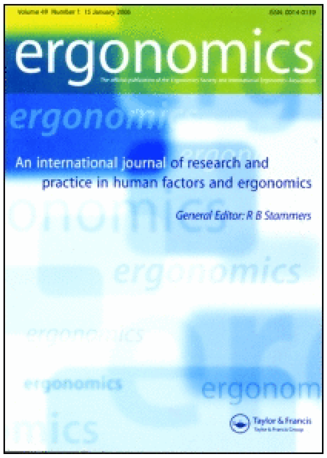

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Driver sensitivity to brake pulse duration and magnitude

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Adaptive cruise control (ACC) requires that the driver intervene in situations that exceed the capability of ACC. A brake pulse might provide a particularly compatible means of alerting the driver to situations in which the acceleration authority of the ACC has been exceeded. This study examined the sensitivity of the driver to brake pulses of five different amplitudes (0.01–0.025 g) and five different durations (50–800 ms). Drivers were sensitive to accelerations as low as 0.015 g. Pulse duration interacted with pulse amplitude, such that moderate duration pulses were more detectable than long and short duration pulses at intermediate levels of pulse amplitude. A power function with an exponent of 1.0 accounted for 99% of the variance in drivers' sensitivity to pulse amplitude; however, a power function with an exponent of 0.23 accounted for only 70% of the variance in drivers' sensitivity to pulse duration. These results can help designers create ACC algorithms and develop brake pulse warnings.

Keywords: Collision warning; Adaptive cruise control; Brake pulse; Haptic; Vestibular

1. Introduction

Automation with a high level of authority and little feedback can degrade event detection and response (Wickens and Kessel 1981, Endsley and Kiris 1995, Sarter and Woods 1995, 1997). As a form of automation, adaptive cruise control (ACC) may cause similar problems and therefore may undermine driving safety. ACC operates much like conventional cruise control when no other vehicles are ahead of a driver. When an ACC-equipped vehicle comes upon slower-moving vehicles, ACC uses vehicle-based sensors to estimate the distance and relative velocity of the other vehicles and then modulates the throttle and service brakes to maintain a set distance from the vehicle ahead (Fancher *et al.* 1998). ACC does not engage the full braking potential of the vehicle and, in

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situations that require severe braking, the system alerts the driver to the need to intervene to avoid striking the rear of the vehicle ahead. Drivers' ability to intervene in a timely manner is critical in these situations. In one simulator study, approximately one-third of drivers were not successful in assuming control in an emergency braking scenario (Stanton *et al.* 1997).

Feedback regarding the state of the ACC allows drivers to determine when they must intervene and helps them develop accurate expectations of ACC behaviour (Stanton and Young 1998). Depending on the algorithm, drivers will experience mild to moderate decelerations with the onset of ACC braking. The haptic and vestibular cues associated with these decelerations depend on the control algorithms of the ACC system and could serve as an early warning of a traffic situation that requires intervention. However, if these decelerations are too pronounced, drivers may interpret these cues as annoying harshness. In fact, smooth deceleration has important comfort and environmental benefits (Marsden *et al.* 2001). Drivers may be best at detecting these decelerations and managing the transitions from ACC to manual control if the operational limits of ACC behaviour correspond to the natural boundaries between speed regulation/car-following and active braking (Goodrich and Boer 2003). More specifically, drivers often follow a counter-clockwise trajectory in phase space defined by the inverse time to collision and time headway. ACC algorithms that follow this natural trajectory and provide noticeable cues during the transition from car-following to active braking will help drivers to assume control in emergency braking scenarios.

Even if transitions from ACC to driver control correspond to natural boundaries, drivers may need alerts to signal the point at which they need to intervene. Such alerts and feedback regarding the state of the ACC are also essential in helping the driver develop accurate expectations of ACC behaviour (Stanton and Young 2005, Seppelt and Lee 2007). The alert type has an important influence on driver performance and acceptance. Potential alerts include auditory cues, such as tones or verbal commands, haptic cues, such as seat vibrations, steering wheel resistance and brake pulse, and visual displays, such as icons located in the instrument cluster or on a head-up display (Hirst and Graham 1997, Graham 1999, Kiefer *et al.* 1999, Tijerina *et al.* 2000, Lee *et al.* 2004).

Of the possible collision warning cues, brake pulses are quite promising, but little researched. In one of the few studies of brake pulse alerts for driving, a 0.6 s brake pulse with a 0.26 g peak deceleration effectively alerted drivers to potential crash situations, but led to slightly slower reaction times compared to auditory cues (Kiefer *et al.* 1999). Another study compared brake pulses, composed of a linearly increasing deceleration (0.08 g/s, 0.20 g/s, 0.32 g/s) for different durations (0.25 s, 0.65 s, 1.0 s; Tijerina *et al.* 2000). Larger brake pulses led drivers to brake harder, but larger brake pulses did not induce a greater degree of inappropriate braking in response to false alarms. These results show that brake pulses can warn drivers effectively, but little research has systematically assessed drivers' sensitivity to various levels of brake pulse amplitude and duration.

Others have investigated sensitivity to acceleration in non-driving environments. In early experiments, Travis and Dodge (1928) found a detection threshold of 8.0 cm/s^2 (0.0082 g) for periods of oscillation between 1–8 s (0.125–1 Hz). When the detection threshold is defined by 74% correct response, people detected lateral acceleration levels of 12.1 cm/s^2 (0.012 g) with a ramp 2.8 cm/s^3 (Gianna *et al.* 1996). Participants were more sensitive to step onset of acceleration, 4.84 cm/s^2 (0.0049 g), compared to ramp and parabolic. Similarly, the threshold of acceleration was estimated as 5.7 cm/s^2 (0.0058 g) (Benson *et al.* 1986). Gundry reviewed 18 studies that examine acceleration threshold and found that the threshold drops as frequency increases, but for frequencies above 1 Hz it is unclear, whether the threshold rises or falls (Gundry 1978). Most psychophysical studies of acceleration have focused on acceleration associated with signals of approximately 0.1–0.5 Hz, equivalent to single pulse durations of approximately 1–10 s. In this range, the threshold for detection drops as the duration of the pulse increases, but this relationship may not hold for shorter duration pulses. Driver response to shorter duration pulses is of interest for automotive applications. In particular, the influence of pulse duration on sensitivity to short pulses is unknown.

The objective of this study is to assess driver sensitivity to pulses of different magnitudes and duration. Quantifying driver sensitivity to brake onset could inform the development of ACC algorithms and presentation of collision warnings. Scaling driver sensitivity to brake pulses would also make it possible to compare brake pulse cues with cues from other warning modalities. The task of selecting alert modalities in the design of collision warnings would benefit from a more precise description of driver sensitivity to brake pulse cues.

2. Method

Ten people drove in a high-fidelity motion-base driving simulator and experienced four practice brake pulses and a further series of 100 brake pulses over 30 min. The pulses were defined by a factorial combination of five levels of amplitude and five levels of duration and were randomly presented with four repetitions of each pulse. Consistent with the psychophysical method of constant stimuli, drivers were instructed to depress the turn signal stalk every time they detected a pulse.

2.1. *Participants*

Five female and five male drivers, with ages from 20 to 40 (mean age 31) years, participated in this study. Participants drove between 5021 km and 41 847 km per year (mean 17 032 km/year) and had held a valid driving licence for an average of 15.9 years. The total participation time for each person was approximately 90 min. Participants completed a demographic questionnaire and received pre-drive instructions that took approximately 20 min to administer. Following the verbal instructions, participants began a 30-min drive that included a brief practice portion at the beginning. Participants were paid $15/h for participation.

2.2. *Experimental design*

A 5^2 within-subject factorial design presented the drivers with 25 mono-pulse braking events, each of which was experienced four times. Five levels of pulse amplitude and five levels of pulse duration defined the braking events. These pulses were created so that approximately 25% were below the threshold of perception. Pulse durations ranged between 50 to 800 ms, with each level of pulse duration double the next lower level. Pulse amplitudes ranged between 0.005 g to 0.025 g, with each level of pulse amplitude 0.005 g greater than the next lower level. A sine function defined the profile of the pulse, with acceleration beginning at zero, increasing to the peak amplitude and then smoothly decreasing to zero. As a result, the amplitude of the jerk, the rate of change of acceleration, for each pulse was the amplitude of acceleration divided by twice the duration of the pulse. Jerk increased as the duration decreased.

All drivers received the 100 brake pulses in the same random order. The time between the pulses varied according to a uniform distribution with a mean and median of 12 s, a minimum of 8 and a maximum of 16 s. Two brake pulses did not match the commanded brake pulse and were dropped from the analyses. The two pulses dropped from the analysis were a 100 ms 0.015 g pulse and a 50 ms 0.025 g pulse. The drive was a series of interstate highways connected by interchanges that required the participant to exit and merge periodically. The pulses were planned, such that they occurred on the straight portions of the highway, but not on the interchanges.

The National Advanced Driving Simulator (NADS) was used for this experiment. This simulator includes 360 by 40° view and a motion base capable of replicating sustained accelerations of 0.6 g and vibrations from 3 to 40 Hz. A sound system provides 3-D auditory cues that include wind and road noise, as well as the sound of other vehicles. The experiment was conducted with a 1996 Chevrolet Malibu cab and used the NADS Dyna dynamics system. The motion base vibrated and moved according to the road surface, just as an actual car would. This provides a realistic background that reflects the masking that might obscure the perception of brake pulse cues in an actual driving situation.

2.3. *Procedure*

Once in the simulator, participants drove on an open roadway. Their speed was automatically maintained at 65 mph (104.6 kph). No other traffic was present and drivers needed only to steer the vehicle and detect brake pulses by depressing the turn signal as quickly as possible. During the first 4 min they experienced four practice brake pulses (0.04 g for 200 ms, 0.03 g for 600 ms, 0.018 g for 200 ms and 0.015 g for 600 ms). Drivers were told that the brake pulses occurred at random and that some pulses were quite subtle. Following the instructions, the simulator was prepared for the 30 min main drive. The pulses began approximately 4 min after the drive began.

3. Results

A MatLab program reduced the data, extracting the pulse start time, pulse amplitude, pulse duration, reaction time and button press response. The first four practice pulse events were not included in the analysis. A signal detection approach was used in the analysis, in which hits were defined as a button press occurring within 6 s following the start of a pulse. Misses were defined as failure to respond within 6 s of the start of a pulse. A false alarm was then defined as any button press 6 s after the pulse, but before the onset of the following pulse. The 6-s threshold was chosen because it accommodated the vast majority of response latencies in previous studies (Gundry 1978, Macmillan and Creelman 2005). When multiple button presses occurred within the first 6 s of the start of a pulse, the first button press was considered a hit, but the following ones were considered false alarms. For each participant, d' was calculated for each of the 25 combinations of pulse amplitude and duration.

The d' and mean reaction time for each of the 25 pulses for each of the ten drivers was compiled for further analysis. The reaction time for several pulses was coded as a missing variable because reaction time could only be calculated if at least one of the four pulses was detected. The reaction time and d' data were then analysed using a within-subject, repeated measures ANOVA using SAS PROC MIXED (SAS Institute, Cary, NC, USA).

Drivers detected approximately 46.5% of all brake pulses and had a false positive rate of 5.1%. In terms of d', the ease with which pulses were detected depended on amplitude ($F(4,32) = 72.0$, $p < 0.0001$), duration ($F(4,32) = 17.5$, $p < 0.0001$) and the interaction between the duration and amplitude ($F(16,128) = 2.5$, $p = 0.0049$). Drivers' reaction time also depended on amplitude ($F(4,26) = 8.4$, $p < 0.0001$), duration ($F(4,32) = 8.9$, $p < 0.0001$), and the interaction between the duration and amplitude ($F(16,71) = 2.9$, $p = 0.0011$).

Figure 1 shows that drivers generally failed to detect very low amplitude brake pulses (0.005 g) and that at this level of pulse amplitude, pulse duration had little effect on d'. For higher amplitude pulses, the longer duration pulses were increasingly detectable. Interestingly, for moderate amplitude pulses of 0.01 and 0.015 g, the long-duration pulses were less detectable than slightly shorter pulses.

Figure 2 shows that drivers detect high amplitude brake pulses more quickly than low amplitude brake pulses. Depending on the amplitude of the brake pulse, drivers respond to short and long pulses slowly and moderate duration pulses quickly. Similar to the detection of long-duration pulses, at intermediate levels of brake amplitude, drivers seem less sensitive to long pulses and respond more slowly to long-duration pulses than to intermediate-length pulses. Response time and d' show generally similar effects for some conditions, such as shorter response times and larger d's with increasing pulse amplitude; however, reaction time and d' are not strongly correlated (0.12, $p > 0.05$).

Figure 3(a) shows that a power law describes the relationship between drivers' ability to detect pulses and the amplitude of the pulse. A power function with an exponent of 1.0 accounts for 99% of the variance for pulse amplitude.

Figure 3b shows that the effect of pulse duration does not follow a power law relationship, accounting for only 70% of the variance with an exponent of 0.23. A quadratic function fits the data much better, accounting for 98% of the variance.

4. Discussion

Not surprisingly, amplitude and duration each strongly affected the ability of drivers to detect brake pulses. Amplitudes of 0.015 to 0.020 represent the approximate threshold for correctly detecting 75% of brake pulses. This compares to thresholds of approximately

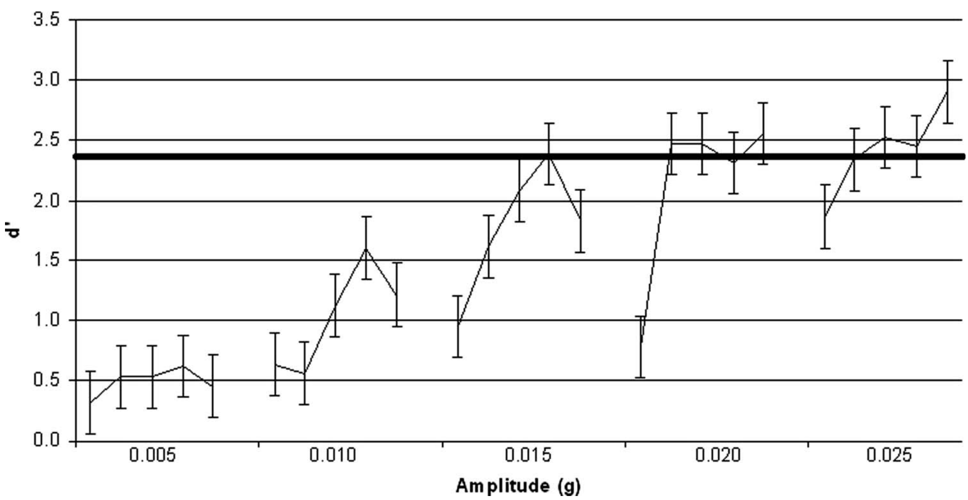

Figure 1. Drivers' sensitivity (d') to brake pulses with durations of 50, 100, 200, 400, 800 ms and amplitudes of 0.005, 0.010, 0.015, 0.020, and 0.025 g. The bold line indicates point at which drivers detected 75% of the brake pulses.

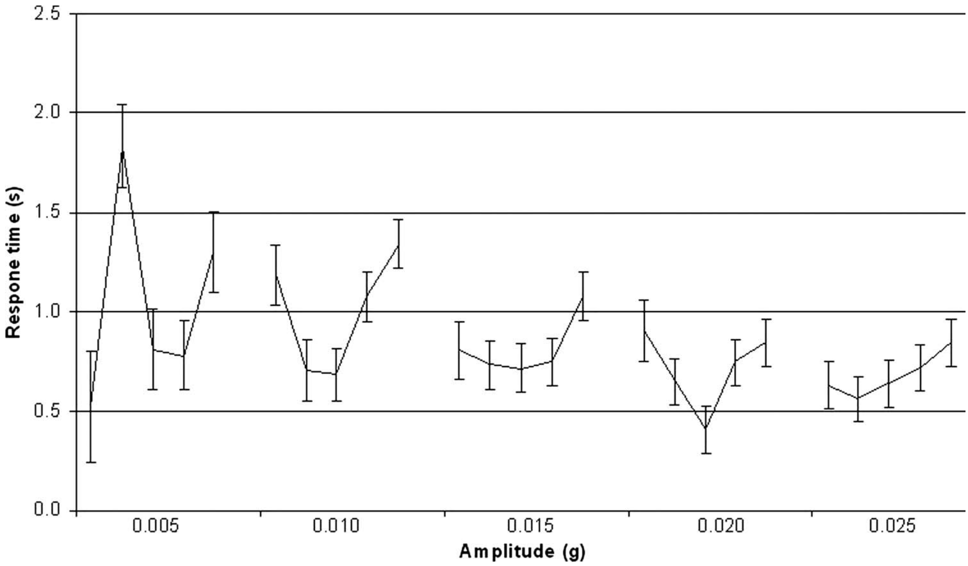

Figure 2. Drivers' reaction time to brake pulses with durations of 50, 100, 200, 400, 800 ms and amplitudes of 0.005, 0.010, 0.015, 0.020, and 0.025 g.

0.005 to 0.010 g in laboratory studies (Benson *et al.* 1986, Gianna *et al.* 1996). The ambient vibration, vehicle suspension and seat tend to dampen and mask the brake pulse. For these reasons, it is also not surprising that the thresholds in this study are greater than those in more controlled laboratory environments. Application of psychophysical data from laboratory studies to the vehicle context should consider such effects. The driving environment also includes visual and auditory cues that might augment drivers' ability to detect ACC braking response and brake pulse alerts. Considering that many ACC systems can engage the service brakes to decelerate the vehicle at 0.20 g, these results suggest that drivers are quite likely to detect the onset of severe braking of the ACC. The results of this study also show that drivers are likely to detect the onset of mild braking at the level of approximately .02 g, but what is less clear is the degree to which drivers might detect transitions between mild and moderate braking.

The pulse duration had less effect on the ability to detect the pulses compared to pulse amplitude – even the shortest pulse of 50 ms was relatively detectable at the highest pulse amplitude. In addition, the influence of pulse duration depended on pulse amplitude such that high and low duration pulses were less detectable than intermediate duration pulses. One explanation for this effect is the contribution of jerk, which was highest for the short-duration pulses and lowest for the long-duration pulses. The curvelinear effect of pulse duration may reflect the joint contribution of jerk and acceleration. These factors both play an important role in the perception of self-motion. In this study, longer duration pulses were more detectable, because they produced a large deceleration cue. In contrast, short pulses produced a large jerk cue. Intermediate pulses have a substantial component of jerk and acceleration. This is consistent with previous studies, which have found signals below 1 Hz engage vestibular mechanisms, whereas above 1 Hz the somatosensory contributions become relevant (Gundry 1978). This study used a simple pulse that had a smoothly increasing and decreasing acceleration. The complex effect of pulse duration on pulse detectability suggests that pulse profile might strongly influence drivers'

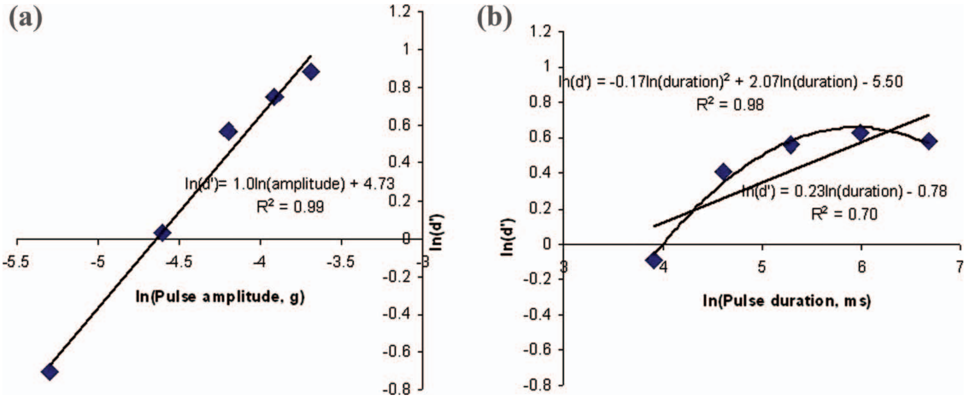

Figure 3. Power law fit for brake pulse amplitude (a) and duration (b).

response to brake pulse alerts. A relatively long pulse with a high-jerk onset may be most easily detected.

A power law relationship describes the effect of pulse amplitude on driver's ability to detect the pulses very well. Power law exponents greater than 1.0 reflect expansive relationships in which a change in the stimulus magnitude leads to a greater change in perceived magnitude. The power law exponent of 1.0 found in this study compares to a power law exponent of 1.45–2.2 found in previous studies of acceleration detection (Boff and Lincoln 1988). One explanation for the lower value found in this study is the relatively low-duration pulses considered; previous studies used pulse durations greater than 1000 ms, compared to the 50 to 800 ms durations in this experiment. The ease of detection increased with increasing pulse amplitude more quickly for long pulses compared to short pulses.

The strong power law relationship for pulse duration suggests the potential to match brake pulse signals to the magnitude of other potential warning signals. From Stevens' power law (equation 1), equation 2 shows the stimulus intensity (ϕ_2) of a second stimulus needed to match the perceived magnitude of the first.

$$\psi = k\phi^{\beta} \tag{1}$$

$$\phi_2 = \frac{k_1}{k_2}\phi_1{}^{\beta_1/\beta_2} \tag{2}$$

The power law exponent for loudness of a 3000 Hz tone is 0.67 (Stevens 1957). This exponent compares to 1.0 for the brake pulses tested in this experiment and suggests that drivers are substantially more sensitive to changes in brake pulse amplitude than they are to sound pressure level. To match the perceived intensity of a 10 dB increase in auditory warning intensity requires only a 6.7 dB increase in brake pulse amplitude. However, the physical limits of vehicle deceleration and the consequences for inappropriate alerts severely limit the magnitude of brake pulses. The range from 0.02 to 0.80 g is only 32 dB, which provides a stimulus range similar to a 47 dB range for a simple tone.

These results point towards a need for further research. The degree to which drivers detect transitions between mild and moderate braking is unclear. An experiment that considers transitions from a range of mild braking levels to a range of moderate braking levels could help specify ACC braking profiles that naturally signal the transition from car following to active braking. Another issue that merits consideration is a more thorough investigation of the driving context. The detection threshold in the simulator was nearly twice that of more controlled laboratory experiments. One approach would be to use the same protocol and change the venue from the simulator to an actual roadway. The additional masking associated with vibration and uneven road surface might require even greater values of duration and amplitude to support detection compared to those found in the simulator. The current study considered brake pulses in the absence of any identifiable source. The detection thresholds might be substantially different, if they were paired with a decelerating lead vehicle and ACC. More generally, this study points towards the need to understand how well drivers perceive the subtle vehicle dynamics that are modulated by advanced vehicle automation (Walker *et al.* 2006).

This study focused on drivers' sensitivity to brake pulse amplitude and duration. The results show that drivers are sensitive to relatively small levels of acceleration (0.015–0.02 g) and relatively short duration pulses (100–200 ms). These values represent important lower bounds for using brake pulse cues to help drivers understand the state of the ACC. Further research should evaluate the degree to which these thresholds depend on the ongoing deceleration profile. In addition, the degree to which pulse amplitude and duration influence perceived annoyance and urgency are critical questions, if brake pulse cues are used to support drivers (Edworthy and Adams 1996, Hellier and Edworthy 1999, Wiese and Lee 2004).

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