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Transition to manual: Driver behaviour when resuming control from a highly automated vehicle

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ABSTRACT

A driving simulator study was designed to investigate drivers' ability to resume control from a highly automated vehicle in two conditions: (i) when automation was switched off and manual control was required at a system-based, regular interval and (ii) when transition to manual was based on the length of time drivers were looking away from the road ahead. In addition to studying the time it took drivers to successfully resume control from the automated system, eye tracking data were used to observe visual attention to the surrounding environment and the pattern of drivers' eye fixations as manual control was resumed in the two conditions. Results showed that drivers' pattern of eye movement fixations remained variable for some time after automation was switched off, if disengagement was actually based on drivers' distractions away from the road ahead. When disengagement was more predictable and system-based, drivers' attention towards the road centre was higher and more stable. Following a lag of around 10 s, drivers' lateral control of driving and steering corrections (as measured by SDLP and high frequency component of steering, respectively) were more stable when transition to manual control was predictable and based on a fixed time. Whether automation transition to manual was based on a fixed or variable interval, it took drivers around 35–40 s to stabilise their lateral control of the vehicle. The results of this study indicate that if drivers are out of the loop due to control of the vehicle in a limited self-driving situation (Level 3 automation), their ability to regain control of the vehicle is better if they are expecting automation to be switched off. As regular disengagement of automation is not a particularly practical method for keeping drivers in the loop, future research should consider how to best inform drivers of their obligation to resume control of driving from an automated system.

1. Introduction

The 'driverless car' concept has received a great degree of attention in recent years, partly due to the considerable outreach activities undertaken by companies such as Google, and also following legislation in favour of the operation of 'autonomous cars' by the States of Nevada (March 2012), Florida (April 2012) and California (September, 2012). For example, see USA today (2014). In the UK, the government has recently pledged the testing of driverless cars "on UK roads by 2013" (BBC news, 2013). The notion is also much favoured by the automotive industry who are currently quoted in the

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media on an almost daily basis, for instance, with Nissan (Wall Street Journal, 2013), General Motors (USA today, 2013) and Mercedes (Daily Mail, 2013) all committing the sale of 'self-driving cars' by 2020.

However, from the policy and research perspective, activities in this domain have been a little more gradual, and at least an understanding of the impact of such vehicles on overall road traffic management are not yet well understood (Excell, 2013). Whilst the technology to allow the realisation of such cars is perhaps relatively advanced and more readily available, the challenge for human factors professionals and researchers is to ensure that the operators of such vehicles: i.e. the drivers – are able to comprehend the capabilities and limitations of the systems in place for automated driving.

In the late 1990s and early 2000s, human factors research on automation in vehicles, which was mainly focused on drivers' interaction with Adaptive Cruise Control (ACC) argued that increases in automation could lead to reductions in drivers' situation awareness, contributing to impaired performance during system limitations or failures (Endsley & Kaber, 1999). In recent years, a number of projects in this area (conducted mainly in Europe) have attempted to progress beyond the ACC, adding lane keeping assistance, for example, and transferring the degree of automation from Level 1 (Function specific automation, see NHTSA, 2013) to Levels 2 (combined function automation) and 3 (limited self-driving). Examples of such projects, which have considered human factors implications of automated vehicles in particular, include CityMobil (see Merat & Jamson, 2009; Toffetti et al., 2009), InteractIVe (Hesse et al., 2011) and HAVEit (Happee et al., 2008).

However, there is only a very limited understanding of drivers' behaviour and performance during this Level 3 of automation. Here, the driver is expected to be "available for occasional control, but with sufficiently comfortable transition time" (NHTSA, 2013). The need is therefore for drivers to remain 'in-the-loop' and maintain their situation awareness to an adequate level which will allow them to resume control of driving, when required. The reasons for this resumption of control may be the inability of the automated system to manage a particular driving situation/environment, or because the driver wishes to depart from the current driving environment, e.g. by leaving the motorway environment with infrastructure supporting vehicle automation, to enter an unsupported urban environment. However, research on understanding the human factors of how drivers are involved in the "occasional control" of the vehicle and what constitutes "comfortable transition time" is currently very limited.

In recent years, work conducted in our laboratories, as part of the UK funded EASY project (Effects of Automation on SafetY) has studied drivers' interaction with Level 3 automation, their situation awareness of the surrounding traffic and their involvement in other (non-driving-related) secondary tasks. We have shown, for example, that drivers' visual attention to the road centre decreases as the level of automation increases and that when drivers were supported by a lateral controller (lane keeping system) but had to maintain longitudinal control, their visual attention towards the road centre was lower than when driving was manually controlled, yet similar to when both lateral and longitudinal support were provided (Carsten, Lai, Barnard, Jamson, & Merat, 2012). We argue therefore, that apart from levels of automation, the *type* of automation support provided to drivers (lateral versus longitudinal) results in different levels of driver engagement and performance.

As the level of automation increased in our studies, drivers were also seen to engage more in other activities, such as watching a DVD. Such engagement in secondary tasks was not found to be detrimental to driving if the driving environment was relatively straightforward, but when drivers were faced with a demanding driving task, e.g. during increased traffic density, their attention to the roadway increased (Jamson, Merat, Carsten, & Lai, 2013) and their performance deteriorated when there was an obligation to resume control of driving, e.g. to change lane due to an incident in the road, (Merat, Jamson, Lai, & Carsten, 2012). Therefore, whilst automation may have reduced workload during relatively straightforward driving conditions, the need to resume control when attention is actually directed towards another (non-driving related) task leads to dangerous and sudden changes in workload which can be detrimental to driving safety (see also Rudin-Brown & Parker, 2004).

Yet, one argument for increased levels of automation in vehicles has been that of enhanced safety (POSTnote, 2013), with driver error and inattention cited as a major contributory factor to crashes (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006; National motor vehicle crash causation survey, 2008). Certainly, the attraction of such systems to drivers is the freedom they offer for engaging in other tasks. However, engagement in other tasks is directly linked to the removal of drivers' attention from the road, and as outlined above, may lead to reduced driving performance. It is therefore important for an automated system to be aware of drivers' state, and have the power to re-engage the driver back into the loop, when the driving environment necessitates such re-engagement.

Previous work on systems that detect driver distraction in real time has used both eye tracking data and vehicle-based measures such as speed and lateral position/steering (e.g. Ahlström & Kircher, 2010; Donmez, Boyle, & Lee, 2007, 2008, 2009). As vehicle metrics were managed by the automated controllers in the current study, eye and head tracking measures were used to determine drivers' distraction away from the road, during Level 3 automation (highly automated driving) and control was either transferred to drivers at a fixed pace, or in real time; when they were judged to be looking away from the road centre for too long or too often (see Section 2 for exact criteria used). Previous research in this area has used a variety of measures to determine the thresholds of such distraction, ranging from average duration of glances away from the road in a 4.3 s-wide sliding window (Zhang, Smith, & Dufour, 2008), to the percentage of on-road gaze points in a 60-s sliding window (Victor, 2005).

The aim of the current study, also conducted as part of the EASY project, was therefore threefold:

(i) to determine whether a system, based on real-time assessment of drivers' attention to the roadway, could be used to ensure that only attentive drivers, i.e. those fully engaged in system monitoring, were supported by the automation. The system used real-time measurement of drivers' eye and head tracking to bring drivers back into the loop
(ii) whether this real-time technique was more or less effective than a system based on fixed intervals and
(iii) to investigate how quickly drivers were able to re-engage in manual control, when it was required, using easily observable driving performance and eye tracking metrics.

2. Method

2.1. Participants

Following approval from the University of Leeds Research Ethics Committee, participants were recruited using a newspaper advertisement, and via the driving simulator database. As this was the third of three studies on vehicle automation, all participants had experience of using the driving simulator and its automated system, although practice was provided as outlined below. Forty-six participants completed the study (25 male) and were paid £25 for taking part. Due to missing data from 12 participants, results are reported for the remaining 37. The age range of the participants included in the data analysis was 28–67 years (Mean = 47.35, SD = 10.33). No particular criteria were used for recruiting participants, but they were required to be experienced drivers. Therefore, all participants had more than 10 years' driving experience, and drove 27,207 miles a year on average (SD = 20,790 miles).

2.2. Design and procedure

The University of Leeds Driving Simulator (UoLDS) was used for this study. The vehicle cab for the simulator, based around a Jaguar S-type vehicle, has all driver controls fully operational and is housed within a 4-m diameter spherical projection dome. The front road scene encompasses a horizontal field of view of 250°, and three rear projectors display the scenes in the rear view and side mirrors. The simulator is also equipped with v4.5 of the Seeing Machines faceLAB eye-tracker, with its cameras mounted on the vehicle dashboard.

In the manual driving condition, participants were entirely responsible for the manipulation of standard longitudinal (accelerator and brake pedals) and lateral (steering wheel) controls. In the highly-automated condition, equivalent control inputs were made by a pair of second-order controllers. The longitudinal controller was effectively an ACC with a default target speed of 70 mph, the speed limit of the virtual driving scenario. The target headway was fixed at 1.5 s and could not be adjusted by the driver. The system was modelled in the simulator according to the specification outlined by Ioannou, Xu, Eckert, Clemons, and Sieja (1993), constrained to a maximum acceleration of 0.1 g and deceleration of 0.2 g.

The lateral controller resembled a Lane Keeping System (LKS). Its algorithm was based on Sharp, Casanova, and Symonds (2000), projecting a series of look-ahead points in front of the vehicle before calculating the error from the desired trajectory, weighted according to the proximity of the look-ahead points. On activation of the LKS, the resulting steer angle command attempted to maintain the vehicle in the centre of the current lane occupied. A small LCD panel below the speedometer was backlit and displayed ''ACC/LKS'' when the highly-automated system (lateral plus longitudinal control) was active.

A within-participant design was implemented, whereby all drivers completed three experimental drives (Baseline, Variable, Fixed) which were completed in a counterbalanced order. Each drive consisted of an 88 km long 3-lane motorway, incorporating gentle s-shaped curves. As this was the third of three studies on automation, using the same participants, all participants were familiar with the driving simulator and automated controllers, but they participated in a 25 min practice session before starting the experimental drives.

For the Baseline drive, driving started in the manual mode, with drivers in control of the vehicle operations. Drivers were required to move to the middle lane at the earliest opportunity. After approximately 2 km (just before the first junction), when drivers were positioned in the centre of the middle lane, the automated controllers were switched on. The controller then remained on for almost the entire drive. Around 5.8 km before the end of the drive, the three lanes of the motorway were reduced to one (over a distance of around 300 m), requiring drivers to resume control of driving by moving to the free lane. Variable Message Signs were used to provide information to drivers about the particular incident. Examples of incidents in the road included stranded vehicle and road works (see Fig. 1 for one such example).

For the 'Fixed' and 'Variable' drives, the automated controllers were engaged after the initial 2 km, in the same way as the Base drive. However, the controllers were engaged/re engaged periodically (Fixed drive) or using a real-time algorithm via the faceLAB eye and head tracking cameras (Variable drive). The main aim of the Variable drive was to re-engage drivers back into the loop, if they were looking away from the road for 10 s or more. Further details of the algorithms used for the Fixed and Variable drives are shown in Table 1.

As with the Baseline drive, manual driving was required during the last 5.8 km of the Fixed and Variable drives, when drivers were required to resume control due to an event in the road, posted by a VMS.

Fig. 1. An example of the type of VMS message and scenario used at the end of the drive, requiring drivers to resume manual control for the last time in the drive.

3. Results and discussion

Due to some missing data from 12 participants' eye tracking measures, results are reported for the remaining 37. With respect to disengagement of automation, analyses showed large variability in the number of drivers disengaging the automated controllers in the Variable drive condition. As shown in Fig. 2, only one participant was inattentive to the extent that the Variable system disengaged the maximum of nine occasions, with around half of the drivers learning to keep the controllers engaged (by keeping their head and eyes towards the road centre) by the 3rd disengagement incident.

To allow a formal statistical comparison between results of the Fixed and Variable drives, ANOVAs were only conducted for the measures obtained when manual control was imposed for the first time, in each drive. Although this analysis does not consider the effect of drivers' ability to learn the system's operation criteria, it does show, for the first time, how drivers' visual attention (measured here by eye tracking value of 'Percent Road Centre' – see Victor, Harbluk, & Engstrom, 2005) was distributed just after transition of control from the automated systems, and how long it took the drivers of this study to refocus their visual attention to the road centre, when required to resume manual control of the car, and whether there was a difference in performance and regain of manual control when control was transferred in a system-specified (Fixed) or driver-specified (Variable) fashion.

Two analyses were performed and are reported below. First, a 1-way Analysis of Variance (ANOVA) with two factors of Driving Condition (Fixed, Variable) was conducted for lateral and longitudinal driving performance and eye tracking measure of PRC. Here, mean values for the entire manual section, when control from automation was transferred to drivers for the first time (T1) were compared.

PRC was defined as the proportion of gaze data points, labelled as fixations, which fell within the road centre area, a 6° circular region located around the driver's most frequent fixation location. PRC has previously been demonstrated to be a sensitive indicator of visual distraction (Victor, Harbluk, & Engström, 2005) with lower values indicating less attention is dedicated to the visual demands of driving. Longitudinal driving performance was measured using mean and minimum values of speed. For lateral control, data on Standard Deviation of Lane Position (SDLP), number of 1° steering reversals per minute and High Frequency Control of steering (in the 0.3–0.6 Hz band) are reported. High frequency control of steering (HFS, see McLean & Hoffmann, 1971) is normally associated with driving task demand, and defined as the ratio between the

Table 1
Criteria used for engaging the automation in the Fixed and Variable drives.

Road	Disengagement criteria	Re-engaged	Criteria for re-engagement
Fixed	After 6 min	1 min after disengagement	i. Close to Centre of Lane ii. Small (2.5 m/s) lateral velocity
Variable	i. If driver looked away from 'road centre', for 10 s or more. The 'road centre' was defined as an ellipse with a 10° major and a 6° minor radius	1 min after disengagement	i. Close to Centre of Lane ii. Small (2.5 m/s) lateral velocity

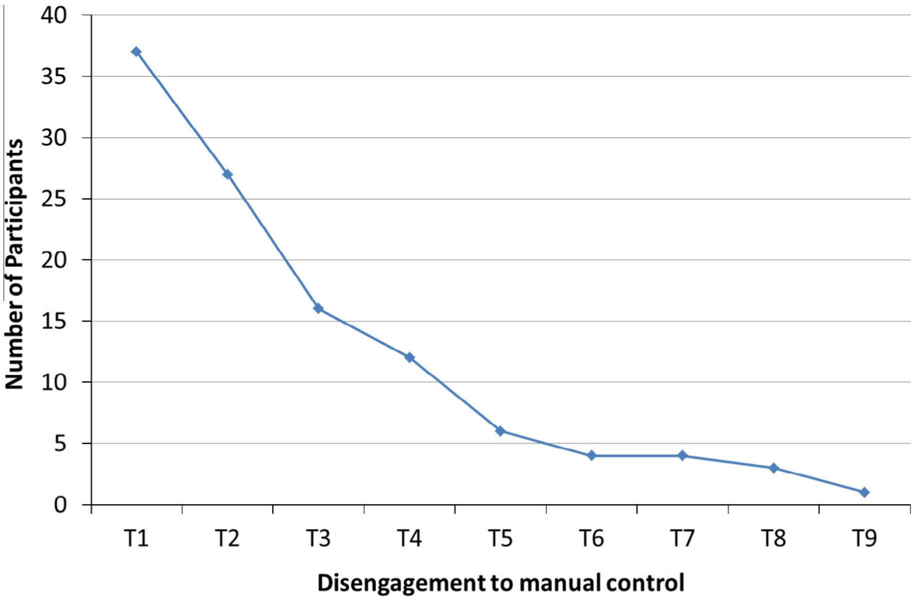

Fig. 2. Number of drivers disengaging the automated system in the variable drive condition (T = time of manual transfer. Total number of manual transfers from automation = 9).

power of the high frequency component and all other steering activity. This magnitude of the high frequency band of steering wheel angle aims at excluding the effect of open loop behaviour measures, focusing on immediate, compensatory steering corrections (McLean & Hoffman, 1973).

As shown in Table 2, a significant difference in mean values between the Fixed and Variable drives was only observed in driving speed. Both average and minimum speed were higher when manual driving resumed after automated control for a Fixed duration, compared to when transfer to manual control was at Variable times across drivers. Therefore, apart from significant differences in driving speed, the two methods of automation disengagement seemed to result in similar average values for measures of driver performance and attention allocation.

To investigate the time taken by drivers to resume manual control, and observe where drivers' visual attention was located just after the automation was deactivated, driving and PRC data were also plotted at 5 s intervals, for the first 60 s after disengagement of the controllers. A repeated measures ANOVA was then conducted on these measures with two within-participant factors of Drive (Fixed, Variable) and Time (T1–T12). Assumption of sphericity for the data was confirmed as Mauchly's tests were not significant.

With respect to visual attention, results did not show an overall difference in Percent Road Centre between the Fixed and Variable Drives. However, a significant effect of Time and an interaction between Time x Drives was noted ($F(11,275) = 1.87$, $p < .05$, $\eta^2 = .07$ and $F(11,275) = 2.85$, $p = .001$, $\eta^2 = .10$, respectively). As shown in Fig. 3, compared to the Fixed Drive, drivers' visual attention to the road centre was generally more diverse during the first minute of manual control after the Variable Drive. Post hoc paired-sample *t*-tests showed a significant increase in PRC in the 5–10 s time period after automation was disengaged, compared to the 0–5 s slot ($t(26) = -2.05$, $p < .05$). This significant increase in PRC after the first 5 s was also observed when manual control was required for the second time (T2) in the Variable drive ($t(15) = -2.20$, $p < .05$). Following a sharp increase in PRC during the 15–20 s time slot, drivers' visual attention is seen to drop again steadily until around the 40–45 s time slot. This changing pattern of fixations in the manual section after the Variable drive is in contrast to the relatively steady pattern seen after the Fixed drive. The results can be realised both in terms of the system's response to driver behaviour and the subsequent response of drivers to the two different types of disengagement: in the Variable drive, the

Table 2
Driving performance measures for the Fixed and Variable drives.

Measure	Fixed drive mean (SD)	Variable drive mean (SD)	Degrees of freedom	*F* value and significance
Mean speed (m/s)	32.76 (2.16)	31.40 (3.06)	1.73	4.80*
Minimum Speed (m/s)	29.50 (1.75)	26.53 (6.36)	1.73	7.5**
1° Steering reversals (Frequency)	32.67 (17.80)	36.44 (18)	1.73	.82
SDLP (m)	.27 (.06)	.51 (1.24)	1.73	1.39
PRC (centre)	73.10 (13.73)	71.66 (10.97)	1.71	.24

* $p < 0.05$.
** $p < 0.01$.

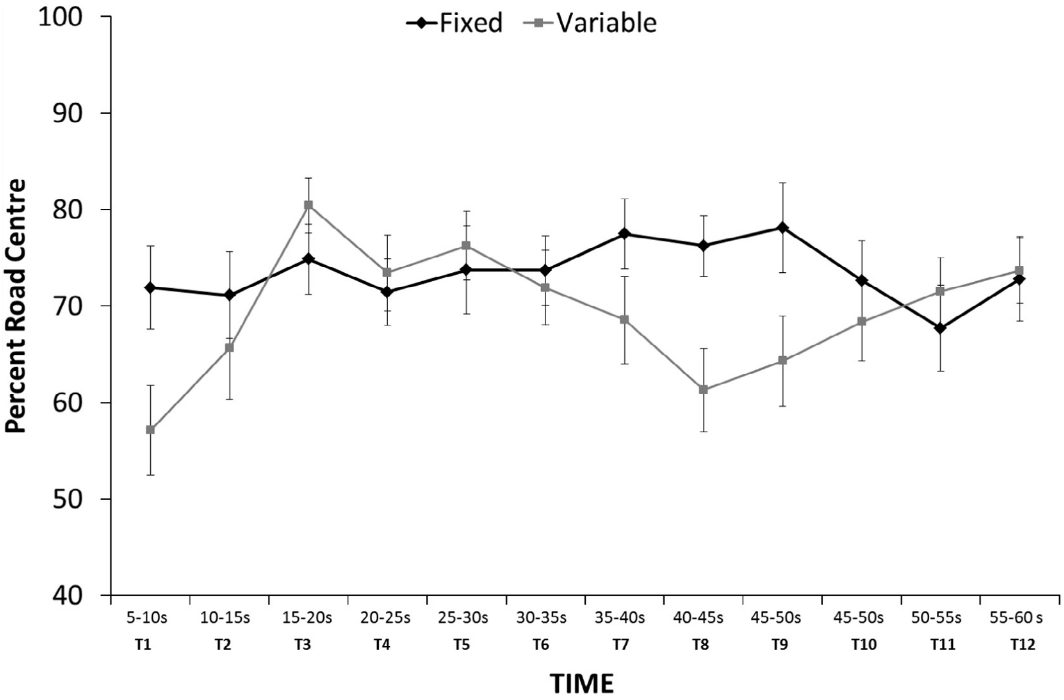

Fig. 3. Percent road centre values during the first minute after control is transferred back to the drivers for the the fixed and Variable drives (Error bars represent standard errors).

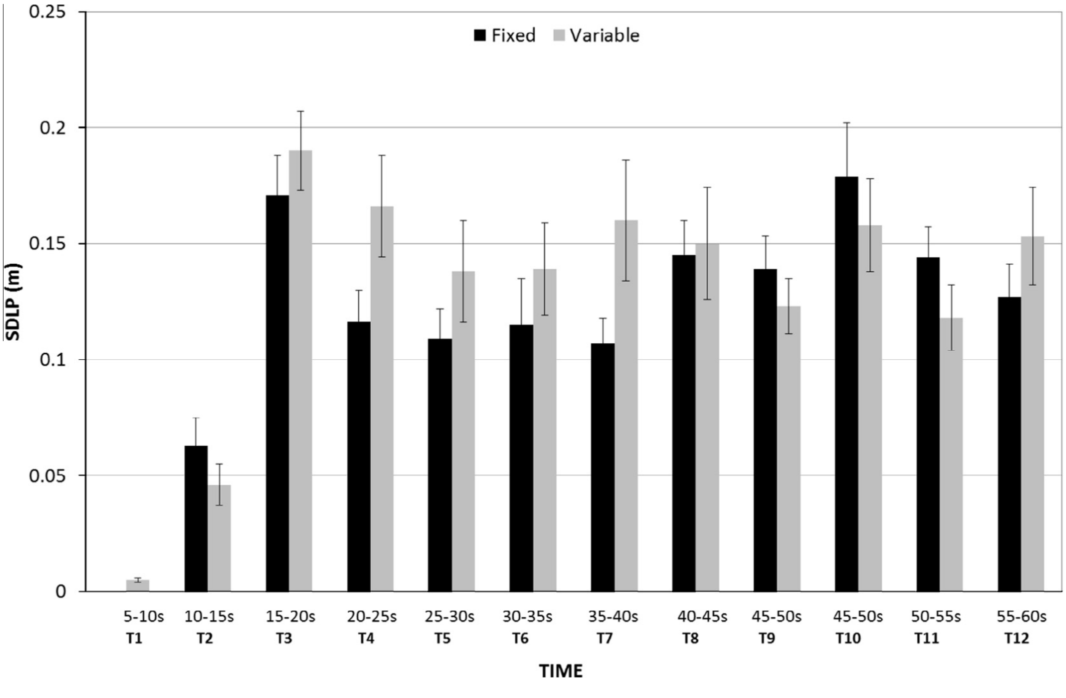

Fig. 4. standard deviation of lane position during the first minute after control is transferred back to the drivers for the the fixed and variable drives (values plotted are those before transformation was conducted – Error bars represent standard errors).

automated system disengaged because drivers were looking away, and it took drivers around 15–20 s to refocus their attention back towards the road centre. However, unlike manual control after the Fixed system, drivers' visual attention continued to be diversely distributed after the Variable drive. It can therefore be argued that drivers were generally paying more visual attention to the road when automation was disengaged at a Fixed interval.

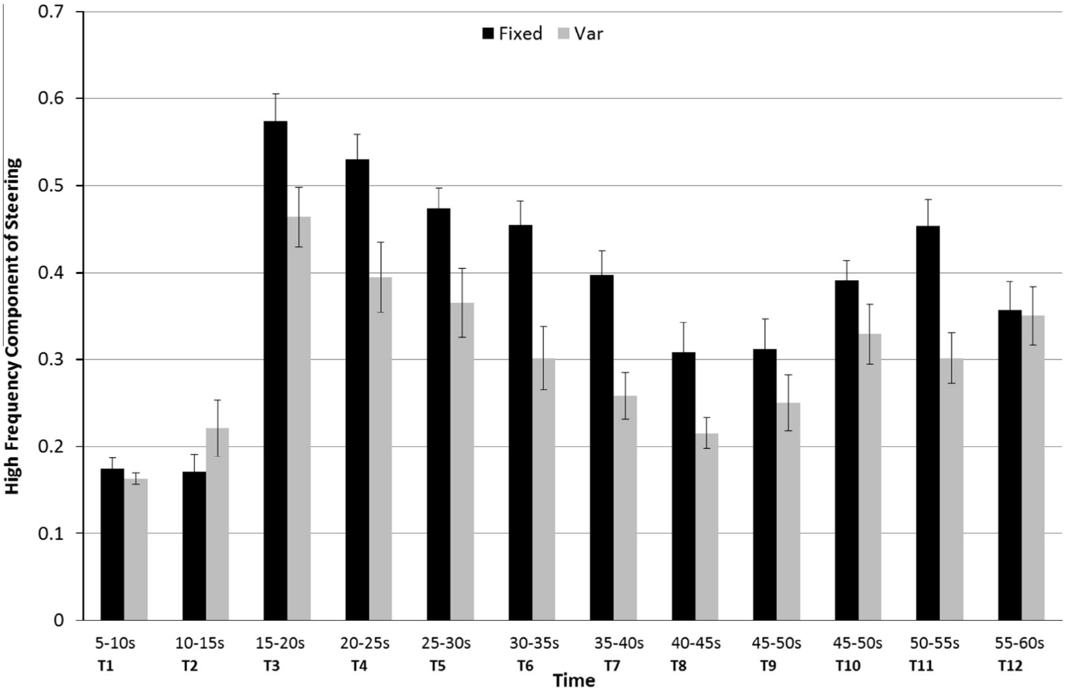

Fig. 5. High frequency component of steering during the first minute after control is transferred back to the drivers for the Fixed And Variable drives (Error bars represent standard errors).

With respect to lateral control of driving, a 2 (Drive: Fixed, Variable) × 12 (Time: T1-T12) repeated measures ANOVA on Standard Deviation of Lateral Position (SDLP) did not show a significant difference between the two drives. However, there was a significant effect of Time ($F(11,209) = 17.88$, $p < .0001$). For both drives, SDLP was much lower for the first 10 s, before equalizing to between 0.1 and 0.2 m (see Fig. 4). As with the PRC data, there was a large increase in SDLP 10–15 s after manual control was transferred back to drivers. Although differences were not statistically significant, more variability in SDLP is seen after the Variable drive compared to the Fixed condition, until around 35 s.

Changes in steering control measures for the two drives were also calculated, using the high frequency component of steering angle, which measures operational control and steering corrections (HFS). HFS values were found to be highly skewed and analyses were therefore conducted following a logarithmic transformation of the data, although the non-transformed data are plotted. The 2 (Drive: Fixed, Variable) × 12 (Time: T1–T12) ANOVA on the transformed data showed a highly significant difference between HFS values in the two drives, with more steering corrections in the Fixed drive ($F(1,23) = 45.45$, $p < .0001$, $\eta^2 = .66$). There was also a significant effect of Time ($F(11,253) = 25.45$, $p < .0001$, $\eta^2 = .52$) and an interaction between Drive and Time ($F(11,253) = 3.68$, $p < .0001$, $\eta^2 = .14$). Post hoc t-tests showed the number of steering corrections to be significantly lower in the first 10 s, for both drives. Following a dramatic rise in the number of corrections after 10 s, they are seen to stabilize after around 35–40 s. Therefore, whether control was passed to drivers after a Fixed or Variable time, it took around 10 s for drivers to resume control and this was seen by an exaggeration in steering corrections in the next 10–15 s, which then steadied after around 35–40 s. A higher number of steering corrections were seen after manual control was resumed in the Fixed drive, which is also reflected in better lateral control and lower SDLP values, as shown above. These results may be explained by a more strategic control of driving after the Fixed drive, compared to the Variable drive, perhaps because in the latter, participants' attention is not yet completely dedicated to the driving task, as confirmed by their eye fixation pattern (see Fig. 5).

4. Conclusions

Increasing road safety by removing human involvement in driving is argued to be one reason for implementing automated systems in vehicles (Simonite, 2013). However, fully automated vehicles which can guarantee 100% crash-free driving are not yet a reality. There is therefore an immediate need to understand the interaction between the human driver and an automated system which is able to handle a large number of (but not all) driving environments and conditions. Although automated systems are developing at a fast pace, they will continue to have some limitations and drivers' trust and acceptance of these will change as these limitations diminish. Current limitations mean that, for example, a system designed for a quiet and predictable highway environment may need to transfer control back to the driver as it enters a more populated urban environment. The best method and time by which control is transferred back to the driver, the Human

Machine Interface used to convey this transfer and how this resumption of control is managed by the driver are just some of the many research questions which need to be addressed when investigating the human factors of vehicle automation.

The aim of this study was to determine whether the pace and manner by which highly automated (Level 3) control of a vehicle is transferred to drivers had a subsequent effect on participants' ability to resume control of driving, and how such different methods of transferring control affected driver performance and visual attention to the driving task. In particular, we investigated the time taken by drivers to resume manual control of the drive and refocus their attention towards the road centre, the location of most driving-related hazards (Victor et al., 2005).

Results showed an overall better performance by drivers when control was transferred after a Fixed duration of 6 min, compared to when the automated system disengaged if drivers removed their visual attention away from the road centre. Overall, resumption of manual control (in terms of steering behaviour in particular) was worse when the system disengaged due to a lack of driver attention towards the road centre, and this visual attention continued to be erratic for up to 40 s after the transfer of control, compared to when disengagement was predictable after a Fixed pace. Both lateral driving measures and eye fixations showed a 10–15 s lag time between disengagement of the automation and resumption of control by the driver. For these measures, initial large values at around 15 s after transfer of control lead to a more stabilised value after around 35–40 s. Although only the first minute of manual control is reported here, the same patten was seen for consequent 60 s periods. Since all measures used showed the same pattern; i.e. that drivers' ability to regain control stabilised after around 40 s, we can also argue that the 1-min period used is this study was an adequate time period for investigating drivers' ability to regain control from automation.

The implications of these results are important for understanding the criteria needed for appropriate design of Human Machine Interfaces in automated driving conditions, to ensure that messages regarding transfer of control are given in a timely and appropriate manner. Understanding how to keep drivers in the loop during such automation, whilst allowing drivers to safely engage in other, non-driving-related tasks, is another important area in need of further research. Further research in this area is also needed to consider how the 30–40 s needed to resume adequate control of driving affects drivers' situation awareness and ability to manage sudden or unexpected scenarios which, for example, may not be handled by the automated system, due to its limitations. These results provide some indication of how the 'occasional control' required by drivers in NHTSA's Level 3 of automation (limited self-driving) may influence driving control. This study also suggests that drivers require around 40 s to resume adequate and stable control of driving from automation, which might be considered a 'comfortable transition time' as stipulated by the NHTSA guidelines on Level 3 automation (NHTSA, 2013). Finally, the current study used a highly advanced, motion-based driving simulator, which allowed the administration of repeatable and highly controllable experiments, for understanding drivers' interaction with automation. Clearly, field studies in the real world will further our understanding of drivers' performance with these systems, especially regarding the trust and acceptance of automated vehicles, as well as their perceived risk.

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