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Is drivers' situation awareness influenced by a highly automated driving scenario?

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Abstract

This paper presents results from a study conducted for the European FP6 project *CityMobil*. The experiment described here is part of four cross-site experiments designed to study the human factors issues associated with various degrees of automated driving. Thirty-nine drivers were asked to drive a simulated route with two zones in a within-subjects design, with a main factor of automation. Driver behaviour in "manual" driving, where all driving manoeuvres and decisions were made by the drivers, was compared to "highly automated" driving, where lateral and longitudinal control of the driving task was dictated by the "automated system". In this condition, drivers were asked to take their foot off the pedals and their hands off the steering wheel and allow the vehicle to be driven for them. Situation awareness in both driving environments was measured by computing drivers' response time to a series of unexpected/critical traffic events. Results showed that drivers' response to these events was significantly later in the highly automated condition, implying both reduced situation awareness and perhaps an excessive trust in the automated system.

Introduction

The driving task is becoming more and more automated and it is now possible for various aspects of driving to be controlled by a range of automation and assistance systems. Examples of such systems include Adaptive Cruise Control (ACC), Intelligent Speed Adaptation/Assistance (ISA) and Lane Keeping Assistance System (LKAS), as well as various collision warning and avoidance systems, which use radar detection devices. The idea behind the implementation of most such systems is that they will provide assistance and comfort to the driver, reducing the number of road accidents by increasing safety. Indeed, in the case of a highly automated driving scenario, there is no longer a need for the driver to be involved in the driving task, and his/her role moves from one of an operator to a system supervisor, simply monitoring the functioning of the automated vehicle. However, as suitably highlighted by McKnight & McKnight (2003), the task of maintaining a vehicle in the centre of the road and ensuring a steady speed are perhaps not the most difficult aspects of the driving task, and would indeed be relatively easy to achieve on an empty road, even by novice drivers. However, problems arise when the automated vehicle is required to interact with more complex road environments, as well as

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pedestrians and other road users, the (unpredictable) behaviour of which can result in unwanted and unsafe interactions with the automated vehicle. Since the devices currently available in the market are not capable of dealing with all such eventualities, the role of the human as an attentive and capable supervisor is even more important. Unfortunately, however, it is well accepted that "*monitoring is a role for which humans are generally ill-suited*" (Endsley & Kaber, 1999). Despite such obvious and understandable concerns, advances in technology mean that there is now a general move towards the introduction of progressively more automation and assistance systems into vehicles, and the ensuing research issues are now more about how best to design systems to exploit their capability with the driver in mind, including how they might influence the driving task and how to ensure that safety is not comprised.

Whilst a great degree of research has been conducted on examining the effect of automation on performance, much of it has been carried out in aviation. Therefore, many of the concepts around how automation might affect car drivers' performance are based on results from studies on pilots (e.g. Hancock & Parasuraman, 1992). Clearly, creating such associations between the pilot and car driver must be done with some caution, as the task of monitoring the road is a much more continuous one, with the possibility of many more interactions for the car driver. In addition, the car driver has to be vigilant at all times, keeping their eyes almost exclusively on the road. In contrast, the pilot's attention to the outside world is really only required during take off and landing, and during emergency situations (see Harris & Harris, 2004 for further discussion).

To date, a large proportion of the work investigating the effects of automation in car drivers has concentrated on examining the effects of ACC on performance (e.g. Rudin-Brown & Parker, 2004; Seppelt & Lee, 2007; Stanton & Young, 1998). In general, both theoretical and empirical papers suggests that the introduction of automation to tasks traditionally done by human operators can change the role of the driver and result in a new set of human factors issues which need to be addressed, if they are not to compromise safety (see also Bainbridge, 1983). These include unwelcome and unexpected changes in workload (both underload and overload, Parasuraman & Riley, 1997), potential for a loss of skill (Stanton & Marsden, 1996), and reduced situation awareness (SA) (Parasuraman, Malloy & Singh, 1993), to name but a few. For instance, the intention in introducing an automated system which handles the longitudinal and lateral control of the vehicle is that it causes a comfortable reduction in drivers' workload, providing them with more processing resources for other tasks, such as consulting the satellite navigation system, or reading an email. However, any sudden and unexpected faults or limitations in the automated system will require the driver to come back into the loop and could result in unmanageably high levels of workload. Similarly, if such high automation of the vehicle is the default approach to driving, drivers' skill in controlling the vehicle will slowly diminish with time, resulting in problems when they are required to regain control of the driving task, in case of faults or limitations in the system or infrastructure.

There is currently a growing need and desire in Europe to increase the amount of automation in road transport systems, to allow better management of the road network, increase road safety and reduce fuel consumption. This has been one of the aims of the EU funded project CityMobil, which has involved the introduction of advanced urban transport systems on a large scale. Whilst much of the research conducted in this project is concerned with 'driverless' vehicles such as Cybercars and Personal Rapid Transits (PRTs), there is also some effort dedicated to the implementation of 'dual-mode' vehicles, where the driving task can either be controlled completely by the driver (manual driving) or various aspects of the driving task can be automated.

As outlined by Flemisch et al. (2008) dual-mode driving, involving the transition between manual and fully automated driving, is not necessarily a two-stage process, and includes a number of intermediate stages (see Figure 1). For instance, whilst the addition of an ACC can be considered an example of 'assisted' driving, 'highly automated' driving is more likely to involve full longitudinal and lateral control of the vehicle by an automated system, although the driver is still required to monitor the task in this condition and driving is still not 'fully automated', which is when the driver is effectively acting as a passenger and is totally removed from the driving task. Similar models, with varying levels of automation have been offered by Sheridan & Verplanck (1978) and Kaber & Endsley (1997), as well as others.

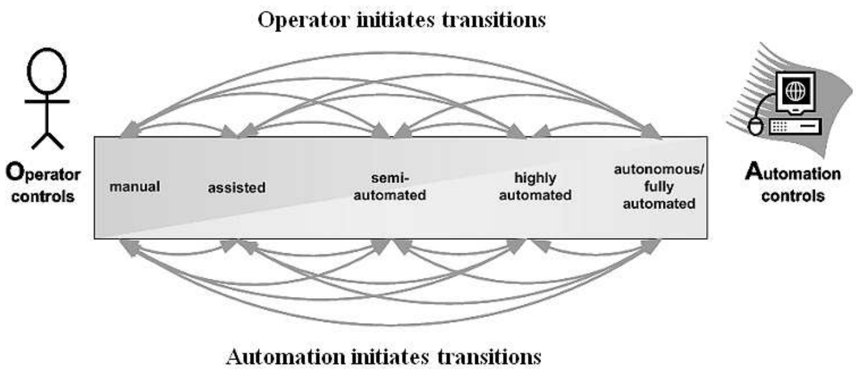

Figure 1. Automation spectrum, regions and transitions as described by Flemisch et al. (2008).

With respect to the human factors of such dual-mode driving, it can be argued that (unwanted) changes in workload, situation awareness and skill can apply to each of the above stages, whilst there are also many research questions about the processes involved during transitions between the driver and the system, from one region of automation to another (and back again, as depicted by the arrows in Figure 1). Whilst many of these issues still remain to be investigated, the study described in this paper attempted to investigate the nature and degree of any changes in drivers' *situation awareness* between manual and highly automated driving.

Situation awareness as outlined by Endsley (2000) refers to a 3 level process of "knowing what is going on". This involves the *perception* of stimuli and cues (Level 1), the *comprehension* of their meaning and relevance to the task at hand (Level 2) and finally *projection* and the ability to anticipate a future status (Level 3). Therefore, in terms of the driving task, good situation awareness (SA) can include an awareness of where the vehicle is in relation to the road and other vehicles, how it can be driven and how its various controls can be used to respond to unfolding events in the road. As the levels of automation increase in the driving task, and more automated and assistance systems are included, drivers' understanding of the capabilities and limitations of these systems, and issues such as whether (and how) the system handles different traffic scenarios are also part of the general concept of their situation awareness.

Method

Participants

A total of thirty nine participants (20 male, 19 female) took part in this study. The participants were all regular drivers, driving an average of 10,000 km per year and aged between 23 and 63 years (mean: 41 years). Average driving experience was 21 years (range: 21 to 42 years).

Design and procedure

The experiments were conducted in the University of Leeds Driving Simulator. A within-subjects design was used, where drivers' situation awareness in manual driving was compared to that of highly automated driving, by assessing driver response to three 'critical' longitudinal events. Automated driving involved control of the car by a lateral and longitudinal *automated system*.

Upon arriving at the driving simulator, all drivers were provided with a detailed written description of the workings of the simulator and its controls, followed by further clarification by the experimenter, if required. They were then given the opportunity to drive the simulator, practicing the operation of the car, and the automated system (lateral and longitudinal controllers). Once drivers were familiar with the simulator and had driven the practice road, they had a short break, followed by the experimental drive which lasted around 40 minutes. This experimental drive consisted of a section of urban road with two zones. Each section zone was approximately 18km in length and 7.3m wide, with a lane width of 3.65m in each direction. The road consisted of straight and curved sections with radius varying between 750m and 1000m. The layout and geometry of the two zones was almost identical, although one zone was driven manually (i.e. with the driver controlling all aspects of the driving task) whilst for the other, drivers were encouraged to hand over the longitudinal and lateral control of driving to the vehicle's automated system by pressing a button on the steering wheel. The order of these 'manual' and 'highly automated' driving tasks was counter balanced across subjects.

The highly automated driving occurred on ‘eLanes’, and was supported by an in-vehicle interface, which communicated the workings of the automated system to the drivers (see Figure 2). The automated system’s lateral controller kept the vehicle in the centre of the lane, and the longitudinal controller kept the speed at 40 mph and maintained a headway of 2 seconds with a lead car. If drivers failed to transfer control to the vehicle after about one minute of entering the eLane, they were reminded by the experimenter that they should switch the automated system on, although all drivers pressed the button as soon as the automated system was available. Upon transferring control to the car, drivers were asked to take their foot off the accelerator pedal and their hands off the steering wheel, effectively supervising the automated system whilst it drove the vehicle for them. However, drivers were reminded that they should oversee the driving task at all times.

Figure 2. The eLane (left) and in-vehicle interface (right) used in this study

If, for whatever reason, drivers decided to switch the automated system off, they were able to regain control of the driving task using any or a combination of the following methods: by pressing the button on the steering wheel, by moving the steering wheel, or by depressing the brake pedal. If this occurred in the eLane, they would then hear the following message: “you have control”, and both lateral and longitudinal management of the vehicle was given back to the driver at the same time. However, in order to maximise data collection in the eLane, drivers were encouraged to pass control back to the car as soon as they were ready.

Participants were reminded that both the lateral and longitudinal controllers were comfort devices that could only manage gentle manoeuvres, but could not respond in a critical situation. In other words, there was a limit to how much the longitudinal controller could decelerate, whilst the lateral controller would always maintain lane centre regardless of any static obstacle(s) in the road. Drivers were told that if the longitudinal controller was not able to respond to a situation, it would warn them to take control of the vehicle. This was signified with an auditory alarm, which the drivers were familiarised with during the practice drive. This alarm was based on a time to collision warning: at 60Hz, the system calculated the deceleration of the simulator required to match the speed of the lead vehicle without collision. If this deceleration exceeded the maximum available system deceleration (0.25 g), then the audible warning was presented.

In order to maximise longitudinal data collection, most of the driving task involved a car following scenario, for both the highly automated and manual drives. To measure drivers’ situation awareness to the events taking place in the driving scene, three longitudinal events were implemented for each driving zone (manual and highly automated). All of these critical events occurred at intersections and required a quick and appropriate response from the driver. To reduce any learning effects the order of these critical events was changed between the manual and highly automated drive. Learning was also minimised by interspersing the critical events with at least two non critical longitudinal events where the lead car was forced to decelerate between 0.5 m/s^2 and 2 m/s^2. This lead vehicle deceleration was therefore well within the limits of the longitudinal controller. Whilst there was no data collection for these scenarios, their presence was thought to create a more realistic driving task.

For the three critical longitudinal events, the lead car decelerated at a rate of 6 m/s^2 in response to an upcoming traffic scenario, and the brake lights of the lead vehicle illuminated when its deceleration exceeded 0.1g. In each case, drivers were required to take action in order to avoid a collision with the lead car. The longitudinal events used were as follows:

i. A vehicle emerged from a side road and joined the experimental road, pulling in just in front of the lead car ('emerger from left' event). The emerger was visible some 3s before the lead vehicle actually started to brake, allowing the participant to anticipate the event.

ii. A set of traffic lights changed from green to amber to red as they were approached by the lead car ('traffic lights' event). The lead vehicle only braked as the lights changed to red, allowing the 3s amber signal available for the participant to anticipate the event.

iii. An oncoming vehicle turned across the traffic to enter a side road ('oncomer turns across' event). Again, participants had an opportunity to anticipate the event, as the oncomer began its turn 3s before the lead vehicle began to brake.

Since in each case participants were able to observe the unfolding critical event, in the manual driving condition, participants' situation awareness was a measure of how quickly they anticipated and responded to these events. In the highly automated condition, the longitudinal controller was unable to decelerate sufficiently to these events, which meant that drivers had to regain control of the car. As outlined above, the driver was also warned about an imminent collision, with an auditory alarm. The rate at which drivers regained control of the driving task was used as a measure of their anticipation of the unfolding events and therefore their situation awareness. This was measured from the time at which they started steering again or when they depressed the brake pedal, or both.

Results

Drivers' situation awareness was assessed by comparing minimum time to contact, minimum headway to the lead car and 'anticipation' in the manual and highly automated drives, using a 2 (Drive: manual, automated) x 3 (Event: oncoming turns across, traffic lights, emerger from left) repeated measures ANOVA.

Anticipation was measured as the difference in time between the initiation of the lead car's brake lights and that of the participant applying their brakes. Each critical longitudinal event was choreographed to allow at least 3s for the participants to predict the impending deceleration of the lead vehicle. Therefore, if the driver braked before the lead car, they had a better anticipation of the unfolding events, and a negative value was achieved for anticipation. Similarly, if they braked after the lead car, they had less of an anticipation of the emerging events and the higher the number, the less their anticipation.

Anticipation

There was a significant effect of drive on anticipation (F(1,38) = 212.83, p < .0001), with drivers braking 0.4 seconds after the lead car braked in the manual condition, compared to 1.892 seconds in the highly automated condition. The repeated measures ANOVA also showed a significant effect of 'event' (F (2,76) = 85.21, p < .0001), where anticipation was found to be best for the traffic light event with an average value of 0.043 seconds across the two drives. Finally, the ANOVA revealed a significant interaction between drive and event (F (2,76) = 49.36 p < .0001), with a significantly earlier anticipation of the traffic light event by drivers in the manual condition. As shown in Figure 3, participants always braked earlier in the manual driving condition than the automated condition, regardless of event type.

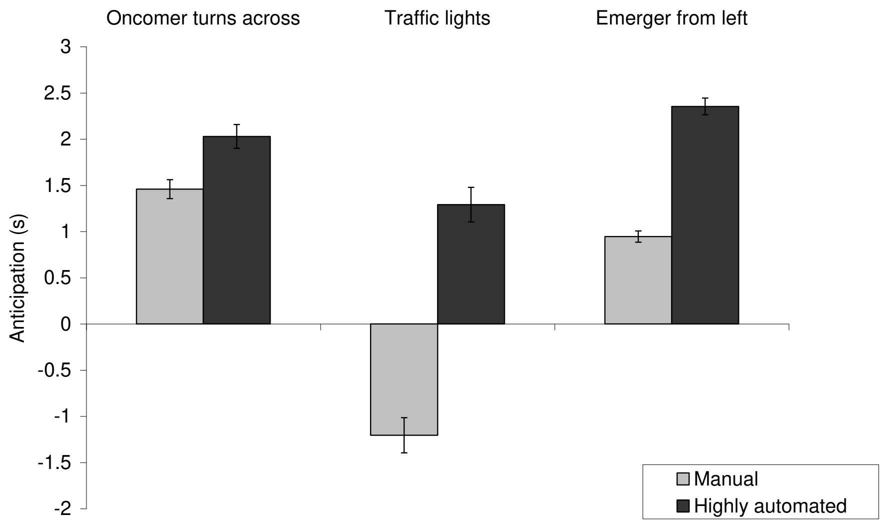

Figure 3. Drivers' anticipation of each oncoming longitudinal event

Minimum Time to Contact

The ANOVA showed a significant effect of drive on minimum time to contact with a significantly longer time to contact during the manual drive (1.82 seconds, versus 1.44 seconds in the highly automated drive, (F (1, 38) = 13.77, p = .001). There was no difference in this value between the three event types, but there was a significant interaction between drive and event (F (2,76) = 5.31, $p < .01$), where the event involving the emerger from left instigated a particularly short time to contact with the lead car in the highly automated driving condition.

Minimum headway

During the critical longitudinal events, there was a significant difference in minimum headway between the manual and highly automated drive (F (1,38) = 60.47, $p < .0001$), with a much smaller minimum headway during the highly automated drive (1.60 seconds versus 2.54 seconds). The ANOVA also showed a significant effect of event (F (2,76) = 11.20, $p < .0001$), with a significantly longer headway during the traffic light event, compared to the other two events. There was a significant interaction between drive and event type, (F (2,76) = 5.02, $p < .01$), where the longest minimum headway was seen during the traffic light event in the manual drive, whilst the shortest was observed during the highly automated driving when a car joined the road from the left.

Response to the automation alarm

Almost all of the 39 drivers failed to respond quickly enough to the 'emerger from left' event, perhaps having the least awareness of this event. In contrast, the traffic light event was perhaps easier to spot, which may explain why only 20 out of the 39 drivers braked after the alarm (see Figure 4).

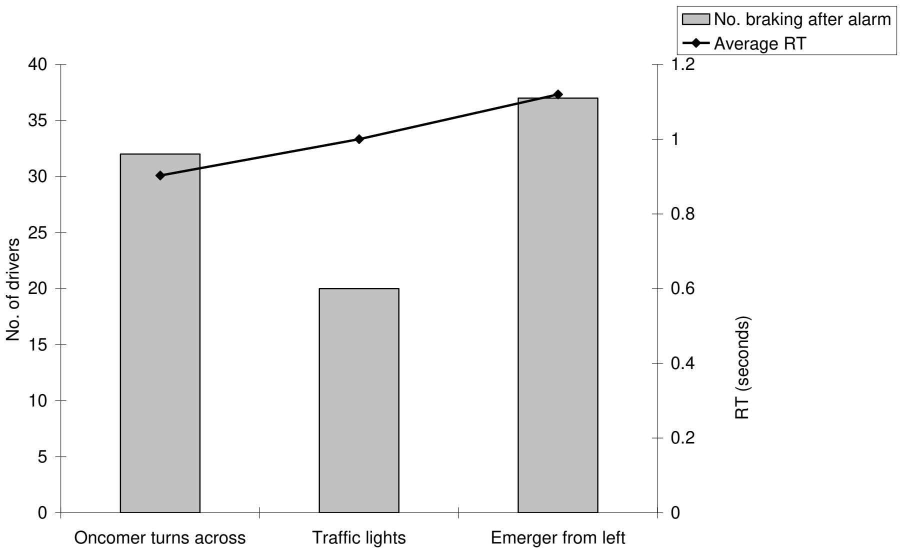

Figure 4. Drivers' response with respect to the auditory alarm

Discussion

The aim of this study was to compare drivers' situation awareness for events which occurred in the driving scene during two different driving conditions: one in which control of the vehicle was managed completely by the driver, and one in which lateral and longitudinal control of the vehicle was dominated by an automated system.

Situation awareness was measured by studying drivers' response to a number of critical events, all of which required an immediate reaction from the driver (braking) to avoid collision with a lead vehicle. In each case, drivers' understanding of the unfolding events and therefore their response (and rate of this response) to the event was used to infer their situation awareness.

Results showed significant differences between manual and highly automated driving, whereby drivers' response to critical events was always much later in the highly automated driving condition. This was confirmed by driver behaviour measures such as time to contact and minimum headway with the lead car, which were both shown to be considerably lower in the highly automated condition. We also used a new measure of 'anticipation' whereby drivers' ability to foresee and understand the unfolding events was used as a measure of their situation awareness. Anticipation was measured as the difference in time between the lead car's brake lights coming into sight and when drivers depressed their brake pedal. Therefore, if drivers braked before the lead vehicle's brake lights were seen, they had better anticipation and were more situation aware. Results showed a much better anticipation of the unfolding events in the manual driving condition than the automated driving condition.

Whilst all three of the above driver behaviour measures showed a better understanding of the significance of each critical event in the manual driving condition, they may also suggest a high (perhaps too high) degree of trust of the automated system by participants. In other words, the late brake response which lead to a low time to contact and small minimum headway in the highly automated condition may have simply been because participants expected the automated system to manage the situation and were then forced to take control when they realised (perhaps later than was safe) that the system was not able to handle the critical situation. Therefore, drivers' situation awareness in the highly automated driving condition was certainly influenced by their trust in the automated system. This is certainly confirmed by results which show that many drivers braked after the alarm was emitted.

Some interesting interactions were seen between the two driving conditions and the three longitudinal events which are worth some discussion. In particular, participants' reaction to the sudden change to red of the traffic lights was quite good in the manual condition, probably because the changing traffic lights were the most visible of the three longitudinal events and therefore allowed the highest anticipation by drivers. In contrast, drivers were worst at predicting the merger of a vehicle from the junction to their left during the highly automated drive, which produced low time to contact and time headway values to the lead car, in this driving condition. This is partly confirmed by looking at drivers' response time with respect to the alarm, which shows the largest number of brakes occurring after the alarm in the 'emerger from left event', whilst the lowest number is seen in the traffic lights event.

To summarise, this study has revealed some interesting results about drivers' attitude to and behaviour with a highly automated vehicle. In particular, the drivers in this study were found to react much later to critical events when driving was controlled by an automated system. Whilst this may have implications about their situation awareness about unfolding critical events, it may also suggest an artificially high degree of trust in the system, which may well be detrimental in a real driving situation.

Acknowledgements

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