Accident Analysis and Prevention 108 (2017) 9–18

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Coming back into the loop: Drivers' perceptual-motor performance in critical events after automated driving

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ARTICLE INFO

Keywords:
Driver behaviour
Automated driving
Situation awareness
Reaction time
Critical event kinematics

ABSTRACT

This driving simulator study, conducted as part of the EU AdaptIVe project, investigated drivers' performance in critical traffic events, during the resumption of control from an automated driving system. Prior to the critical events, using a between-participant design, 75 drivers were exposed to various screen manipulations that varied the amount of available visual information from the road environment and automation state, which aimed to take them progressively further 'out-of-the-loop' (OoTL). The current paper presents an analysis of the timing, type, and rate of drivers' collision avoidance response, also investigating how these were influenced by the criticality of the unfolding situation. Results showed that the amount of visual information available to drivers during automation impacted on how quickly they resumed manual control, with less information associated with slower take-over times, however, this did not influence the timing of when drivers began a collision avoidance manoeuvre. Instead, the observed behaviour is in line with recent accounts emphasising the role of scenario kinematics in the timing of driver avoidance response. When considering collision incidents in particular, avoidance manoeuvres were initiated when the situation criticality exceeded an Inverse Time To Collision value of $\approx 0.3\ \mathrm{s}^{-1}$. Our results suggest that take-over time and timing and quality of avoidance response appear to be largely independent, and while long take-over time did not predict collision outcome, kinematically late initiation of avoidance did. Hence, system design should focus on achieving kinematically early avoidance initiation, rather than short take-over times.

1. Introduction

The advent of automated vehicles promises a number of benefits, including an increase in the flow and capacity of the road network (Kesting et al., 2008; Ntousakis et al., 2015), a wide range of economic benefits (Fagnant and Kockelman, 2015), an increase in shared mobility (Fagnant and Kockelman, 2015), and a reduction in energy consumption (Anderson et al., 2014). Many of these forecasts have received a great deal of attention in recent years, including those predicting that vehicle automation will result in a reduction in road traffic accidents (Bertoncello and Wee, 2015).

The aim of partial (SAE, 2016; Level 2; L2) automated driving systems is to relieve drivers of the moment-to-moment demands of the control (lateral and longitudinal), yet not supervision, of the driving task. In conditional (SAE Level 3; L3) automated driving systems, drivers can relinquish both control and supervision of the driving task. However, drivers are still expected to be responsible for the safety of the vehicle when operating these systems, and should be available to resume manual control, should the system reach some limit, for example, due to poorly marked lane boundaries. During automated driving, drivers may shift their attention away from information relevant to the driving task, for instance, the traffic environment or the status of the automated driving system, to one of a range of non-driving related activities (Carsten et al., 2012). This shift in attention potentially impairs drivers' ability to perceive, comprehend, and predict events in the road scene, diminishing their situation awareness (SA) (Endsley, 1995; De Winter et al., 2014). A key human factors concern regarding L2 and L3 systems is that drivers with deteriorated SA may be ill-prepared to regain the attention and motor control necessary to safely navigate the vehicle, if a system limit is reached and manual intervention (or 'take-over') is required; an issue often referred to as the out-of-the-loop (OoTL) performance problem (Endsley and Kiris, 1995).

There is evidence to suggest that the non-driving related task drivers engage in during automation may affect how quickly moreover, safely they can resume control (Gold et al., 2013; Zeeb et al., 2015; Radlmayr et al., 2014; Merat et al., 2014; Louw et al., 2015a,b), though there is little consensus. For instance, Merat et al. (2012) compared drivers' responses to critical incident scenarios, while engaging in a verbal "20

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http://dx.doi.org/10.1016/j.aap.2017.08.011
Received 22 February 2017; Received in revised form 4 August 2017; Accepted 7 August 2017
0001-4575/

Questions Task" (TQT). Compared to when drivers were not engaging in the TQT, the TQT had no effect on how long it took drivers to start the lane change, but it did affect their ability to reduce the vehicle's speed to a safe level quickly. In contrast, Neubauer et al. (2012) found that drivers engaging in a mobile phone conversation during a take-over, had shorter brake reaction times to a lead vehicle, compared to those who were not engaging in a mobile phone conversation. This lack of consensus is not surprising as studies have employed different experimental traffic scenarios (Naujoks et al., 2014; Radlmayr et al., 2014), with varying time-budgets (Gold et al., 2013; Damböck et al., 2012; van den Beukel and van der Voort, 2013), and human–machine interfaces (HMI), and in simulators of varying degrees of fidelity. As non-driving related tasks demand different levels of drivers' visual attention, it is important to compare the effect of a range of tasks.

In this study, conducted as part of the EU AdaptIVe project, we aimed to systematically take drives OoTL, by applying a number of screen manipulations that, to varying degrees, limited the amount of system and environmental information available to drivers during automation, before presenting critical and non-critical take-over events. During these events, instead of a 'take-over request', we used an 'uncertainty' alert, which required drivers to monitor the road scene and determine whether there was a need to resume control from automation. These manipulations were introduced by Louw et al. (2015a,b, 2016) and Louw and Merat (2017), and are detailed further below. Previously, we showed that, during automated driving, drivers' eye-gaze concentration was differentially affected by the OoTL manipulations (Louw and Merat, 2017), as was the location of drivers' first eye-fixations in the road scene, after the manipulations ceased (Louw et al., 2016). However, these differences resolved within 2 s of the manipulations ceasing. While these studies have illustrated how vehicle automation affects drivers' visual attention when 'coming back into the loop', precisely whether and how the degree of visual information available to drivers during automation affects their perceptual-motor performance during the take-over is not clear, nor is what constitutes 'good' performance, in this context. This study aimed to investigate these issues.

A number of measures and metrics have been used to study drivers' take-over process once they have resumed control, including time to hands-on the steering wheel (Zeeb et al., 2015), time to disengage automation (take-over time; Damböck et al., 2012; Gold et al., 2014; Zeeb et al., 2015, 2016), reaction time to an obstacle (Neubauer et al., 2012), first gaze to the road centre (Gold et al., 2013; Louw et al., 2016). Take-over time in particular has been used widely to judge driver performance during the resumption of control (for a review see Eriksson and Stanton, 2017). However, we have previously argued that take-over time measures may not be the most appropriate indicator of drivers' preparedness for, or appreciation of the unfolding situation (Louw et al., 2015a,b), as drivers could simply be reacting to take-over requests (TOR) from the system. Indeed, as reported in studies on braking behaviours in manual driving, there exists a driver-related delay between initial brake application and full emergency braking (Ising et al., 2012; Hirose et al., 2008; Perron et al., 2001; Kiesewetter et al., 1999; Yoshida et al., 1998). Therefore, the current study analysed not only drivers' take-over time, but also, the time it takes for them to react to a threat in the road environment, as was considered by others, such as Petermeijer et al. (2017).

While understanding the timing (Gold et al., 2013) and sequence (Zeeb et al., 2016) of behaviours during the take-over is important, there is also a need to understand whether, and how, automation affects the *quality* of drivers' vehicle control following a take-over, as drivers do not mitigate all risk just by resuming control or initiating a manoeuvre. Quality of vehicle control has previously be described by vehicle-based measures, such as maximum accelerations during vehicle control in the transition (Gold et al., 2013; Zeeb et al., 2015; Hergeth et al., 2016), minimum Time To Collision (TTC; Gold et al., 2013; Louw et al., 2015a,b), minimum time headway to an obstacle (Merat and Jamson, 2009; Merat et al., 2014; Louw et al., 2015a,b). However, their interpretation is often constrained to the particular scenario under investigation. Therefore, to provide scenario-independent measures of drivers' capabilities for vehicle control, and thus take-over quality, a possible solution is to analyse drivers' responses in relation to the kinematics of an unfolding situation, i.e. the criticality at the point at which they respond. Inverse Time To Collision (invTTC), for example, is a measure that accounts for the visual looming effect of a braking lead vehicle (Lee, 1976; Summala et al., 1998; Groeger, 2000; Kiefer et al., 2003, 2005), and is an important crash risk indicator (Kondoh et al., 2008). The looming argument is closely related to the tau hypothesis. Inverse tau is the ratio between the lead vehicle's optical expansion rate on the driver's retina, and its optical size, therefore, describing visual looming. Inverse tau is simply a visually available estimate of invTTC (Lee, 1976), though the latter was used in the current paper due to it being easier to calculate.

Victor et al. (2015) and Markkula et al. (2016) used this measure to show that a majority of drivers involved in naturalistic crash and near-crash scenarios during manual driving, reacted within 1 s of the kinematic urgency of the scenario, reaching values of invTTC $\approx 0.2\,s^{-1}$, which suggests that the *timing* and *response rate* of drivers' initial response appears to be anchored to the criticality of the unfolding event. Based on their findings, Markkula et al. (2016) proposed that how drivers make use of and act on visual looming information from a lead vehicle in manual driving may also explain drivers' response processes when suddenly brought back into the control loop in automated driving. Some evidence of this in automation may be found in an extended interpretation of the work of Gold et al. (2013). The authors found that drivers who were given longer time budgets in a take-over scenario took longer to intervene. However, it may be that the visual looming effect played some part in when drivers decided to intervene, and the current paper seeks to investigate this in more detail. If not being in physical vehicle control due to automation causes a mismatch between drivers' internal model of a vehicle's dynamics and the actual vehicle dynamics (Russell et al., 2016), then their ability to respond in manner that is appropriate for the criticality of the situation in hand may be impaired (cf. Fajen and Devaney, 2006; Fajen, 2008; Markkula et al., 2016).

The current study sought to evaluate this hypothesis, by analysing the timing and rate of drivers' responses (i.e. how fast they move brake pedal and steering wheel) in relation to the kinematics of the unfolding situation, and how this interacts with the degree of visual information available to drivers pre-take-over.

We hypothesised that drivers deprived of all visual information from the system and road environment would be furthest OoTL and, therefore, take-over control later and have the least consistent perceptual-motor control, than those who performed visual and non-visual tasks pre-take-over. However, drivers who had access to all visual information during automation were hypothesised to be the most in the loop and would, therefore, take-over control the earliest and have the most consistent perceptual-motor control during the transition.

2. Methods

2.1. Participants

Following ethical approval from the University of Leeds Research Ethics Committee (Reference Number: LTTRAN-054, seventy-five drivers (41 male), aged 21–69 years ($M = 36$, SD = 12) were recruited via the participant database of the University of Leeds Driving Simulator (UoLDS) and were reimbursed £20 for participation. Participants had normal or corrected-to-normal vision. Their average annual mileage was 8290 miles (SD = 6723), and all participants had held a full driving licence for at least three years ($M = 16$, SD = 12) and drove at least twice a week. Participants details for each group are displayed in Table 1.