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Assessing drivers' response during automated driver support system failures with non-driving tasks

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ABSTRACT

Introduction: With the increase in automated driver support systems, drivers are shifting from operating their vehicles to supervising their automation. As a result, it is important to understand how drivers interact with these automated systems and evaluate their effect on driver responses to safety critical events. This study aimed to identify how drivers responded when experiencing a safety critical event in automated vehicles while also engaged in non-driving tasks. *Method:* In total 48 participants were included in this driving simulator study with two levels of automated driving: (a) driving with no automation and (b) driving with adaptive cruise control (ACC) and lane keeping (LK) systems engaged; and also two levels of a non-driving task (a) watching a movie or (b) no non-driving task. In addition to driving performance measures, non-driving task performance and the mean glance duration for the non-driving task were compared between the two levels of automated driving. *Results:* Drivers using the automated systems responded worse than those manually driving in terms of reaction time, lane departure duration, and maximum steering wheel angle to an induced lane departure event. These results also found that non-driving tasks further impaired driver responses to a safety critical event in the automated system condition. *Conclusion:* In the automated driving condition, driver responses to the safety critical events were slower, especially when engaged in a non-driving task. *Practical application:* Traditional driver performance variables may not necessarily effectively and accurately evaluate driver responses to events when supervising autonomous vehicle systems. Thus, it is important to develop and use appropriate variables to quantify drivers' performance under these conditions.

1. Introduction

The general goal of automation is to improve comfort and safety (Endsley, 1996; Fukunaga, Rabideau, Chien, & Yan, 1997; Scheding, Dissanayake, Nebot, & Durrant-Whyte, 1999; Sheridan, 1992). Specific to the automotive context, automated driver support systems (DSSs) aim to make the driving task more comfortable, efficient, and safe for drivers (Bishop, 2000). Several types of such DSSs have been or are being developed by vehicle manufacturers, some examples being adaptive cruise control (ACC) and lane keeping (LK) systems. ACC is designed both to maintain a constant vehicle speed and, more importantly, to reduce it when approaching a slower leading vehicle (Xiong, Boyle, Moeckli, Dow, & Brown, 2012), while a LK system controls the lateral position of the vehicle within a lane (Stanton & Young, 2000). When these two systems are engaged, both the longitudinal and lateral positions the vehicle are controlled.

Many studies have documented that the out-of-the-loop problem induced by the implementation of automation, resulting in impaired performance when operators regain control of the systems because of unexpected automation failures (Saffarian, De Winter, & Happee, 2012; Wickens, Hollands, Banbury, & Parasuraman, 2013; Wiener & Curry, 1980). Being out-of-the-loop, operators are less likely to monitor the functioning of the system, losing situational awareness of both it and their surroundings (Bailey & Scerbo, 2007; Parasuraman & Manzey, 2010). This conclusion was supported by earlier research conducted by Endsley (1996), who analyzed several airplane crashes, finding the human operators were not aware of the critical features of the systems they were supervising. One potential explanation for this lack of awareness is that operators experiencing automation complacency may reallocate their attention from supervising the automation to other non-safety tasks (Parasuraman & Manzey, 2010). Further, research has found that the level of automation has an impact on operator behavior consequences (Curry & Weiner, 1980; Kessel & Wickens, 1982; Rasmussen, 1981). This inevitable redefinition of operator roles from controlling operators to supervisors of automated systems results in operators having less situation al awareness and lower response rates to unexpected system failures (Endsley & Kiris, 1995). For example, it has been found that pilots working with high levels of automation were more likely to lose track of their current status and become absorbed in other tasks and thus were out-of-the-loop (Bergeron,

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1981; Endsley & Kiris, 1995). Similar results have been found in the ground surface transportation domain for drivers using both the ACC and LK systems: they were more apt to be engaged in such non-driving tasks as drinking, texting/e-mailing, and other risky behaviors like extended glances off the forward roadway than when they were using only ACC (Llaneras, Salinger, & Green, 2013).

Recently, a National Highway Traffic Safety (NTHSA) report has defined a continuum of five levels of automation, ranging from level 0 (i.e., manual driving) to level 4 (i.e., fully autonomous vehicles; Blanco et al., 2015). Automation at level 1 (L1) assumes limited control from the primary controls of the vehicles. Drivers in level 2 (L2) automated vehicles cede multiple controls of the vehicle to automated systems in certain limited situations but drivers are required to supervise the function of the automated systems and are expected to regain control of the vehicles when required. Vehicles at level 3 (L3) automation allow drivers to cede full control of the vehicle to the automation and require that drivers take control of the vehicle occasionally, but with sufficient transition time. Drivers in level 4 (L4) automated vehicles are not expected to be available for controlling the vehicles at any time during the trips. That is, the vehicle performs all safety-critical driving functions. Thus, based on these definitions, the vehicle are at L1 if only one subsystem (e.g., ACC) is engaged and the vehicles at L2 have multiple (e.g., both the ACC and LK systems) engaged.

An increasing amount of research has focused on drivers' interaction with L1 automated vehicles with the ACC engaged (e.g., Merat, Jamson, Lai, & Carsten, 2012; Xiong et al., 2012) and L2 with both the ACC and LK systems engaged (e.g., Desmond, Hancock, & Monette, 1998; Shen & Neyens, 2014). For example, Rudin-Brown and Parker (2004)found that drivers who engaged the ACC had longer reaction times to the leading vehicle's brake lights than those who manually controlled their vehicles. More recently, Bato and Boyle (2011) and Xiong et al. (2012) found that risky drivers were more likely to report not only setting higher speeds when using ACC but also believing this system could function in some situations when it may not (e.g., when approaching a stationary vehicle or object). Drivers who did not understand the limitations of ACC were more likely to exhibit dangerous behaviors compared to those who were aware of the ACC limitations (Dickie & Boyle, 2009). Merat et al. (2012) found that in the absence of a non-driving task, the differences in driver responses to a potential forward collision between driving manually and driving with the ACC were not detectable; however, when engaged in a non-driving task, the responses to a potential forward collision of drivers who used the ACC were worse than their peers who manually controlled the vehicles. While the use of ACC has seen much research, few studies have focused on evaluating the effects of the malfunction (i.e., failure) of the LK system on driver responses to lane departure events, especially when drivers are in the vehicles at L2 and also engaged in a non-driving task. In one such study, Desmond et al. (1998) found that the drivers' lateral control of the vehicle was impaired when wind gusts simulated the drift of the vehicles with the failure of the LK system compared to the drivers with manual control.

When driving with the ACC and LK systems engaged, both the longitudinal and lateral positions are controlled by automation. In this context, drivers are functioning at a higher level of automation (L2) than when only the ACC is engaged (L1), with which only the longitudinal position of the vehicle is controlled by automation. As mentioned earlier, drivers are using both the ACC and LK systems, they are more willing to be involved in non-driving tasks or engage in risky behaviors compared to when they were driving with only the ACC engaged (Llaneras et al., 2013). Thus, it is reasonable to predict that the drivers' involvement in a non-driving task with both the ACC and LK systems engaged would exacerbate their behaviors during unexpected failures of the DSSs.

One common non-driving task is driver interactions with audiovisual entertainment systems such as in-vehicle video players, which are becoming increasingly popular devices in the United States (TI, 2001). Though the United States bans the use of screens not designed to assist drivers mounted within their fields of view, it is still possible that an in-vehicle display may be added to the center console after a vehicle is purchased (Young, Lee, & Regan, 2008, chap. 12). Past research has found that the performance of drivers manually controlling their vehicles has the potential to degrade (e.g., slower reaction times) when they watch movies (Funkhouser & Chrysler, 2007; Hatfield & Chamberlain, 2005; Knutsson, 2003; White et al., 2006). As drivers have lower driving demands when supervising the functions of the automated systems and it is not necessary for them to provide continuous inputs to the automated vehicles, the tendency to engage in such non-driving tasks (e.g., using attached or mobile equipment) may increase in highly automated vehicles (e.g., L2 automated vehicles; Kun, Boll, & Schmidt, 2016). Thus, it is of great importance to understand drivers' behaviors in L2 automated vehicles when they attend to non-driving tasks that result in eyes-off the road.

While several studies have evaluated the effects of the malfunctions (i.e., failures) of the ACC or the LK systems on drivers' behaviors, there is limited research on the effects of the failures of the LK systems on behavior when drivers are involved in a non-driving task. To address this issue, one of the objectives of this study was to investigate drivers' behaviors in L2 automated vehicles when the longitudinal and lateral positions of the vehicle were controlled. Moreover, this study aimed to evaluate driver responses to lane departure events (following the failure of the LK system) in L2 automated vehicles especially when they were engaged in a non-driving task. Finally, the relationship between drivers' characteristics and attitudes towards automation and their responses to a safety critical event in the L2 automation condition was also investigated.

2. Method

2.1. Participants

Fifty-five native English speakers who had valid U.S driver's licenses for at least one year and drove at least three times per week participated in this study. Of these, seven participants were excluded from the analysis as two failed to respond to the safety critical events during an automated system failure, four experienced experimental errors, and one withdrew due to experiencing simulator sickness during the experiment. Therefore, the final sample totaled 48 participants, 24 males and 24 females between the ages of 18–25 ($M = 21.17$, $SD = 1.91$). Only one of these had previously used the ACC and LK systems.

2.2. Apparatus

The study was conducted using a National Advanced Driving Simulator (NADS) MinSim maintained by the Ergonomics and Applied Statistics Laboratory at Clemson University. A more detailed description of the standard NADS MinSim can be found in Xiong et al. (2012). The 7-inch LCD monitor used as the in-vehicle display was attached to the right of the steering wheel, with its center being approximately 3 cm from the top and 25 cm from the center of the dashboard display. The angle of this in-vehicle display could be adjusted by the participants as needed.

2.3. Procedure

Upon arrival to the lab, the participants were given a brief introduction to the experiment and completed an informed consent approved by Clemson University (IRB# IRB2014-398). As some components of the non-driving task required color vision, the participants' color vision was assessed using Ishihara color blindness test plates. Next, the participants were given a more detailed overview to this experiment. The participants in the higher level of automation condition were also instructed on how to use the ACC and LK systems, including how to stop their functioning. In addition, while they were instructed to keep