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Transition to manual: Comparing simulator with on-road control transitions

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ABSTRACT

Background: Whilst previous research has explored how driver behaviour in simulators may transfer to the open road, there has been relatively little research showing the same transfer within the field of driving automation. As a consequence, most research into human-automation interaction has primarily been carried out in a research laboratory or on closed-circuit test tracks.
Objective: The aim of this study was to assess whether research into non-critical control transactions in highly automated vehicles performed in driving simulators correlate with road driving conditions.
Method: Twenty six drivers drove a highway scenario using an automated driving mode in the simulator and twelve drivers drove on a public motorway in a Tesla Model S with the Autopilot activated. Drivers were asked to relinquish, or resume control from the automation when prompted by the vehicle interface in both the simulator and on road condition.
Results: Drivers were generally faster to resume control in the on-road driving condition. However, strong positive correlations were found between the simulator and on road driving conditions for drivers transferring control to and from automation. No significant differences were found with regard to workload, perceived usefulness and satisfaction between the simulator and on-road drives.
Conclusion: The results indicate high levels of relative validity of driving simulators as a research tool for automated driving research.

1. Introduction

Self-driving vehicles have gone from a futuristic dream to an engineering reality (Stanton, 2015), fuelled by Moore's law (Moore, 1965). Continued development of ADAS systems such as Anti-lock Braking, Automatic Emergency Brake (Banks and Stanton, 2017), Adaptive Cruise Control (Larsson et al., 2014; Seppelt and Lee, 2007; Stanton and Young, 2005; Young and Stanton, 2007), and Lane Keeping Assist (Ishida and Gayko, 2004; Young and Stanton, 2007) are introduced as standard features on many contemporary vehicles . Vehicle manufacturers are trying to combine these function specific assistance systems (NHTSA, 2013) into a holistic solution, called combined function assistance (NHTSA, 2013) or Highly Automated Driving (HAD). Examples of such technology emerging into the marketplace include 'Integrated Cruise Assist' (Bosch, 2015), 'Autopilot' (Tesla Motors, 2016), 'Intellisafe Autopilot' (Volvo Cars, 2016) and 'Highway Pilot' (Daimler, 2016). These systems automate both longitudinal and lateral aspects of driving, as well as automating some of the traditional decision-making tasks of the driver, such as anticipation of velocity reduction, monitoring lane position, and adherence to speed limitations (Banks et al., 2014; Kircher et al., 2014; Stanton et al., 1997; Stanton and Young, 2005). This is a form of "driver initiated automation", where the driver is in control of when the system is engaged or disengaged (Banks and Stanton, 2015, 2016; Lu and de Winter, 2015). Such HAD systems could enable the driver to become hands-free and feet-free (Banks and Stanton, 2014).

One of the main benefits of HAD is its potential for reducing the number of road traffic accidents. In 2010, NHTSA reported that the cost of motor vehicle crashes amounted to $242 billion per annum and 32,999 fatalities in the United States (Blincoe et al., 2015), and over 1.2 million fatalities worldwide (World Health Organization, 2009). Elon Musk, CEO of Tesla Motors stated that *"The probability of having an accident is 50% lower if you have Autopilot on. Even with our first version. So we can see basically what's the average number of kilometers to an accident – accident defined by airbag deployment. Even with this early version, it's almost twice as good as a person."*- Musk (2016). Furthermore, Ross (2016) showed that Tesla Autopi-

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lot maintains its distance to the lane centre more consistently than manual drivers. Whilst it remains to be seen whether HAD features can yield significant decreases in accident rates (Kalra and Paddock, 2016), it is estimated that HAD could greatly reduce societal costs such as medical, legal, emergency service (EMS), insurance administration and congestion costs, property damage, and workplace losses resulting from accident involvement (Blincoe et al., 2015). This could help progress towards the goal of the European Commission to halve the number of road deaths in the European Union by 2020 (European Commission, 2010).

Even so, HAD should not be viewed as a panacea in driving safety (Kalra and Paddock, 2016). HAD features are unable to cope with all possible driving scenarios. This was demonstrated by the recent Tesla incident where a vehicle crashed in to a trailer with the Autopilot engaged (Levin and Woolf, 2016). HAD features operate within strict functional limits and once these limits are reached, ceases to function effectively, if at all (SAE J3016, 2016; Stanton, 2015). Despite the good intentions of HAD, the sudden increase in demand resulting from a transition between HAD to manual control (De Winter et al., 2014; Stanton et al., 1997), could pose a significant problem for drivers of HAD vehicles as driving is a very demanding activity that comprises of over 1600 sub-tasks (Walker et al., 2015).

Human Factors research into automated driving has been ongoing since the mid–90 s (Nilsson, 1995; Stanton and Marsden, 1996). As the motor-industry advances toward HAD, research conducted in driving simulators will become ever more important (Boer et al., 2015). Driving simulators have the advantage of allowing the evaluation of driver reactions to new technology within a virtual environment without the physical risk found on roads (Carsten and Jamson, 2011; De Winter et al., 2012; Flach et al., 2008; Stanton et al., 2001; Underwood et al., 2011). It is widely accepted that driving simulation offers a high degree of controllability and reproducibility as well as providing access to variables that are difficult to accurately determine in the real world (Godley et al., 2002), such as lane position and distance to roadway objects (Santos et al., 2005; Van Winsum et al., 2000).

When evaluating the validity of a simulator, Blaauw (1982) distinguished between two types of simulator validity; physical and behavioural validity. Physical validity refers to the level of correspondence between the physical layout, the configuration of the driver cabin, components and vehicle dynamics in the simulator and a real world counterpart. Behavioural fidelity, or the correspondence in driver behaviour between the simulator and its on-road counterpart, is arguably the most important form of validity when it comes to the evaluation of a specific task (Blaauw, 1982). Behavioural fidelity can be further extended into absolute validity and relative validity. Absolute validity is obtained when the absolute size of an effect measured in a simulator is the same as the absolute effect measured in its on-road counterpart. Relative validity on the other hand describes how well the relative size, or direction of an effect measured in the simulator corresponds to real driving (Blaauw, 1982; Kaptein et al., 1996).

There is plenty of research the design of Human Machine Interfaces, driver errors and task load, very little of the research has demonstrated transfer from the simulated environment to the open road (Mayhew et al., 2011; Santos et al., 2005; Shechtman et al., 2009; Stanton et al., 2011; Stanton and Salmon, 2009; Stanton et al., 2001; Wang et al., 2010). Most of the research showing how drivers interact with highly automated vehicles outside of simulators have taken place on closed test tracks (Albert et al., 2015; Llaneras et al., 2013; Stanton et al., 2011). Only a minority of studies on HAD being performed on the road (Banks and Stanton, 2016). Those remaining studies have investigated sub-systems such as Adaptive Cruise Control (Beggiato et al., 2015; Morando et al., 2016) and Lane Keeping Assistance systems (euroFOT, 2012; Ishida and Gayko, 2004; Stanton et al., 2001). This means that there is a paucity of research into the relative validity of driver behaviour in simulated HAD vehicles. This lack of studies could be attributed to the costs and risks associated with non-professional drivers driving prototype vehicles (such as the Mercedes S/E-class and Tesla vehicles equipped with these features, for road testing (Mercedes-Benz, 2015; safecarnews.com, 2015; Tesla Motors, 2016)) Consequentially, most research into human-automation interaction has been limited to simulators (for a review on control transitions in the simulator see Eriksson and Stanton, 2017) or closed test tracks (e.g. Albert et al., 2015; Llaneras et al., 2013; Stanton et al., 2011). A disadvantage of testing on closed test track compared to on road testing is the reduced complexity and dissonance between driver behaviour on the track and normal on road driving as well as the lack of other road users.

The purpose of the research reported in this paper was to explore whether control transitions between automated driving and manual driving observed in a driving simulator study are similar to real-world driving. A recent meta-analysis found that drivers of manual vehicles (SAE Level 0) take approximately 1 s to respond to sudden events in traffic (Eriksson and Stanton, 2016). It was also found that drivers of "function specific automation" (ACC and assistive steering, SAE Level 1 and 2) took an additional 1.1–1.5 s to respond to a sudden automation failure and that drivers of HAD vehicles (SAE level 3) took on average 2.96 ± 1.96 s to respond to a control transition request leading up to a critical event, such as a stranded vehicle (Eriksson and Stanton, 2016). In contrast, Google (2015) reported that it takes their professional test drivers 0.84 s to respond to automation failures of their autonomous (SAE Level 4/5) prototypes whilst driving on public roads based on 272 discrete events. Moreover, the meta-analysis showed that the response time varies with the lead-time between the control transition request and a critical event. The reported lead times to the critical event at the point the request from manual control was issued varied between 2 and 30 s, and was 6.37 s on average. This is somewhat problematic as the SAE guidelines for level 3 automation states that the driver: *"Is receptive to a request to intervene and responds by performing dynamic driving task fallback in a timely manner"* (SAE J3016, 2016, p. 20). A decision to explore control transitions in non-urgent situations was made due to the lack of research into driver-paced transitions of control, which arguably is one of the more common use-cases for HAD control transitions, when for example leaving a highway.

2. Method

This paper is based upon the results of a two-phase between-participant research project. The first phase involved collecting times for control transitions within a simulated driving environment and the second phase collected the same data from the open road. The experimental design and procedure for each study are discussed in turn.

2.1. Phase 1

2.1.1. Participants

Phase one of the study used 26 participants (10 females, 16 males) between 20 and 52 years of age (Mean = 30.27 *SD* = 8.52) with a minimum one year driving experience (Mean = 10.57, *SD* = 8.61). This part of the study had been approved by the Southampton University ERGO ethics committee (RGO number 17771). Participants had no previous experience with ADAS systems.

2.1.2. Equipment

The study was carried out in a fixed based driving simulator located at the University of Southampton. The simulator was a full