Back to the future: Brake reaction times for manual and automated vehicles
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Back to the future: Brake reaction times for manual and automated vehicles

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Rear-end collisions are often quoted as being a major cause of road traffic accidents. In response to this, a great deal of ergonomics research effort has been directed towards the analysis of brake reaction times. However, the engineering solution has been to develop advanced systems for longitudinal control, which, it is argued, will mitigate the problem of rear-end collisions. So far, though, there have been few empirical studies to determine how brake reaction times will be affected by such vehicle automation. This paper presents a literature review summarizing the current state of knowledge about driver responses in non-automated vehicles. The review covers driver factors, vehicle factors and situational factors. Following the review, some empirical data are presented from a driving simulator experiment assessing brake reaction times of skilled and unskilled drivers under two different levels of automation. When compared to previous data gathered during manual driving, there seems to be a striking increase in reaction times for these automated conditions. Implications for the design and safety of automated vehicle systems are discussed.

Keywords: Automation; Brake reaction time; Driving; Skill

1. Introduction

In analyses of road traffic accidents, rear-end collisions are estimated to cause between 25% (Gilling 1997) and 40% (McKnight et al. 1989) of all crashes. The most likely explanation for such a high percentage is that the headway chosen by drivers is very often much shorter than it should be. Most motoring authorities stipulate a minimum time headway of 1–2 s (Taieb-Maimon and Shinar 2001), with more conservative criteria being based on worst case scenarios of driver reaction times. Sohn and Stepleman (1998) recommended using 85th or 99th percentile data to calculate these values and from a meta-analysis determined that a value of 1.75 s would be more appropriate. Yet the majority of drivers choose actual headways of less than 1 s (Shinar 2000, Taieb-Maimon 2001).

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and Shinar 2001), raising the question of whether drivers can even react in the time they have allowed themselves.

Driver reactions to events in the roadway ahead can be broken down into several phases. For example, if the leading vehicle brakes suddenly, the following vehicle driver has to perceive the slowing of the vehicle and the illumination of the brake lights, interpret this as braking behaviour, decide whether or not to intervene, select the appropriate braking and/or steering response and initiate the chosen response(s). The only observable elements of this process are the presence of the stimulus (i.e. the braking of the leading vehicle) and the initiation of the host driver’s response (the braking of the host vehicle). All other elements are covert, internal, mental activities. Thus, only three elements of the response can be measured: brake reaction time (BRT; the time from presentation of the brake lights by the lead vehicle to the release of the accelerator pedal by the driver of the host vehicle), movement time (MT; the time from the release of the accelerator pedal to the depression of the brake pedal by the driver of the host vehicle), which added together make up total braking time (TBT; Liebermann et al. 1995). TBT is therefore defined as the time required to process information from the environment and implement the appropriate response. TBT does not include system response time (the time it takes for the vehicle to respond to the driver’s depression of the brake pedal).

Sohn and Stepleman’s (1998) study revealed considerable variation in TBT distributions, which were influenced by both the country of origin (US drivers tended to be slower than non-US drivers) and the awareness of the driver (responses are generally slower where the driver is not aware of the hazard). The components of TBT (i.e. BRT + MT) can therefore be affected by a combination of factors involving the driver, the vehicle and the situation (cf. Warshawsky-Livne and Shinar 2002). These factors are now considered in turn.

1.1. Driver factors

Most studies focusing on driver factors consider whether the driver is aware or unaware of an impending braking event, usually in response to a lead vehicle braking. The findings of Sohn and Stepleman (1998) in this regard have already been stated above; this section considers some of the specific studies.

A study by van der Hulst et al. (1999) considered the effect of expectations on BRT. Two scenarios were investigated. In the unexpected scenario, the host driver had no cues that the lead car was about to decelerate. In the expected scenario, the host vehicle driver could see that the lead car would have to give way to another car emerging from the right-hand side of the road. Both scenarios involved the lead car decelerating from 50 mph (80 kph) to 37 mph (60 kph). The deceleration was set at either $-1\text{ m s}^{-2}$ (slow deceleration) or at $-2\text{ m s}^{-2}$ (fast deceleration). The brake lights did not illuminate as the deceleration was only intended to represent a release of the accelerator pedal. Therefore, the deceleration rates were relatively subtle. Again, the fastest BRT (3.6 s) was in the condition where the driver was expecting the lead vehicle to decelerate and the speed of the lead vehicle deceleration was fast. This compares to 6.3 s when deceleration was slow and unexpected. The reason for the longer BRT data in this study is due to the relatively slow rate of deceleration compared to the braking scenarios that other researchers have investigated.

Similarly, Schweitzer et al. (1995) compared three levels of awareness on TBT. These ranged from no-awareness (where the driver did not expect emergency braking of the
leading vehicle), through partial-awareness (where the driver was expecting to react to a
variety of driving situations including emergency braking), to full-awareness (where the
driver was instructed to apply the brakes as quickly as possible as soon as they saw the
brake lights of the leading vehicle). They found that the greater awareness of the driver
leads to a reduction in mean (and maximum) TBT. Moreover, TBT increases in line with
the size of the gap between vehicles. On the basis of their data, the worst case scenario
should assume a TBT of 1.5 s in a car-following task. Schweitzer et al. (1995) also
compared TBT between male and female drivers, but whilst females were marginally
slower, the differences were not statistically significant.

Three levels of uncertainty were also used by Warshawsky-Livne and Shinar (2002) to
investigate BRT and MT in a simulator. Uncertainty was manipulated by the interval
between lead car brake light activation (constant, varying or varying interspersed with
no-braking trials). Again, BRT increases with uncertainty from a minimum of 0.36 s to a
maximum of 0.42 s, although MT actually decreases slightly. Warshawsky-Livne and
Shinar (2002) also considered the effects of age, with younger drivers (aged less than 25
years) demonstrating the fastest BRT (0.35 s), ages 26–49 years were slightly slower
(0.39 s), while those over 50 years were slowest (0.43 s).

In another simulator study looking at the responses of elderly drivers, Warnes et al.
(1993) split drivers into two groups: the control group (drivers aged between 30 and 44
years); and the elderly group (drivers aged between 55 and 89 years). The lead car was
travelling at approximately 43 mph (70 kph) and it changed its speed on three occasions.
Drivers were instructed to follow a lead car at a safe and comfortable distance. A head-up
warning was provided, which was activated if the two cars were closer than 26 m. In
addition a distraction task was provided. At random points a light would be illuminated
and had to be cancelled by pressing a switch on the indicator stalk. The only statistically
significant difference was the response time with the presence of the warning plus
distraction task. In this condition the elderly drivers responded quicker (2.61 s) to
changes in the lead vehicle’s speed than the control drivers (3.89 s). Warnes et al. (1993)
hypothesized that this is probably due to the older drivers’ ability to focus on the driving
task, even with the presence of a distraction task. Without the warning or distraction
task, elderly drivers were slightly (although non-significantly) slower than controls (2.45 s
vs. 2.33 s).

Thus, in these car-following situations, reaction times generally increase with age and if
the driver is unaware of the impending situation. One paper found a reverse trend,
however. Dingus et al. (1998) reviewed a series of studies into driver reaction time to two
emergency scenarios and one non-emergency (i.e. anticipated) stopping scenario. In
contrast to the previous studies, the fastest reaction times (0.65 s) were reported for a
truly surprising event – as participants drove around a test track at 55 mph (88 kph), a
barrel was fired into their path without warning. For a fixed obstacle, which is arguably
less surprising, response times were slower (1.1 s). Even slower response times (1.3 s) were
recorded when stopping at an intersection for traffic lights – a wholly anticipated
scenario. Possibly, the discrepancy with regard to expectations was due to the fact that
these were not reactions to a lead vehicle braking, but were instead related to obstacles in
the vehicle’s path.

Table 1 summarizes the key data from each of these studies. For brevity, conditions
have been notated as ‘aware’, ‘partially aware’ and ‘unaware’, regardless of whether the
particular study looked at expected or anticipated events. Where studies have multiple
conditions, a representative condition for a comparable dataset has been selected. Results
have been divided according to BRT, MT or TBT.
1.2. Vehicle factors

The influence of the vehicle on driver response times has become more relevant in recent years as more technology is introduced into cars. In reflection of this concern, much of the work in this area has concentrated on in-car distractions, such as mobile (cell) phones, but this area is especially pertinent for the current paper on vehicle automation (as evinced by Rudin-Brown and Parker 2004).

Consiglio et al. (2003) compared mobile (cellular) conversations in both handheld and hands-free formats with listening to the radio and conversing with a passenger. Contrary to popular opinion (and that of most legislative bodies), BRT was slower with both phone formats as well as the passenger conversation, with times increasing by around 19%. Listening to the radio had no effect on BRT. However, the authors conceded that the conversation task in each condition was of a forced-pace nature – whereas passenger conversations in real life might well be self-paced.

Speech-based email systems were the focus of a study by Lee et al. (2001), in an effort to determine whether a non-visual and non-manual system would attenuate performance decrements. Unfortunately, the results were not positive for the speech-based system, with BRT increasing by 30%. In comparing their data with previous research, Lee et al. (2001) concluded their findings were in alignment with those for an expected braking event.

Table 2 summarizes these data for vehicle factors, incorporating the adaptive cruise control (ACC) data from Rudin-Brown and Parker’s (2004) study. Whilst the scale of response times vary widely between studies, it is clear that in-car distractions can dramatically increase BRT to a lead car braking event.

1.3. Situational factors

Situational factors are largely concerned with the external environment – other road users, weather and traffic conditions, etc. As such, vehicle speeds, following distances and
deceleration rates are the main areas of investigation here. Again, some of this work overlaps with that on driver factors (e.g. Schweitzer et al. 1995, van der Hulst et al. 1999), which was covered above, and so only the pertinent findings will be recapped here to avoid repetition.

Liebermann et al. (1995) asked drivers to drive at two different speeds (80 kph and 60 kph) and at two fixed distances from the leading vehicle (6 m and 12 m). Drivers were in a continuous following task and were expecting the lead car to brake at random points in the trial. The driver of the leading vehicle applied their brakes to a level that was ‘moderately strong such that an estimated maximal deceleration (not measured objectively) was assumed’. Liebermann et al. (1995) found that whilst MT remains fairly consistent, BRT decreases with speed but increases with separation distance (from 353 ms to 436 ms at the extremes). This suggests that as drivers have longer time available to react to the braking of the lead vehicle, they devote this extra time to cognitive, rather than physical, activities. This strategy makes sense – given the consistency of the MT it would be better to devote the time to making sure that the response is appropriate. The same independent variables were used by Schweitzer et al. (1995), with a similar pattern of results in the comparable condition (driver partially aware).

Table 3 presents a summary of the key data for situational factors from these studies. As with table 1, representative conditions have been selected where relevant to make a comparable dataset.

1.4. Summary

In the on-road study by Taieb-Maimon and Shinar (2001), a quarter of drivers adopted headways of 0.5 s or less – which, if the lead car braked, would test the reactions of primed drivers under the most optimal laboratory conditions reviewed here. Given that reaction times to unexpected events can be as high as 6 s (van der Hulst et al. 1999), it is not surprising that the accident rate due to rear-end collisions is so high. Since automation is often implemented with the intention of reducing such human errors, this paper now turns to consider the impact of technology on driver reaction times.

2. Experimenting with automation

About half of all accidents can be attributable to driver inattention (Shinar 1978). Consequently, there have been a number of studies in ergonomics attempting to find ways of shortening the driver’s reaction time (Warshawsky-Livne and Shinar 2002).

Table 2. Summary of driver response times from the literature review for vehicle factors (Times are presented as mean brake reaction time in ms).

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Lee et al. (2001)</td>
<td>Control 1010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rudin-Brown and Parker (2004)</td>
<td>Control 2000</td>
<td>ACC (1.4 s headway) 2600</td>
<td>ACC (2.4 s headway) 2800</td>
<td></td>
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</tr>
</tbody>
</table>

ACC = adaptive cruise control.
One notable ergonomics success story (as reported by Sanders and McCormick 1993) is the central high-mounted stop light, which has been shown to reduce rear-end collisions by around one-sixth. Other innovations have met with limited success, however. A study into an advance brake warning system, which illuminates the brake light if the accelerator is suddenly released, found the effectiveness and potential benefits of the device to be limited (Shinar 2000).

New developments in vehicle technology are allowing manufacturers to introduce advanced longitudinal control devices, such as ACC. ACC maintains speed and headway from leading vehicles without any need for driver intervention. Some manufacturers have already released cars equipped with ACC (e.g. Audi, BMW, Jaguar; Ma and Kaber 2005); future systems will build on this capability and offer collision warning and avoidance capabilities. Arguably, then, ACC and its descendents could improve safety by reducing the frequency of rear-end collisions. Based on US data, automating longitudinal control would purportedly save around 1000 lives every year (Gilling 1997). There is conflicting evidence surrounding this viewpoint. Ma and Kaber (2005) used a medium-fidelity driving simulator to show that ACC reduced workload and improved driving performance in terms of speed, headway and lateral variability. Some, however, are more cautious about the potential safety benefits (e.g. Chira-Chavala and Yoo 1994). A test-track study by Rudin-Brown and Parker (2004) found that whilst ACC still reduced workload, this was associated with increased reaction times to a hazard detection task and fewer safe braking interventions by drivers. Moreover, drivers failed to detect a failure of ACC for an average of 23 s. Rudin-Brown and Parker (2004) concluded that drivers’ behavioural adaptation to ACC would reduce its effectiveness in preventing rear-end collisions by 33%.

Apart from these few studies, though, there is a relative paucity of research into how automated systems will affect driver response times when compared with similar knowledge for ‘normal’ (i.e. manual) driving. The following study gathers new data from a driving simulator experiment with automation, to determine the implications of vehicle automation for performance in emergency braking scenarios. Young and Stanton (2001) have already reported that the quality of driver interventions to a critical automation failure event is diminished with increasing levels of automation; the present study takes these data a step further in analysing the quantitative response time data.

### Table 3. Summary of driver response times from the literature review for situational factors (Times are presented as mean in ms).

<table>
<thead>
<tr>
<th></th>
<th>BRT 60 kph</th>
<th>BRT 80 kph</th>
<th>MT 60 kph</th>
<th>MT 80 kph</th>
<th>TBT 60 kph</th>
<th>TBT 80 kph</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 m separation</td>
<td>380*</td>
<td>353*</td>
<td>229*</td>
<td>229*</td>
<td>608*</td>
<td>581*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>584†</td>
<td>552†</td>
</tr>
<tr>
<td>12 m separation</td>
<td>436*</td>
<td>427*</td>
<td>250*</td>
<td>252*</td>
<td>683*</td>
<td>682*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>655†</td>
<td>632†</td>
</tr>
<tr>
<td>Slow deceleration</td>
<td>4200‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast deceleration</td>
<td>3600‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

†Schweitzer et al. (1995); driver partially aware condition.  
‡van der Hulst et al. (1999); driver aware condition.

BRT = brake reaction time; MT = movement time; TBT = total braking time.
2.1. Method

2.1.1. Design. The present experiment used the Brunel University Driving Simulator (BUDS) to investigate whether different levels of automation or driver skill would affect participants’ reaction times in recovering control of the vehicle following an automation failure event. To the best of the authors’ knowledge, there are no such prior studies in the published literature, particularly with regard to the driver factor of skill level. Previous studies on driver factors (as reviewed earlier in this paper) have examined age or driver awareness of the impending event, but not skill.

Driver skill was thus manipulated as a between-subjects factor with two levels (learner vs. expert). Two levels of automation were used as a within-subjects independent variable. In one condition, drivers used ACC, while in the other condition, ACC was supplemented with active steering (AS). AS is essentially a lane-keeping device, which keeps the vehicle in the centre of its lane until the system is disengaged or manual steering input is received from the driver. As with ACC, technology is now becoming available to implement AS devices on cars (e.g. Honda’s advanced driver assistance system). The track layout was a simple mixture of curved and straight sections, with no hills or wind gusts to disturb longitudinal or lateral control. Participants were required to follow a lead vehicle, which was travelling at a maximum 70 mph (112 kph), but at pseudo-random intervals the lead vehicle braked to around 30 mph (48 kph) before accelerating again. Time headway of the ACC system was set at approximately 1.75 s. This corresponds with the upper end of real ACC systems, which can typically be adjusted between 1 s and 2 s time headway.

The experiment was designed to collect objective data about participants’ responses to an automation failure event. The failure consisted of the ACC system disengaging without warning at the same time as the lead car braking. Participants had to intervene if a collision was to be avoided. If no action was taken, collision with the lead vehicle occurred approximately 4 s after the failure. Minimal feedback was given about the failure, except for the ‘CC’ icon on the screen extinguishing and a very slight change in engine note. The failure event occurred in both automation conditions to see if participants were more effective in reclaiming control when expecting the failure, compared to when they were naïve. This was to test whether participants who were investing effort in monitoring for a failure were more effective than those who were naïve and is comparable to previous studies on driver awareness of an impending critical event (e.g. Schweitzer et al. 1995, Dingus et al. 1998, Sohn and Stepleman 1998, van der Hulst et al. 1999, Warshawsky-Livne and Shinar 2002). In keeping with the previous terminology in this paper, drivers could be considered as unaware and partially aware across these two trials.

In this experiment, the primary concern was response to the automation failure. For all participants who reacted to the failure, three reaction time variables were recorded: BRT; MT; and TBT. The simulator recorded data on TBT (i.e. time from onset of the automation failure to first pressure on the brake pedal) and an infra-red camera in the footwell was used to record MT (i.e. time to move the foot from its resting position to the brake pedal – note that the foot was resting on the floor since ACC made pedal inputs redundant). BRT was then calculated by subtracting the MT from TBT (cf. Liebermann et al. 1995). This statistic gives time from the failure event to first reaction, in other words, the participants’ thinking time.

2.1.2. Participants. This experiment consisted of 20 learner participants (12 male) and 24 experts (14 male). Learners were defined as having undertaken formal driving lessons
but not yet passed the UK driving test, while experts had held a full licence and were regularly driving for at least 1 year. Mean age of learners was 19.9 (SD 6.49) years, that of experts was 23.3 (SD 7.18) years.

The learners averaged 23.5 (SD 12.5) h of formal lessons and 9.10 (SD 7.85) h of informal lessons. Six participants had failed one driving test, two had tried three times and one participant had made four attempts. Experts drove on average 5438 (SD 4362) miles per year and had held their licences for an average of 5.15 (SD 6.43) years. The mileage data for expert drivers in this experiment are somewhat lower than the population mean, due to the dependence on student participants who did not drive regularly. The total experience of these drivers, though, is certainly sufficient to categorize them as experts.

2.1.3. Brunel University Driving Simulator. BUDS is a medium-fidelity, fixed-base driving simulator. The driver interacts with a virtual road via a standard steering wheel and pedal configuration of the donor car (a Ford Orion). A medium-resolution colour monitor displays a view of the road and a simulated instrument panel, both of which are generated by an Acorn Archimedes computer, which runs the simulation software. The area of the screen occupied by road view is approximately 2 m wide by 1.1 m high and approximately 2.9 m from the participant’s eyes. The visual angle subtended at the eye point is therefore approximately 40° horizontal by 20° vertical. The display shows the single-carriageway road, in solid colour with a central broken white line, other traffic in both directions and simple roadside objects such as speed limit signs. Collisions with other vehicles or the edge of the road are detected and lead to simulated crashes. Other vehicles follow a fixed path with scripted speed changes.

BUDS software records data at a rate of 2 Hz. The following data are logged: speed; lateral position on the road; distance from the vehicle in front; distance from oncoming vehicle; steering wheel and pedal positions; collisions. The simulator was set up to run with automatic transmission at all times.

Simulator studies have several advantages for research of this nature (Senders 1991). First, they can be used to put people into situations that would not be ethical in the real environment, particularly where such situations compromise safety. Second, simulators can be used in controlled experimental studies. Differences in driver performance can then be attributed to the manipulated variables with a high degree of confidence and the influence of confounding variables can be minimized. Finally, it was possible to compress experience and to collect data on a whole range of situations that were unlikely to be encountered in the natural environment in a short time frame.

2.1.4. Procedure. Participants were given a 5-min practice run in the simulator to allow them time to acclimatize to the controls. Following the practice run, the two automation conditions were explained to participants and operation of the automation controls was demonstrated. The two experimental conditions, each of 10 min duration, were then presented to the participant in randomized and counterbalanced order. In all conditions, participants were told that the lead vehicle would brake periodically. They were instructed to stay behind the lead vehicle, relying on the ACC system to maintain headway as much as possible. However, participants were also informed that if they felt the need to intervene, they should do so, treating the drive as much like a real situation as possible. In both conditions, the automation failure event was programmed to occur 51 s from the end of the run.
Prior to the first condition, participants were given no specific instructions with regard to automation failure. They were simply told to treat it as much as possible like a real road situation and to behave accordingly. However, after the failure in the first trial, participants were informed before the second trial that the automation was not perfect (as had been observed in the first run) and should it fail again they were to take over manual control as quickly and effectively as possible.

On completion of the experiment, participants were thanked for their time and fully debriefed about the nature of the study.

3. Results

Not all participants reacted to the automation failure; consequently, the sample size for all of the variables is somewhat reduced from the participant numbers. Therefore, non-parametric statistics were used for all tests: Wilcoxon signed ranks tests for the within-subjects factor of automation level; Mann-Whitney tests for the between-subjects factor of driver skill. Reaction time data across skill groups and automation conditions are presented in tables 4, 5 and 6.

For those participants who actually did react, Wilcoxon tests revealed that there was no effect of automation on BRT, MT or TBT in either skill group. To determine if there were any learning effects from trial 1 to trial 2, a further analysis by trial was carried out. In the learner driver group, differences in BRT, MT and TBT between trials were non-significant. For experts, BRT was quicker in trial 2 ($Z_{10} = -2.19, p < 0.05$) and TBT decreased ($Z_{10} = -2.75, p < 0.01$). These results are indicative of better performance in trial 2 for expert drivers.

Repeating the automation analyses within each trial did not reveal any significant results. Between-subjects comparisons for BRT, MT and TBT were also non-significant. The most notable conclusion to be drawn from these data, then, is that in trial 2, the performance of experts markedly improves on all variables except MT. This result would be expected on the basis of previous studies, which have found MT to be relatively consistent within individuals (Liebermann et al. 1995) and that TBT is generally slower when the driver is unaware of the hazard (Sohn and Stepleman 1998). Level of automation had no influence on the results in this experiment, but when the data are compared with previous experiments on manual driving (see tables 1, 2 and 3), on the whole reaction times are substantially longer when using automated systems. Indeed, the present results are in line with the BRT data collected by Rudin-Brown and Parker (2004). Thus, it seems that automation can slow drivers’ braking responses by around 1.0–1.5 s. The implications of this will be discussed in the next section.

4. Discussion and conclusions

It has been suggested that ACC systems can reduce traffic congestion, increase road capacity and improve safety by eliminating irregular human driving styles and allowing for safe driving at higher speeds and shorter following distances (Chira-Chavala and Yoo 1994, Gilling 1997, Hoedemaeker 1999). However, the human driver’s capacity to cope with critical events could actually increase the risk associated with such devices. It has been shown (Taieb-Maimon and Shinar 2001) that drivers choose shorter headways than their fastest reaction times. Since ACC systems are typically set with a maximum time headway of 2 s (usually this is adjustable by the driver down to 1 s), the question may reasonably be asked as to whether the driver can intervene in a timely fashion if they need to.
It is immediately apparent that reaction times in the present experiment are vastly inflated from previous results. Mean data for TBT when driving with automation are around three times higher than those gathered under manual driving conditions. Even the results for MT, which is typically invariant in previous studies, are increased by a similar factor when automation is used. Interestingly, where differences were observed in the present experiment (i.e. between trial 1 and trial 2 for expert drivers), MT did remain constant, suggesting an invariance within the automation conditions. This is probably due to the fact that drivers do not have their foot on the accelerator pedal and are perhaps slower in moving from the floor to the brake than they are between adjacent pedals.

Table 4. Descriptive statistics for brake reaction time (BRT) across skill groups and automation conditions* (Times reported in ms).

<table>
<thead>
<tr>
<th></th>
<th>Learners</th>
<th></th>
<th>Experts</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BRT&lt;sub&gt;1&lt;/sub&gt;</td>
<td>BRT&lt;sub&gt;2&lt;/sub&gt;</td>
<td>BRT&lt;sub&gt;overall&lt;/sub&gt;</td>
<td>BRT&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>ACC</td>
<td>2990</td>
<td>2160</td>
<td>2370</td>
<td>2330</td>
<td>2080</td>
</tr>
<tr>
<td>Min</td>
<td>2620</td>
<td>320</td>
<td>320</td>
<td>1920</td>
<td>860</td>
</tr>
<tr>
<td>Max</td>
<td>3480</td>
<td>3140</td>
<td>3480</td>
<td>2660</td>
<td>2920</td>
</tr>
<tr>
<td>SD</td>
<td>444</td>
<td>863</td>
<td>848</td>
<td>375</td>
<td>588</td>
</tr>
<tr>
<td>ACC + AS</td>
<td>2410</td>
<td>2370</td>
<td>2380</td>
<td>2900</td>
<td>2140</td>
</tr>
<tr>
<td>Min</td>
<td>1220</td>
<td>1000</td>
<td>1000</td>
<td>1920</td>
<td>1180</td>
</tr>
<tr>
<td>Max</td>
<td>3600</td>
<td>3300</td>
<td>3600</td>
<td>3680</td>
<td>3260</td>
</tr>
<tr>
<td>SD</td>
<td>1680</td>
<td>840</td>
<td>971</td>
<td>507</td>
<td>590</td>
</tr>
<tr>
<td>Overall</td>
<td>2760</td>
<td>2240</td>
<td>2740</td>
<td>2100</td>
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<tr>
<td>Min</td>
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<tr>
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<td>952</td>
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<td></td>
<td>528</td>
<td>579</td>
</tr>
</tbody>
</table>

*Suffixes refer to experimental trial 1 or 2, or the overall statistics.
ACC = adaptive cruise control; AS = active steering.

Table 5. Descriptive statistics for movement time (MT) across skill groups and automation conditions*.

<table>
<thead>
<tr>
<th></th>
<th>Learners</th>
<th></th>
<th>Experts</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MT&lt;sub&gt;1&lt;/sub&gt;</td>
<td>MT&lt;sub&gt;2&lt;/sub&gt;</td>
<td>MT&lt;sub&gt;overall&lt;/sub&gt;</td>
<td>MT&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>ACC</td>
<td>680</td>
<td>564</td>
<td>593</td>
<td>840</td>
<td>651</td>
</tr>
<tr>
<td>Min</td>
<td>520</td>
<td>360</td>
<td>360</td>
<td>600</td>
<td>80</td>
</tr>
<tr>
<td>Max</td>
<td>880</td>
<td>1240</td>
<td>1240</td>
<td>1080</td>
<td>1160</td>
</tr>
<tr>
<td>SD</td>
<td>183</td>
<td>271</td>
<td>249</td>
<td>240</td>
<td>301</td>
</tr>
<tr>
<td>ACC + AS</td>
<td>840</td>
<td>632</td>
<td>691</td>
<td>730</td>
<td>760</td>
</tr>
<tr>
<td>Min</td>
<td>400</td>
<td>200</td>
<td>200</td>
<td>320</td>
<td>240</td>
</tr>
<tr>
<td>Max</td>
<td>1280</td>
<td>1080</td>
<td>1280</td>
<td>2080</td>
<td>1320</td>
</tr>
<tr>
<td>SD</td>
<td>622</td>
<td>387</td>
<td>418</td>
<td>594</td>
<td>312</td>
</tr>
<tr>
<td>Overall</td>
<td>744</td>
<td>580</td>
<td></td>
<td>760</td>
<td>707</td>
</tr>
<tr>
<td>Min</td>
<td>400</td>
<td>200</td>
<td></td>
<td>320</td>
<td>80</td>
</tr>
<tr>
<td>Max</td>
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<td>1240</td>
<td></td>
<td>2080</td>
<td>1320</td>
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<tr>
<td>SD</td>
<td>348</td>
<td>307</td>
<td></td>
<td>511</td>
<td>303</td>
</tr>
</tbody>
</table>

*Suffixes refer to experimental trial 1 or 2, or the overall statistics.
ACC = adaptive cruise control; AS = active steering.
When comparing the BRT data, there is again a very large increase in mean response times when using automation (around 2.4 s) over normal driving as observed by Liebermann et al. (1995; around 0.4 s). Although the results of van der Hulst et al. (1999) were apparently higher still, it was noted earlier that the design of that study was somewhat different to those of other researchers, in that the deceleration rate was relatively slow. Nonetheless, the results of the present experiment are more in line with textbook values of response times for unprimed drivers, which can be in the region of 2–4 s (Sanders and McCormick 1993, Wickens et al. 1998). Perhaps, then, this indicates that drivers using automation are simply less anticipative of having to make an emergency response than they would be when driving manually. However, even primed expert drivers, who demonstrated an improvement over when they were naïve to the automation failure, took nearly 3 s on average to press the brake after the stimulus was presented. Moreover, in practical terms many researchers favour the use of statistical upper fences as the basis upon which to make recommendations. The maximum TBT value for primed expert drivers was 3.5 s. In previous studies, the highest latencies were under 2 s, whether the braking was expected or otherwise. It should also be noted that these values are before system response times are taken into account.

One implication of automation is the reduction of mental workload (MWL). The positive argument (e.g. Bar-Gera and Shinar 2005) suggests that car-following and headway monitoring is a demanding task and devices such as ACC can relieve these demands, thereby enhancing ‘comfort and convenience’ for the driver (Richardson et al. 1997). Sometimes this may be desirable, since an overloaded driver is likely to make errors. Indeed, Ma and Kaber (2005) argue that ACC relieves MWL and hence improves situation awareness, which in turn enhances performance. However, Stanton and Marsden (1996) argue that driver workload is only excessive in exceptional circumstances. Most of the time, therefore, vehicle automation will relieve the driver of demands that they can quite readily cope with. Automated systems, therefore, have the potential for imposing mental underload. Underload is at least as serious an issue as overload (Leplat 1978, Schlegel 1993) and can be detrimental to performance (Desmond and Hoyes 1996).

<table>
<thead>
<tr>
<th></th>
<th>Learners TBT1</th>
<th>Learners TBT2</th>
<th>Learners TBToverall</th>
<th>Experts TBT1</th>
<th>Experts TBT2</th>
<th>Experts TBToverall</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
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<td>2960</td>
<td>3170</td>
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<td>2820</td>
</tr>
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<td>1000</td>
<td>1000</td>
<td>3000</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Max</td>
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<td>3500</td>
<td>4000</td>
<td>3500</td>
<td>2500</td>
<td>3500</td>
</tr>
<tr>
<td>SD</td>
<td>289</td>
<td>833</td>
<td>838</td>
<td>289</td>
<td>564</td>
<td>541</td>
</tr>
<tr>
<td>ACC + AS</td>
<td>3250</td>
<td>3000</td>
<td>3070</td>
<td>3630</td>
<td>2900</td>
<td>3220</td>
</tr>
<tr>
<td>Min</td>
<td>2500</td>
<td>2000</td>
<td>2000</td>
<td>3000</td>
<td>2500</td>
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</tr>
<tr>
<td>Max</td>
<td>4000</td>
<td>3500</td>
<td>4000</td>
<td>4000</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>SD</td>
<td>1060</td>
<td>612</td>
<td>673</td>
<td>354</td>
<td>460</td>
<td>548</td>
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<tr>
<td>Overall</td>
<td>3500</td>
<td>2820</td>
<td>3500</td>
<td>3500</td>
<td>2810</td>
<td>3500</td>
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<tr>
<td>Min</td>
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<td>3000</td>
<td>2500</td>
<td>1500</td>
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<tr>
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<td>4000</td>
<td>2500</td>
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</tr>
<tr>
<td>SD</td>
<td>612</td>
<td>750</td>
<td>512</td>
<td>387</td>
<td>512</td>
<td>512</td>
</tr>
</tbody>
</table>

*Suffixes refer to experimental trial 1 or 2, or the overall statistics.
ACC = adaptive cruise control; AS = active steering.
Young and Stanton (2001) attributed the subdued response rates with automation to mental underload. Measures of situation awareness and trust in automation were ruled out as explanatory variables and the authors’ Malleable Attentional Resources Theory (MART) was proposed to account for the findings. MART states that attentional resources shrink in underload conditions, thus rendering operators less capable of coping with a sudden increase in demands (as in the automation failure scenario). Possibly, then, the benefits of ACC may only be realized in ‘normal’ (i.e. non-critical) driving situations. This would explain why studies such as Ma and Kaber’s (2005) found performance advantages for ACC under non-critical circumstances, but the present study (and that of Rudin-Brown and Parker 2004) seems to show increased reaction times in an emergency scenario – whether anticipated or otherwise.

Since ACC and other longitudinal control devices are primarily aimed at reducing headway in order to increase road capacity, it seems ironic that the evidence suggests drivers actually need more time to react in emergency situations. ACC designers face a dilemma of defining safe headway in terms of the vehicle’s capabilities or the driver’s reaction times (cf. Taieb-Maimon and Shinar 2001, Goodrich and Boer 2003). Clearly, the emphasis so far has been on the vehicle’s limits, with typical systems providing headways of between 1 and 2 s – far below the drivers’ reaction times in the present study.

As an alternative design philosophy, perhaps automation should be problem-driven rather than technology for its own sake (Owens et al. 1993). A problem-focused approach might use the same technology to provide a different solution. Given that the problem of rear-end collisions is so significant, it follows that drivers have some difficulty perceiving the closing speed of leading traffic. ACC radar sensors could be used to provide drivers with information about the relative (or actual) speed of the lead vehicle, perhaps warning them if this crossed some threshold. This is more in line with a driver assistance philosophy and resembles some ideas about collision warning systems (Janssen and Nilsson 1993, Broughton and Markey 1996, Gilling 1997). This would also solve the problem of drivers not expecting the automation to fail, as now the system simply provides them with extra information about the task they normally perform. For now, though, it would appear that drivers using automation will have to be more attentive than ever before.

References


Chira-Chavalta, T. and Yoo, S.M., 1994, Potential safety benefits of intelligent cruise control systems. Accident Analysis and Prevention, 26, 135–146.


