TOR (IH and INH). But with the conventional TOR, 9 participants crashed (6 with headphone and 3 without headphone) in the Lane change scenario and 5 participants missed the TOR warning (3 with headphone and 2 without headphone) in the Pullover scenario. This indicates that the integrated TOR effectively reduced the likelihood of crash and missing TOR warning.

Table 4-13. Crash or missed TOR rate for conventional and integrated TOR

	Lane change scenario	Pullover scenario
CH	30%	14%
IH	0	0
CNH	14%	9%
INH	0	0

The comparison of various driving performance parameters in this subsection shows that the integrated TOR system generally improved post-takeover performance compared to the conventional TOR system. Therefore, hypothesis H_2 (Improved takeover performance) was accepted.

The results also indicate that the impact of the integrated TOR on post-takeover performance varies with the urgency of the takeover situation. During the Lane change scenario when the participants were required to react quickly to avoid a crash, the impact of the integrated TOR was more significant on post-takeover performance. On the other hand, the impact of unobserved variables on post-takeover performance was more significant for less urgent traffic situations in the Pullover scenario.

4.3 Subjective Mental Workload

Table 4-14 and Figure 4-6 compare the participants' subjective mental workload data from NASA TLX questionnaire. In all cases, the integrated TOR shows lower mental workload than the conventional TOR.

In the Lane change scenario, the difference in mental workload between the integrated and conventional TOR was greater for the scenario with the use of headphone than the scenario without the use of headphone. This shows that integrating TOR can be more effective while wearing headphone compared to not wearing headphone.

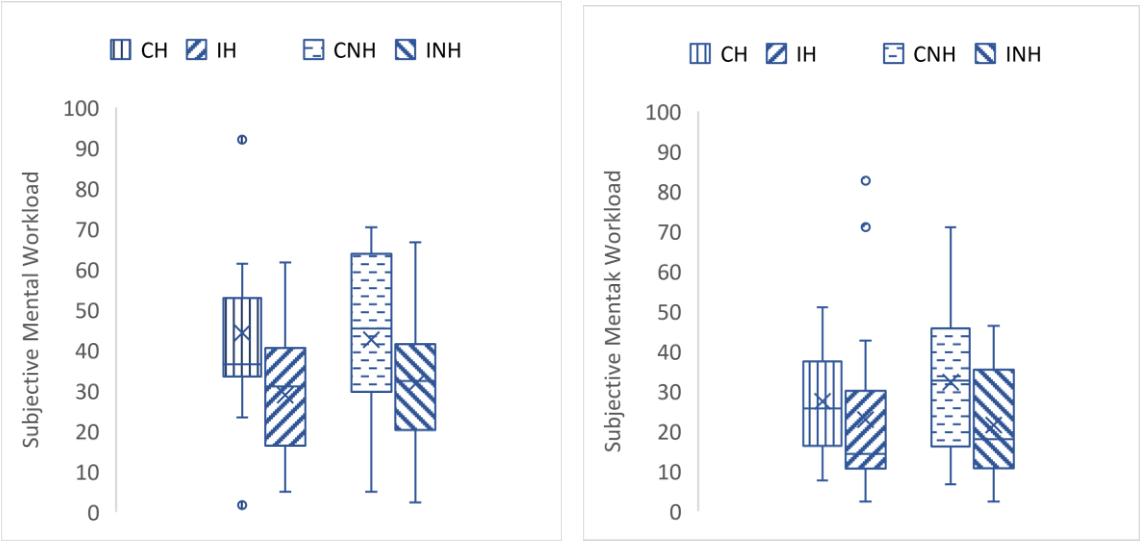
Table 4-14. Subjective mental workload (Range: 1-100) for conventional and integrated TOR

(a) Lane change scenario

	Mean	Std	Min	Max
CH	44.24	24.39	1.67	92.67
IH	28.9	15.91	5.00	61.67
CNH	42.54	20.29	5.00	70.33
INH	31.67	15.93	2.33	66.67

(b) Pullover scenario

	Mean	Std	Min	Max
CH	27.39	13.95	7.67	51
IH	22.9	21.56	2.33	82.67
CNH	32.21	17.34	6.67	71
INH	21.51	14.22	2.33	46.33



(a) Lane Change Scenario (b) Pullover Scenario

Figure 4-6. Subjective mental workload for conventional and integrated TOR

No variable was significant in the generalized linear model for mental workload in the Lane change scenario. Although the integrated TOR was significant in the model for the Pullover scenario as shown in Table 4-15, the model fit was poor (R^2 = 0.0886 for 82 observations). Therefore, hypothesis 3 (Reduced subjective mental workload) cannot be tested in this study.

Table 4-15. Estimated parameters of generalized linear model for subjective mental workload in Pullover scenario

Variable	Parameter	Standard error	t-statistics	p-value
Constant	1.40781	0.05163	27.27	<.0001
Integrated TOR	-0.19888	0.0713	-2.79	0.0066
$R^2 = 0.0886$				

4.4 Preference and Experience for Automated Driving and TOR Warning

Survey results showed that 86% of the participants would prefer the integrated TOR system over the conventional TOR system. Only 1 participant mentioned not being able to read the visual warning from the tablet during integrated TOR but was able to take over safely by monitoring the driving environment.

Fifty nine percent of the participants stated that they are likely to use headphone during level 3 automated driving. Figures 4-7 and 4-8 compare the participants' subjective comfort level and safety level between the two types of TOR, respectively. A majority (65%) of the participants reported maximum comfort level for the integrated TOR whereas only 3% of the participants reported the same comfort level for the conventional TOR. Similarly, a majority (73%) of the participants reported maximum safety level for the integrated TOR but only 13% of the participants reported the same safety level for conventional TOR. Thus, the participants felt higher comfort and safety levels with the integrated TOR than the conventional TOR.

Therefore, the hypothesis H_4 (Safer, comfortable and reliable automated driving) was accepted. Results from the subjective questionnaire also indicated that 81% of participants would prefer the time budget longer than 10 seconds.

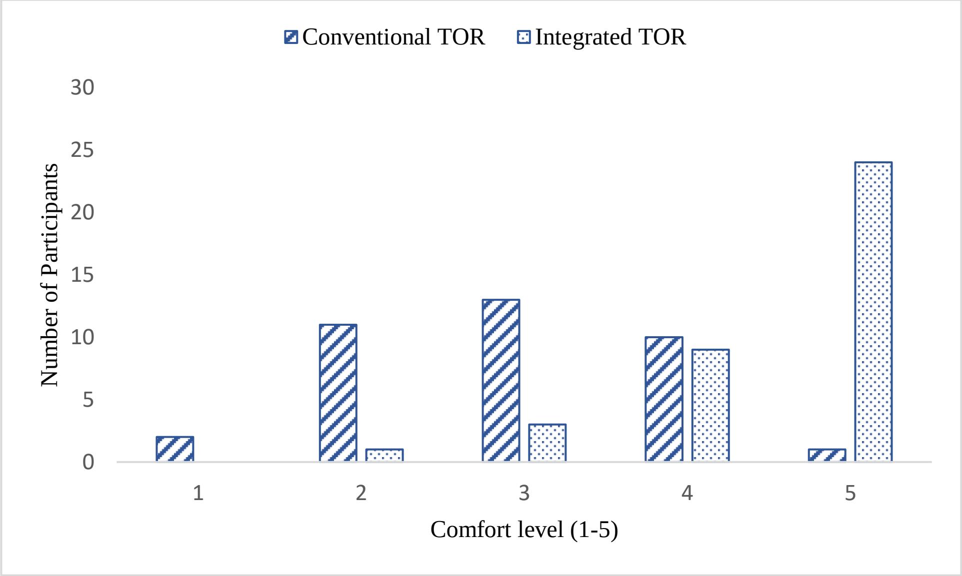


Figure 4-7. Subjective comfort level for conventional and integrated TOR

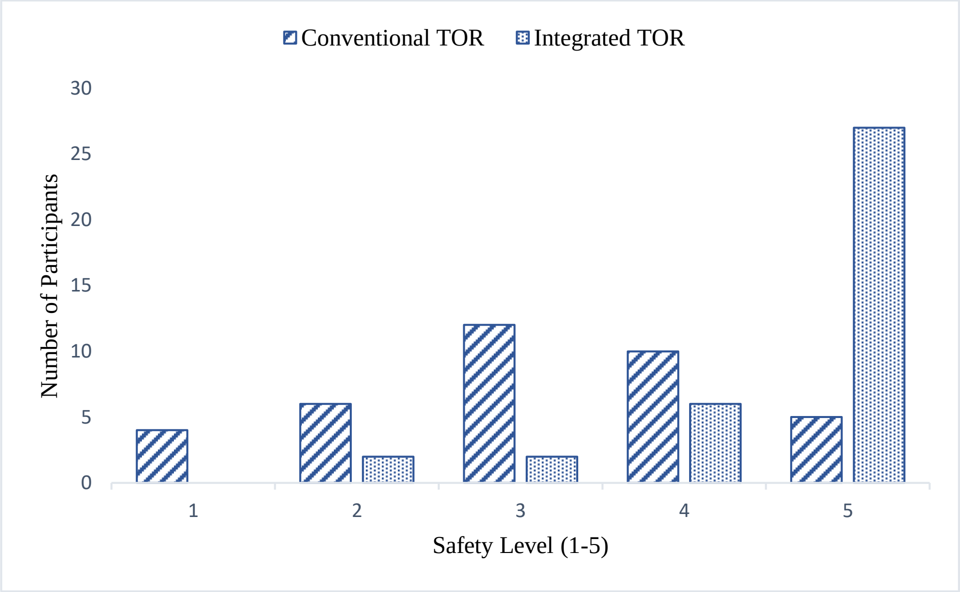


Figure 4-8. Subjective safety level for conventional and integrated TOR

5 Conclusions and Recommendations

This study investigated the effects of integrating takeover request (TOR) with a personal portable device (PPD) on takeover time and post-takeover performance in level 3 automated driving. For this purpose, 44 drivers' takeover behaviors were observed using MiniSim driving simulator with an automated driving feature. The participants received TOR warning in two types of scenario – 1) Lane change scenario where they were requested to change lane to avoid a collision with the stopped vehicle and 2) Pullover scenario where they were requested to pull over to the right shoulder. Takeover time and post-takeover performance were compared between the integrated TOR warning system (visual and audio warning from both simulator and tablet) and the conventional TOR warning system (visual and audio warning from the simulator only). Additionally, subjective mental workload and opinions related to level 3 automated driving and TOR were compared between the two TOR systems. The primary findings of this research are summarized as follows:

1. The integrated TOR system reduced average takeover time with or without the use of headphones. But the reduction was highest when the participants used headphones for secondary task. The standard deviation of takeover time was also reduced in most scenarios with integrated TOR. Participants with longer driving experience had shorter takeover time. Male participants also had shorter takeover time compared to female participants. Results also indicated that the takeover time was relatively longer for the Lane change scenario compared to the Pullover scenario. These results indicates that when the participants had to analyze the driving environment, they needed more time before decision making, which delayed

the takeover process compared to the Pullover scenario where there were no surrounding vehicles. As a result, they felt safer and were able to take over quickly.

2. The participants generally showed better post-takeover performance with the integrated TOR system than the conventional TOR system. The integrated TOR increased the minimum time-to-collision (TTC) and decreased the lane change duration (in the Lane Change scenario). Also, integrating TOR resulted in decreased standard deviation of steering angle and the maximum deceleration (in the Pullover scenario).
3. There was no crash and missing TOR warning with the integrated TOR system unlike the conventional TOR. This demonstrates that the integrated TOR system can more effectively alert users to take over the vehicle control and prevent crashes.
4. The impacts of TOR warning system on takeover time and post takeover-performance were more significant in more urgent takeover situation (Lane change scenario) than less urgent takeover situation (Pullover scenario).
5. The integrated TOR system reduced the average value of subjective mental workload for both Lane change and Pullover scenarios. Although the integrated TOR showed a significant effect on reducing mental workload during the Pullover scenario, the effect was not significant during the Lane change scenario.
6. Most participants were willing to use headphones while doing secondary tasks even though the high risk was involved. The participants also preferred the integrated TOR over the conventional TOR due to higher subjective safety and comfort levels.

The main contributions of this study are as follows:

1. Unlike previous studies on the integrated TOR, this study used multiple driving performance variables to analyze the effect of the integrated TOR on post-takeover performance. This study also proposed providing audio alerts from the PPD, which was also not explored in the previous studies. Providing audio alert from PPD can reduce the takeover time particularly while using headphone.
2. Watching video was the only secondary task considered in this study. But unlike the previous studies, the participants were allowed to choose the video they want to watch for their secondary task, which increased their involvement in the task.
3. This study analyzed the effects of using headphone on the takeover time and post-takeover performance. As people are more likely to use headphone for better sound quality during the automated driving, understanding the effects of wearing headphone can improve the effectiveness of the integrated TOR system in reducing the takeover time.

However, the study has several limitations. First, most participants were in younger age group and there were more male participants than female participants. The younger driving groups in this study have a wide range of driving experience, which may cause statistical analysis to be skewed. Also, the study could not identify the mechanism of how the integrated TOR can reduce different time components of the physical and visual readiness time during the takeover process.

For future studies, it is recommended to conduct the experiment for participants with wider range of age, driving experience and equal number of male and female participants for generalized results. It is also recommended to measure individual time components of takeover process using eye tracker and motion capture system. These data will help better understand how the integrated TOR can reduce the takeover time and improve post-takeover performance.

Lastly, the effectiveness of integrated TOR may vary in different weather, road geometry and traffic conditions. According to Chen et al. (2019), weather conditions and road geometry have substantial impacts on driving behavior. In adverse weather conditions or changes in slopes, the driver’s perceived risk increases. Higher traffic density also influences risk perception. As a result, drivers are less likely to be involved in the secondary task or more likely to monitor their surroundings regularly. On the contrary, when involved in a secondary task, higher traffic density and adverse weather conditions delay the takeover time and deteriorate post-takeover control (McDonald et al., 2019). Therefore, it is recommended to test the effectiveness of the integrated TOR system in different road geometry, traffic, and weather conditions while participants engage in different types of secondary tasks.

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APPENDICES

Appendix A

CONSENT TO PARTICIPATE IN RESEARCH

Title of Study: Developing warning strategies to reduce takeover time and improve post-takeover performance in Level 3 automated driving

You are asked to participate in a research study conducted by Mr. Niloy Talukder (Principal Investigator), Dr. Chris Lee, Dr. Francesco Biondi, Dr. Yong Hoon Kim, and Dr. Balakumar Balasingam at the University of Windsor. The result will be contributed to the graduate students' theses. The study is sponsored by Social Sciences and Humanities Research Council of Canada (SSHRC).

If you have any questions or concerns about the research, please feel to contact any of the following Investigators:

Mr. Niloy Talukder (Civil and Environmental Engineering), Email: talukdern@uwindsor.ca, Phone: (226) 246-9586

Dr. Chris Lee (Civil and Environmental Engineering), Email: cclee@uwindsor.ca, Phone: (519) 253-3000 Ext. 2544

Dr. Francesco Biondi (Kinesiology), Email: francesco.biondi@uwindsor.ca, Phone: (519) 253-3000 Ext. 2444

Dr. Yong Hoon Kim (Civil and Environmental Engineering), Email: yonghoon.kim@uwindsor.ca, Phone: (519) 253-3000 Ext. 2536

Dr. Balakumar Balasingam (Electrical and Computer Engineering), Email: singam@uwindsor.ca, Phone: (519) 253-3000 Ext. 5431

PURPOSE OF THE STUDY

Partial driving automation involves both manual and autonomous driving. However, operating partial driving automation will make drivers pay less attention to driving and it may delay drivers' reaction when they are requested to take over the control of vehicle followed by automated driving (this is called the system disengagements). Consequently, their collision risk is likely to be higher at the time of the system disengagements. The goal of this project is to examine the potential effects of different warning strategies on drivers' take-over time and driving performance after the system disengagement.

PROCEDURES

1) You enter the lab and are briefed about the experimental setup, tasks to be performed and the purpose of research and are asked to sign a consent form which will be provided in advance.
2) You are assigned an Experiment ID.
3) You will watch the simulated driving automation and also test drive the driving simulator for 4-5 minutes. After the test drive, you will be asked whether you feel comfortable in the simulated traffic environments.
4) If you feel comfortable, you can proceed to participate in the driving simulator experiment. Otherwise, you can withdraw from the experiment.
5) You will have an option to leave your e-mail addresses if you wish to receive the reports on the results of the driving simulator experiment.

The total time required to complete the procedure is 1.5 - 2 hours.

POTENTIAL RISKS AND DISCOMFORTS

You may feel temporary motion sickness during the driving simulator experiment. To reduce this risk, if you are prone to motion sickness or dizziness due to pre-existing condition, you should not participate in this experiment. If you are taking the Investigators' courses at the time of the experiment, you may have misconception that your participation will have a positive or negative impact on his evaluation of your performance in the courses. Therefore, you are advised that the participation is voluntary, and you would not get any advantage or disadvantage in their course evaluations due to your participation in this study.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

You will learn how engineering and psychological measures can be used to understand the effects of partial automation on driver's cognitive load and safety. Your participation in this study is essential for observing actual driver behavior during the system engagements. As partially automated vehicles will be prevalent in the future, this study will help understand safety impacts of partially automated driving and develop strategies to improve driver safety.

COMPENSATION FOR PARTICIPATION

You will be paid $20 in cash. If you do not complete the study, the compensation will be prorated based on the amount of time you engage in the study.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission.

PARTICIPATION AND WITHDRAWAL

You can request withdrawal from the project at any time. Upon withdrawal from the research, your data will be deleted. Furthermore, you shall not bear any consequences as a result of the withdrawal. You will still be paid even if you do not complete the experiment. However, you cannot request withdrawal of your data after you accept the compensation and leave the lab.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE PARTICIPANTS

A summary report of the research findings will be sent to you by e-mail if you request. The report will be available on the REB website at https://scholar.uwindsor.ca/research-result-summaries/ in December 2021.

SUBSEQUENT USE OF DATA

These data may be used in subsequent studies, in publications and in presentations.

RIGHTS OF RESEARCH PARTICIPANTS

If you have questions regarding your rights as a research participant, contact: Research Ethics Coordinator, University of Windsor, Windsor, Ontario, N9B 3P4; Telephone: 519-253-3000, ext. 3948; e-mail: ethics@uwindsor.ca

SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I understand the information provided for the study “Developing warning strategies to reduce takeover time and improve post takeover performance in Level 3 automated driving” as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Participant

____ ______________________

Signature of Participant Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

____ ______________________

Signature of Investigator Date

Appendix B

REB Approval

Tue 2021-08-31 11:20 AM
To: Chris Lee <cclee@uwindsor.ca>; Francesco Biondi <Francesco.Biondi@uwindsor.ca>; Yong Hoon Kim <YongHoon.Kim@uwindsor.ca>; Bala Balasingam <Balakumar.Balasingam@uwindsor.ca>
Cc: ETHICS <ethics@uwindsor.ca>

August 31, 2021

Our File No: **36244**
Project Title: **REB# 19-147: "Effect of partially-automated driving on driver cognitive load: Developing warning strategies to minimize collision risk"**
Status: **Active**

Dear Dr. Lee,

Thank you for submitting your request to revise for "REB# 19-147: "Effect of par ally-automated driving on driver cognitive load: Developing warning strategies to minimize collision risk"".

This request has been reviewed and you are now cleared to proceed with the proposed modification on of the procedures and the inclusion of a new student investigator.

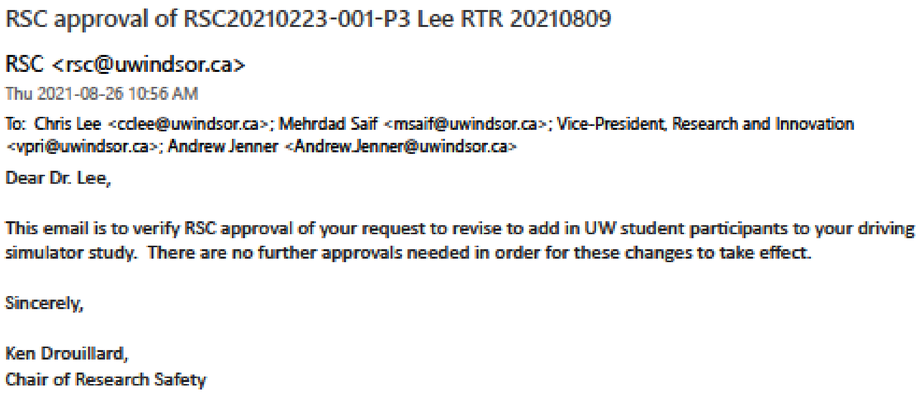
If we can be of any further assistance, please do not hesitate to contact our office.

Sincerely,

Suzanne McMurphy, Ph.D., MSS, MLSP
Chair, Research Ethics Board
University of Windsor
2146 Chrysler Hall North
519-253-300 ext. 3948
Email: ethics@uwindsor.ca

Appendix C

RSC Approval



RSC approval of RSC20210223-001-P3 Lee RTR 20210809

RSC <rsc@uwindsor.ca>

Thu 2021-08-26 10:56 AM

To: Chris Lee <cclee@uwindsor.ca>; Mehrdad Saif <msaif@uwindsor.ca>; Vice-President, Research and Innovation <vpri@uwindsor.ca>; Andrew Jenner <Andrew.Jenner@uwindsor.ca>

Dear Dr. Lee,

This email is to verify RSC approval of your request to revise to add in UW student participants to your driving simulator study. There are no further approvals needed in order for these changes to take effect.

Sincerely,

Ken Drouillard,
Chair of Research Safety

Appendix D

Calculation details of R^2 for Generalized Linear Model

For any linear regression, R^2 is a highly recommended metric to measure the model's performance. The R^2 value helps to understand how close the data is to the fitted regression line. The range of R^2 value is from 0 to 1 where the value closer to 1 indicates better model fit. The R^2 is calculated using the following equation:

$$R^2 = 1 - \frac{SSE}{SST}$$

(SST = Total variance in data,
SSE = Unexplained variance)

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}$$

where n is the sample size, $\hat{y}$ is the predicted TTC, y is the observed TTC and $\bar{y}$ is the mean of the observed TTC. Sample calculation of R^2 of the GLM for minimum TTC during the Lane change scenario is shown as follows:

$$R^2 = 1 - \frac{119.9801}{205.8330}$$

$$R^2 = 0.4171$$

VITA AUCTORIS

NAME:	Niloy Talukder
PLACE OF BIRTH:	Chittagong, Bangladesh
YEAR OF BIRTH:	1994
EDUCATION:	Ahsanullah University of Science and Technology, Dhaka, Bangladesh (2013-2017) B.Sc. Civil Engineering.
	University of Windsor, Windsor, ON, Canada (2020-2022) M.A.Sc. Civil and Environmental Engineering