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Research Paper

Behavioural changes in drivers experiencing highly-automated vehicle control in varying traffic conditions

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Abstract

Previous research has indicated the ironies of high levels of vehicle automation resulting in reduced driver situation awareness, but has also highlighted potential benefits of such future vehicle designs through enhanced safety and reduced driver workload. Well designed automation allows drivers' visual attention to be focused away from the roadway and toward secondary, in-vehicle tasks. Such tasks may be pleasant distractions from the monotony of system monitoring. Hence, this study was undertaken to investigate the impact of voluntary secondary task uptake on the system supervisory responsibilities of drivers experiencing highly-automated vehicle control. Independent factors of Automation Level (manual control, highly-automated) and Traffic Density (light, heavy) were manipulated in a repeated-measures experimental design. 49 drivers participated using a high-fidelity driving simulator that allowed drivers to see, hear and, crucially, feel the impact of their automated vehicle handling. Drivers experiencing automation tended to refrain from behaviours that required them to temporarily retake manual control, such as overtaking, accepting the resulting increase in journey time. Automation improved safety margins in car following, however this was restricted to conditions of light surrounding traffic. Participants did indeed become more heavily involved with the in-vehicle entertainment offered than they were in manual driving, affording less visual attention to the road ahead. This might suggest that drivers appear happy to forgo their supervisory responsibilities in preference of a more entertaining highly-automated drive. However, they did demonstrate additional attention to the roadway in busy traffic, implying that these responsibilities are taken more seriously as the supervisory demand of vehicle automation increases. These results may dampen some concerns over driver underload with vehicle automation, assuming vehicle manufacturers embrace the need for positive system feedback and drivers also fully appreciate their supervisory obligations in such future vehicle designs.

1. Introduction

Advanced Driver Assistance Systems (ADAS), which have the potential to improve both road transport safety and driver comfort, are becoming a major focus in emerging vehicle designs. There is a recent history of European automobile manufacturers co-operating on their development of such systems, for example through the ADASE II (Advanced Driver Assistance Systems in Europe) project supported through the European Union's Fifth Framework Programme. This particular project, involving Peugeot Citroen, Jaguar Land Rover, Fiat and BMW, culminated with a roadmap outlining how the current manual driving task might be gradually automated by on-board systems. Follow-on projects, such as HAVEit (Highly Automated Vehicles for Intelligent Transport) have focussed on improving sensor technology and system architecture in order to make highly-automated driving on public roads an achievable ambition over the coming years.

Many ADAS supporting semi-automated vehicle control already exist. A plethora of manufacturers now offer Adaptive Cruise Control (ACC), which automatically manages longitudinal control of the vehicle to achieve driver-selected values for speed and following headway. Amongst other executive models, the BMW 5, 6 and 7 series and the Mercedes Benz S and CL-class all offer full ACC, which is able to bring the car to a complete stop without any driver intervention. Similarly, lateral support is commonly provided through Lane Departure Warning, typically informing the driver of encroachment toward the current lane boundary either by auditory or haptic warnings. In more extreme cases, such as the Honda Inspire, the vehicle will actually provide a gentle torque to the steering column to maintain itself in lane.

As increasing attention is afforded to the development of such systems and accordingly highly-automated, self-driving vehicles (e.g. Google's automated Toyota Prius which, it is claimed[1], has logged over 140,000 miles around Northern California), it is inevitable that average motorists will eventually find themselves no longer actively involved in routine vehicle handling, taking on a purely supervisory role in ensuring that their vehicle suitably performs the required control actions on their behalf. Considering the driver's ability to undertake such a role is therefore becoming increasingly vital.

1.1 **Human factors of semi and highly-automated driving**

The interaction between the human driver and the automated vehicle has been a focus of applied research for some time (e.g. Nilsson, 1995). During this period, such technologies were expected to provide significant benefits, highlighted in a review by Stanton and Marsden (1996) as improved well-being through the reduction of driver workload and the enhancement of safety through a reduction in error associated with the inherent restriction on individual driving style. Such studies have since been refined to include models of driver behaviour in such circumstances (Boer and Hoedemaeker, 1998; Goodrich and Boer, 2003).

The work presented here characterises driver behaviour with vehicle automation by way of reference to two well-accepted models. The first, Michon's (1985) hierarchical analysis of the driving task, describes driver behaviour at three distinct levels: the highest *strategic* level outlining the process of route choice, the middle *tactical* level concerning the planning of specific driving manoeuvres to best achieve the chosen route and the lowest *control* level depicting the closed-loop control of vehicle inputs required to action these manoeuvres. The second, Parasuraman, Sheridan and Wickens' (2000) task analysis of automation, proposes four information-processing stages: information acquisition, information analysis, decision making and action. The highest level of stage 3 automation (decision making) defines the control undertaken by the highest level of stage 4 automation (action) without requiring, or even allowing, any human involvement.

Although focused toward a representation of situation awareness, in an apparent combination of these two task analyses, Ma and Kaber's (2005) proposed driver model suggests successful completion of tactical and control level driving tasks is achieved through high quality information processing, regardless of whether this information is processed by the vehicle sensors' (in the case of highly-automated driving) or by the human operator's (in the case of manual driving) perception of the

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[1] New York Times, 9th October 2010, "Google Cars Drive Themselves, in Traffic"

driving environment. In highly-automated driving, categorised by Parasuraman et al.'s (2000) stage 3 and stage 4 automation, information processed by the vehicle sensors is used to command the vehicle control inputs. The remaining, and unenviable, responsibility of the driver is to continually process information on the suitability of these vehicle control inputs by supervisory management of the vehicle automation system. The ironies of automation concerning the suitability of a human operator to undertake such a role of monotonous monitoring are long established (Bainbridge, 1983).

In the driving context of automated driving, such concerns over the incompatible information processing demands of the system and the driver have often been modelled at the tactical and control levels with consideration to driver situation awareness (e.g. Ward, 2000; Matthews, Bryant, Webb and Harbluk, 2001). Endsley (1995) suggests that good situation awareness is achieved by a strong appreciation of the driving environment at three distinct levels: perception, comprehension and projection. Reduced awareness has been associated with a delay in an appropriate braking response when faced with failures in ACC both in a driving simulator (Young and Stanton, 2007) and in more naturalistic, test-track conditions (Rudin-Brown and Parker, 2004). Similar work has also uncovered complacency and delay when drivers are confronted by the malfunction of lane keeping systems (Desmond, Hancock and Monette, 1998).

These observations have been attributed to reduced driver workload, commonly associated with semi-automated driving when compared to manual driving (Stanton, Young and McCaulder, 1997). Indeed, Bainbridge (1983) points out that from a performance perspective, the passive role of monitoring an automated system is less satisfactory than the active role of manual control. Hence, basic research into workload calls for an optimum level of automation that neither overloads nor underloads the individual operator (see Parasuraman and Riley 1997 for a review). The reduced workload from the automation of driving can result in an underload that is equally hazardous to road safety as overload (Hancock and Parasuraman 1992, Hancock and Verwey 1997). To combat such issues, vehicle manufacturers have been urged to design automated systems that provide up-to-the-minute communication about their operation (Norman, 1990). Empirical evidence supports such a viewpoint, for example that prominent and understandable feedback results in a more expeditious response to ACC failure (Seppelt and Lee, 2007).

1.2 **Experimental aims**

However, rather than designing a system that demands more attention, even if well presented, surely one of the main advantages of highly-automated driving is the freeing-up of attentional resources, allowing the driver greater capacity to attend to secondary tasks whilst driving? In laboratory-based experiments, there is strong evidence to suggest that semi-automated driving does allow drivers the capacity to perform better in abstract secondary tasks (Stanton et al., 1997; Young and Stanton, 2004). If such capacity could be focussed on self-selected, driver-paced activities and presuming that drivers were still motivated and capable to attend to their role of monitoring the highly-automated vehicle, can potential concerns relating to underload be alleviated by a more stimulating highly-automated drive?

This question motivated the present study, devised to investigate driver behaviour with and without full vehicle automation in varying traffic conditions, providing changing demands in terms of information processing and supervisory requirements. The existing literature suggests the effect of escalating traffic density on increasing driver demand (e.g. Miura, 1986; Verwey, 2000), but does not appear to contain studies of automated driving that have employed such an ecologically valid method of manipulating such demands. Although undertaken in the controlled environment of a driving simulator, the objective was to create as genuine an environment as possible for participants to reduce automation underload by engaging at will with naturalistic secondary tasks associated with in-vehicle entertainment. While levels of driver motivation could be queried, the highly immersive nature of the simulator and its large amplitude motion system did provide the expected inertial cues of longitudinal and lateral acceleration associated with vehicle control inputs made by a highly-automated system. This afforded a more realistic representation of vehicle automation in terms of its feel to the driver when compared to previously published studies, typically undertaken using fixed-base or desktop facilities.

The varying simulated traffic conditions also provided the opportunity to assess whether drivers could recognise the associated increased processing/supervisory demand in conditions that represented an increased hazard from the either the performance limitations of the automated system or its failure. Of interest was whether drivers might mitigate their uptake of the secondary tasks in such circumstances in order to better oversee safe operation of the vehicle. As a result, the specific research hypothesis which could be evaluated was that well-behaved highly-automated vehicle control, by freeing up the opportunity for engagement with secondary tasks unrelated to driving, has the potential to a more captivating driving environment without serious implications on traffic safety. This hypothesis is based on emerging evidence that concurrent secondary tasks might diminish the effects of vigilance decrements associated with driver underload and reduced situation awareness (Atchley and Chan, 2011). Furthermore, it assumes that automation continues to show beneficial effects on safety margins without driver interaction (Carbaugh, Godbole and Sengupta, 1998).

With some notable exceptions (e.g. Desmond et al, 1998; Stanton, Young, Walker, Turner and Randle, 2001; Toffetti, Wilschut, Martens, Schieben, Rambaldini, Merat and Flemisch, 2009) there is a paucity of published literature that focuses on the human factors and safety implications in highly-automated driving. The present research attempts to fill this gap, in the process helping to develop the existing knowledge base on role of the driver in future motoring. It is hoped its impact may help inform the concepts and designs of manufacturers as they move towards highly-automated vehicle designs.

2. Method

2.1 **Apparatus**

The University of Leeds Driving Simulator (UoLDS) was employed to mimic the vehicle automation system (Figure 1). The vehicle cab is based around a 2005 Jaguar S-type, housed within a 4m diameter, spherical projection dome. Eight visual channels are rendered at 60 frames/s, predominantly at a resolution of 1920×1200. The five forward channels are front-projected providing a horizontal field of view of

250°. The three rear channels can be seen through the vehicle's central view and side mirrors, the latter both physically modified to accommodate 960x480 LCD panels. The simulator also incorporates an eight degree-of-freedom electrical motion system. This consists of 500mm stroke-length hexapod motion platform, carrying the 2.5t payload of the dome and vehicle cab combination, and allowing movement in all six orthogonal degrees-of-freedom of the Cartesian inertial frame. Additionally, the platform is mounted on a railed gantry that allows a further 5m of effective travel in surge and sway. In this study, driver eye-tracking was recorded by a Seeing Machines faceLAB v4.5 eye-tracker, mounted as a stereo camera pair on the top dashboard just below the driver's eyeline (Figure 1).

Figure 1 about here

Virtual traffic in the simulator is handled as a number of intelligent agents, individually controlling their longitudinal and lateral accelerations through a series of third-order controllers with behavioural parameters to manage speed, headway, time to collision, lane choice and heading (Wright, Ward and Cohn, 2002). They exist within an area of interest around the position of the driven vehicle using the concept of sources and sinks where agents arrive and leave the virtual environment respectively (Nagel and Schreckenberg, 1992). This gives the impression to the simulator driver of continuous ambient and realistically behaved traffic, but traffic which is also adaptable to experimental requirements.

2.2 **Experimental Design**

A two-factor, repeated-measures design was employed with the independent variables defined as Automation Level and Traffic Density.

Automation Level described the degree of automation available to the driver at two levels: manual and highly-automated. 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 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 1.5s 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 0.1g and deceleration of 0.2g. 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. Highly-automated driving was activated on request by depressing a built-in button mounted next to the left-hand grip of the steering wheel. It was deactivated by either pushing the same button (toggle on/off), moving the steering wheel by more than 3° from its current position or by depressing the brake pedal. A small LCD panel below the speedometer was backlit and displayed “ACC/LKS” when the highly-automated system was active.

The behaviour of the intelligent virtual traffic was manipulated to control Traffic Density at two levels: light and heavy. This was achieved by moving the location of the sources and sinks in the area of interest around the simulator vehicle and each agent’s behavioural parameters. Light and heavy virtual traffic conditions were managed by the simulation (adjusting behavioural parameters and the proximity of sources and sinks) to correspond to a lane count of 500 and 1500 vehicles per hour per lane respectively (Figure 2). The light traffic flowed consistently, whilst the density of the heavy traffic resulted in varying speeds of the virtual vehicles as their flow was disturbed. Whilst on occasions following headways could become much shorter than the desired 1.5s due to the longitudinal controller’s 0.2g maximum deceleration limit, fluctuations in the virtual traffic were managed to ensure that the controller was always able to handle speed without risk of a collision.

The driving scenario consisted throughout of a standard U.K. three-lane motorway, with lane widths, road markings and junction layouts as described in Chapter 5 (Road Markings) of the U.K. Department for Transport’s Traffic Signs Manual (2003). Data were collected over two 20.4 mile (32.6 km) sections of roadway, during which each level of Traffic Density existed. Between each section, a further 6.8 miles (10.9 km) allowed time for traffic conditions to be modified, unnoticeable to the participant; data were not recorded during this period.

Figure 2 about here

2.3 **Procedure**

Data were collected during a single session, lasting around two hours. On arrival at the simulator participants were briefed on the requirements of the study, their ethical rights, the risks of simulator operation and safety measures employed to mitigate these risks. On completion of informed consent, participants were familiarised by the accompanying researcher with the functionality of the simulator when driven manually and by the highly-automated system. Each Automation Level was completed in a separate driving trial, taking around 45 minutes to complete and separated by a short break. Along with Traffic Density, this order was counterbalanced such each participant undertook two of four possible permutations (manual/light + manual/busy, manual/busy + manual/light, auto/light + auto/busy + auto/busy + auto/light). Use of the highly-automated system was voluntary, but in such condition participants were briefed to “hand control over ... or back to the car as soon as you are comfortable”. Drivers were told to imagine that they were on a leisurely motorway journey without significant time pressure and given a destination junction at which to exit the motorway.

In order to investigate the tendency for secondary task uptake, participants were allowed to interact freely with a range of in-vehicle entertainment. First, they were permitted to choose from a variety of sweets, magazines and hand-held games to take into the simulator with them. They were also allowed to choose from a collection of films and TV programmes, which could be viewed whenever they wished via a DVD player located in the vehicle and displayed on a LCD panel mounted in the central console of the dashboard. Finally, participants were also permitted to use the in-vehicle radio to select a station of their choice at any time during the trials and informed that they were free to engage in any activities if and when they felt it was appropriate to do so. Involvement in each activity was logged manually by the researcher viewing drivers remotely from the simulator’s control room. Logging, equating to the duration for which a task was adopted, was networked to the main simulation so that activities could be matched with eye-tracking and recorded driving behaviour.

2.4 **Participants**

High-mileage drivers (defined as over 6,000 per annum) were recruited from the local population from advertisements in the local press or by a volunteers' section on the simulator's website. Of those that had experience of the simulator, none had been involved with previous studies involving automation. 49 drivers took part with their demographics outlined in Table 1. They were paid for their participation.

Table1 about here

3. Results

The effects of experimental manipulations of Automation Level and Traffic Density were examined using a repeated-measures ANOVA. The assumptions of ANOVA were not violated in any of the data presented.

3.1 **Driver behaviour**

The nature of the automation intrinsically influences many of the more typical metrics of driver behaviour, such as lane keeping or speed choice. Such variables have limited merit since they tend to describe the constrained behaviour of the system rather than the more untamed actions of the driver. Hence, driver behaviour was assessed predominantly by drivers' lane choice (willingness to minimise journey time by overtaking slower traffic) and safety margin in traffic (management/supervision of car following).

Figure 3 shows the proportion of time spent in each of the three available driving lanes. As expected, in heavy traffic participants showed a highly significaint propensity tended to move towards the right lanes in order to overtake slower moving traffic (U.K. driving style). However, with high vehicle automation, however, there was much less of a predilection to change lane. Instead participants generally appeared content let the system takes its course, showing a lack of desire to disengage and retake manual control in order to embark on an overtaking manoeuvre:

- Increase in lane 2 occupation from manual (49.5%) to auto (71.5%); $F_{(1,48)}=24.1$, $p<.001$, $\eta^2=.34$
- Decrease in lane 3 occupation from manual (32.3%) to auto (13.3%); $F_{(1,48)}=27.3$, $p<.001$, $\eta^2=.36$

Figure 3 about here

There was also a significant interaction of Automation Level and Traffic Density for lane 3 occupation; $F_{(1,48)}=5.77$, $p=.020$, $\eta^2=.11$. Compared to manual driving, when they experienced highly-automated control of their vehicle, drivers spent a significantly smaller proportion of their journey overtaking in lane 3 even in heavy traffic conditions.

The margin of longitudinal safety was assessed with respect to time-exposed-time-to-collision (TETTC). Time-to-collision was defined as the time that would elapse, if both the simulator car and lead car maintained their current speeds, before a collision occurred between them. $TETTC_{20}$ was defined as the percentage of journey time in which time-to-collision was less than 20s, although almost identical results were observed for varying threshold values of 2s, 5s and 10s. TETTC has been previously used as a determinant of traffic safety with a high value indicating increased potential for rear-end collisions (Minderhoud and Bovy, 2001).

There was evidence to suggest that automated driving appeared to improve safety margins as $TETTC_{20}$ decreased from manual (8.26%) to highly-automated driving (5.82%); $F_{(1,48)}=14.8$, $p<.001$, $\eta^2=.24$. However, those improved margins tended to be limited only to light traffic conditions (Figure 4), a significant interaction of Automation Level and Traffic Density being observed suggesting that in busy traffic the automated system handled longitudinal control not dissimilarly to manual drivers; $F_{(1,48)}=4.65$, $p=.031$, $\eta^2=.08$.

Figure 4 about here

3.2 **Driver fatigue**

Saxby, Matthews, Hitchcock, Warm, Funke and Gantzer (2008) observed that vehicle automation has the potential to induce driver fatigue. PERLCOS, the proportion of time that a driver's eyes are closed during a fixed moving time window, has been validated as a measure of such drowsiness (Wierwille, Ellsworth, Wreggit, Fairbanks and Kirn, 1994) and hence was recorded using data gleaned from the eye-tracker. There was evidence to suggest that automation tended to reduce driver arousal, with PERCLOS[2] significantly increasing from 0.018 in manual driving to 0.038 in the corresponding highly-automated condition; $F_{(1,48)}=6.10$, $p=.018$, $\eta^2=.13$. There was also a significant interaction ($F_{(1,48)}=5.39$, $p=.027$, $\eta^2=.09$) of Automation Level and Traffic Density (Figure 5) to suggest that heavy traffic conditions did tend to mitigate reduced arousal levels in automated driving compared to when the road was quiet. More fatigue was evident than demonstrated in manual driving, which in contrast appeared unaffected by Traffic Density.

Figure 5 about here

3.3 **Secondary task uptake and eye-movements**

Drivers experiencing high levels of automation did show an inclination to become more heavily engaged in secondary activities associated with in-vehicle entertainment, be they visually demanding or not. Use of the radio significantly increased from 41.1% in manual driving to 54.1% with automation; $F_{(1,48)}=8.59$, $p=.018$, $\eta^2=.13$. There was also a dramatic rise in drivers playing their chosen DVD in automated conditions (32.5%) as opposed to manual control (2.6%); $F_{(1,48)}=22.3$, $p<.001$, $\eta^2=.32$.

Such partiality to the entertaining tasks may have contributed the significantly shorter durations that drivers spent fixated within the road centre area under automated vehicle control (Figure 6). To assess this, eye-tracking data were processed to obtain Percent Road Centre (PRC), the proportion of gaze data points,

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[2] In the present study, the threshold of closure was 75%, the moving window being 180s.

labelled as fixations, that 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 and Engström, 2005). PRC decreased significantly from 74.5% when driving manually to 54.0% when automated, associated here with a reduction in visual attention to the primary driving task and an increase to those associated with the entertaining secondary tasks; $F_{(1,48)}=64.9$, $p<.00001$, $\eta^2=.63$.

Figure 6 also shows the observed interaction of Automation Level and Traffic Density; $F_{(1,48)}=4.41$, $p=.042$, $\eta^2=.11$. When driving manually, participants demonstrated the same visual attention to the roadway regardless of the surrounding traffic. However, with high- automation, although generally spending longer periods fixated away from the road, drivers were motivated to demonstrate additional visual attention in heavy traffic.

Figure 6 about here

4. Discussion

The focus of this research was to investigate the likely impact of emerging vehicle designs on driver behaviour, specifically the current trend towards the development of highly-automated vehicle control. By reducing the visual and attentional demands of the driver, such systems have the potential to engineer a more pleasurable environment for the motorist. Hence, the investigation reported here was designed to evaluate whether the implementation of such well-behaved highly-automated vehicle control could facilitate a more stimulating driving environment for the motorist.

Evaluations of driver behaviour were limited by the major influence that automated vehicle design has on typical metrics such as speed or lane control. However, there was a suggestion that high levels of automation contribute towards a safer driving environment, demonstrated by the significantly shorter period exposed to low time-to-collision when compared to manual driving. Such a finding concurs with previous work, particularly focused on ACC (e.g. Stanton and Young, 1998; Young and Stanton, 2004). Whilst these improved margins were limited to conditions of light traffic conditions only, the significant interaction of Automation Level and Traffic Density observed suggests that, even in heavy traffic, the highly-automated system handled longitudinal control no worse than drivers controlling the vehicle manually. There was no evidence observed to suggest that automation resulted in any increased risk of rear-end accidents nor more hazardous situations encountered even in busy traffic.

Whilst mean speed did reduce under automation, this was a result of drivers' reluctance to intervene, limiting their propensity to move into faster moving lanes to facilitate overtaking and therefore becoming held up by traffic. To overtake in the highly-automated condition, participants had to disengage the system, manually perform the lane change/overtaking manoeuvre, return to the lane of choice and re-engage the system. Clearly, this was something that either consciously or sub-consciously they were not prepared to do, even though this resulted in a longer journey time than necessary. This result may have been exaggerated, however, by the artificial environment of simulated rather than real driving and the lack of any time pressure stressed in the instructions to participants. These instructions also encouraged considerable use of the system, which, along with participants' inexperience of its functionality (apart from the 15-20 minute familiarisation period) may have also increased the likelihood for drivers to simply leave the system engaged, even though overtaking opportunities were plentiful.

The consequence of vehicle automation to free up attentional resources was most definitely exploited by drivers, who showed strong propensity to become involved in secondary activities, especially those related to in-vehicle entertainment, when under automated rather than manual control. This effect was observed both for the more traditional, non-visually demanding use of the radio, and even more strongly for the less familiar (and more visually conflicting) opportunity to watch a personally-selected DVD whilst driving. Such inclination to embrace the in-vehicle tasks was coupled with significantly longer durations of visual attention away from the road. Clearly, participants were willing to compromise their requirements to continually monitor the automated system, exhibiting much confidence in its ability, probably amplified by the lack of dangerous scenarios simulated and the well-behaved nature of the automation. This said, the significant interaction of Automation Level and Traffic Density was highly relevant. Manual drivers showed the same visual attention to the roadway regardless of the traffic conditions. Automated drivers on the other hand spent a significantly longer period fixating away the road, but were gripped to demonstrate more visual attention as traffic conditions became heavier. This promising finding suggests that drivers are able to divert visual attention back to the roadway as supervisory demand increases, circumstances in which the performance limitations of the automation or its failure imply a significant collision risk.

By willingly undertaking more secondary in tasks in favour of a more entertaining automated drive, drivers were also able to mitigate some of the effects of automation fatigue. The PERLCOS data suggest that vehicle automation reduced arousal, in line with the observations of Saxby et al. (2008). However, the observed interaction of Automation Level and Traffic Density does however add weight to the proposition that, once again, drivers respond to the increasing demand of busy traffic, this time with evidence of increased arousal complementing the increase in visual attention in such conditions.

4.1 **Study limitations**

One caveat which must be made is that the functionality of the vehicle automation presented in this study focussed on a single specific realisation. It is difficult, therefore, to extract more general behaviours from those observed with the actual system modelled here. However, it should be stressed that that functionality was based on well-accepted engineering literature (Ioannou et al., 1993; Sharp et al., 2000) describing operation of similar systems. Given confidentiality issues in obtaining manufacturers' specific designs, it is difficult to envisage an alternative method of simulating such systems.

Many of the results discussed here are impacted by participants' motivation to become engaged with the highly-automated driving system, including the need to activate and deactivate its operation to maintain progress through the driving environment. However, system use might have been influenced by the artificialness of the experimental setting, drivers activating vehicle automation simply because they were requested to do so. It is debatable whether in a similar real-life situation, similar levels of system usage would have been observed. Furthermore, it is open to discussion whether the in-vehicle entertainment tasks, especially those conflicting with the visual demands of driving, would have been taken up quite so readily in a more perilous and threatening real driving environment.

However, both of these points are tempered by the huge logistical and safety issues involved with undertaking a similar real-world study. There appears little option to research futuristic vehicle automation systems without the concerted but controlled use of driving simulation.

5. Conclusions

This study has attempted to provide an original and robust investigation into a topic area relevant to modern trends in vehicle design. Given the caveats above, the following observations are presented:

- Driver experiencing high vehicle automation are less inclined to change lanes in order to overtake slower moving traffic than when driving manually. Even in heavy traffic conditions, there is a tendency to let the automation take its course and remain in a central driving lane. Drivers seem unconcerned that this lane choice results in increased journey time.

- In light traffic, high levels of automation improve safety margins associated with car following. In heavy traffic these margins are reduced to those observed in manual driving.

- Drivers demonstrate increasing symptoms of fatigue with vehicle automation. However, this is tempered as traffic conditions become more congested and place increasing demands on drivers' supervisory management of the automated system.

- With high levels of vehicle automation, drivers show more of a propensity to become involved with in-vehicle tasks. Whilst these undeniably have the potential to distract from their supervisory role, they are receptive to the changing demands imposed by heavy traffic, focussing more visual attention to the roadway in such conditions.

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7. References

Atchley, P. & Chan, M. (2011). Potential benefits and costs of concurrent task engagement to maintain vigilance: a driving simulator investigation. Human Factors, 53(1), pp. 3-12.

Bainbridge, L. (1983). Ironies of automation. Automatica, 19(6), pp. 775-779.

Boer, E.R. and Hoedemaeker, M. (1998). Modelling driver behavior with different degrees of automation : a hierarchical decision framework of interacting mental models. Proceedings of the 17th European Annual Conference on Human Decision Making and Manual Control, Valenciennes, France, 14th-16th December 1998.

Carbaugh, J., Godbole, D.N. & Sengupta, R. (1998). Safety and capacity analysis of automated and manual highway systems. Transportation Research Part C: Emerging Technologies, 6(1), pp. 69-99.

Department for Transport (2003). Traffic signs manual 2003, chapter 5, road markings. Published for the Department for Transport under licence from the Controller of Her Majesty's Stationery Office.

Desmond, P.A., Hancock, P.A & Monette, J.L. (1998). Fatigue and automation-induced impairments in simulated driving performance. Transportation Research Record, 1628, pp. 8-14.

Endsley, M.R. (1995). Toward a theory of situation awareness in dynamic systems. Human Factors, 37(1), pp. 32-64.

Goodrich, M.A. and Boer, E.R. (2003). Model-based human-centered task automation: a case study in ACC system design. IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans, 33(3), pp. 325-336.

Hancock, P.A. & Parasurmaran, R. (1992). Human factors and safety in the design of Intelligent Vehicle Highway Systems. Journal of Safety Research, 23(4), pp. 181-198.

Hancock, P.A. & Verwey, W.B. (1997). Fatigue, workload and adaptive driver systems. Accident Analysis and Prevention, 29(4), pp. 495-506.

Ioannou, P., Xu, Z., Eckert, S., Clemons, D. & Sieja, T. (1993). Intelligent Cruise Control: theory and experiment. Proceedings of the 32nd IEEE Conference on Decision and Control, San Antonio, Texas, December 1993, pp. 1885-1890.

Ma, R. & Kaber, D. B. (2005). Situation awareness and workload in driving while using adaptive cruise control and a cell phone. International Journal of Industrial Ergonomics, 35(10), pp. 939-953.

Matthews, M.L, Bryant, D.J., Webb, R.D. & Harbluk, J.L. (2001). Model for situation awareness and driving. Transportation Research Record, 1779, pp. 26-32.

Michon, J.A. (1985). A critical view of driver behavior models: what do we know, what should we do? In: L. Evans & R. C. Schwing (Eds.). Human behavior and traffic safety. New York: Plenum Press, pp. 485-520.

Minderhoud, M.M. & Bovy, P.H.L. (2001). Extended time-to-collision measures for road traffic safety assessment. Accident Analysis & Prevention, 33(1), pp. 89-97.

Miura, T. (1986). Coping with situational demands: a study of eye movements and peripheral vision performance. In: A.G. Gale, I.D. Brown, C.M. Haselgrave, P. Smith and S.H. Taylor (Eds.), Vision in Vehicles-II, Elsevier, Amsterdam.

Nilsson, L. (1995). Safety effects of adaptive cruise controls in critical traffic situations. Proceedings of the Second World Congress on Intelligent Transport Systems, Yokohama, Vol. 3, pp. 1254-1259.

Nagel, K. & Schreckenberg, M. (1992). A cellular automaton model for freeway traffic. Journal de Physique I France, 2(12), pp. 2221-2229.

Norman, D.A. (1990). The problem of automation: inappropriate feedback and interaction, not over-automation. In: D.E. Broadbent, A.D. Baddeley & J.T. Reason (Eds.), Human Factors in Hazardous Situations, Oxford: Clarendon Press.

Parasuraman, R. & Riley, V. (1997). Humans and automation: use, misuse, disuse, abuse. Human Factors, 39(2), pp. 230-253.

Parasuraman, R., Sheridan, T. B. & Wickens, C. D. (2000). A model of types and levels of human interaction with automation. IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans, 30(3), pp. 286-297.

Rudin-Brown, C.M. & Parker, H.A. (2004). Behavioural adaptation to Adaptive Cruise Control: implications for preventive strategies. Transportation Research Part F: Traffic Psychology and Behaviour, 7(2), pp. 59-76.

Saxby, D.J., Matthews, G., Hitchcock, E.M., Warm, J.S., Funke, G.J. & Gantzer, T. (2008). Effects of active and passive fatigue on performance using a driving simulator. Proceedings of the Human Factors and Ergonomics Society 51st Annual Meeting, pp. 1237-1241. Santa Monica, CA: Human Factors and Ergonomics Society.

Seppelt, B.D. & Lee, J.D. (2007). Making Adaptive Cruise Control limits visible. International Journal of Human Computer Studies, 65(3), pp. 192-205.

Sharp, R.S., Casanova, D. & Symonds, P. (2000). A mathematical model for driver steering control with design, tuning and performance results. Vehicle System Dynamics, 33(5), pp. 289-326.

Stanton, N.A. & Marsden, P. (1996). From Fly-By-Wire to Drive-By-Wire: safety implications of automation in vehicles. Safety Science, 24(1), pp. 35-49.

Stanton, N.A., Young M.S. & McCaulder, B. (1997). Drive-By-Wire: the case of driver workload and reclaiming control with adaptive cruise control. Safety Science, 27(2/3), pp. 149-159.

Stanton, N.A., Young, M.S., Walker, G.H., Turner, H. & Randle S. (2001). Automating the driver's control tasks. International Journal of Cognitive Ergonomics, 5(3), pp. 221-236.

Stanton, N.A. & Young, M.S. (2005). Driver behaviour with adaptive cruise control. Ergonomics, 48(10), pp. 1294-1313.

Toffetti, A., Wilschut, E.S, Martens, M.H., Schieben, A., Rambaldini, A., Merat, N. & Flemisch, F. (2009). Citymobil: human factor issues regarding highly automated vehicles on eLane. Transportation Research Record, 2110, pp. 1-8.

Victor, T.W., Harbluk, J.L. & Engström, J. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. Transportation Research Part F: Traffic Psychology and Behaviour, 8(2), pp. 167-190.

Verwey, W.B. (2000). On-line driver workload estimation: effects of road situation and age on secondary task measures. Ergonomics, 43(2), pp. 187–209.

Ward, N.J. (2000). Automation of task processed: an example of intelligent transportation systems. Human Factors and Ergonomics in Manufacturing, 10(4), pp.395-408.

Wierwille, W.W., Ellsworth, L.A., Wreggit, S.S., Fairbanks, R.J., and Kirn, C.L. (1994). Research on vehicle-based driver status/performance monitoring: development, validation and refinement of algorithms for detection of driver drowsiness. Final Report (DOT HS 808 247). Washington, D.C.: National Highway Traffic Safety Administration.

Wright, S., Ward, N. & Cohn, A. (2002). Enhanced presence in driving simulators using autonomous traffic with virtual personalities. Presence: Teleoperators & Virtual Environments, 11(6), pp. 578–590.

Young, M.S. & Stanton, N.A. (2004). Taking the load off: investigations of how adaptive cruise control affects mental workload. Ergonomics, 47(9), pp. 1014-1035.

Young, M.S. & Stanton, N.A. (2007). Back to the future: brake reaction times for manual and automated vehicles. Ergonomics, 50(1), pp. 46-58.

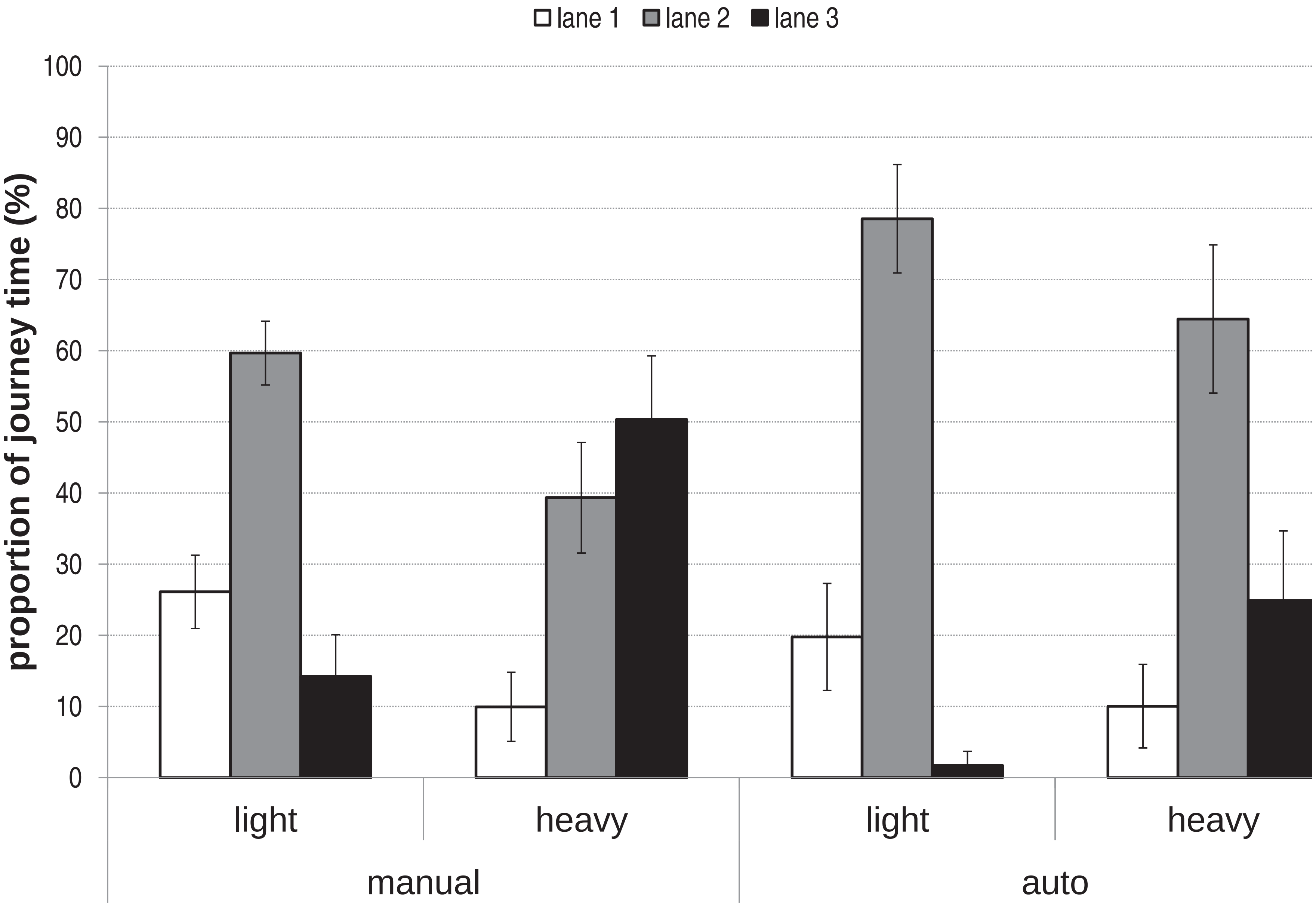
Captions

Table 1	Participant demographics
Figure 1	The University of Leeds Driving Simulator
Figure 2	Screenshots taken during the light (left) and heavy (right) traffic density
Figure 3	Lane occupation in the three available driving lanes (error bars show 95% confidence intervals)
Figure 4	Minimum time to collision (error bars show 95% confidence intervals)
Figure 5	Proportion of eye closure (error bars show 95% confidence intervals)
Figure 6	Percent road centre (error bars show 95% confidence intervals)

Figure 1

Figure 2

Figure 3



□ lane 1
▨ lane 2
■ lane 3
100
90
80
70
60
50
40
30
20
10
0
proportion of journey time (%)
light
heavy
light
heavy
manual
auto

Figure 4

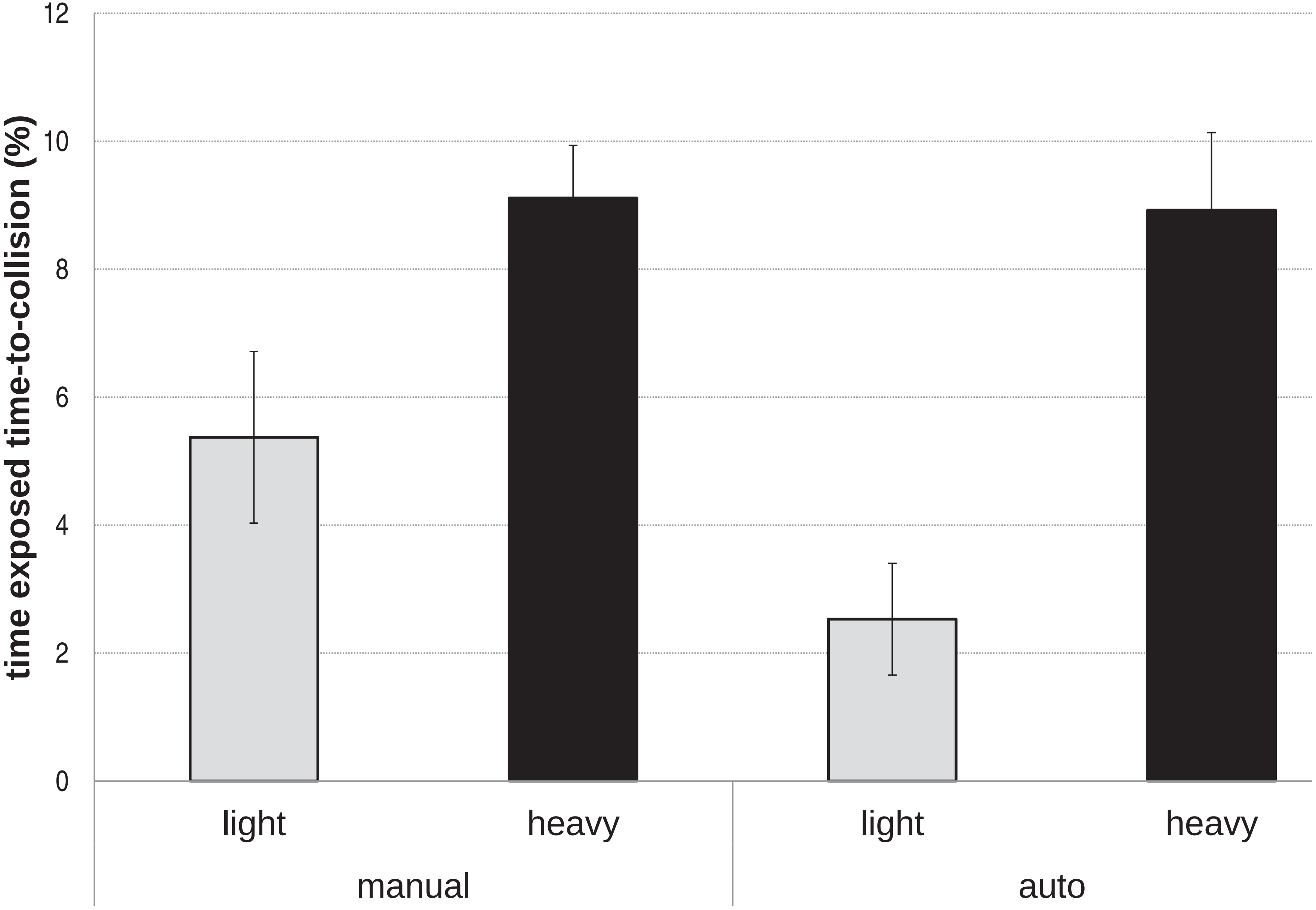

12
10
8
6
4
2
0
time exposed time-to-collision (%)
light
heavy
light
heavy
manual
auto

Figure 5

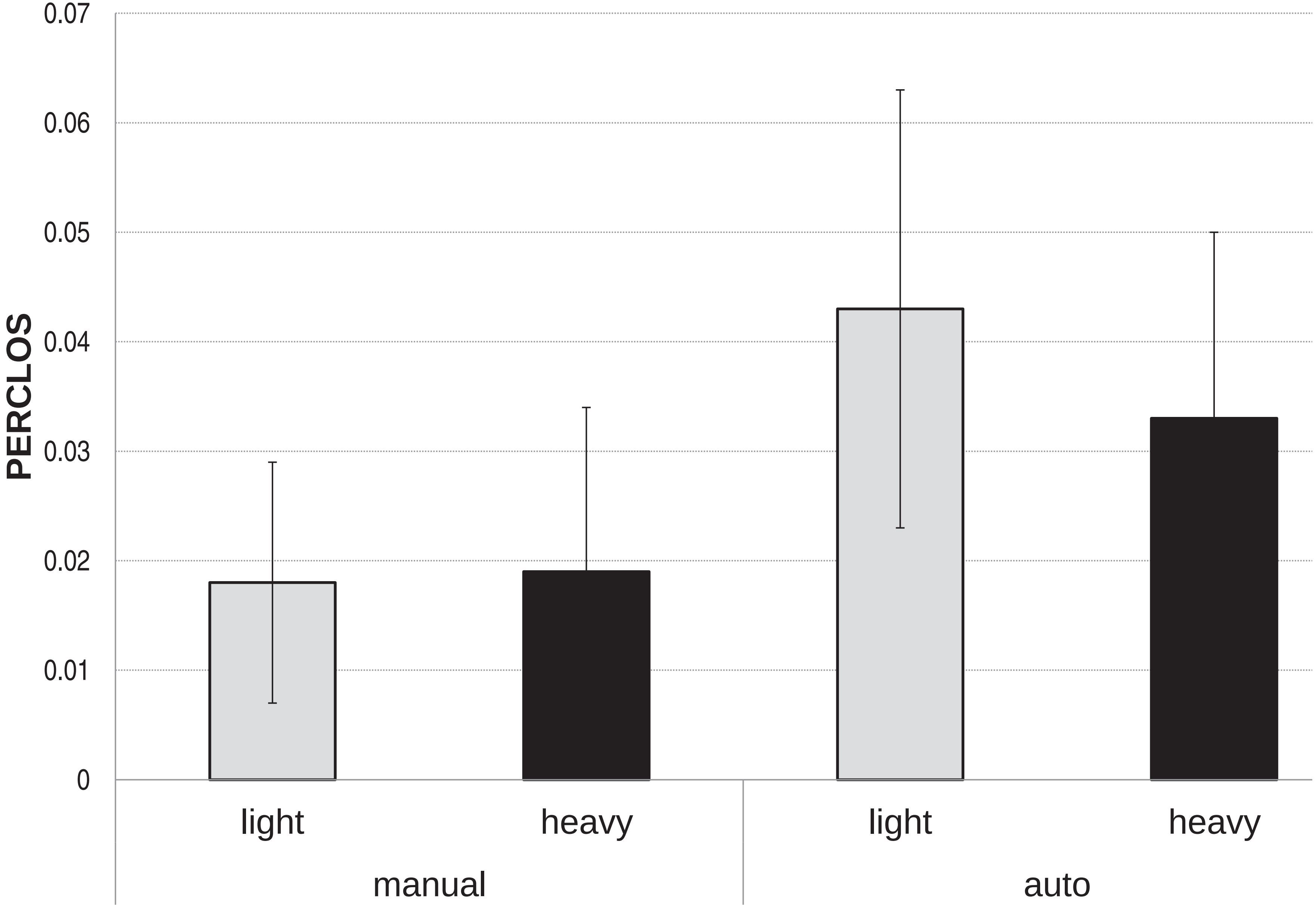

PERCLOS
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
light
heavy
light
heavy
manual
auto

Figure 6

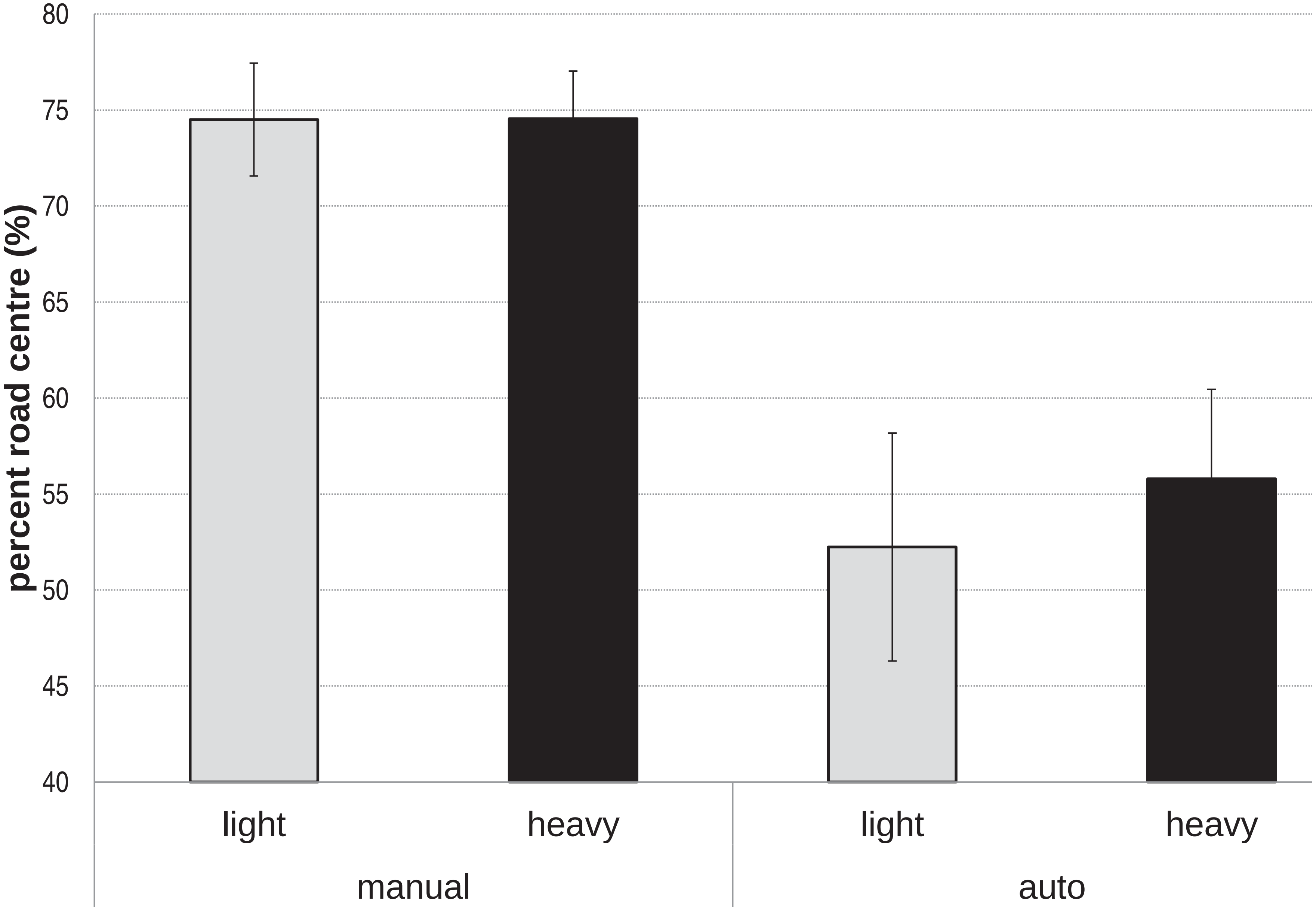

percent road centre (%)
80
75
70
65
60
55
50
45
40
light
heavy
light
heavy
manual
auto

Table 1 Participant demographics

	age (♂/♀)	years licensed (♂/♀)	annual mileage (♂/♀)
mean	37.1 / 36.6	17.7 / 17.4	8846 / 9286
standard deviation	10.2 / 7.4	11.0 / 7.3	2968 / 1496