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Incandescent Bulb and LED Brake Lights: Novel Analysis of Reaction Times

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ABSTRACT Rear-end collision accounts for around 8% of all vehicle crashes in the UK, with the failure to notice or react to a brake light signal being a major contributory cause. Meanwhile traditional incandescent brake light bulbs on vehicles are increasingly being replaced by a profusion of designs featuring LEDs. In this paper, we investigate the efficacy of brake light design using a novel approach to recording subject reaction times in a simulation setting using physical brake light assemblies. The reaction times of 22 subjects were measured for ten pairs of LED and incandescent bulb brake lights. Three events were investigated for each subject, namely the latency of brake light activation to accelerator release (*BrakeAcc*), the latency of accelerator release to brake pedal depression (*AccPdl*), and the cumulative time from light activation to brake pedal depression (*BrakePdl*). To our knowledge, this is the first study in which reaction times have been split into *BrakeAcc* and *AccPdl*. Results indicate that the two brake lights containing incandescent bulbs led to significantly slower reaction times compared to eight tested LED lights. *BrakeAcc* results also show that experienced subjects were quicker to respond to the activation of brake lights by releasing the accelerator pedal. Interestingly, analysis also revealed that the type of brake light influenced the *AccPdl* time, although experienced subjects did not always act quicker than inexperienced subjects. Overall, the study found that different designs of brake light can significantly influence driver response times.

INDEX TERMS Brake light reaction time, brake light stimulation, bulb vs. LED response time, LED brake light, road safety.

I. INTRODUCTION

Recent reports from the World Health Organization (WHO) have highlighted a worldwide increase in road traffic accidents, reaching 1.35 million in 2018 [1]. According to the US National Highway Traffic Safety Administration (NHTSA), rear-end crashes accounted for 7.2% of total crashes in 2017 [2]. In the same year, the Department of Transport (DoT) UK reported 13,374 slowing or stopping related car accidents [3]. Rear-end collisions are mostly attributed to either delayed brake response or lack of braking force due to slower reaction times, when the following drivers do not react sufficiently quickly to the behaviour of a lead vehicle due to inadequate or late detection of its deceleration [4]. Many

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research studies have examined ways of alerting drivers to avoid rear-end crashes through improved technology either inside or outside the vehicle [5]–[9].

For example, optical looming was experimented with within a dynamic brake light system, where the brake light luminance continually and gradually expands outwards from the brake light enclosure, improving both visibility and attention of the following driver [9]. Stanton *et al.* explored a graded deceleration display technique by replacing the steady illumination of a rear centre high mounted stop lamp (CHMSL) to change brightness based on the degree of deceleration. This elicited more accurate deceleration information allowing following drivers to better gauge deceleration changes by the lead vehicle [10]. To improve the attention of the following driver, an imminent warning rear light concept was explored by Walter *et al.* to direct the follow-

ing drivers' visual glance to the lead vehicle as it brakes rapidly to stop or slow down [11]. Trials reported that mean brake activation time reduced from 0.35s for ordinary rear lighting to 0.25s. The effectiveness of flashing brake and hazard systems in avoiding rear-end crashes was investigated by Li *et al.*, revealing brake response time reductions of 0.14 ~ 0.62s for various situations tested [8].

Studies have also explored various types of stop lamps [12]–[14], revealing that reaction time varies by the type of lamp used in a brake light. Most automotive stop lamp types are incandescent, sweeping neon or LED. Bullough *et al.* evaluated these variants for CHMSLs, reporting that incandescent lamps had higher reaction times than LED or neon devices [12]. For standard incandescent lamps, discernible optical output begins around 50 ms after activation, taking around 250 ms to reach 90% of steady state output [15]. LED CHMSLs also led to shorter reaction times than neon since the high-luminance point source nature provides a stronger stimuli than the more diffused neon lamp [16]. Recently OLEDs also have emerged as a new light source for modern cars, which do not require an additional reflector. The efficacy of such designs is yet to be explored [17], [18].

Most traffic safety studies measure driver reaction time (RT). This is a concept that traffic safety researchers have repeatedly made use of when designing experimental studies or analysing driver behaviour in crashes [19]–[21]. Considering braking response, effectiveness has traditionally been measured in terms of brake reaction times (BRTs). Influential factors are usually driver age, gender, cognitive load and the various other stimuli that the driver needs to consider [22]–[24]. Additionally, driver reaction times differ markedly depending upon the situation; slower at lower speeds, faster in a real emergency. Their response is also affected by other issues including driver height, shoe design, pedal location, seat placement, etc. To decouple those environmental factors from the influence of the brake light design, it is necessary to separately measure how quickly a driver perceives a brake signal, and then how quickly s/he responds to it.

As far as we are aware, there have been no extensive studies to date that used real brake lights to evaluate the effects of brake light design on the reaction time of the driver. More importantly, in this study, for the first time, we analyse reaction times by studying accelerator release timings as well as the usual brake pedal depression timings. Our experiments used ten physical brake light assemblies (two pairs containing incandescent bulbs and eight pairs containing LEDs, all of recent design) in a simulation setting, activated in a random fashion using custom built hardware.

The remainder of the paper is organised as follows. Section II describes the experimental methodology, hardware design, data acquisition and analysis approach. Section III presents and discusses the results and then Section IV concludes the paper.

II. METHODOLOGY

The experimental paradigm relied upon custom built hardware and software to present random brake light events to subjects in a simulation setting, while recording responses from a number of associated sensors.

A. EXPERIMENTAL SETUP

The experiments were conducted in a distraction and noise-free simulation room of size 7.12 × 14.96m with a projection screen at one end sized 5.00 × 3.75m for replaying a highway traffic simulation video. Volunteers were seated in an automotive-style chair at a distance of 5m facing the screen.

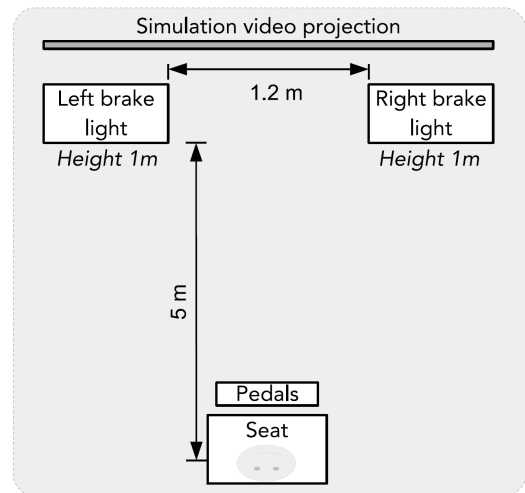


FIGURE 1. Experimental design: Brake light distances with room layout.

Volunteers were provided with an accelerator and brake foot pedal assembly (QLOUNI Industrial Foot-switch Momentary Metal Foot Pedal, part number: 611702431551), mounted in front of their seat in an arrangement as shown in Figure 1. Custom firmware was developed to generate random braking events along with marker signals which are recorded and time stamped by an event recorder during the experiment. The firmware was programmed to generate 45 brake light events to turn on (and then off) the brake lights, and similarly to activate the 100mm diameter yellow distractor rings in random order. Brake light activation occurred for random periods of between 2 and 4s, with the distractor activation being random for between 3 and 5s. The control system was programmed to ensure that the distractors and brake lights were not activated simultaneously.

B. EXPERIMENTAL HARDWARE

The experiment controller was designed using a custom 32-bit microcontroller system connected to the switch sensors and a set of MOSFET driver circuits as shown in Figure 2. The control console shown was used by the person overseeing the experiments. The event recorder stored all of the timestamped

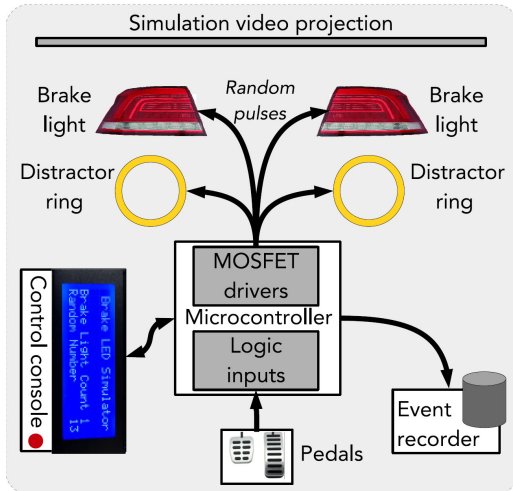


FIGURE 2. Brake light simulator design blocks.

information to file for later analysis. The collected information consisted of time-stamped brake signal onset and offset times as well as onset and offset times from the two pedals.

Ten sets of brake light assemblies from different car manufacturers, selected on the basis of representing a range of distinct light shapes from common models, were used in the experiments. Table 1 lists the precise part numbers and bulb types used.

TABLE 1. Details of brake light assemblies used in the experiments.

Manufacturer	Vehicle	Part number	Bulb type
Ford (Bulb)	Focus (2018)	1825320	Red 1490659
		1825318	
Fiat (Bulb)	Fiat 500 (2007)	OEN 52007424	OSRAMTAIL B001497
		OEN 52007422	
Audi (LED)	Q5 (2016)	8R0945093C	Audi-LED
		8R0945094C	
Fiat (LED)	Fiat 500 (2007)	OEN 52007424	82CRCANR-1
		OEN 52007422	
Ford (LED)	Focus (2017)	1825320	82CRCANR-1
		1825318	
Honda (LED)	Civic (2015)	ULT514226	PY21W LED
		ULT514202	
Mercedes (LED)	CLS-218 (2015)	OEN A2189067800	Benz-LED
		OEN A2189067700	
Alfa Romeo (LED)	Mito (2019)	LL0604	LED P21W
		LL0605	
Nissan (LED)	Leaf (2010)	OEN 265503NL0A	Nissan-LED
		OEN 265553NL0A	
Volkswagen (LED)	Golf (2017)	5G0945208C	VW-LED
		5G0945207C	

Figure 3 shows one of the light pairs used in this study. The brake light pairs were changed in arbitrary order between the subjects. Figure 3(a) shows the distractor rings when active while Figure 3(b) shows the activated brake light.

Eight of the brake light assemblies employed LEDs, while the remaining two sets employed incandescent bulbs. In order to make the LED/bulb comparison fairer, we included two same-vehicle model assemblies with different bulb types. Specifically, these were two sets of Ford Focus hatchback

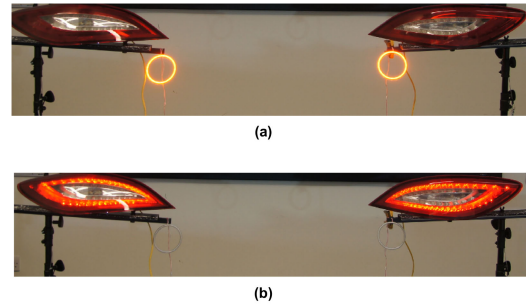


FIGURE 3. Experimental design: (a) Yellow distractor ring with unlit Mercedes brake light (b) Mercedes brake light activated and distractor rings unlit.

and Fiat 500 units. The units for each vehicle had, respectively, identical exterior mouldings but employed different light technologies (i.e. there was a version using incandescent bulb and one using LED for each vehicle).

C. EXPERIMENTAL PROTOCOL

The particular brake light unit pair under test were fitted to the mounts, aligned and tested. All brake lights were positioned at the same height from the base. An experimental subject was then seated 5m from the screen, as noted above in Figure 1. All experiments were conducted in daylight.

A motorway (UK highway) video was projected on the screen, accompanied by the natural traffic and vehicle sounds as recorded – including tyre, engine and wind noise from the interior of the simulation vehicle as well as from passing vehicles. Subjects were given a task during the test with the aim of keeping their attention focused on the road. Specifically, they were asked to keep count of the number of times brake lights were illuminated by other vehicles during the session.

Each session was designed as a simulated driving paradigm with the brake light assembly in front of the participant representing a leading vehicle. Those brake lights were activated at random intervals as noted above.

Subjects were instructed to continuously depress the accelerator pedal until they perceived an activation of the brake light in the simulated leading vehicle. At that point they were told to immediately release the accelerator and depress the brake pedal. They were asked to ignore any flashes or activations of the yellow distractor rings.

The experiment consisted of two sessions, taking place on separate days, each evaluating the efficacy of five different brake light configurations. The order of presentation of the lights was randomised across subjects.

Data was recorded from a total of 22 volunteers (age 27.4 ± 5.9 years, $M = 11, F = 11$). All possessed valid UK driving licenses and had normal or corrected-to-normal vision. Half of the subjects were classed as experienced drivers, with more than four years of driving experience. All volunteers were naive subjects recruited from the local area, and were compensated with £100 (£50 for each session) in gift vouchers for their time.

TABLE 2. Mean latency and standard deviation (*BrakeAcc*, *AccPdl*, in seconds) for each brake light from all subjects.

Subject	Bulb		LED							
	Ford	Fiat	Audi	Fiat	Ford	Honda	Mercedes	Alfa Romeo	Nissan	Volkswagen
Experienced	0.61 ± 0.17	0.59 ± 0.15	0.45 ± 0.08	0.45 ± 0.10	0.44 ± 0.09	0.44 ± 0.08	0.46 ± 0.08	0.45 ± 0.08	0.44 ± 0.08	0.47 ± 0.11
Inexperienced	0.63 ± 0.16	0.60 ± 0.17	0.48 ± 0.15	0.49 ± 0.11	0.46 ± 0.12	0.48 ± 0.17	0.51 ± 0.14	0.50 ± 0.18	0.49 ± 0.11	0.51 ± 0.15
All subjects	0.62 ± 0.16	0.60 ± 0.16	0.46 ± 0.12	0.47 ± 0.10	0.45 ± 0.11	0.46 ± 0.13	0.48 ± 0.12	0.48 ± 0.14	0.46 ± 0.10	0.49 ± 0.13
Subject	<i>AccPdl</i>									
Experienced	0.35 ± 0.14	0.34 ± 0.11	0.33 ± 0.12	0.32 ± 0.11	0.33 ± 0.10	0.33 ± 0.12	0.32 ± 0.12	0.32 ± 0.11	0.33 ± 0.11	0.32 ± 0.12
Inexperienced	0.35 ± 0.13	0.33 ± 0.17	0.31 ± 0.11	0.34 ± 0.12	0.32 ± 0.13	0.33 ± 0.15	0.33 ± 0.11	0.32 ± 0.16	0.32 ± 0.13	0.34 ± 0.12
All subjects	0.35 ± 0.13	0.33 ± 0.15	0.32 ± 0.11	0.33 ± 0.12	0.33 ± 0.11	0.33 ± 0.14	0.33 ± 0.11	0.32 ± 0.14	0.33 ± 0.12	0.33 ± 0.12

Ethics approval for all experiments were obtained from the Faculty of Science Research Ethics committee at the University of Kent.

D. DATA ANALYSIS

Data analysis was based on reaction time latencies evoked by the different brake lights. Calculations were based on three events; the time from brake light activation to accelerator release (*BrakeAcc*), the time from accelerator release to brake pedal depression (*AccPdl*), and the combined brake light activation to brake pedal depression (*BrakePdl*) duration.

BrakeAcc indicates the response time after the brake light appears and the subject releases their foot from the accelerator. This time can be considered to relate mainly to the cognitive element that starts as soon as the subject recognises the brake light, plus the time required to lift their foot from the accelerator. This is followed by the more automated reflex action where the subject moves their right foot from the accelerator to depress the brake pedal. That time is denoted as *AccPdl*. It is evident that the total reaction time from brake light flashing to brake pedal depression is $BrakePdl = BrakeAcc + AccPdl$.

As mentioned previously, each type of brake light was tested for a total of 45 onsets for each subject, providing 180 timing events, and thus 1800 timing events per volunteer.

The outputs of all analysis measures were subjected to Kruskal-Wallis tests (with $\alpha = 0.05$ as significance threshold) to gauge statistical significance, since the normality of data distribution was not assumed. Post-hoc Mann Whitney U testing with Bonferroni corrections were then applied where significant differences in the Kruskal-Wallis test was indicated, and thus determine any significant pair-wise differences. The overall hypothesis is that more efficient brake lights will induce shorter response times (i.e. lower latencies).

III. RESULTS AND DISCUSSIONS

Tables 2 and 3 present the mean ± standard deviation for *BrakeAcc* and *AccPdl* measurements, respectively. As can be observed from Table 2, experienced subjects responded quicker (i.e. released the accelerator pedal faster upon seeing the brake light activation) than the inexperienced subjects. Statistically, this was different for every brake light (all pair-wise cases $p < 1e-3$) except the Fiat bulb unit ($U = -0.79, p = 2.13e-1$). This is in line with an expectation that

experienced subjects might be more subconsciously assertive to the brake signal than inexperienced subjects.

TABLE 3. Mean latency and standard deviation (*BrakeAcc*, *AccPdl*, in seconds) from all brake lights for experienced drivers 1–11 (top) and inexperienced drivers 12–22 (bottom).

Subject	<i>BrakeAcc</i>	<i>AccPdl</i>
1	0.52 ± 0.10	0.46 ± 0.05
2	0.49 ± 0.11	0.25 ± 0.04
3	0.46 ± 0.13	0.31 ± 0.07
4	0.49 ± 0.10	0.47 ± 0.06
5	0.42 ± 0.08	0.22 ± 0.05
6	0.55 ± 0.13	0.34 ± 0.07
7	0.47 ± 0.12	0.49 ± 0.07
8	0.47 ± 0.14	0.32 ± 0.09
9	0.51 ± 0.15	0.22 ± 0.05
10	0.45 ± 0.07	0.20 ± 0.03
11	0.47 ± 0.14	0.34 ± 0.06
Average exp.	0.48 ± 0.03	0.33 ± 0.11
12	0.48 ± 0.10	0.29 ± 0.06
13	0.42 ± 0.09	0.24 ± 0.06
14	0.45 ± 0.12	0.44 ± 0.06
15	0.53 ± 0.11	0.24 ± 0.04
16	0.55 ± 0.17	0.32 ± 0.05
17	0.46 ± 0.11	0.32 ± 0.06
18	0.57 ± 0.11	0.37 ± 0.09
19	0.58 ± 0.21	0.55 ± 0.17
20	0.60 ± 0.18	0.22 ± 0.11
21	0.48 ± 0.16	0.35 ± 0.07
22	0.54 ± 0.19	0.30 ± 0.14
Average inexp.	0.52 ± 0.06	0.33 ± 0.10
Overall average	0.50 ± 0.05	0.33 ± 0.10

From Table 3, it can be seen that different brake lights also evoked different delayed responses from accelerator release to brake pedal depression (*AccPdl*). The abilities of experienced vs inexperienced subjects were mixed in this regard, showing that some brake lights have an influence on the speed of the subjects’ responses while some do not. Experienced subjects were quicker statistically in moving their foot from the accelerator to the brake pedal for the Ford bulb, Fiat LED and Volkswagen LED, but were slower for the Fiat bulb and Ford LED (all pairwise cases $p < 3e-1$).

Figures 4 and 5 show boxplots of latencies for *BrakeAcc* and *AccPdl*, respectively. It is evident from the figures that the median values of *BrakeAcc* were smaller for experienced subjects compared to inexperienced ones, which was true for every brake light (for *AccPdl*, it was mixed though). Figures 6 and 7 show the quantile-quantile (Q-Q) plot for *BrakeAcc* and *AccPdl* latencies for experienced vs inexperienced subjects. It can be seen that the inexperienced subjects

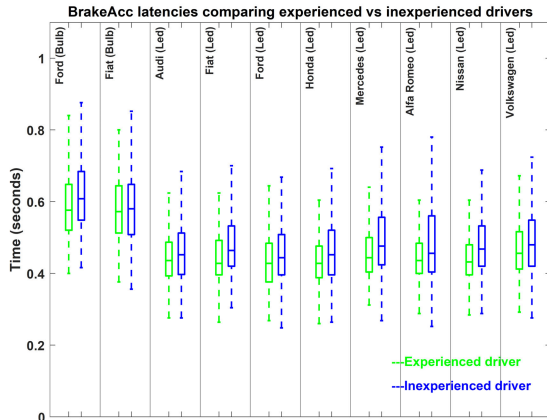


FIGURE 4. BrakeAcc latencies comparing experienced vs inexperienced subjects.

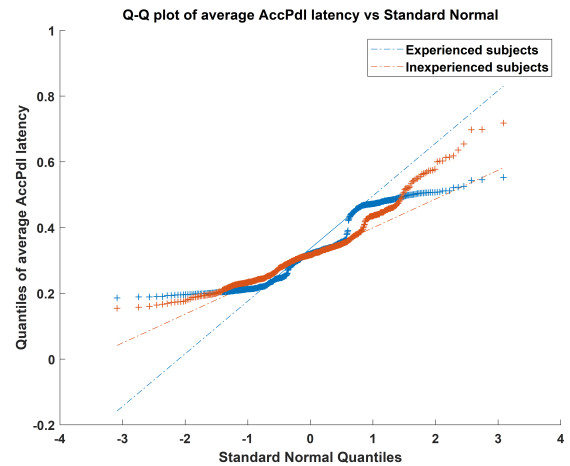


FIGURE 7. Accelerator release to brake pedal latency (*AccPdl*) subject wise for ALL brake lights.

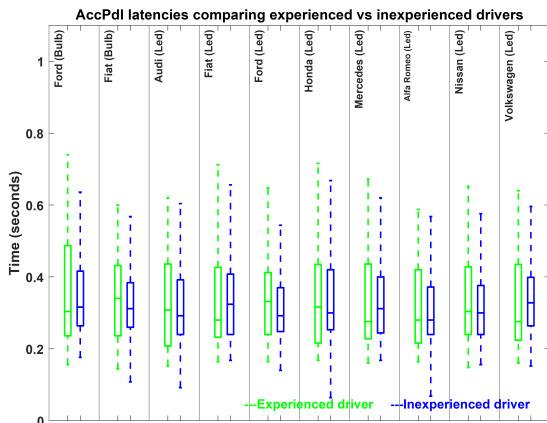


FIGURE 5. *AccPdl* latencies comparing experienced vs inexperienced subjects.

This *slowness* in response is very important as it could be a causal factor in accidents; where drivers are slow to respond and thus crash into the the car in front. However, this difference was not clearly evident for *AccPdl* latency, despite divergence later on showing the slowness of response for inexperienced subjects.

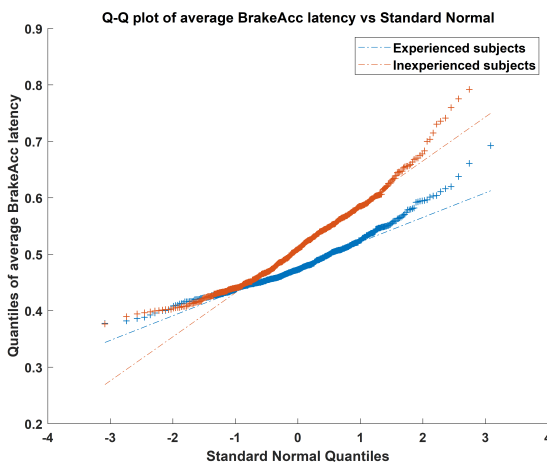


FIGURE 6. Accelerator release latency (*BrakeAcc*) subject wise for ALL brake lights.

had much longer *BrakeAcc* distributions (the distributions are similar early on, but diverge later). This showed that their overall medians were longer than for experienced subjects, but more importantly at the slow end of the reaction time distribution, inexperienced subjects were especially slow.

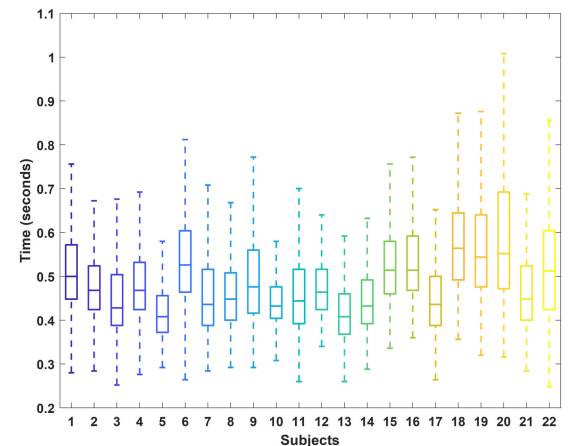


FIGURE 8. Accelerator release latency (*BrakeAcc*) subject wise for ALL brake lights (the first 11 subjects were experienced drivers).

Comparing all the subjects (as shown in Figures 8 and 9), a statistical difference was also noted for both response latencies showing that subjects' responses were dissimilar: *BrakeAcc*: ($H(9) = 2352.05, p = 0$), *AccPdl*: ($H(9) = 46.91, p = 4.08e-7$). The first 11 shown in the figures were experienced subjects with the rest being inexperienced.

Brake light reaction times for the 11 experienced subjects based on *BrakeAcc* and *AccPdl* are shown in Figure 10. As can be seen from the plot (the blue portion of the bars), both bulb versions of the brake assemblies from Ford and Fiat have the highest *BrakeAcc* response times (which was statistically significant from the eight LED lights, ($H(8), p = 0$)).

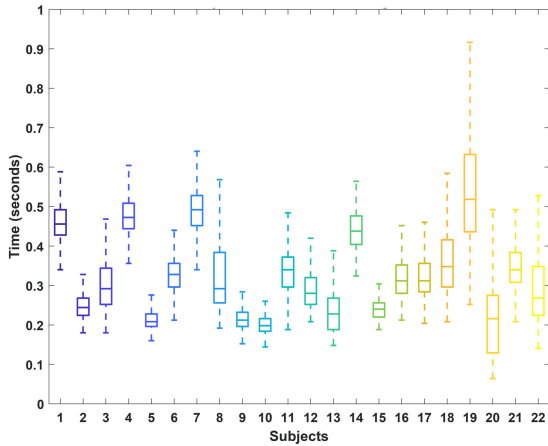


FIGURE 9. Accelerator release to brake pedal latency (*AccPdl*) subject wise for ALL brake lights (the first 11 subjects were experienced drivers).

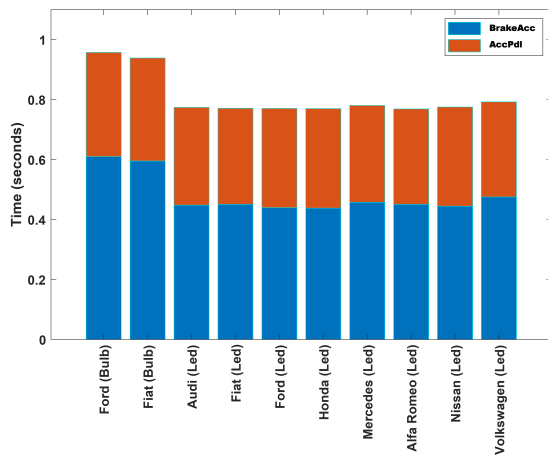


FIGURE 10. Mean latencies (*BrakeAcc*, *AccPdl*) for ALL brake lights (for the experienced drivers).

denoting that they were the slowest lights to draw a response. Between the two bulb units, there was no significant difference statistically ($U = -1.38, p = 0.16$). Among the LED brake lights, the slowest (i.e. the highest latency) was from Volkswagen which was statistically significant from every other LED light (all pairwise cases $p < 1e-9$), while the next slowest was Mercedes – however this was significant only compared to the Ford ($U = -3.84, p = 6.11e-5$) and Honda ($U = -3.81, p = 7.05e-5$) units. The lowest *BrakeAcc* latency (i.e. the fastest light) were the Ford, Honda and Nissan units, although only Volkswagen and Mercedes indicated statistically significant differences in terms of the slower latencies as mentioned. This could possibly be due to their distinct characteristics: the Ford LED having the largest lit area, the Honda LED being the brightest, and the Nissan unit having the longest vertical lit dimension. Our previous studies based on brain response to LED light shapes revealed significant influence on cognitive responses for various shapes, orientations and brightness [25]–[27].

Considering the reaction times for the 11 experienced subjects based on *AccPdl* responses (the red portion of the bar),

the general thought is that there should be no difference in terms of *AccPdl*. It should be relatively constant for each subject. However, the results indicated otherwise. The Ford bulb timings were significantly slower than for the Audi ($U = -2.86, p = 2.10e-3$), Alfa Romeo ($U = -3.72, p = 1.01e-4$) and Volkswagen ($U = -3.63, p = 1.41e-4$) LED units. Meanwhile the Fiat bulb timings were slower than the Audi ($U = -2.84, p = 2.20e-3$) and Alfa Romeo LED lights ($U = -3.74, p = 9.21e-5$). This indicated that the bulb had an additional negative effect which acted to reduce the reflex response component, in addition to the cognitive component. While we are analysing this effect further, we conjecture that the shape and/or illumination level influences not only how quickly a subject can detect the brake signal, but how tentative or decisive the consequent response is.

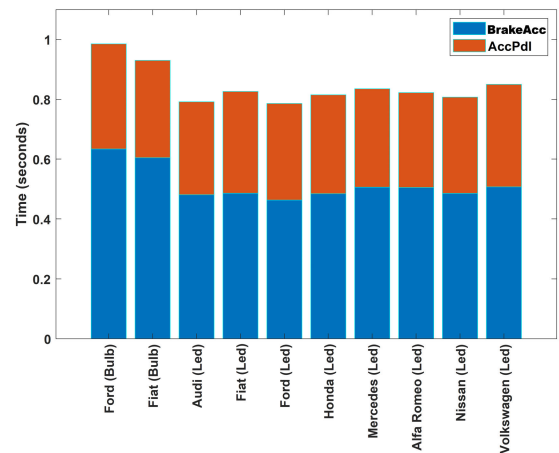


FIGURE 11. Mean latencies (*BrakeAcc*, *AccPdl*) for ALL brake lights (for the inexperienced drivers).

Considering the total reaction time, *BrakePdl* (as shown in Figure 11, the full bars, both blue and red sections), in line with the other results, reports both the bulbs being statistically slower than any of the LED lights ($H(8), p = 0$). However, within the LED lights, there was no statistically significant difference between units ($H(7) = 4.99, p = 0.66$). However, from the plot we can see that Volkswagen LED tended to be the slowest, followed by the Mercedes unit.

The *BrakeAcc* responses from the inexperienced subjects is shown in Figure 11 (as the blue portion of the bars). The slowest responses were from both the bulbs ($H(8), p = 0$); between the bulb assemblies, the Ford was slower than the Fiat, ($U = 4.49, p = 3.62e-6$). Among the LED units, the slowest was from Volkswagen (statistically significant against all other LED units, ($H(7) = 72.83, p = 3.96e-13$). This was followed by the Mercedes, which was statistically slower than the Audi ($U = 4.94, p = 3.97e-7$), Ford LED ($U = 6.38, p = 9.14e-11$) and Honda LED ($U = 4.78, p = 8.61e-7$). The fastest light was the Ford LED (which was statistically different from all but the Audi

($U = 1.19, p = 1.17e-1$) and the Honda unit ($U = 1.36, p = 8.66e-2$)).

In terms of *AccPdl* (shown in Figure 11 as the red portion of the bars), the expectation is again that there should not be any difference between the lights since the reflex response is what is being analysed. However both the Ford bulb and Volkswagen LED are statistically slower than the Alfa Romeo and Nissan LED units (all pairwise cases $p < 1e-5$).

As expected from analysis of *BrakeAcc* and *AccPdl*, both the bulbs were slower than any of the LED lights when considering the total reaction times (the full bars in Figure 11) ($H(8), p = 0$). Among the LED units, there were more differences exhibited than there were for the experienced subjects. For example, the Volkswagen was statistically slower than the Audi, Nissan, Alfa Romeo, Ford, and Honda units (all pairwise $p < 1e-4$). Meanwhile the Ford LED unit was quicker statistically than those from Mercedes and Fiat (all pairwise $p < 1e-4$).

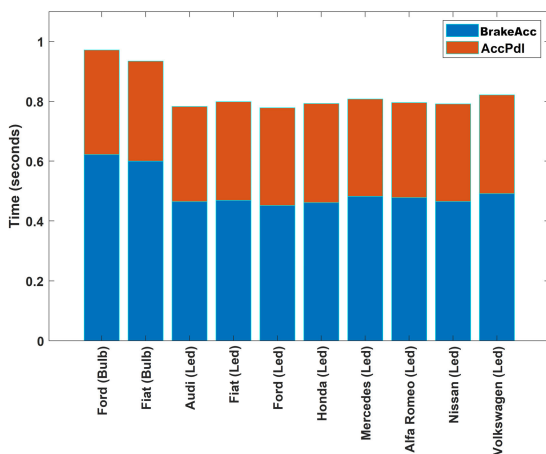


FIGURE 12. Mean latencies (*BrakeAcc*, *AccPdl*) for ALL brake lights (for ALL subjects).

Figure 12 compares the *BrakeAcc*, *AccPdl* and *BrakePdl* results (blue, red, full bars, respectively) for each brake light for all 22 subjects combined. Combining the *BrakePdl* analyses from both experienced and inexperienced subjects, both the bulbs are slower statistically than any of the LED lights ($H(8), p = 0$). The fastest LED was from Ford – statistically significant against all LED lights except the Audi and Honda (all pairwise $p < 1e-3$). The slowest was the Volkswagen unit (statistically significant from all other LED lights ($H(7) = 124.23, p = 1.00e-23$), followed by the Mercedes LED (though it is statistically significant from the Audi, Ford, Honda and Nissan LED lights only (all pairwise $p < 1e-4$)).

Even though this study was focused on the cognitive response invoked by the various brake lights, interestingly the brake lights also influenced the reflex time taken for the foot to release from the accelerator and depress the brake pedal. Combining *AccPdl* from both experienced and inexperienced subjects, the Ford bulb was statistically slower than the Alfa

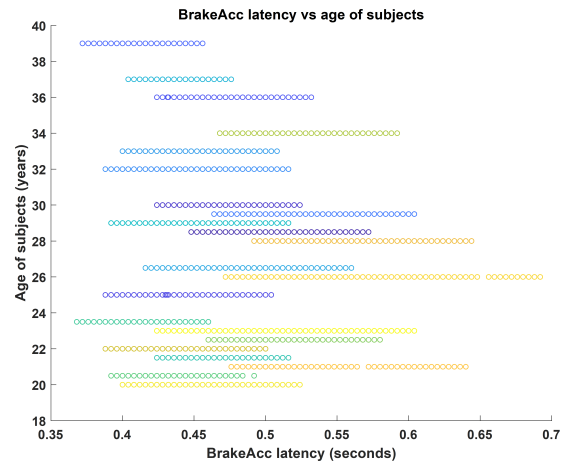


FIGURE 13. *BrakeAcc* latency with respect to subject age.

Romeo, Mercedes, Audi and Nissan LED lights (all pairwise $p < 1e-4$) while the Fiat bulb was slower than the Audi and Alfa Romeo LED lights (all pairwise $p < 1e-3$). Among the LED lights, there were some significant differences ($H(7) = 16.5, p = 2.09e-1$) with the Alfa Romeo being faster than the Honda ($U = 2.86, p = 2e-3$) and the Volkswagen units ($U = -3.26, p = 5.64e-4$).

The full bars of Figure 12 present the total reaction timings for all subjects. *BrakePdl* for both bulbs was statistically slower than for any of the LED lights (all pairwise cases $p < 1e-53$). Among the LED units, the Volkswagen was slower than the Audi, Ford, Honda, Alfa Romeo and Nissan units (all pairwise cases $p < 5e-3$) while the Mercedes unit was slower than the Ford ($U = -4.53, p < 2.89e-6$). We speculate the results from the Volkswagen unit was at least partially a result of pattern in which it illuminates (see Section IV).

The results also showed that *BrakeAcc* is statistically longer than *AccPdl* for every brake light (all pairwise $p = 0$, indicating that it took longer for subjects (0.50 ± 0.05 s) to act on the detected brake light illumination than to depress the brake pedal (0.33 ± 0.10 s). This indicated that more time was required by subjects to perceive the activation of brake lights, but they are generally quicker to act once brake light activation is recognised. Among the LED lights, the best and worst responses were mixed for each subject as shown in Table 4. Nevertheless, the results do indicate that the time between seeing the brake light illuminating, and releasing the accelerator, is the critical interval where the different types of lights can influence the speed of braking reaction.

Figure 13 shows the *BrackAcc* latency versus the age of all the subjects (in years). There was no significant correlation ($r^2 = 0.0385, p = 3.82e-1$), indicating clearly that age, within the range tested, had no influence on the speed of recognition of the brake light activation.

Figure 14 plots *AccPdl* latency versus the experience of all the subjects (in months). There was no significant correlation statistically ($r^2 = 0.15, p = 7.52e-2$), although the small p

TABLE 4. LED brake lights with the fastest and slowest response times for all subjects.

Subject	BrakeAcc latency		AccPdl latency		BrakePdl latency	
	Fastest LED	Slowest LED	Fastest LED	Slowest LED	Fastest LED	Slowest LED
1	Ford	Volkswagen	Alfa Romeo	Volkswagen	Ford	Volkswagen
2	Fiat	Ford	Alfa Romeo	Ford	Fiat	Ford
3	Ford	Mercedes	Volkswagen	Honda	Volkswagen	Honda
4	Mercedes	Honda	Ford	Fiat	Ford	Nissan
5	Honda	Volkswagen	Audi	Nissan	Honda	Nissan
6	Nissan	Alfa Romeo	Alfa Romeo	Alfa Romeo	Honda	Alfa Romeo
7	Ford	Volkswagen	Ford	Honda	Ford	Volkswagen
8	Honda	Fiat	Mercedes	Honda	Mercedes	Ford
9	Ford	Fiat	Audi	Mercedes	Audi	Fiat
10	Alfa Romeo	Volkswagen	Volkswagen	Ford	Audi	Ford
11	Honda	Ford	Mercedes	Ford	Mercedes	Ford
12	Fiat	Mercedes	Alfa Romeo	Audi	Fiat	Audi
13	Alfa Romeo	Mercedes	Audi	Mercedes	Audi	Mercedes
14	Ford	Mercedes	Nissan	Honda	Ford	Fiat
15	Fiat	Mercedes	Fiat	Alfa Romeo	Fiat	Mercedes
16	Fiat	Honda	Honda	Fiat	Audi	Volkswagen
17	Audi	Mercedes	Audi	Volkswagen	Audi	Mercedes
18	Ford	Mercedes	Ford	Honda	Ford	Nissan
19	Honda	Alfa Romeo	Audi	Alfa Romeo	Audi	Alfa Romeo
20	Volkswagen	Alfa Romeo	Alfa Romeo	Volkswagen	Ford	Mercedes
21	Honda	Volkswagen	Ford	Mercedes	Ford	Volkswagen
22	Alfa Romeo	Volkswagen	Ford	Volkswagen	Ford	Volkswagen

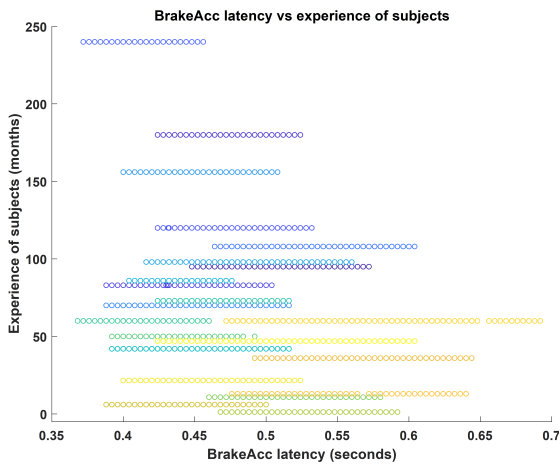


FIGURE 14. BrakeAcc latency vs experience level of subjects.

value and $r^2 = 0.15$ do indicate that there is some correlation between driving experience and speed of recognition of the brake light activation, i.e. more experienced subjects are quicker to respond.

There was no significant correlation statistically when comparing *AccPdl* latencies with age ($r^2 = 0.0164, p = 5.70e-1$) showing that age does not have an influence on the reflex action. There was no significant correlation statistically when comparing *AccPdl* latencies with experience ($r^2 = 0.0648, p = 2.53e-1$) showing that age and experience do not have an influence on the reflex action, which could likely be more influenced by the subject's physical ability and innate speed of reflex movements.

The probability distributions for experienced and inexperienced subjects using averaged *BrakeAcc* latencies are shown in Figure 15. The dotted red lines indicate the normal

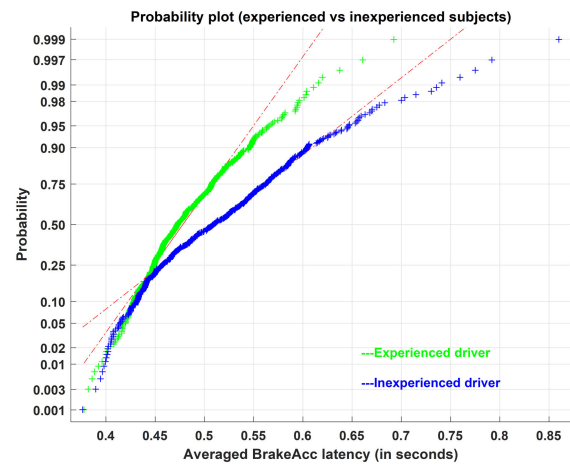


FIGURE 15. Probability plot (experienced vs inexperienced subjects).

distribution and it can be seen that there is greater variation for inexperienced subjects (shown with a less steep red line). For example at 0.95 probability (5%), we can see that experienced subjects took an average 0.56s to release the brake pedal while inexperienced subjects took an average of 0.65s.

Comparing three brake lights (slowest overall, slowest LED and fastest overall), Figure 16 shows the probability distribution for all subjects in terms of total reaction latencies (*BrakePdl*). At 0.95 probability (5%), the latencies were 1.03, 1.14 and 1.36s for the Ford Bulb, Volkswagen LED and Ford LED unit. Considering the fastest speed of 1.03s, the probability would stand at 0.89 and 0.68 for the Volkswagen LED and Ford Bulb respectively. Thus, 6% more subjects were slower when comparing the Volkswagen and Ford LED lights and 27% more subjects were slower when comparing the Ford bulb and Ford LED.

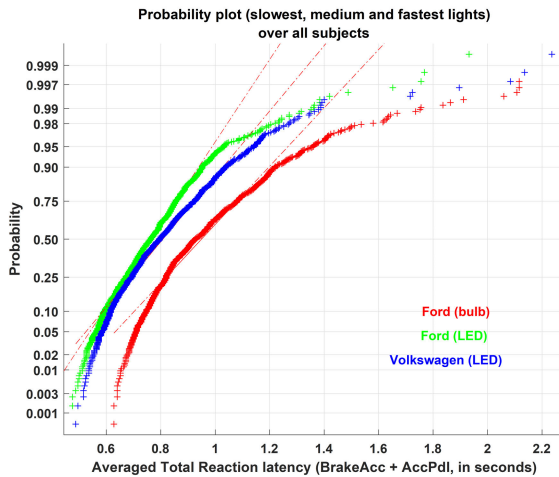


FIGURE 16. Probability plot (slowest, medium and fastest lights) over all subjects.



FIGURE 17. The tested Ford brake light units.



FIGURE 18. The tested Volkswagen brake light units.

IV. CONCLUSION

Reaction time data from 22 subjects for ten brake light assemblies were experimentally captured and analysed statistically. Results indicate that versions of the brake lights containing incandescent bulbs (e.g. Ford and Fiat) induced statistically slower reaction times than all of the tested LED units. It is known that incandescent bulbs take longer to illuminate (generally no discernible optical output for around 50 ms post switch on), but the cognitive reaction time delay difference was found to be about 170 ms between the incandescent bulb and LED equivalents (e.g. between the Ford LED and bulb assemblies). This clearly reveals that LED units have the potential to evoke brain responses quicker.

It was also shown that experienced subjects were quicker to realise the activation of a brake light, and hence release the accelerator quicker. A noteworthy finding here is that the brake light type also influenced the time between accelerator release and brake pedal depression. Furthermore, experienced subjects did not always act quicker than inexperienced subjects in this regard. These points are probably worthy of further analysis from the cognitive perspective, especially in terms of the relationship between shape and cognition.

The Ford brake light shell (Figure 17) had a larger lit area than the other brake lights, which could have led to improved visibility. The Volkswagen brake light (Figure 18) had a unique dispersed illumination pattern, with the major lit area being towards the exterior and less focused to the centre

of the brake light unit. Similarly, the Mercedes brake light also had an elliptical illumination pattern with the centre unlit. Both lacked illumination at the centre of the brake shells, which could have contributed to the slower times associated with them.

For our future work, we are planning to analyse the actual cognitive responses from the braking events using electroencephalogram (EEG) signals as this would allow us to understand the brain processes involved in the recognition of the lights and the corresponding braking actions. Brake light shape, orientation and luminance could all have an effect which could be explored in future. We will also be exploring running the experiments in real-life traffic conditions (i.e. live, on the road) to assess any deviation from the responses obtained in the laboratory environment.

ACKNOWLEDGMENT

The research was conducted with the aim of increasing road safety, and did not have the involvement of any manufacturer. The authors note that only one type of light assembly from a single vehicle within each manufacturers range was assessed, and results are therefore not to be interpreted as applying to any other vehicles or brake light assemblies, and certainly not as any endorsement or otherwise of a particular manufacturer. We also acknowledge that the sample sizes here are quite small.

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