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Exploring drivers' mental workload and visual demand while using an in-vehicle HMI for eco-safe driving

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ABSTRACT

Eco-safe driving is a promising approach to improve road safety while reducing transport emissions. The application of an eco-safe driving system is feasible with the support of vehicle-to-vehicle/infrastructure technologies. To guarantee system usability and safety appropriateness, a key precondition is to ensure that driver mental workload and visual demands required for using the system are reasonable. This study explored how drivers' mental workload and visual demands were affected when driving with an eco-safe driving HMI (human-machine-interface). Four in-vehicle eco-safe HMI information conditions were evaluated, including baseline, advice only, feedback only, and advice & feedback. Two traffic scenarios (stop-sign intersection with traffic vs. stop-sign intersection without traffic) were simulated using an advanced driving simulator. Behavioural variables (e.g. brake force, acceleration), visual variables (e.g. blink metrics, pupil size) and subjective workload scores were collected from 36 licensed Australian drivers. The experiment results showed that the HMI prompted drivers to apply a smooth and stable brake force when they approached the intersection and a smooth acceleration when they left the intersection. Drivers' mental workload indicated by visual measurements were consistent with their subjective reported workload levels. Drivers had a higher mental workload when they received and processed additional eco-safe information in the advice & feedback condition. An increase in mental workload induced by the in-vehicle cognitive task initiated more blink activities while the increase in visual demand caused by a complex road situation led to blink inhibition. The study shows the HMI could significantly promote eco-safe driving behaviours without causing excessive mental and visual workload of drivers.

1. Introduction

Vehicles are being transformed based on the innovations leading towards automated driving. Although in the short-to-medium-term, highly automated vehicles will not be commercially available, the driving experience is being transformed by a wide range of supporting technologies during the transition period. Various driver assistance systems are being installed in an increasing number of vehicles (Viereckl et al., 2016). These systems offer drivers important road/traffic information and driving instructions based on V2X communication technologies which include Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I). These emerging technologies will be relied on to improve both sustainability and safety of the entire road traffic system.

Eco-driving is a driving style that has been advocated for decades to help promote environmental sustainability by reducing fuel consumption and traffic emissions (Barkenbus, 2010; Zarkadoula et al., 2007). Traditionally, eco-driving refers to drivers adjusting their behaviours and applying relevant techniques to reduce fuel consumption and emissions, without necessarily upgrading vehicle technology. Different from eco-driving, eco-safe driving emphasises the integration of eco-driving behaviours, such as smooth acceleration or deceleration, with safe-driving behaviours, such as adhering to the speed limit or maintaining a safe headway distance (Filho et al., 2012; Vaezipour et al., 2016). In recent years rapid advancements have occurred in the transportation industry, and in-vehicle human-machine-interfaces (HMI) were designed and developed to promote eco-driving (Strömberg and Karlsson, 2013; Barth and Boriboonsomsin, 2009) or safe driving

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behaviours (Birrell et al., 2014; Park and Kim, 2015). Eco-driving in-vehicle systems are associated with reductions in fuel consumption by 5 %–20 %, depending on the driving scenarios (Barth and Boriboonsomsin, 2009; Birrell et al., 2014; Strömberg and Karlsson, 2013). Many studies have also demonstrated the positive impacts of safe driving in-vehicle systems on road safety outcomes (Demmel et al., 2011; Zhang et al., 2016; Xiang et al., 2016). Such systems include a variety of collision warning systems (e.g., adaptive braking, blind-spot warning), as well as more targeted devices such as Intelligent Speed Adaptation (ISA).

The emergence of connected and automated vehicles have hastened the development of V2V and V2I technologies (Anderson et al., 2014), which provide technological support to assist in eco-safe driving (Outay et al., 2019). With V2V technology, the vehicular communication systems can provide drivers with traffic information and safety warnings, and thus help them to avoid traffic congestion and collisions (Zardosht et al., 2017). With V2I technology, the vehicles can acquire roadway information in real-time to help drivers better negotiate curves, follow the speed limit, and take appropriate actions at intersections (Anderson et al., 2014).

Experimental research has shown the advantages of in-vehicle eco-safe driving system designed based on V2X technologies (Vaezipour et al., 2018 & 2019). A driving simulation experiment conducted in Australia found that an in-vehicle eco-safe driving system could reduce fuel consumption by 6.7 %, increase the rate of smooth acceleration adoption by 33 % and smooth deceleration by 25 %, shorten the speeding time by 50 %, and also improve safe following behaviour by increasing vehicle headway by 16.7 % (Vaezipour et al., 2018 & 2019). Additionally, by analysing the drivers' glance behaviour, the system enhanced drivers' visual attention to the forward roadway without causing visual distraction (Li et al., 2019).

Despite the objective benefits of an eco-safe HMI system, an in-vehicle HMI introduces additional information to drivers to guide their behaviours, which may lead to an overload of mental and visual workload. To guarantee usability and safety appropriateness of an in-vehicle HMI, the visual demands and mental workload induced by the system must be practical. However, many studies seemed to purely focus on drivers' performance changes caused by their systems, and overlook the importance of evaluating drivers' mental and/or visual workload while using those systems (Barth and Boriboonsomsin, 2009; Strömberg and Karlsson, 2013; Birrell et al., 2014). This is even more important when considering that drivers often report that these systems are visually and cognitively distracting (Oviedo-Trespalacios et al., 2019a,b). Regarding the other types of in-vehicle driver assistance or entertainment systems, some studies considered drivers' workload when examining the interaction with the systems. For instance, Strayer et al. (2019) investigated drivers' workload and visual/cognitive demand associated with using different types of in-vehicle information systems such as CarPlay, Android Auto, and native equipment manufacturers systems. In their study, drivers' reaction time and hit rate of standard Detection Response Task were collected and analysed, and the results showed that Carplay and Android Auto led to lower levels of workload than the native equipment manufacturers systems. Graichen et al. (2019) conducted a study which compared the effects of gesture-based interaction and touch-based interaction with in-vehicle system and reported higher acceptance and lower workload of gesture-based interaction.

Drivers' mental workload and visual demand vary according to the tasks in the vehicle (a primary driving task with/without assistance tasks) and the complexity of the road environment. Thus, visual attention and mental workload need to be allocated dynamically among various information sources. Many studies have indicated that blinks and pupil size are valid indicators of cognitive activities (Čegovnik et al., 2018; Zhang et al., 2019; Chen and Epps, 2014). Eye blinks, especially the endogenous eye blinks, can measure the mental workload associated with tasks that involve the processing of attention and response programming and execution (Stern et al., 1984). A great deal of previous research has found that as the task demands (both mental and visual) increase, blink durations decrease (Benedetto et al., 2011). In terms of the blink rate/frequency, mixed results with mental and visual workload have been reported. For instance, Recarte et al. (2008) reported that blink rate is influenced by both mental workload and visual demand, with the former leading to an increase and the latter leading to a decrease in blink rate.

Pupil size, or pupil diameter, is another measurement indicator of driver's mental workload, and it has been widely applied in simulated driving environments (Marquart, et al., 2015). Some studies reported a recorded pupil dilation with increased mental workload due to secondary cognitive tasks (Čegovnik et al., 2018; Li et al., 2018). It has been identified that Task Evoked Pupillary Response (TEPR) with changes of the pupil diameter up to 0.5 mm is a typical reaction of participants to the cognitive processing tasks (Beatty and Lucero-Wagoner, 2000).

Though many studies have used eye blinks and pupil size as indicators to examine drivers' mental workload, most of them were related to the secondary cognitive tasks, such as an auditory task, mental arithmetic, or mobile phone conversation (Benedetto et al., 2014; Li et al., 2018,2020; Oviedo-Trespalacios et al., 2016). It remains largely unknown regarding how mental workload changes with the processing of eco-safe driving information introduced by an in-vehicle HMI system, and how visual demand is allocated among driving tasks, in-vehicle tasks, and the road environment.

1.1. Study aims

As previously stated, an in-vehicle HMI system represents a promising approach to facilitate eco and safe driving behaviours. However, there is a paucity of research that has evaluated the impact of an eco-safe driving HMI on drivers' mental workload and visual demands. Additionally, drivers' mental workload and visual performance are not only expected to be affected by the in-vehicle task demand, but also by the road environment situations. Therefore, the specific aims developed for this study include (i) comparing drivers' mental workload when various types of eco-safe in-vehicle HMI information are conveyed to them; (ii) exploring the allocation of visual demands when drivers experience different road situations while using the HMI system; and (iii) verifying whether the workload level indicated by eye-movement measurements is consistent with driver's subjective workload (NASA-TLX). Three hypotheses were developed corresponding to the three research aims: (i) drivers' mental workload increases as the amount of information conveyed to drivers increases; (ii) when using the HMI system, drivers experience higher visual demand and workload at more complex road situations; and (iii) the change tendency of workload indicated by eye-movement measurements should be consistent with the reported subjective workload. Through the analysis of eye-tracking data and subjective measures of driver workload collected in a driving simulator experiment, this paper will contribute to the understanding of drivers' visual demand and workload while using an eco-safe driving HMI. Such information can be utilised to improve the design characteristics of an in-vehicle HMI to enhance both eco and safe driving while avoiding information overload.

2. Methodology

2.1. Apparatus and scenario

The CARRS-Q advanced driving simulator was used in the experiment, which is capable to simulate realistic driving situations safely in a controlled environment. The simulator contains a real passenger vehicle cabin (Holden Commodore, automatic transmission) and a surround-sound system for the engine and environmental noise. The vehicle is mounted on a motion platform with six degrees of freedom which can move and twist in three dimensions. The simulator uses the SCANeR™ studio from AV Simulation (formerly OKTAL) linked with eight computers and three projectors to provide a 180° front field-of-view as well as the left, right, and rear-view mirror views (see Fig. 1.a). The front-view images were projected at 60 Hz frequency at a 1400 × 1050 pixels resolution. The wing mirrors and rear-view mirror were replaced by LCD monitors that can present images at 60 Hz frequency and 800 × 600 pixels. The faceLAB™ eye-tracking system which includes a set of cameras inside the vehicle was used to collect drivers' eye movement (i.e., eye blink and pupil size) as numerical data. As a non-intrusive eye-tracking device, it allows participants to make free head movements within the active working zone of the eye-tracker.

The designed driving route was composed of urban and suburban areas, which were similar to the typical roads in Brisbane, Australia. The speed limit was 40 km/h in the urban area and 60 km/h in the suburban area. The driving route was around 7 km long and it consisted of a variety of scenarios such as stop-sign intersections (with/without crossing traffic), signalised intersections, car-following, and pedestrian crossing to enrich the participants' experience. Participants drove in the left lane of the road. The traffic scenarios processed for analysis include (i) a stop-sign intersection with traffic where drivers needed to stop and yield to the crossing vehicles; and (ii) a stop-sign three-way intersection without traffic, where drivers still needed to stop before moving forward. The roads in both scenarios were two-way, two-lane with each lane 3.15 m in width. In both situations, drivers needed to perform deceleration and acceleration manoeuvres, and if the manoeuvres were executed appropriately, significant fuel consumption could be saved significantly.

2.2. Design of the eco-safe HMI system

The prototyped in-vehicle HMI was designed and developed following a human-centred design approach (Vaezipour et al., 2017) and based on the availability of V2X technologies that can obtain real-time traffic and roadway information (e.g. vehicle GPS information, traffic sign/signal information, and inter-vehicle distance, etc.). The design was guided by the Technology Acceptance Model (TAM) for its theoretical framework given its proven ability to capture the concepts of perceived usefulness, usability, ease of use, and intention to use as measures of driver acceptance to a specific technology (Davis, 1989). An iterative, human-centred design process with a series of focus groups and expert workshops was conducted to explore concepts in TAM regarding (i) the perceived system acceptability (i.e. usefulness, usability, ease of use), (ii) the perceived impact on eco-safe driving behaviours, (iii) the perceived difficulties associated with the interface and ideas for improvements, and (iv) the self-reported intentions to purchase and use (Vaezipour et al., 2016 & 2017).

The system consisted of an Android smartphone mounted in a 3D-printed upholder (See Fig. 1). The smartphone screen was used to display the eco-safe driving information and it was mounted at the middle bottom of the front windscreen within the driver's field of view without blocking the view of the road environment and speedometer (see Fig. 1.b). The position of HMI was tested to be suitable in pilot studies and it was at a similar position than other in-vehicle eco-driving displays presented in prior studies (e.g. Kircher et al., 2014; Rouzikhah et al., 2013). An eco-safe algorithm was developed to determine the constraints of releasing an eco-safe driving message based on real-time information provided by V2X technologies. The HMI displayed three types of eco-safe driving information:

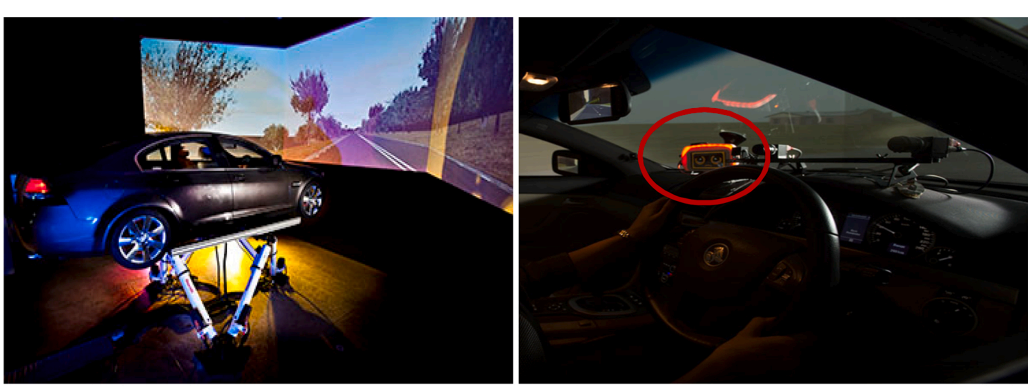
(1) Real-time advisory information

Advisory information was designed in the form of icons and simple text on a yellow background to encourage the eco-safe driving style (see Fig. 2). The information was presented on the smartphone screen when drivers approached specific traffic events (crossing intersections in this study). For example, as the drivers arrived 30 m in front of an intersection, the advisory information of "smooth braking" would be shown on the display until the drivers completed braking at the stop line. The advisory information of "smooth acceleration" was triggered 5 s after the drivers came to a complete stop. Once triggered, the information was shown on the display as long as the drivers were less than 40 m away from the intersection they were leaving.

(2) Real-time feedback information

The feedback information was designed to enhance driver knowledge and awareness of their performance, with the aim of increasing driver motivation to improve eco-safe driving. It was conveyed through an anthropomorphic "face", a smaller icon on the right bottom, and LED lights illumination around the screen (see Fig. 3). The feedback information was provided in real-time and it was triggered by vehicle data (i.e. location, speed, acceleration and deceleration). After the driver completed an deceleration or acceleration action, the feedback information would be presented depending on whether the behavioural performance of the driver was appropriate (i.e., happy face and a green light for smooth acceleration/braking behaviours) or inappropriate (i.e., sad face and a red light for sharp acceleration/braking behaviours), see Fig. 3. Note that the acceleration and deceleration patterns were directly obtained from the driving simulator software. The display duration for feedback information was 5 s. The algorithm that calculated the optimal speed, acceleration, and deceleration profiles of eco-safe driving to inform feedback information was developed based on the Nouveliere et al. (2012)'s study which presented the design and test process of an Eco-driving Assistance System.

(3) Combined advisory and feedback information



(a) The driving simulator (b) The in-vehicle HMI

Fig. 1. The driving simulator and the in-vehicle HMI.

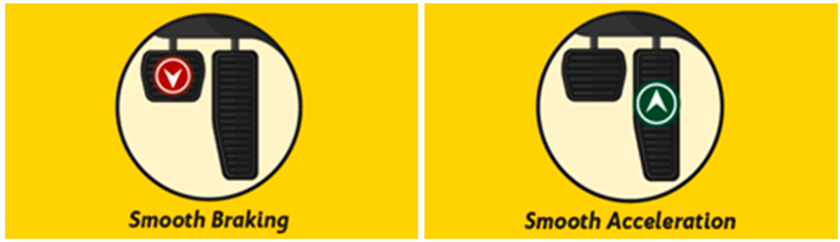


Fig. 2. Examples of the advisory information.

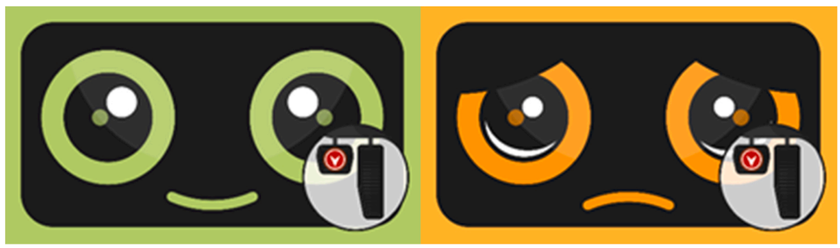


Fig. 3. Examples of the feedback information.

The combined advisory and feedback information means that both advisory and feedback information was presented to the drivers. Advisory information was provided prior to specific traffic events (e.g. crossing the intersections) and feedback provided after the driver performed the brake or acceleration action. An example was shown in Fig. 4.

2.3. Participants

Fifty-three participants were recruited for the study from Brisbane, Australia. However, only thirty-six (18 females vs. 18 males) finished the experiment with complete data collection. The rest were excluded due to motion sickness (15 participants) or missing data from the eye-tracking equipment (3 participants). Participants were required to have a valid Australian driver licence and their age range was 18–65 years with a mean age of 31.44 year-old (SD = 12.12). Participants' previous experience with using in-vehicle assistance technology (e.g. in-vehicle safety technology, eco-driving technology, and other HMI technology) were investigated before the experiment. Overall, 46.7 % of them had less than intermediate experience with in-vehicle assistance technology and 53.3 % of them had intermediate and above intermediate experience.

2.4. Experimental procedure

Before the experiment, all participants were introduced to the experimental procedure and signed the consent form. Participants then completed a practice drive to get familiar with the simulator operations. Following the practice drive, participants completed a motion sickness assessment questionnaire to identify any motion sickness symptoms. Participants who had moderate to high level of sickness were suggested to end the experiment due to health and safety precaution. Before the formal experimental drive, the researcher explained the in-vehicle eco-safe HMI system using the InVision user interface prototyping platform on an iPad, and the participants were also provided some time to familiarise themselves with the in-vehicle HMI. During the experiment, all participants drove the experimental route four times, and for each time a different eco-safe information display condition was provided. The four display conditions included:

(1) Baseline (BL): no eco-safe information was presented;
(2) Advice only (AO): only advisory information was presented on the HMI;
(3) Feedback only (FO): only feedback information was presented on the HMI;
(4) Advice and feedback (AF): both advisory and feedback information were presented on the HMI.

The analysed scenarios in this study were a stop-sign intersection with traffic and a stop-sign three-way intersection without traffic. During each drive, drivers experienced the two scenarios once. The whole experiment lasted approximately one hour for each participant, with each drive taking about 10 min to complete. The order and the start point of the four drives were counterbalanced to mitigate the order effect and learning effect. After each drive, participants were required to complete the NASA Task Load Index (NASA-TLX) scale to measure their subjective workload and then they were arranged to rest for 5 min. Upon completion of the experiment, participants completed the motion sickness assessment questionnaire again to monitor the adverse effect of motion sickness on them. Finally, all participants who completed the

Fig. 4. Examples of the combined advisory and feedback information.

experiment were offered an A$70 shopping voucher as a compensation for their time and contribution.

2.5. Data collection and variables

Eye movement data collected from faceLAB™ (sampled at 60 Hz) and vehicle control data collected from the simulator (sampled at 20 Hz) were processed. The analysed scenarios were the stop-sign intersection with traffic (Scenario 1) and without traffic (Scenario 2). The visual data extraction range for each scenario was 30 m before the intersection stop line to 80 m after it. The vehicle control variables were extracted from when the drivers started to brake/accelerate to cross the intersections. The independent variables included maximum brake force (in N), brake force standard deviation (SD, in N), average acceleration (in m/s^2), total blink time (in s), average blink duration (in s), blink frequency (in number/s), pupil size (average pupil diameter, in mm) and NASA-TLX scores.

The three behavioural variables (i.e., maximum brake force, brake force SD and average acceleration) were used to examine the effectiveness of the eco-safe HMI in improving drivers' deceleration and acceleration performance while approaching and leaving the intersections. Differences of all the visual variables among four HMI conditions were examined to explore the effects of the HMI on drivers' mental workload and visual demand. The visual variables were also compared between Scenario 1 and Scenario 2 to identify how the eye movement changed across different traffic situations when the eco-safe driving HMI was applied. The data were checked for the assumptions of parametric tests. As all the behavioural and visual variables violated the normality distribution assumption, the Friedman test was performed (Friedman, 1937). Wilcoxon type post-hoc test was conducted for pairwise comparison. As the NASA-TLX score followed the assumptions of parametric test, the repeated-measures ANOVA with post-hoc pairwise comparison was conducted. All statistical tests were based on a significance level of 0.05.

3. Results

3.1. Differences between HMI conditions

3.1.1. Behavioural variables

Table 1 lists the descriptive statistics of the behavioural variables in each HMI condition of each scenario and the Friedman test results of the variables. Regarding the deceleration behaviours, the different HMI conditions had significant influence on drivers' maximum brake force and brake force SD in Scenario 1 (i.e. stop-sign intersection with traffic) while the influence was not significant in Scenario 2 (i.e. stop-sign intersection without traffic). Specifically, Wilcoxon type post-hoc test results show that drivers' maximum brake force in advice and feedback condition was significantly lower than those in baseline, advice only and feedback only conditions (AF-BL: z=-2.514, $p < 0.05$; AF-AO: z=-2.214, $p < 0.05$; AF-FO: z=-2.402, $p < 0.05$) (see Fig. 5.a). Likewise, the brake force SD in AF condition was significantly lower than those in BL, AO and FO conditions (AF-BL: z=-3.001, $p < 0.01$; AF-AO: z=-2.425, $p < 0.05$; AF-FO: z=-2.372, $p < 0.05$) (see Fig. 5.b).

In terms of the acceleration behaviours at the intersections, Friedman tests show that HMI conditions significantly influenced drivers' average acceleration at both intersections. At the stop-sign intersection with traffic, the average acceleration in FO condition was smallest compared to that in BL, AO and AF conditions (FO-BL: z=−3.692, $p < 0.001$; FO-AO: z=−2.985, $p < 0.01$; FO-AF: z=−3.252, $p < 0.01$), and the average acceleration in AF condition was also significantly smaller than that in BL condition (AF-BL: z=−2.011, $p < 0.05$) (see Fig. 5.c). At the stop-sign intersection without traffic, the average accelerations in AO, FO and AF conditions were all significantly smaller than that in BL condition (AO-BL: z=−3.456, $p < 0.01$; FO-BL: z=−3.802, $p < 0.001$; AF-BL: z=−4.258, $p < 0.001$), and the average acceleration in AF condition was also significantly smaller than that in AO condition (AF-AO: z=-2.451, $p < 0.05$) (see Fig. 5.d).

3.1.2. Blink

The descriptive statistics and test results of the blink variables are listed by scenario and HMI conditions in Table 2. At the stop-sign intersection with traffic (Scenario 1), the total blink time and blink frequency were significantly different under different HMI conditions. Pairwise comparisons show that the total blink time in advice & feedback condition was significantly longer than that in baseline, advice only and feedback only conditions (AF-BL: z=-3.529, $p < 0.001$; AF-AO: z=-2.744, $p < 0.01$; AF-FO: z=-3.908, $p < 0.001$), and the blink frequency in advice & feedback condition was higher than that in baseline and advice only conditions (AF-BL: z=-2.796, $p < 0.01$; AF-AO: z=−2.665, $p < 0.01$) (see Fig. 6.a&b). Similarly, in Scenario 2 (stop-sign intersection without traffic), significant differences in total blink time and blink frequency were also observed among different HMI conditions. A pairwise comparison shows that the total blink time in FO, AF, and AO conditions was significantly longer compared with the BL condition (AF-BL: z=-3.279, $p < 0.01$; AO-BL: z=−4.083, $p < 0.001$; FO-BL: z=−4.522, $p < 0.001$), and the blink frequency in AF and FO conditions was also significantly higher (AF-BL: z=-2.832, $p < 0.01$; BL-FO: z=−3.325, $p < 0.01$) (see Fig. 6. c&d).

3.1.3. Pupil size

The descriptive statistics and Friedman test results of pupil size under four HMI conditions at the stop-sign intersection with traffic scenario (Scenario 1) and without traffic scenario (Scenario 2) are shown in Table 3. However, no significant difference in pupil size was observed among four HMI conditions in either scenarios.

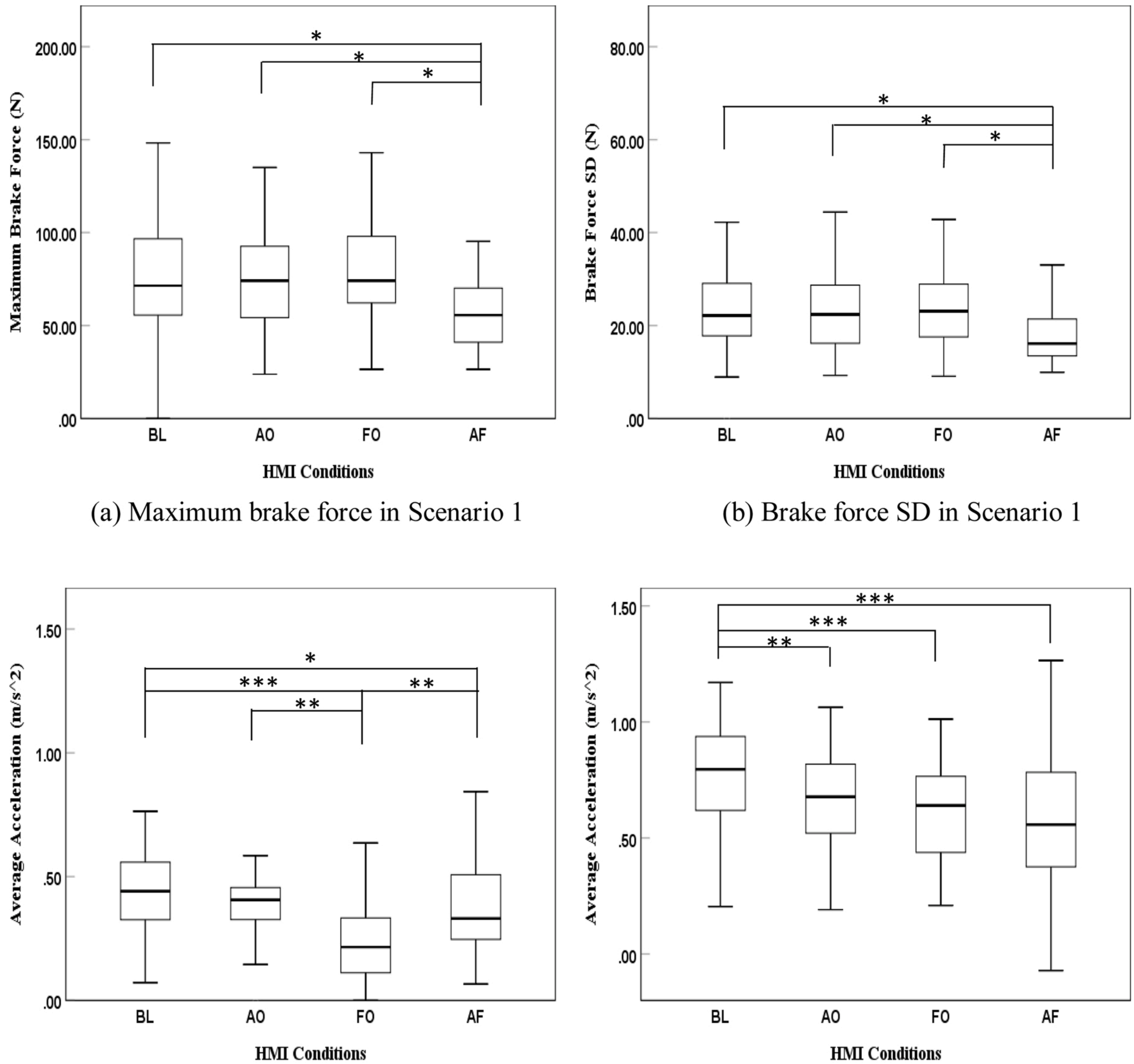
3.2. Differences between road traffic situations

Means and Standard Deviations (SD) of the variables in three HMI conditions (AO, FO and AF) were calculated and examined by the Wilcoxon type pairs test between the two scenarios (see Table 4). The variables were significantly different between the two scenarios. The total blink time, average blink duration, and blink frequency were

Table 1
Descriptive statistics and Friedman test of behavioural variables under four HMI conditions.

Scenarios	Variables	HMI condition								Friedman test		
		BL		AO		FO		AF		N	df	χ^2
		M	SD	M	SD	M	SD	M	SD			
Scenario 1	Maximum brake force	84.85	44.58	76.76	33.99	76.25	26.32	64.41	33.73	36	3	9.896*
	Brake force SD	26.86	15.24	24.30	10.82	23.49	9.14	19.74	10.67	36	3	10.633*
	Average acceleration	0.44	0.17	0.39	0.17	0.29	0.33	0.39	0.19	36	3	24.933[a]
Scenario 2	Maximum brake force	82.97	38.11	75.18	35.68	72.68	27.79	71.01	33.04	35	3	2.252
	Brake force SD	27.00	11.42	23.58	11.36	23.64	10.95	23.54	12.47	35	3	5.571
	Average acceleration	0.77	0.23	0.66	0.22	0.62	0.22	0.57	0.26	36	3	27.067[a]

[a] 0.001 significant level. **0.01 significant level. * 0.05 significant level.



(a) Maximum brake force in Scenario 1

(b) Brake force SD in Scenario 1

(c) Average acceleration in Scenario 1

(d) Average acceleration in Scenario 2

Fig. 5. Differences of behavioural variables among four HMI conditions.

Table 2
Descriptive statistics and Friedman test of blink variables under four HMI conditions.

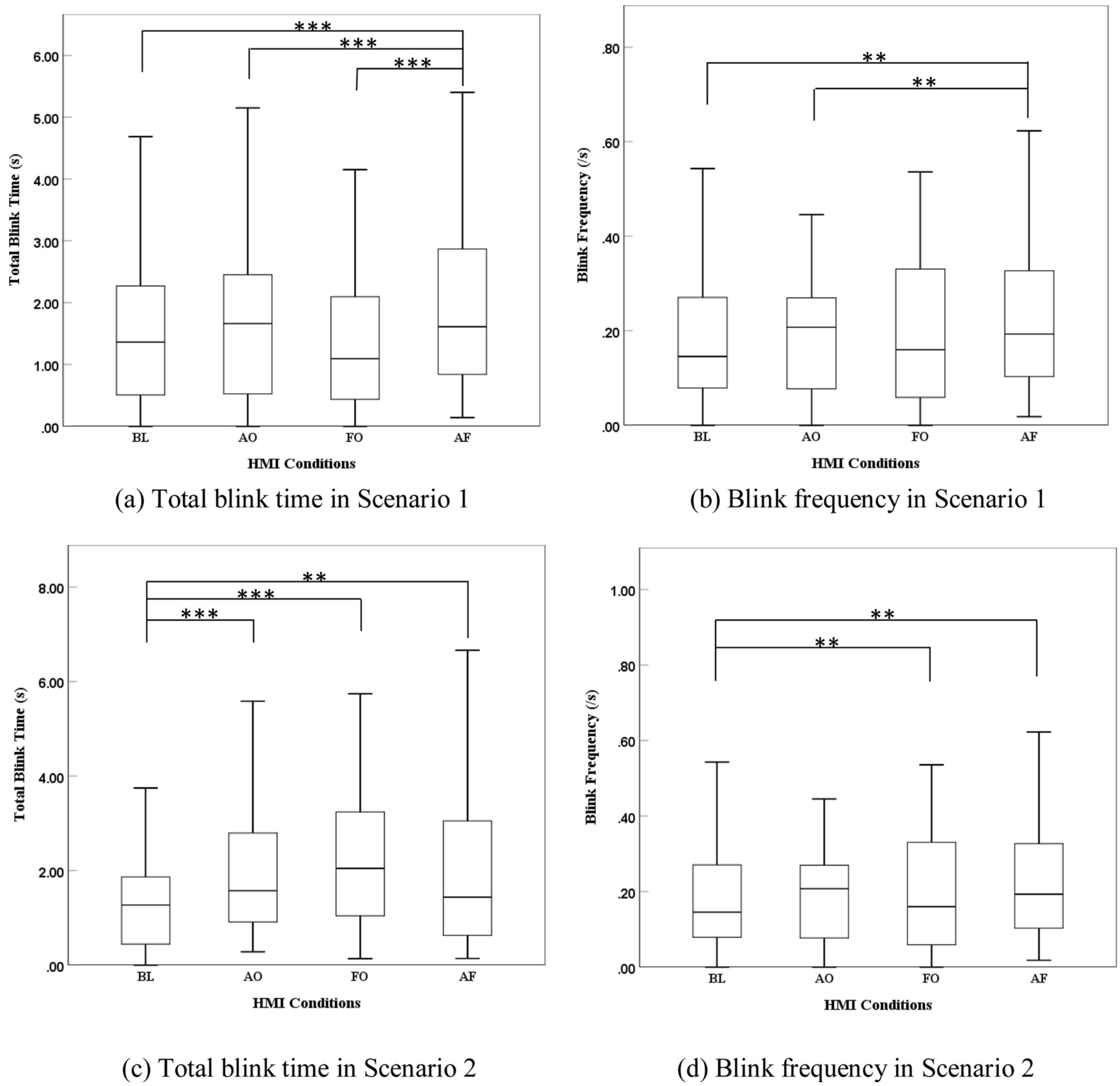
Scenarios	Variables	HMI condition								Friedman test		
		BL		AO		FO		AF		N	df	χ^2
		M	SD	M	SD	M	SD	M	SD			
Scenario 1	Total blink time	1.77	1.72	1.82	1.56	1.58	1.41	2.30	2.17	30	3	20.638[a]
	Average blink duration	0.14	0.05	0.20	0.15	0.20	0.16	0.23	0.17	30	3	3.080
	Blink frequency	0.19	0.15	0.20	0.15	0.20	0.16	0.23	0.17	30	3	10.365*
Scenario 2	Total blink time	1.50	1.35	2.19	1.70	2.53	1.95	1.99	1.68	31	3	24.213[a]
	Average blink duration	0.24	0.16	0.27	0.17	0.31	0.21	0.27	0.17	31	3	0.794
	Blink frequency	0.24	0.16	0.27	0.17	0.31	0.21	0.27	0.17	31	3	10.548*

[a] 0.001 significant level. * 0.05 significant level.

significantly smaller at the intersection with traffic (Scenario 1) in comparison to the intersection without traffic (Scenario 2), while the pupil size was larger at the intersection with traffic than without traffic (see Fig. 7).

3.3. Subjective driver workload measure

Table 5 provides the descriptive statistics of NASA-TLX scores as well as the repeated-measures ANOVA results across different eco-safe driving HMI conditions. Repeated-measures ANOVA test shows that HMI condition had a significant main effect on driver's workload ($F(3, 36) = 9.016$, $p < 0.001$, $\eta^2 = 0.45$). Specifically, pairwise comparison shows that drivers' subjective workload in AF and FO conditions were significantly higher compared with AO and BL conditions (AF-AO: Mean Difference (MD) = 8.468, $p < 0.001$; AF-BL: MD = 9.315, $p < 0.001$; FO-AO: MD = 7.597, $p < 0.01$; FO-BL: MD = 8.426, $p < 0.01$).



(a) Total blink time in Scenario 1
(b) Blink frequency in Scenario 1
(c) Total blink time in Scenario 2
(d) Blink frequency in Scenario 2

Fig. 6. Differences of blink variables among four HMI conditions.

Table 3
Descriptive statistics and Friedman test of pupil size under four HMI conditions.

Scenarios	Variables	HMI condition								Friedman test		
		BL		AO		FO		AF		N	df	χ^2
		M	SD	M	SD	M	SD	M	SD			
Scenario 1	Pupil size	5.81	0.92	5.70	0.99	5.78	1.01	5.73	0.95	29	3	7.055
Scenario 2	Pupil size	5.36	0.91	5.28	0.90	5.40	0.89	5.40	0.94	29	3	4.531

Table 4
Descriptive statistics and Friedman test of variables in different road traffic situations.

Variables	Scenario 1		Scenario 2		Pairs test (Wilcoxon type)	
	M	SD	M	SD	N	Z
Total blink time	1.78	1.57	2.14	1.62	36	−3.393**
Average blink duration	0.14	0.04	0.16	0.04	36	−2.749**
Blink frequency	0.20	0.15	0.27	0.17	36	−4.603[a]
Pupil size	4.94	1.94	4.68	1.81	36	−4.387[a]

[a] 0.001 significant level. ** 0.01 significant level.

4. Discussion

The use of the eco-safe driving HMI system was a driving-related assistance task, from which drivers received eco-safe driving-related information (AO, FO and AF), in contrast to the primary driving task. The analysis of behavioural data indicated that when both advice and feedback information was provided through the eco-safe driving HMI, drivers tended to apply a smoother and more stable brake control as they approached the intersection compared to the baseline condition. However, the effect of the HMI on deceleration performance was only significant at the complex intersection with crossing traffic (Scenario 1). The effects of the eco-safe driving HMI in improving drivers'

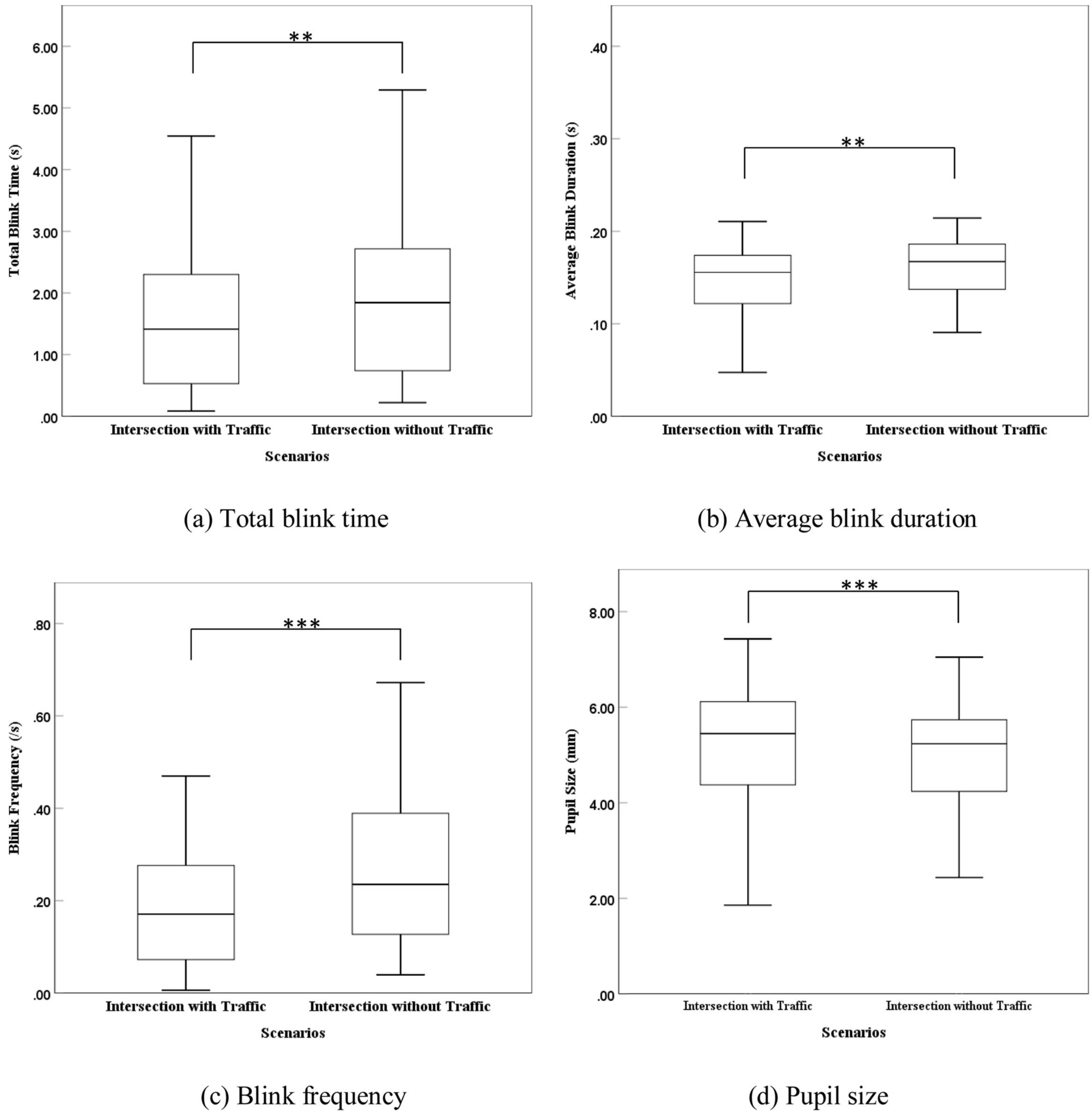


Fig. 7. Differences of visual variables between two traffic scenarios.

Table 5
Descriptive statistics and ANOVA results of NASA-TLX scores under four HMI conditions.

Variables	HMI condition								Repeated-measures ANOVA		
	BL		AO		FO		AF		N	df	F
	M	SD	M	SD	M	SD	M	SD			
NASA-TLX Scores	28.4	12.8	29.2	14.8	36.8	14.4	37.7	13.8	36	3	9.016[a]

[a] 0.001 significant level.

acceleration behaviours were significant at both intersections. When drivers accelerated to cross the intersection after a complete stop, they applied a smaller acceleration rate when the eco-safe information was provided. The results demonstrated the effectiveness of the proposed eco-safe driving HMI in improving drivers' behavioural performance at intersections.

During this intersection crossing process, it was found that drivers had more blink activities when using the eco-safe HMI display than without using it, especially when both advice and feedback information were provided. In both intersection scenarios (with and without traffic), the total blink time and blink frequency of AF condition were significantly larger than those in the baseline condition, indicating a significant increase in mental workload when drivers received consecutive advice and feedback information. This finding was in line with previous studies showing that the introduction of a concurrent, non-driving cognitive task could increase the drivers' mental workload level indicated by the blink response (Tsai et al., 2007; Savage et al., 2013). Moreover, the present study showed that total blink time and blink frequency tended to be more reliable indicators of mental workload in comparison to single blink duration given that no significant difference was observed on single blink duration among different HMI conditions in either scenario. Together, these findings suggest that the driver-HMI interactions have a similar directional impact on blink activities compared with non-driving-related secondary tasks.

When the primary driving task was considered, i.e., road and traffic information perception, collection and processing, steering wheel control, as well as accelerator and brake pedal control, contrary results were observed with respect to the eco-safe HMI task. Drivers had reduced blink activities when they passed an intersection with crossing traffic in comparison to an intersection without traffic. Earlier research had confirmed that an increase in the road environment complexity or primary driving task difficulty, especially the visual-related tasks, could lead to blink inhibition, as drivers need to minimize information loss and cope with more visual information (Faure et al., 2016; Recarte et al., 2008; Hancock et al., 1990). In this study, the main difference between Scenario 1 and Scenario 2 was that some crossing vehicles were arranged in Scenario 1, and drivers needed to pay attention to those vehicles and give way to them before they could safely pass the intersection. Therefore, visual demand in the scenario with traffic was higher than that without traffic. This finding helped explain the mixed results related to visual and mental workload regarding the blink rate in earlier studies and also supported the hypothesis presented by Recarte et al. (2008).

Though pupil diameter has been widely applied as an indicator of mental workload and dilated pupil size is related to increased mental workload, the pupil dilation was not observed when drivers drove with the eco-safe HMI system. However, the pupil size did increase when drivers drove the more complex scenario. This is supported by previous studies' findings that pupil dilation increases when participants perform more complex and difficult cognitive tasks (Benedetto et al., 2014; Čegovnik et al., 2018). In addition, previous research argued that unlike the blink rate, it is challenging to differentiate pupil dilations related to mental workload and visual workload (Marquart et al., 2015). According to the present study, it could be inferred that the Task Evoked Pupillary Response was more sensitive to the increased visual workload related to changing driving situations, in comparison to the mental workload induced by in-vehicle cognitive tasks. This finding is supported by a recent study conducted by Li et al. (2018) when drivers need to react to the sudden brake of a leading vehicle while using a mobile phone. The results showed that the pupil size did not change because of the mobile phone task while it increased significantly after the leading vehicle started braking. The finding that pupil dilation and blink behaviour are associated with workload has potential applications for the development of technology to manage multiple tasks during driving. Workload management systems are being suggested as a way to mitigate the impact of non-driving-related tasks on road safety (Oviedo-Trespalacios et al., 2018 & Oviedo-Trespalacios et al., 2019a,b).

Drivers experienced highest mental workload level in AF condition, followed by the FO condition. Though not directly comparable, the patterns observed in the eye movement data and the NASA-TLX scores showed that blink response was consistent with the subjective reported workload level. The finding further confirmed that blink frequency and total blink time could serve as valid mental workload indicators. It should be noted that with the same subjective workload measure, the NASA-TLX score in the present study (with the highest value of 37.7 in AF condition) was at a similar level with the in-vehicle eco-driving assistance system designed by Hibberd et al. (2015). In Hibberd et al. (2015)'s study, drivers reported a median score of 39.8 (recalculated value based on a 0–100 scale) on the visual-auditory eco-driving assistance system. In Lee et al. (2010)'s study, drivers reported higher workload score (50–60) after driving with an eco-driving system compared with normal driving. According to a literature review conducted by Grier (2015), the average NASA-TLX global workload scores regarding driving a car task was 41.52. Therefore, it is reasonable to infer that the system in this study did not cause excessive workload for drivers.

Drivers' mental workload when using an in-vehicle driving assistance system, to a great extent, determines the usability and acceptance of the system. The findings of the study imply that it is necessary to evaluate drivers' mental workload using an eco-safe driving HMI system from both objective and subjective perspectives. Compared with subjective workload measures (i.e., the NASA-TLX), eye-movement measures allow a temporal demonstration of changes in mental workload in specific situations. Consecutive eco-safe driving information conveyed to drivers increased their visual and mental workload, but the overall workload fell within a reasonable range. This is probably related to the design of the interface, where intuitive icons are preferred over complex text or numbers that requires more visual attention of drivers. Additionally, this study used a high-fidelity driving simulator which could be representative of real-world driving. A previous study validated that drivers' behaviours in the real-world can be recreated in the simulator used in the present study (Larue et al., 2018). However, the effectiveness of the in-vehicle system should be validated in a field study as previous research reported that drivers' motivation to use in-vehicle assistance systems and their risk perception might be different in the real-world driving compared to the simulator driving (Pauwelussen and Feenstra, 2010).

Eye-tracking devices are currently commercially available and could potentially be utilised to develop driver support systems to manage the excessive workload of secondary tasks. The in-vehicle camera based eye-tracking technology (faceLAB™) was adopted as a passive measuring device in this study. This has the advantage of allowing participants to move freely and naturally compared to a glasses-based eye-tracker that requires the participant to wear uncomfortable and restrictive goggles. However, it should be noted that the collection of some eye-movement metrics is restricted in a dynamic driving environment, such as the pupil diameter, which is very sensitive to the lighting conditions. The simulator experiment could guarantee a relatively stable lighting intensity within the simulation room, but it is difficult to create such condition in real-world driving, which may limit the application of pupil diameter in practice.

Recent advances in connected and automated vehicles have been incremental, but there are still barriers to their widespread implementation, such as costs, driver acceptance, and changes to the road infrastructure. A well-designed driver assistance system presents an opportunity to support drivers during the transition period to highly automated vehicles by improving driver performance on the road while avoiding workload overload (Chen and Epps, 2014). Though previous studies have demonstrated the effectiveness of an eco-safe HMI system in promoting drivers' fuel-efficient and safe driving behaviours (Vaezipour et al., 2018), it was not clear how driver mental and visual workload was influenced by the system. Through objective and subjective measurements, this study clarified whether, and how, the eco-safe HMI system impacted drivers' mental workload and visual demand in different eco-safe information display conditions.

Inevitably, the study has some limitations that should be acknowledged. Firstly, the study did not find significant differences in blink duration between different driving conditions. One reason might be that the study used an average mean duration of all blinks instead of a detailed division according to the length of blinks. Previous studies found significant changes in short blinks, instead of medium and long blinks when drivers were involved in dual tasks (Benedetto et al., 2011). Secondly, the sample size of the study was not large. A larger sample size could help improve the generalisability of our findings. Finally, although similar patterns were observed, the blink data and NASA-TLX scores were not compared directly in the study. Future research may seek an appropriate approach to verify the association between the two measurements with consideration of the differences in scale and sensitivity.

5. Conclusion

The study used a driving simulator to investigate the changes of drivers' mental workload and visual demand when they drove with an eco-safe driving HMI system. The behavioural analysis showed that the eco-safe driving HMI system could facilitate drivers to take smooth brake and acceleration when they crossed the intersections. Drivers had significantly longer blink time and more frequent blinks when they were provided with the eco-safe HMI display compared with the baseline, especially in Advice & Feedback information condition. This indicates an increased mental workload when more eco-safe driving information was conveyed to drivers. Moreover, when using the eco-safe driving HMI, drivers at the intersection with traffic had a shorter blink duration and fewer blinks than drivers at the intersection without traffic. Thus, the study demonstrates that an increase in mental workload led to more active blink activities, and conversely, the increase in visual demand produced by more complex road traffic situation caused blink inhibition. The mental workload indicated by blink measurements was in accordance with the subjective reported workload level. Blink frequency and total blink time both served as valid indicators of drivers' mental workload and visual demand. However, the pupillary response seems to be more sensitive to the increased visual workload related to changing driving situations, in comparison to the mental workload induced by in-vehicle cognitive tasks. The findings of the study can assist in the development of more effective and user-friendly eco-safe driving systems where a reasonable amount of mental workload is imposed on drivers.

Author statement

The authors declare no potential conflicts of interest with respect to the research, authorship, and publication of this article.

CRediT authorship contribution statement

Xiaomeng Li: Validation, Methodology, Data curation, Formal analysis, Writing - original draft. **Atiyeh Vaezipour:** Conceptualization, Investigation, Validation, Methodology, Writing - original draft. **Andry Rakotonirainy:** Conceptualization, Supervision, Writing - review & editing, Funding acquisition. **Sébastien Demmel:** Data curation, Writing - review & editing. **Oscar Oviedo-Trespalacios:** Validation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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