Introducing Driverless Cars to UK Roads

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Handover Issues in Autonomous Driving:
A Literature Review

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Summary

The present review was undertaken to inform a workpackage of the Venturer Project undertaking studies into the handover of control between a human driver and an autonomous road vehicle.

The ‘handover problem’ arises as a feature of the development of autonomous vehicles that are “highly” but not “fully” autonomous (DfT, 2015). As human error is a major cause of road accidents, contributing to over 90% of road collisions, removing the human operator would likely reduce their incidence. (DfT 2015; Reason, Manstead, Stradling, Baxter, & Cambell, 1990). However, levels of automation which do not completely eliminate the role for a driver can themselves provide problems for the human operator (Stanton and Marsden, 1996; Parasuraman & Manzey, 2010; Parasuraman & Riley, 1997), due to required tasks such as ‘handover’.

Four potential types of error from automated driving systems are possible, with the present review focussing on the third and fourth:

1. shortfalls in expected benefits (e.g., object detection failure in collision avoidance system),
2. issues with reliability so that the driver loses trust and prefers to use manual controls,
3. loss of driving skills through lack of practice, leaving the driver dependent on the automated system, and
4. errors resulting from error-inducing equipment designs (e.g., the automated system selecting the wrong speed or distance for ACC, and including mode errors where the driver may believe they are in one mode but are in another).

The potential problem of trust has not been observed in empirical trials. However, there is support for the problem of ‘de-skilling’: whilst reduced cognitive load due to the application of autonomous features was associated with enhanced human driving performance, it also reduced ‘situational awareness’ such as might build up driver experience. This finding might need to be addressed by strategies to ensure sufficient driver exposure to maintain skills.

‘Handover’ typically refers to the staged period during which the AV transfers all controls to the driver (e.g., an alert to indicate imminent takeover required, a delay before manual controls are completely handed over), so that the vehicle can be driven manually, whereas ‘takeover’ tends to refer to the specific time when the driver has regained manual control of the vehicle and automated systems have been deactivated. Conditions that may impact performance include the number and type of critical incidents, traffic density, feedback, distraction, and fatigue (Merat & de Waard, 2014).

To date, handover studies have tended to involve simulator tasks of up to 90 mins duration, and to deploy high-annual mileage drivers, many of whom are experienced with simulator studies, as well as with real-world driving. Additional training is typically given on the simulated autonomous system. Generally, only one automated-to-manual handover event is included, towards the end of the experiment, involving the driver responding to a critical

event (e.g. queuing traffic, pedestrians crossing the road, changing traffic signals), with performance variously assessed in terms of response times, gaze behaviour, vehicle handling, cognitive load and situational awareness. Comparisons are made with paired manual driving conditions.

The work of Merat and her colleagues is particularly important in this area, with the following findings being key:

- Merat and Jamson (2009b): despite immediate response to the handover signal, braking in automated condition not as effective as in the manual condition due to reduced situational awareness.
- Merat et al. (2014): in simulator experiments at 70mph, 35-40 seconds were required for the human driver to achieve stabilised lateral control of the vehicle irrespective of whether handover from the AV and been planned or was in response to a critical event.
- Merat et al. (2012): responses to critical incidents was impaired if participants engaging in simulated automated driving had been performing a task unrelated to driving prior to the handover period.
- Jamson et al. (2014) – drivers in an automated condition showed 2% higher drowsiness than in the manual condition, an example of the influence of fatigue and stress on ‘hybrid’ driving performance.

In summary, most studies on this topic find a deficit in performance during handover from automated-to-manual mode and/or the period immediately following takeover.

In terms of future research, as significant difference of the Venturer Project activities with previous studies is its focus on *urban* environments. Therefore the long durations in simulated highway conditions of the established literature may limit its relevance and building knowledge about the extent to which there are differences between highway and urban driving is a key gap.

It is also important to explore behaviour and performance when handover is required multiple times throughout a driving scenario and to consider the performance of drivers with a range of age and driving experience, in the context that previous studies have generally used middle-aged participants who are highly experienced drivers, and in some cases experienced and trained for simulator studies.

In policy terms the current state of knowledge suggests there is a policy dilemma created by a technology which in aggregate promises to reduce the number of killed and seriously injured road users but also creates new types of risks involving the human driver, but with less certain liabilities. The need for motorists to remain vigilant in a driving environment with reduced stimulation may undermine one of the socioeconomic arguments in favour of road transport automation – that it enables more productive use of travel time – unless such point that full automation is achieved.

Introduction

The present review was conducted as part of a three-year study ‘Venturer: Driverless Cars on UK roads funded by the UK Government innovation agency Innovate UK. The review informed experimentation into the handover of driving control task between autonomous system and conventional human-driven (manual) mode. The experimentation was to involve initial studies with simulators followed by trials with an autonomous Bowler Wildcat vehicle.

The ‘handover problem’ arises as a feature of the development of autonomous vehicles which are “highly” but not “fully” autonomous (DfT, 2015): summarised as Level 3-4 and Level 5 in classifications of autonomised driving capabilities. The key distinction between high and full autonomy is that other than at Level 5, drivers do not need to engage with a range of tasks in the driving process when the autonomous mode is selected, but do need to be able to take control when tasks outside the capability of the autonomous system are encountered. A handover process is also required in the case that an autonomous system includes a procedure to for a human driver to be needed to take control in the case of malfunction or if unexpected circumstances arise. In these cases of unexpected handover, the process can be expected to occur in a context of crisis.

The article first considers work undertaken in recent decades (the ‘historical context’) before focussing on studies from the last five years (‘current research’ in which topics concerning the level of automation, the nature of handover studies (largely undertaken in simulator environments) and the influence of various variables on performance (driver engagement, feedback and support mechanisms, distraction, and fatigue and stress).

The focus of the Venturer study was the development of autonomous cars for urban areas. However, much of the literature focus has been on experimentation with longer-distance highway-environment driving; expected to be an early application of commercial automation in consumer-driven vehicles. Therefore in the final section the review turns to consider the research agenda particularly in the context of the more complex conditions encountered in urban areas compared with extraurban highways, but conditions which generally involve lower speeds, shorter distances and often shorter duration.

Historical Aspects

The level of automation within road vehicles has developed over the last decades, with a focus on comfort/driver fatigue (e.g. cruise control) and safety (e.g. antilock brakes, collision avoidance systems). These changes, together with improvements in roads and the driving environment, have resulted in a reduction in road deaths in Europe, despite increasing traffic density (Sweedler and Stewart 2009). The twenty-first century is seeing a shift away from raw performance towards enhanced intelligent driving systems including automation of driving controls and monitoring of the external environment, much like within aviation and nuclear domains (e.g., Hancock & Parasuraman, 1992). The UK Government has outlined a trajectory for the development of fully automated road going vehicles within 30 years, pointing out the benefits of reduced accidents as well as facilitating ‘productive’ use of the time currently spent driving (Department for Transport/DfT, 2015). The current review considers some key papers in the history of understanding the impact of automation on the driver, the current state of investigations with regards to assessing the handover from automated to manual control, and the need for future research to support and assist in the development of fully automated vehicles.

Although experimental studies of either highly or fully automated driving (HAD, FAD) are relatively recent, ergonomists and human factors psychologists have considered their impact on driving behaviour, as well as undertaking preliminary studies of single automated systems and devices such as adaptive cruise control (ACC) (e.g., Ma & Kaber, 2005; Stanton & Young, 2002, 2005; Rudin-Brown & Parker, 2004). Neville Stanton is perhaps one of the most prominent figures associated with assessing driver interactions with automated vehicles. An early review by Stanton and Marsden (1996) considered the links between aviation and driving, to establish what had been learned from the development of aviation autopilot systems that might be of benefit in the development of automated vehicles.

As human error is a major cause of road accidents, with over 90% of driving accidents due to human failures, removing the human operator would likely reduce accidents (DfT 2015; Reason, Manstead, Stradling, Baxter, & Cambell, 1990). Stanton points out that whilst it is assumed that automation may confer benefits for complex and dynamic systems it can itself provide problems for the human operator so that there are important limitations in the implementation of automation (Stanton and Marsden, 1996, and see also Parasuraman & Manzey, 2010, and, Parasuraman & Riley, 1997). A matrix is included plotting human performance on the X axis against machine performance on the Y axis with resulting regions that favour either human or machine control, as well as an intermediary area where either option may be suitable (Stanton and Marsden, 1996). This matrix approach for assessing human behaviour against driving demands may be a useful approach to handover evaluation, and will be discussed later on in the current review.

Four potential types of problems for driving automation are possible, including

- shortfalls in expected benefits (e.g., object detection failure in collision avoidance system),
- issues with reliability so that the driver loses trust and prefers to use manual controls,
- loss of driving skills through lack of practice, leaving the driver dependent on the automated system, and
- errors resulting from error-inducing equipment designs (e.g., the automated system selecting the wrong speed or distance for ACC, and including mode errors where the driver may believe they are in one mode but are in another).

Some important experimental studies followed. Stanton and Young (2005) carried out a simulator evaluation of ACC assessing workload in the form of traffic density against level of feedback provided in a between-subjects design, finding that locus of control and trust were unaffected, but that situation awareness (see Endsley 1995), workload and stress were reduced by ACC. A later paper by Young & Stanton (2007) focused on mental workload comparing performance against 4 levels of automation from manual to ACC combined with adaptive steering, assessing 4 groups of drivers from novices to advanced drivers using relatively short 10 minute drives for each condition. Increasing automation improved performance on a secondary visuo-spatial task that was not related to driving, suggesting that higher levels of automation provided greater levels of spare cognitive capacity and reduced mental workload. Higher levels of automation resulted in improved driving measures including lateral stability and headway, and reduced the gap between novice and more experienced drivers. Despite these improvements, the authors point out the potential hazard of learner drivers gaining insufficient experience in an automated vehicle to enable them to deal competently in an emergency situation involving manual control of the vehicle. Hence, both of these studies show benefits of vehicle automation through reduced workload, but also disadvantages in the form of reduced situation awareness and a reduction in important driver learning experience as a result automated driving.

These papers provided themes that have been carried forward into current research including the use of secondary, non-driving related distractor tasks in assessing the impact on handover from automated to manual control. The need for intermittent manual driving or other methods of maintaining driver engagement, or keeping them ‘in-the-loop’, and the use of feedback to improve driving performance and accident avoidance. Stanton and Marsden’s original 1996 review also emphasised the need to examine coordination and cooperation between the driver and automated systems if the potential benefits of automation are to be realised, and unforeseen risks avoided. This provides a clear signpost for the experimental evaluation of driver interactions with autonomous vehicles, and together with the matrix approach is carried forward into the proposal for future research.

Current Research

1. Levels of Automation and Handover

Despite more than two decades of research concerning driving behaviour and performance (e.g., Ma & Kaber, 2005; Nilsson, 1995; Seppelt & Lee, 2007; Stanton & Marsden; 1996; Stanton & Young, 2005; Young & Stanton, 2007), there has been little work involving more than one automated system operating simultaneously. Research involving highly or fully automated (HAD and FAD) (and therefore multiple systems) has however begun to emerge over the past five years or so (e.g., Merat & Jamson, 2009a; Merat & de Waard, 2014, and, Walker, Stanton, & Salmon, 2015). HAD tends to involve more than one automated system whereas FAD involves automation of all vehicle systems that a driver would otherwise be expected to control during manual driving (Merat & de Waard, 2014) and these definitions are closely aligned with industry-standard specifications of automation (e.g., Levels 2 and 3 – HAD, Level 4 – FAD: NHTSA, 2013). Recent research on HAD and FAD has been motivated by government technology and transport policies (e.g., within the UK and US) and been possible through the development of driving simulators with advanced automation capabilities (e.g., University of Leeds Driving Simulator/UoLDS, Southampton University

Driving Simulator/SUDS, BMW group). In this section, we critically review HAD and FAD studies with a key focus on the topic of handover issues in autonomous driving.

Much of the research on HAD and FAD has focussed on the handover phase between automated and manual driving with individual studies testing different conditions that may impact performance such as the number and type of critical incidents, traffic density, feedback, distraction, and fatigue (Merat & de Waard, 2014). 'Handover' typically refers to the period where the automated vehicle transfers all controls to the driver so that the vehicle can be driven manually, whereas 'takeover' tends to refer to the specific time when the driver has regained manual control of the vehicle. These terms are sometimes used interchangeably within the literature although the key distinction seems to be that handover can involve stages (e.g., an alert to indicate imminent takeover required, a delay before manual controls are completely handed over) whereas takeover is when the driver has regained control of the vehicle and automated systems have been deactivated (Merat & de Waard, 2014).

2. Key Similarities and Differences between Automated Driving Studies

There are a number of similarities and some differences between studies involving automated driving and handover behaviour and performance. Many adopt fairly long driving scenarios upwards of 90 minutes of mainly motorway driving (e.g., Jamson, Merat, Carsten, & Lai, 2013; Merat, Jamson, Lai, Daly, & Carsten, 2014; Merat, Jamson, Lai, & Carsten, 2012). Some that have employed shorter scenarios tend to also have lengthy practice phases (e.g., 40 minutes in a study by Neubauer, Matthews, Langheim, & Saxby, 2012). Many studies involve experienced (e.g., 10 years+ post-qualification) high annual mileage drivers (e.g., Merat et al., 2012) as well as those with previous experience of driving simulation studies (e.g., Gold, Damböck, Lorenz, & Bengler, 2013a; Gold, Damböck, Bengler & Lorenz, 2013b) including automated driving (e.g., Merat et al., 2014).

Most studies follow a relatively similar procedure. Typically, participants in autonomous conditions receive practice at automated driving followed by an experimental automated driving phase(s). This is followed by at least one automated-to-manual handover phase usually with the requirement to respond to one or more critical event(s) such as queuing traffic, pedestrians crossing the road, changing traffic signals, and so on. In many studies, this handover phase occurs once and towards the end of the driving scenario (e.g., Jamson et al., 2013; Merat et al., 2012, 2014; Neubauer et al., 2012). How participants respond to critical incidents (e.g., decision making, response times, gaze behaviour, vehicle handling) is compared between an autonomous condition (sometimes more than one) and manual condition. Some studies also examine global factors such as mental workload, situation awareness, and opinions towards the automated systems (Merat & de Waard, 2014).

3. Driver Engagement during Handover in Automated Driving

An early study by Merat and Jamson (2009b) examined the effects of lateral and longitudinal lane position automation deployed at a constant speed of 40mph on handover and takeover behaviour and performance. Forty participants took part and all had experience of driving simulation. Participants in the automated condition took control of the simulator in response to critical events involving oncoming vehicles turning suddenly, traffic signals changing, and pedestrians suddenly crossing the road. The simulator safely responded to some incidents (e.g., slowed down and/or stopped) and handed over control to participants for others: signalled by an auditory warning and followed by a brief takeover lag. Following handover, vehicle controls such as braking as well as anticipation time were slower in the automated than manual condition, especially in response to vehicles and pedestrians. Even though those in the automated condition started braking immediately after the auditory alert, the braking response was not as effective as in the manual condition. Merat and Jamson (2009b) concluded that performance impairments were mainly due to a loss of situation awareness, and recommended that frequent updates about the drive might support those ‘being driven’ to better remain in-the-loop and regain vehicle control in a safer manner (see also Walker et al., 2015). However, there were limitations. The automated system dealt with some but not all critical incidents and this may have increased the expectation that manual intervention was not always needed. This could have impacted the decision to brake and the efficiency of the brake response thereafter and also meant that automated and manual conditions were not balanced in terms of the number of critical incidents that had to be dealt with in manual mode. Nevertheless, this study paved the way for further studies involving automated driving and possible handover issues.

To further explore the loss of situation awareness hypothesis, Merat et al. (2014) examined behaviour and performance when handover occurred at regular intervals compared to when it was irregular and initiated in response to time spent looking away from the road. Forty-six experienced high annual mileage drivers (average of 27, 000 miles p/y) took part and were driven (automated condition) or required to drive (manual condition) at 70mph. Gaze patterns (measured with an eye tracker) towards the road ahead were higher and more stable in the regular handover condition whereas drivers in the irregular condition were more susceptible to fixating on environmental distractors. Following takeover, it took drivers a considerable 35-40 seconds to stabilise lateral control of the vehicle irrespective of being in the regular or irregular switch automated condition. Merat et al. (2014) stressed that most ‘real life’ handover situations are likely to be unpredictable and therefore future research is needed to determine how best to alert drivers of an imminent handover event so that situation awareness can be regained and manual driving takeover achieved more efficiently. Also, the particularly long lag required to stabilise the vehicle following takeover suggests that more of a stepped transition from automated to manual driving mode may be necessary even though in reality, might not always be possible, unless perhaps the vehicle decelerates immediately following initiation of handover.

Partial handover has recently been examined by Gold et al. (2013b). They previously demonstrated that the time required to efficiently regain manual control of an automated vehicle in response to a critical event – referred to as the total time budget (TTB) to re-engage in monitoring the road and to take action before an imminent incident – was increased over a non-autonomous condition (Gold et al., 2013a). The range was between 2.1 to 2.89 seconds, although they did not fully examine post-takeover performance beyond responding to critical incidents (e.g., as in the Merat et al., 2014 study). Gold et al. (2013b) tested 32

BMW Group employees and included two critical incidents within six driving scenarios and implemented 6 second TTBs with participants in automated driving conditions receiving optical and auditory monitoring alerts at the beginning of handover. Alerts involved instructing some participants to visually monitor the road ahead (visual condition) and others to do the same and place their hands on the steering wheel (motoric condition). Participants in a manual driving condition were faster to respond to critical incidents than those in automated conditions. Whilst there was a trend towards those in the motoric condition intervening 300ms faster in response to critical incidents than those in the visual condition, the difference was not significant. However, partial automation was perceived to be more comfortable and useful. However, driving speeds averaged more than 70mph even at the beginning of handover periods (as in Merat et al., 2014). Perhaps partial handover would have greater utility at lower speeds although this would also need to be explored within other environments such as urban and rural locations. However, optional selection of automation was found to increase distress and delay responses after takeover in a mixed driving environment (Neubauer et al., 2012). Also, and as in the Gold et al (2013a) study, it is crucial to examine performance with different TTBs and to examine possible interactions between these, driving speed, and road conditions. Finally, less than half of the participants in the Gold et al. (2013b) study had prior experience of driving simulation and the others had no experience. Ideally, this should be avoided to limit possible confounding practice effects.

4. Feedback and Support Mechanisms during Handover

Others have examined whether support mechanisms implemented during handover and trust in automated systems can effect a better transition from automated to manual driving modes. Lorenz, Kerschbaum, & Schumann (2014) tested 46 BMW Group employees and compared two augmented reality systems during handover: ‘system green’ displaying a safe driving corridor and ‘system red’ displaying an unsafe corridor. There were no differences between systems in terms of takeover time but reaction times to incidents were lower in the system green condition. However, and similar to the Gold et al. (2013b) study, almost half of the participants had no prior experience of using a driving simulator and those that did had no experience of automated driving simulation situations. Beller, Heeson, and Vollrath (2013) borrowed from military and aviation domains (e.g., Finger & Bisantz; McGurl & Sarter, 2006) and examined whether introducing a degree of uncertainty in automated systems as well as manipulating automation reliability can, somewhat counterintuitively, improve performance. These situations mimic, for example, when an automated vehicle has to negotiate extreme weather conditions such as fog or snow, as well as unpredictable road conditions like roadworks. Twenty-eight participants drove in situations of reliable and unreliable automation and half-experienced automation uncertainty manipulated using a visual warning symbol. As predicted, indicating possible automation failure (uncertainty) increased the time to collision in situations where automation failed. Also, participants in the uncertainty group had better situation awareness and trusted automated systems more than those in the condition where certainty was not manipulated. Findings from these studies suggest that system feedback during handover is likely to improve not only the efficiency in regaining manual control of the vehicle but also can increase acceptance of and trust in the automated system.

5. Effects of Distractions

If given the option, drivers engage in more non-driving related tasks during automated driving than in manual driving conditions (De Winter, Happee, Martens, & Stanton, 2014). This is perhaps of little surprise given that one of the potential benefits of automated vehicles is that drivers can engage in other tasks whilst being driven. However, many have warned of the dangers of automation in terms of misuse, overuse and abuse especially in situations where supervisory control of automated vehicle systems is sacrificed to engage in other tasks (Banks, Stanton, & Harvey, 2014; Parasuraman & Manzey, 2010; Parasuraman & Riley, 1997). Thus, another potential issue is when drivers are engaged in other non-driving related tasks when a handover situation occurs (Janssen & Kenemans, 2015).

Some studies have examined the effects of performing secondary non-driving related tasks on handover performance. Merat et al. (2012) tested 50 driving experienced high annual mileage drivers with some performing a twenty-question type secondary task prior to handover. Changes in cognitive workload were also examined by measuring variations in blink patterns to assess whether those engaged in the secondary task (‘eyes-off-the-road’) would blink less frequently when regaining control of the vehicle due to a narrowing of attention and increased cognitive demand. As in some other studies, responses to critical incidents were comparable in the automated and manual conditions but performance was impaired if participants in the automated condition had performed the secondary task prior to the handover period. Also, blink patterns were less regular in automated versus manual driving conditions and were especially suppressed during high cognitive workload periods. In a related study, Radlmayr, Gold, Lorenz, Farid, and Bengler (2014) investigated the effects of secondary tasks as well as driving conditions amongst 48 BMW Group employees (some with driving simulator experience). As predicted, higher driving density led to a longer time to take control (takeover) as well as reduced time to collision. Secondary tasks involved an auditory 2-back n-back in one condition (i.e., remember whether a current item is the same as one presented 2-items previously) and a visual Surrogate Reference Task (SURT) that measures response times to visually presented items in another condition. The key difference is that participants were able to keep their eyes on the road when performing n-back (‘mind-off-road’) but not when performing SURT (‘eyes-off-road’ and ‘mind-off-road’). Both tasks were suspended prior to handover and in response to an auditory takeover request (TOR) 7-seconds before potential impact with the crash site. Surprisingly, both secondary tasks had a similar effect on takeover efficiency, although there were more collisions in the SURT condition when traffic density was high. Radlmayr et al. (2014) highlighted that eyes-on-the-road during automated driving does not necessarily guarantee better situation awareness if the operator is mentally engaged in a cognitively demanding secondary task. Neither Merat et al. (2012) nor Radlmayr et al. (2014) varied the TTB (1500m/47.93 seconds and 7-seconds respectively) or driving speed at handover (70 mph and 74.5 mph respectively).

In another distraction study, Jamson et al. (2013) tested 49 participants in 90-minute FAD conditions and allowed voluntary engagement with in-car distractions such as radio and DVD systems. Automation resulted in longer journey times, as participants were less likely to take manual control to avoid traffic situations such as queuing. Participants were also more likely to engage with secondary tasks and take their eyes off the road in FAD conditions and this contributed to the tendency not to retake manual control. However, there was a general increase in attention to the road ahead in conditions of heavy traffic irrespective of the option to engage in distracting tasks. These findings suggest that even in automated driving conditions: the lure of engaging distractions may only take attention away from the road when drivers have faith in automated systems to function better than them (e.g., during low traffic density conditions), although this may not extend to conditions perceived to have a higher potential danger level such as when traffic density is high.

6. Driver State: Fatigue and Stress

Researchers have also begun to examine the effects of automation on driver state – such as fatigue and stress – that may impact behaviour and performance during a handover period. Rauch, Kaussner, Krüger, Boverie, & Flemisch (2009) were amongst the first to highlight the importance of assessing driver state amongst those operating HAD and FAD vehicles, and put forward recommendations for detection systems to support those showing signs of drowsiness to get back into the loop by adjusting to the appropriate level of automation. Jamson et al. (2014) measured drowsiness during automated driving using PERCLOS (PERcentage eyes CLOSed: Wierwille, Ellsworth, Wreggit, Fairbanks, & Kim, 1994) and found a 2% increase in driver fatigue in the automated versus manual condition. Neubauer et al (2012) conducted a study involving 190 participants and a 35-minute monotonous simulated drive (following 40-minutes practice) with a critical incident occurring during the last 5-minutes when the vehicle was in manual mode. Drivers who were fatigued prior to the study did not experience more or less fatigue and stress in the automated condition although were more likely to choose automated drive mode when given a choice. Also, those in the automated condition were slower to steer safely away from critical events, although this did not seem to be directly related to fatigue effects. Studies that included long drives (e.g., Merat et al. 2014) may also have been affected by driver sleepiness which is likely to occur with a 90 minute driving period (Alford, 2009).

Fatigue and stress thus have the potential to impair automated driving performance, although more research is required to investigate different degrees of fatigue as well as different levels of stress possibly induced by cognitive overload. Also, and to date, there has been little consideration of other driver state factors and individual differences that may also affect handover behaviour and performance during automated driving such as personality type, impulsivity, and risk taking.

7. Summary

There have been relatively few studies investigating HAD and FAD and effects on handover and those that exist tend to have been published over the past 5 years or so. However, there has been a recent surge of activity in this area with dedicated *Human Factors* (Vol 54-5, 2012) and *Transportation Research Part F* (27, 2014) journal special editions dedicated to vehicle automation with papers on topics such a driver engagement during handover in automated driving, effects of distractions and secondary tasks on handover, and fatigue and stress effects during automated driving. Most studies find a deficit in performance during handover from automated-to-manual mode and/or the period immediately following takeover although in some cases only when other factors were involved such as performing a secondary task prior to a handover period (e.g., Merat et al., 2012). Researchers have also begun to examine methods to better support safe and efficient transition from automated to manual driving mode, including stepped handover (e.g., Gold et al 2013b), feedback (Lorenz et al., 2014) and trust in the reliability of automated systems to perform efficiently all of the time (Beller et al., 2013). Each of the areas reviewed in this section represent pioneering work within the area although there is much left to do including follow-up studies as well as examination of factors that have yet to be considered. In the next and final section, we will consider such future directions.

Future Directions

Given that HAD and FAD are relatively new topics and that the literature on these topics spans such a short period of time, there are many existing areas that require further investigation as well as topics that have yet to be investigated. A number of these will be explored below.

In terms of existing literature, one key factor relates to the nature of the driving scenarios used within and between studies. Many have opted for long periods of automated driving mainly on motorway/freeway roads (e.g., Jamson et al., 2013; Merat et al., 2014, Merat et al. 2012) and of the few studies that have employed shorter drives, the scenarios tend to involve monotonous driving conditions (e.g., Neubauer et al., 2012). This is perhaps partly due to the expectation that most initial deployment of autonomous vehicles into the public domain will involve them being used on major rather than minor roads. However, Venturer is an example of an autonomous driving project where integrating fit-for-purpose vehicles into *urban* environments (e.g., city and town centres) is a key and important goal. Therefore, further studies examining human behaviour and performance in automated vehicles operating in environments other than motorways/freeways (e.g., city and town centres including higher traffic and pedestrian densities, rural roads, etc.), especially during handover and takeover periods, is required. This should also extend to situations involving shorter (e.g., less than 30 minutes) as well as longer drives with comparisons made within and between different driving environments. Driver sleepiness and its impact on handover as well as situation awareness should also be explored.

It is also important to explore behaviour and performance when handover is required multiple times throughout a driving scenario rather than only at the end of a scenario. This is important to establish whether frequent exposure to handover situations, perhaps representing practice effects as well as involving situation awareness updating, alleviates some of the performance deficits of switching between automated-to-manual modes reported in the literature to date (e.g., Jamson et al., 2013; Merat et al., 2012, 2014). Related to this, we also need to consider the effects of training in automated driving and in handover situations. Whilst all studies on HAD and FAD include a practice driving phase, this is often to provide participants with experience of driving systems and controls (e.g., Merat & Jamson, 2009; Merat et al., 2014) and/or other tasks that are included as part of specific studies (e.g., Merat et al., 2012; Radlmayr et al., 2012). It was noted earlier that some studies included some participants with experience of automated driving (e.g., Gold et al., 2013a, 2013b; Radlmayr et al., 2012) although effects of practice time/experience have not (to our knowledge) been examined.

In terms of newer topics, age and driving experience are factors that may directly impact behaviour and performance during and after a period of handover have not been explicitly examined. Most studies have tested mainly middle-aged participants with an average (mean) age of above 40 years (e.g., Merat & Jamson, 2009; Merat et al., 2012, 2014) and with a high degree of driving experience since qualifying as well as high average miles driven per year (e.g., Merat et al., 2012). Given that part of the policy debate around autonomy features the potential benefits to groups whose driving might be restricted through lack of experience and limited or declining skills, it is therefore important to consider and compare performance of younger less experienced drivers as well as older and very experienced drivers.

Finally, whilst there have already been important studies establishing the boundary conditions associated with partial handover of an automated vehicle to manual mode, these have largely focussed on factors such as TTB during a handover period (e.g., 7 seconds versus 9 seconds before risk of an incident: Gold et al., 2013a) as well as feedback and support mechanisms that may support the driver to regain situation awareness (e.g., Beller et al., 2014; Lorenz et al., 2013). We also need to consider trade-offs between TTB and the speed at which the automated vehicle is travelling when handover initiates. For example, how would behaviour and performance differ when driving at 70 mph with a TTB during handover of 7-seconds versus 5-seconds versus 3-seconds and how would this compare to situations involving the same TTBs but driving speeds of 60 mph, 50 mph, 40, mph, 30 mph and so on? Research into this is crucial so that ‘handover safety-curves’ and corresponding envelopes of safe operational parameters can be created.

Conclusion

In announcing the conditions under which highly autonomous vehicles should be commercially produced and marketed for use by the general public on UK public roads, the Department for Transport (DfT, 2015: para 4.14) argued that

> “Our definition of ‘highly automated’ makes clear that the vehicle has been designed from the outset to allow the driver to <u>disengage</u> from the driving task when in an

> automated mode. The driver cannot be expected to be monitoring the safe operation of the vehicle. The vehicle will therefore need to have been designed to alert the driver to a self-diagnosed failure, and if the driver does not resume control, to bring the vehicle safely to a stop" (emphasis added).

The present review emphasises that significant further research and technical development is necessary before such a view of the operating environment for highly-autonomous vehicles can be achieved, and more importantly, endorsed. Although largely beyond the scope of the knowledge review, it is noted that it is a substantial technical challenge for a vehicle in autonomous mode to be brought to a halt, before any collision arises, and after the control system has sought to engage a human driver, and failed, and for it to achieve this in every conceivable crisis event. This is a greater challenge than would be faced by a fully-autonomous control system which does not attempt to pass control back to human driver before safe failing.

And in terms of the normal operating environment, the current state of knowledge suggests there are some key policy tensions between what is expected of human drivers in high automation and the realities of 'part-time' driving. Findings to date suggest human driver performance is lower on taking control from an automated system than it would have been had the human been driving for the entire period, which suggests that handing back control to humans is best minimised. Potentially, such a strategy would influence both the market and the marketing of highly-autonomous vehicles: the high-income motoring enthusiast who might be expected to embrace early adoption of innovative automotive technology might be deterred if s/he is likely to be pressured by lawmakers and insurance companies to minimise active driving of the vehicle if that runs counter to public safety.

Moreover, performance is further deteriorated if tasks unrelated to driving were taking the attention of the human driver. In other words maximum human driver performance will only be achieved on takeover if s/he was in effect 'co-piloting' the vehicle in attention terms during the autonomous driving event. This is at odds with a key socioeconomic benefit identified by policy: to make available time regarded as wasted during the driving task for other, more productive activities. Hence, it is foreseeable that the roll-out of high automation will need to be accompanied with the advice that in some or all circumstances that the driver must maintain attention to the driving situation and that other activities should be minimised or avoided. The benefit in this case would only be in terms of physical comfort due to reduced need for driver inputs to the vehicle controls.

It is concluded that significant further research is required to understand the safety implications of high autonomy, and particularly so to address its potential application in urban areas. However, the literature to date is consistent with the view that many of the social and safety benefits will only be achieved with full automation. Hence, if automation is to be supported as a policy objective by governments then high automation involving handover should be viewed as a developmental stage to be minimised in the technological transition.

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