Rebuilding drivers' situation awareness during take-over requests in level 3 automated cars

Hannah White[1], David R Large[1], Davide Salanitri[1], Gary Burnett[1], Anneka Lawson[2], Elizabeth Box[2]

[1]Human Factors Research Group, University of Nottingham, UK, [2]RAC Foundation, UK

ABSTRACT

Future, level 3 automated vehicles will enable drivers to undertake non-driving-related secondary tasks while the vehicle is in control. This is likely to impair their situation awareness, and consequently affect their ability to resume control in situations where the vehicle cannot operate autonomously. Nevertheless, proposed take-over requests typically demand that the driver 'take control' without attempting to assess or rebuild their situation awareness. In a longitudinal simulator study, forty-nine experienced drivers completed five 30-minute 'commutes' (Monday-Friday). The route incorporated an extended episode of automated driving enabling drivers to undertake secondary tasks of their choosing. Take-over requests/HMIs were inspired by the driving skills hierarchy, with twenty-five participants receiving novel 'top-down' guidance (tactical followed by control), encouraging them to check for hazards prior to providing control, and the others received traditional 'bottom-up' (control) instruction. In addition, participants were provided with either detailed system feedback during periods of automation, or no feedback. This resulted in four conditions in a 2x2 between-subjects design. Following an unexpected, emergency take-over request on day four, drivers with 'top-down' guidance checked their mirrors significantly more times during the handover. Additionally, recipients of system feedback were demonstrably ready to drive (based on recognised physical indicators) sooner in response to the take-over request. There were no differences in lateral and longitudinal vehicle control and prevalence of unsafe driving behaviours after the emergency handover. Results can inform the design of 'top-down' hand-over HMIs and strategies to help drivers rebuild their situation awareness prior to resuming manual control, following periods of automation.

KEYWORDS

Automated driving, take-over request, situation awareness

Introduction

Fully autonomous vehicles are expected to offer a number of benefits, including improvements in road safety, increased mobility, enhanced driver comfort and reductions in road congestion (Merat et al., 2012). Relinquishing responsibility for vehicle control also allows drivers to use journey time for non-driving-related tasks, providing a more enjoyable and productive experience in everyday car travel (Large et al., 2018).

The Society of Automotive Engineers (SAE) (2014) categorises six levels of ascending automation (from level 0 to 5) that differ in the extent to which the system intervenes in vehicle control, and whether human drivers need to monitor the system (in anticipation of potentially taking over control). Level 3 vehicles ('conditional automation') are expected to be introduced onto public roads in the next few years (DfT, 2015). However, at level 3, the human driver is still firmly responsible for the vehicle, and consequently required to be available to regain control of vehicles in situations the system cannot handle. It has therefore been suggested that level 3 automated vehicles allow drivers to "become hands and feet free, but not necessarily 'mind free'" (Banks et al., 2018). Moreover, the situations in which drivers must regain manual control of automated vehicles may occur unexpectedly and require fast responses, and thus the transfer of control from vehicle to driver may be problematic (Stanton et al., 2011).

A major concern is that drivers are likely to become 'out of the loop' when they are not actively monitoring, making decisions or physical inputs to the driving task, thereby reducing their perception and comprehension of environmental elements and events and the projection of their future status (i.e. 'situation awareness'). Given the absence of responsibility for primary control during automated driving, human drivers will also likely engage in non-driving related activities, which in themselves could contribute to the loss of awareness of the system state and external driving environment. Moreover, Large et al. (2018) revealed that during autonomous driving, secondary activities can be highly captivating – often with high visual, manual and cognitive elements – and this reduces the amount of spare cognitive capacity available to perceive elements of the driving environments. In addition, drivers engaged in non-driving tasks are found to show greater signs of fatigue and mind wandering, and have longer reaction times to takeover requests with regards to the time taken to look at the road, place their hands on the steering wheel and feet on the pedals (often used as indicators of 'readiness to drive') (Zeeb et al., 2015).

The driving skills hierarchy (Michon, 1985) identifies situation awareness as a key element at the 'tactical' level of driving. The hierarchy describes the relationship between control, tactical and strategic elements of the driving task. At the 'tactical' level, drivers apply knowledge based on the directly prevailing circumstances (e.g. interacting with other vehicles, obstacle avoidance etc.), whereas the 'control' level defines the primary control actions associated with safe vehicle control (e.g. steering, braking, mirror checks etc.). Nevertheless, proposed take-over requests typically exist as a 'bottom-up' approach (with respect to Michon's driving skills hierarchy), demanding simply that the driver 'take control', without attempting to assess or rebuild their situation awareness. A re-imagined 'top-down' take-over request could begin by providing 'tactical' information or guiding the driver's attention (i.e. to increase the driver's situation awareness), followed by 'control' advice.

Research has also aimed to determine the optimal time length for pre-alerts to handovers (Eriksson & Stanton, 2017). Gold et al. (2013) found that 5-second requests led to more erratic driving behaviour (fewer rear and side mirror checks and reduced indicator use) in lane changes after handover, whereas 10-second warnings provided a comfortable transition time for drivers (Melcher et al., 2015), also providing sufficient time for drivers to disengage from non-driving tasks and focus attention back to the road scene.

In addition to pre-alerts to handover, researchers have explored Human-Machine Interfaces (HMIs) that provide up-to-the-second feedback about the vehicle's status during periods of automation, to prevent 'out-of-the-loop' problems occurring and improve performance in emergency situations. Ekman and Johansson (2015) advocate a 'God-view' of the car and the state of its sensors, which shows when and where near objects are in relation to the host vehicle ('ego-car') during automated driving. Changes to sensor inputs could be indicated through colour, and auditory alerts provided in the case of an emergency (Davidsson & Chen, 2016).

Aims and Overview of Study

The aim of the current study was to investigate different strategies to help build and maintain situation awareness during routine, vehicle-initiated takeover requests in level 3 highly-automated vehicles. In addition, by inviting participants to attend on five separate occasions in a longitudinal study (inspired by previous work – Large et al., 2018), we aimed to explore if participants adapted their behaviour during the week, in particular, when they were presented with an emergency take-over request, occurring on day four. Specific hypotheses were:

1. Drivers who are prompted to check for hazards during handover will have a higher frequency of mirror checks than participants who are only prompted to resume control.
2. Drivers who receive system feedback during automation will have shorter reaction times in response to an emergency takeover request compared to participants who did not.
3. Drivers who do not receive either system feedback or a prompt to check for hazards will have the greatest difference in driving performance after handover compared to manual driving prior to engaging automation.

Method

The study employed a 2x2 between-subjects design, in which half the drivers were presented with novel 'top-down' guidance (tactical followed by control information), encouraging them to check for hazards prior to providing control, and the others received traditional 'bottom-up' (control) instruction. In addition, participants were provided with either detailed system feedback during periods of automation, or no feedback. This resulted in four conditions: NSF/BU, NSF/TD, SF/BU, SF/TD (Figure 1).

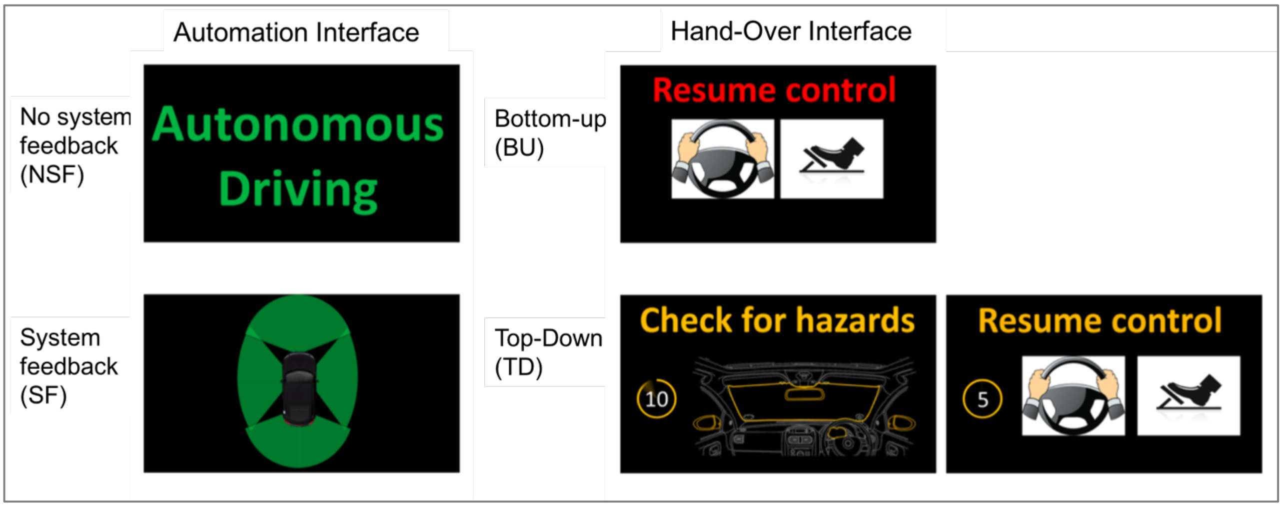

Figure 1: HMI designs, showing system feedback during automation (L) and hand-over advice (R)

The study took place in a medium-fidelity, fixed-base driving simulator at the University of Nottingham, modified to mimic a highly-automated car. A curved screen in front of the Audi TT car and three overhead HD projectors provided a 270 degree forward and side image of the driving scene, with a 55-inch curved LED television positioned behind the vehicle (to provide the rear-view) and two 7-inch LCD screens were used as side ('wing') mirrors. The driving scenario was created using STISIM Drive (v3) software to replicate a typical 'commute' drive, with episodes of suburban, rural and urban environments, including a UK dual-carriageway on which automation was available. The in-car HMI (providing both system feedback during periods of automation and details of the take-over request) was created using Microsoft PowerPoint (controlled remotely) and displayed on a 12-inch tablet positioned in the centre console of the vehicle.

Fifty-one participants were recruited to complete a 30-minute journey at the same time on five consecutive days (Monday-Friday), which was framed as their daily commute to work. All participants were experienced drivers and comprised staff and students from the University of Nottingham. Unfortunately, two participants were unable to complete the study due to simulator sickness, leaving a total of 49 participants (27 male, mean age: 36, range: 21-64; annual mileage: 5735). Participants were matched as closely as possible between groups for age, gender and driving experience. They were recruited via advertisements placed around the University of Nottingham campus and sent via email, and reimbursed £50 in shopping vouchers as compensation. In line with similar, previous studies (e.g. Large et al., 2018), participants were asked in advance to bring with them any objects or devices they thought they might use in an autonomous vehicle (to increase ecological validity of their behaviour), and were invited to use these 'as they saw fit' during the drive. Participants were also told the capabilities of the highly-automated vehicle (i.e. that they may be required to resume manual control during periods of automation).

Participants began by driving manually (i.e. responsible for all primary control actions). Given that the initial deployment of autonomous vehicles in the public domain is expected to occur in 'geo-fenced' areas (e.g. dual carriageways, motorways), automated control was only available to drivers when they joined the dual carriageway. This was activated using a voice command, preceded by the keyword 'AutoCar', e.g. "*AutoCar: start automated driving*". In practice, this prompted the researcher to trigger automated control remotely. Participants were also able to switch between manual and automated driving as and when desired, by using the appropriate command, e.g. "*AutoCar: start manual driving*", etc.

During periods of automation, participants were able to engage in their chosen activities – no restrictions were applied, other than making drivers aware at the start of the study that they may be required to resume manual control given appropriate notice. Towards the end of the dual carriageway, drivers were provided with a scheduled handover, prior to completing their journey in the city using manual control. In preparation for this, the in-car HMI provided participants with a "prepare to drive" multi-modal warning (auditory and visual), delivered 60 seconds prior to takeover. This was followed by a takeover request – either 'resume control' (bottom up) or 'check for hazards/resume control' (top-down), both delivered 10 seconds prior to the provision of control (in line with recommendations (Melcher et al., 2015)).

For those participants receiving system feedback during periods of automation, the in-vehicle HMI displayed the system health by showing the status of the cars sensors as green, amber or red, indicating increasing levels of severity (e.g. the presence of an external hazard or a problem with the operational integrity of the sensor itself). Drivers were notified of changes to sensor status (i.e. green to amber) with a non-intrusive tone, and the associated change of colour. This occurred seldom during the week and only for short periods of time (c. 30-seconds), without any accompanying external stimuli. However, inclement weather (thick fog) on day 4 (Thursday) caused the sensors to 'fail' and necessitate the emergency hand-over of control back to the driver. This was indicated by the sensor display turning red, accompanied by an urgent alarm and the spoken message: 'fog detected', with manual control provided 10-seconds afterwards. For participants who did not receive system feedback, the HMI simply indicated 'autonomous mode' or 'manual driving', as appropriate. After driving for approximately 15 kilometres (c. 8-10 mins), the fog cleared and automation became available again. Those participants who chose to re-engage with automated driving were subsequently provided with the 60/10-second scheduled handover, as before, at the end of the dual-carriageway.

Results and Analysis

For the purposes of this paper, results and analysis focus on drivers' behaviour during the emergency handover on day four. Video coding was used to classify participants' mirror checking behaviour during the take-over request (i.e. following the delivery of the takeover request but before resuming manual control). In addition, 'driver readiness' is defined as the time at which participants had made their first glance to the road scene and had at least one hand on the steering wheel, in line with other research (Zeeb et al., 2015). Driving performance data were extracted from the SISTIM drive software and analysed to provide information on participants' standard deviation of lateral and longitudinal driving control for the first 10 seconds after handover; driving performance was compared to 10-seconds of manual driving on a straight road prior to engaging in automation.

Mirror Checks

A two-way Multivariate Analysis of Variance (MANOVA) showed a significant main effect of handover interface (TD/BU) on checks to right side, left side and rear-view mirrors, $F(3, 43) = 4.818$, $p = .006$, Wilks' $\Lambda = .748$, partial $\eta2 = .252$ (Figure 2). There was no main effect of automation interface (SF/NSF), $F(3, 43) = .278$, $p = .841$, Wilks' $\Lambda = .949$.=, partial $\eta2 = .019$, and no significant interaction effect of the interface during automation and the handover interface on the frequency of mirror checks, $F(3, 43) = .852$, $p = .473$, Wilks' $\Lambda = .94$ partial $\eta2 = .056$. A subsequent one-way Analysis of Variances (ANOVA) revealed that significantly more checks were made to the right and left side mirrors when drivers were provided with top-down guidance. No differences in checks to the rear-view mirror were found between handover interfaces.

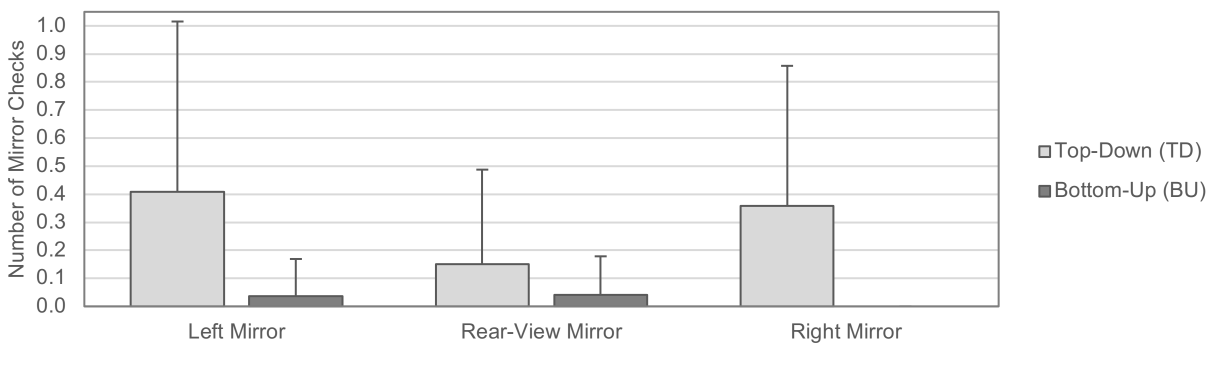

Figure 2: Mean number of mirror checks (there were no right mirror checks during BU advice)

Time to 'Driver Readiness'

A two-way ANOVA revealed that there was a significant main effect of automation interface (SF/NSF) on the time taken to 'driver readiness', $F(1, 45) = 12.714$, $p = .001$, partial $\eta2 = .221$, but no main effect of handover interface (TD/BU), $F(1, 45) = .028$, $p = .869$, partial $\eta2 =.001$. There was no significant interaction between automation interface and handover interface for the time to 'driver readiness', $F(1, 45) = .015$, $p = .901$, partial $\eta2 = .000$. Receiving system feedback resulted in a reduction of 2.1s to 'driver readiness' compared to situations in which there was no feedback.

Standard Deviation of Speed

A two-way mixed ANOVA was conducted, employing a between-subjects factor of Condition (x4) and a within-subjects factor of Sampling Period (manual driving before automation or manual driving after handover). There was no significant main effect of Condition on standard deviation of speed, $F(3, 45) = .394$, $p = .758$, partial η2 = .025, and no statistically significant interaction between Condition and Sampling Period (before automation, after handover), $F(3, 45) = .682$, $p = .568$, partial η2 = .043. However, there was a significant main effect of Sampling Period in standard deviation of speed, $F(1, 45) = 38.591$, $p < .001$, partial η2 = .462, indicating that the standard deviation of speed was 1.92 mph lower before automation.

Standard Deviation of Lateral Lane Position

A two-way mixed ANOVA revealed a significant main effect of Sampling Period on the standard deviation of lane position, $F(1, 45) = 60.160$, $p < .001$, partial η2 = .572, revealing that the standard deviation of lane position was significantly larger in the manual drive after handover (mean difference = .424 feet) compared to the earlier manual drive. There was no significant main effect of Condition, $F(1, 45) = 1.108$, $p = .356$, partial η2 = .069, and no significant interaction between Condition and Sampling Period on the standard deviation of lane position $F(3, 45) = .620$, $p = .605$, partial η2 = .040.

Discussion

The aim of the study was to investigate alternative HMIs/strategies to build and maintain situation awareness for Level 3 automated vehicles. Results show that providing drivers with ‘top down’ guidance (encouraging them to check for hazards) during a 10-second takeover request led to significantly more checks being made to the right and left-side mirrors, *even during the emergency handover*, supporting our first hypothesis. In contrast, no checks were made to the right-side mirror by drivers who received ‘bottom-up’ (“take control”) advice, and only 3.7% of these drivers checked their left-side mirror (compared to 36.4% of ‘top down’ drivers checking both left and right) (although no differences were evident between conditions in the number of checks to the rear-view mirror). Checking external side (‘wing’) and internal rear-view mirrors is considered essential for safe driving and helps drivers to maintain situation awareness (Li & Busso, 2013).

It is worth highlighting that not all drivers who received ‘top-down’ advice actually checked their mirrors, suggesting that prompting participants to check for hazards may not a fully effective method to build situation awareness during handover. Nevertheless, no lane change was required as part of the emergency handover and it is therefore feasible that results may have been different if drivers had been required to undertake a lane-change manoeuvre immediately after resuming control. In addition, the absence of other vehicles in the lane immediately behind participants might explain why rear-view mirror checks were low or not sustained in some conditions. Therefore, whilst the study provides preliminary support for a ‘top-down’ (check for hazards) prompt to build situation awareness during handover, additional work is required to investigate this further, for example, in situations requiring a lane change in the presence of more surrounding traffic.

It is also noteworthy that receiving system feedback during periods of automation had no influence on participants’ mirror checks during the handover, suggesting that keeping participants in the loop during automation has no impact on their behaviour during the transfer of control, and further supporting the need for the provision of additional (top-down) information or guidance during the handover. It is feasible that drivers expected the system feedback interface to highlight potential obstacles at the point of handover, suggesting overreliance and potential errors of omission (drivers failing to implement actions if they are not informed by the vehicle) (Eriksson et al., 2018).

Nevertheless, participants who received system feedback during automation were considered ‘driver ready’ (a glance to road scene and at least one hand on wheel) significantly quicker than participants who did not receive system feedback, supporting our second hypothesis (although, interestingly, driver-readiness was not influenced by handover approach). This supports Ekman and Johansson’s (2015) proposed ‘God-view’ of the car to keep drivers ‘in the loop’ during automation.

A potential issue of determining time to ‘driver readiness’ in this manner is the fact that during the current study, participants brought their own devices/activities with them to use during autonomous driving. Whilst this increased the ecological validity of the study, and is recommended by other researchers (e.g. Walch et al., 2015), the consequence is that secondary devices and activities were not controlled across groups. As such, participants with activities that had high visual, manual and cognitive elements, e.g. working on laptops, may have taken considerably longer to detach from their non-driving activities than participants with less demanding activities, e.g. those casually glancing at their mobile phone. Thus, it is feasible that reaction times may be influenced by the secondary device being used. Although the study design favoured ecological validity at the expense of control (as far as secondary task engagement is concerned), further analysis will consider the types of secondary tasks that were employed, and consider the potential impact of these on the measures reported. Even so, it is interesting to note that none of the participants took the full 10 seconds to be considered ‘driver ready’ (the maximum value was 8.53s) suggesting that a hand-over time of 10 seconds may provide a comfortable transition time, even for drivers undertaking highly-engaging secondary activities (although it is noted that the measure of ‘driver-readiness’ is somewhat coarse in the current study).

Whilst there were differences in mirror checking behaviour and reaction times to the takeover request, no differences were found between conditions in the driving performance measures (standard deviation of lane position, standard deviation of speed) after handover, thereby failing to support our third hypothesis. However, driving performance measures did differ significantly when compared to an equivalent episode of manual driving prior to engaging automation. This may be due to the specific emergency situation chosen for the study, rather than a lack of situation awareness during the emergency handover *per se* – adverse weather conditions, such as fog, can have a significant impact on driving performance in any case. For example, Mueller and Trick (2012) found that drivers had greater speed and steering variability when driving in foggy conditions compared to clear conditions.

It is also feasible that degradations in driving performance post-automation were due to difficulties recalibrating the physical control actions when resuming manual driving. Indeed, Russel et al. (2016) observed significantly different steering control behaviour when resuming manual control in situations in which the steering/torque ratio was modified between each lap of a circuit (even when participants were informed about changes to the steering/torque ratio in advance). Therefore, even if drivers of automated vehicles have sufficient awareness of the driving environment and are aware of what they need to do, they may only be able adjust to physical controls through ‘hands-on’ experience, and this may still result in detriments to driving performance immediately after handover. Nevertheless, it is recognised that participants were presented with significantly differently controls during Russel et al.’s (2016) study, and in the current investigation, the controls remained unchanged and consistent with the primary controls in existing on-road vehicles. Even so, several participants veered into the left lane following handover of control. While this suggests that drivers still had an overall awareness of safety when regaining control (actively steering away from on-coming traffic and towards the roadside), they still took some time to readapt or re-calibrate primary control mechanisms. The results therefore tend to support Russel et al.'s (2016) proposed period of shared control after handover to mitigate the risk associated with the adaption/learning process (although it remains unclear whether 10 seconds is an appropriate time in which to achieve this, and this will be investigated in future work).

Conclusion

As the first longitudinal study of handovers in conditionally automated vehicles, the study has demonstrated the benefits of encouraging drivers to check for hazards during takeover requests (top-down approach) and providing system feedback during automation. However, there were no apparent benefits to driving performance following the provision of system feedback or guidance, although this may be due to participants being physically out of the control loop, rather than them lacking awareness of the driving environment per se. The results have implications for the design of HMIs to support drivers during automated driving and take-over requests. In particular, it is proposed that HMIs should keep drivers appraised of the system/vehicle status during periods of automation, and actively encourage them to check for hazards during the transfer of control. Recommendations for future research include investigating the effect of sharing longitudinal and lateral control actions during handover, or the phased introduction of control elements.

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