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Effects of an in-vehicle eco-safe driving system on drivers' glance behaviour

Xiaomeng Li[a,b,*], Atiyeh Vaezipour[a,b,c], Andry Rakotonirainy[a,b], Sebastien Demmel[a,b]

[a] Center for Accident Research and Road Safety-Queensland (CARRS-Q), Queensland University of Technology, 130 Victoria Park Road, Kelvin Grove, Queensland, 4059, Australia

[b] Institute of Health and Biomedical Innovation (IHBI), Queensland University of Technology, 60 Musk Avenue, Kelvin Grove, 4059, Australia

[c] RECOVER Injury Research Centre, The University of Queensland, 4006, Australia

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ABSTRACT

We have designed a new in-vehicle eco-safe driving system and shown its effectiveness in prompting drivers to execute a fuel-saving and safe driving style (Vaezipour et al., 2018, submitted for publication). However, the system could also bring potential negative outcomes, i.e. driver distraction. This simulator study investigated drivers' glance behaviours as indicators of driver distraction when using our Eco-Safe Human-Machine-Interface (HMI). Four types of eco-safe information display conditions (baseline, advice only, feedback only, both advice and feedback) were tested on different traffic situations with varied road traffic complexity. Results showed that the eco-safe HMI system did not cause visual distraction. In contrast, the advice only or feedback only information improved forward gazing on the roadway. In addition, drivers tended to adapt their visual scanning strategies according to the traffic situations. In the car-following situation they paid longer glances to the forward roadway, while in the intersections they spent more time to look at the HMI system. The findings indicated that our eco-safe driving system improved drivers' eco-safe behaviours and meanwhile enhanced their visual attention on road while no evidence showed that drivers were distracted by it.

1. Introduction

With the increasing number of motor vehicles on roads, exhaust emission from vehicles has been identified as a major contributor to global air pollution (Ghio et al., 2012). Modern medical health research has comprehensively established the association between air pollution and diseases caused by respiratory and cardiovascular diseases (Brook and Rajagopalan, 2007). Given the pressing pollution issues related to road traffic, the concept of eco-driving was brought up into public to advocate a greener driving style that helps save fuel consumption and reduce fuel emission.

Eco-driving includes behaviours such as accelerating/decelerating moderately, anticipating traffic flow and signals to avoid sudden starts and stops, driving an even speed at or safely below the speed limit and eliminating unnecessary idling (Barkenbus, 2010). Evidence to date indicates that eco-driving could on average reduce fuel consumption between 5% and 10%, and for excellent performers, the reduction could be up to 20–50% (Barkenbus, 2010; Martin et al., 2012). In order to engage the public into eco-driving, the automotive market has started to produce vehicles with in-built eco-driving systems, providing advice to drivers and feedback on their fuel efficiency. Many studies have reported the positive effects of eco-driving systems on drivers' fuel efficiency. Zhao et al. (2015) developed a driving simulator based eco-driving support system providing both dynamic and static feedback to improve drivers' eco-driving behaviour, and a reduction of 5.37% for CO_2 emissions and 5.45% for fuel consumption were achieved in their study. Staubach et al. (2014) evaluated an eco-driving support system and showed fuel saving between 15%–19% as participants shifted up earlier and used more coasting strategies when using the system than without using it.

Whilst the eco-driving system shows fuel efficiency, some research argued that the advised eco-driving style may compromise safety occasionally (Young et al., 2011). The eco-driving system usually provides guidance on how to achieve optimal fuel efficiency through accelerator/brake pedal control, but it cannot adjust its guidance based on the ambient traffic and road situation (Jamson et al., 2015). For example, when drivers follow a heavy vehicle and move slowly, the system may advise them to accelerate for fuel economy while such advice might decrease headway to the leading vehicle and affect their ability to react timely. Strategy of maintaining a constant speed through

* Corresponding author at: Center for Accident Research and Road Safety-Queensland (CARRS-Q), Queensland University of Technology, 130 Victoria Park Road, Kelvin Grove, Queensland, 4059, Australia.

E-mail addresses: xiaomeng.li@qut.edu.au (X. Li), a.vaezipour@uq.edu.au (A. Vaezipour), r.andry@qut.edu.au (A. Rakotonirainy), sebastien.demmel@qut.edu.au (S. Demmel).

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the avoidance of braking may be detrimental for safety when drivers approach a curve or drive over a downhill section (Young et al., 2011).

In addition to the safety compromise due to change in driving styles, potential distraction was another safety concern caused by the use of in-vehicle eco-driving system device. Previous studies classified driver distraction into four categories: visual, auditory, bio-mechanical (physical) and cognitive distraction (Young et al., 2003). Many in-vehicle devices induced drivers to perform visual, auditory, vocal, manual or cognitive-related secondary tasks and they were normally associated with more than one type of distraction (Oviedo-Trespalacios et al., 2017a, 2017b; Oviedo-Trespalacios, 2018; Oviedo-Trespalacios et al., 2018). For example, an in-vehicle eco-driving display system could result in both visual distraction and cognitive distraction. The visual distraction occurs when drivers look at the display instead of the road for an extended period of time (e.g. longer than 2 s). The cognitive distraction happens when drivers think about the information presented on the system. It was believed that visual distraction plays a more important role than cognitive distraction in a way that degrades drivers' performance more remarkably (Ranney, 2008).

To assess the distraction effect of in-vehicle secondary tasks, eye glance is one of the most commonly used metrics as the eye glance data contains important information for understanding the attentional mechanism involved in distraction (Ahlstrom and Kircher, 2017; Birrell and Fowkes, 2014; Kraft et al., 2018). Besides, most eco-driving systems provide guidance through a visual interface, thus the primary concern for distraction emerges when the guidance information shows up and the driver interacts actively with it. Therefore, drivers' glance behaviour when interacting with the system becomes a major focus as the glances on the system display may compete for drivers' visual attention allocated to the main driving task (Kraft et al., 2018; Purucker et al., 2017). Hallihan et al. (2011) investigated the effects of an eco-driving hybrid interface on driver distraction. In their study, the percentage of time that participants looked at the interface was reduced from the time that they looked at the roadway ahead, and the time looking at the roadway was reduced by 12% after using the hybrid interface. Ahlstrom and Kircher (2017) found in a field study that drivers' glance behaviour away from the windscreen was slightly increased when using a visual eco-driving system in comparison to baseline condition. Overall, although no strong negative impact of using an eco-driving system on glance behaviour was reported in prior research, an increase of visual attention on the system and meanwhile a decrease on the forward roadway seems to be a prevalent result in these studies.

Despite prior research demonstrating the effectiveness of eco-driving systems in fuel saving, there is a legitimate concern regarding the effects of such devices on road safety still. Therefore in this study, a new eco-safe driving system was tested. Eco-safe driving is defined as a driving style aims not only to reduce fuel consumption and emission, but also keep the driver's on-road safety through behaviours such as conducting smooth acceleration/deceleration, complying with the speed limit and keeping a safe following distance, etc. For some specific circumstances in which the goals of green and safe driving might be in conflict, the pursuit of safe driving is prioritised over eco-driving. Our previous study has described the design process of the eco-safe in-vehicle HMI system (Vaezipour et al., 2016, 2017) and a driving simulator experiment was conducted to test the effectiveness of the system on eco-safe driving performance (Vaezipour et al., 2018, submitted for publication). The presented advice/feedback information about eco-safe driving was found to be significantly associated with improvements in fuel consumption, smooth acceleration and deceleration, as well as speeding behaviour and safe headway.

Existing research has focused a lot on the effectiveness of eco-driving systems from different aspects while effort on the ecological & safe driving concept has never been comprehensively attempted. Although our previous study has identified the effects of eco-safe driving system on drivers' eco-safe driving behaviours, it is yet not clear whether the system changes drivers' visual performance and causes driver distraction. Therefore, the main focus of the current study is to investigate the effect of eco-safe system on drivers' glance behaviour, and to assess whether it causes distraction when drivers interact with the system by using eye glance metrics as the distraction measurement. It is hypothesized that an eco-safe driving system should draw driver's attention when it attempts to convey information to drivers. If a system did not attract any attention at all, it means the system was not well designed (Kircher et al., 2014). Therefore, another research focus of the study is *(i)* to investigate in which situation and how the eco-safe driving system attracts drivers' attention, and *(ii)* to understand the visual search strategy that drivers employ to cope with the additional information provided the system in different driving situations. More specifically, the following four questions were addressed in the research:

(1) What are the differences in glance behaviour when drivers drive with and without the eco-safe driving system?
(2) Does the eco-safe HMI display cause driver distraction and take visual attention away from forward roadway?
(3) Does different types of eco-safe information display such as advice, feedback, or both advice and feedback, lead to differences in drivers glance behaviour and visual attention?
(4) When interacting with the eco-safe driving system, will drivers adopt different visual attention allocation strategies according to the varied driving difficulty in different traffic situations?

2. Methodology

2.1. Eco-safe driving HMI design

The purpose of the in-vehicle HMI was mainly to encourage an eco-safe driving style. The system was designed and developed based on the assumption of access to technologies such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) that obtain real time information about ambient traffic situation. Thus, real-time advice and feedback information was provided to drivers through the HMI display to inform them of the on-road situation and their behaviour performance. The design of HMI followed the user-centred design approach from the International Organisation for Standardization (ISO, 2010). A series of focus groups were conducted with drivers to collect user requirements of the in-vehicle HMI characteristics (Vaezipour et al., 2016, 2017). A multidisciplinary workshop was also conducted with experts from various disciplines, including intelligent transportation systems, traffic psychology, human computer interaction, user experience design and industrial design.

Prototype of the system included an Android cell phone (Samsung Galaxy S5, size 142 × 72.5 × 8.1 mm) with a 3D printed casing outside and a securing bracket on the windscreen to place the cell phone (see Fig. 1). Advice and feedback information about eco-safe driving was displayed through the cell phone screen (see Fig. 2) with intuitive figures so that information could be conveyed to drivers directly. The advice information was presented with icon and simple text (e.g., smooth braking) on a yellow background to notify drivers of specific traffic events, such as approaching a signalized intersection, so that they can drive in an anticipatory style. Correspondingly, the feedback information was conveyed through an animated “face” with “eyes” and “mouth”, and the illumination of LED lights around the screen, which together notified the drivers whether their behaviour performance was appropriate (i.e., happy face and green light) or inappropriate (i.e., sad face and red light).

2.2. Apparatus

The experiment was conducted by using the Centre for Accident Research and Road Safety- Queensland (CARRS-Q) advanced driving simulator (see Fig. 3). The simulator consists of a real vehicle cabin

Fig. 1. The eco-safe driving HMI.

(Holden Commodore) with automatic gearbox, a surround-sound system for engine and environmental noise, and a six degree of freedom motion platform that 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 mirror view. The faceLAB™ system was used as the eye-tracking equipment to collect participants' eye movement data. It uses a set of cameras and a computer with the software installed as a passive measuring device, which means the system is non-intrusive and the participants can move naturally without wearing uncomfortable and restrictive goggles, wires or other sensing devices. Images from the cameras were analysed to extract characteristics of a participant's face, including the 3D head position and orientation, blink and saccade estimates, gaze data for each eye, pupil diameter and other measurements.

2.3. Scenario

The simulated driving scenario was designed based on the Brisbane city area and surrounds which consisted of urban and suburban areas to provide participants a driving environment with high realism and familiarity. The speed limits was 40 km/h in urban city areas and 60 km/h in suburban areas. The total driving route was approximately seven kilometres long and it contained abundant traffic situations including stop-sign intersections with/without crossing traffic, signalized intersections with/without crossing traffic, pedestrian crossing, car-following and change of speed limit to mimic a real-life driving scenario.

In this study, three traffic situations were chosen for data analysis. They were the car-following section, the signalized intersection with crossing traffic and the stop-sign intersection without crossing traffic. Drivers in these situations dealt with frequent deceleration/acceleration manoeuvres where significant fuel saving could potentially be achieved by appropriate speed control. Moreover, the three situations were considered because of their apparently different complexity and requirements on driving skills (Yan et al., 2014). With the signal light change and the crossing traffic, situation in signalized intersection was more complex than that in stop-sign intersection. The car-following situation was supposed to be the most complex, as it was more safety-related with unpredictable manoeuvre of the leading vehicle, and drivers need to keep high attention on it in case a rear-end collision might occur. More specific descriptions of the three situations were listed as following:

2.3.1. Situation 1: car-following (CF)

In this road section, the drivers followed a leading vehicle at a speed limit of 40 km/h. The leading vehicle was triggered to move forward when the participant's vehicle approached and the gap distance was reduced to 50 m. Meanwhile, advice information to remind drivers of the leading vehicle ahead was displayed on the HMI (see the third image in the upper line of Fig. 2). During the car-following process, when the time headway between two vehicles was smaller than 2.5 s, feedback information would be displayed (see the third image in the lower line of Fig. 2). The total distance of car-following section was 250 m. Drivers need to adjust their speed according to the movement of the leading vehicle to keep a safe gap distance. A flow of ambient vehicles were arranged on the opposite lane so that drivers cannot overtake.

2.3.2. Situation 2: signalized intersection (SLI)

When the drivers approached the intersection, the signal light turned into red. Ambient vehicles were arranged to drive across the intersection at the same time. Advice information of smooth braking would be displayed on the HMI when drivers got to 30 m in front of the intersection stop line, and feedback information of drivers' braking performance would show up when they arrived at the stop line.

2.3.3. Situation 3: stop-sign intersection (SSI)

The drivers were required to stop completely at a stop-sign and then move forward. The stop-sign intersection was a three-way junction with no other vehicles presented when drivers approached. Similarly to the

Fig. 2. Examples of advice (upper line) and feedback (lower line) information.

Fig. 3. The CARRS-Q Advanced Driving Simulator.

signalized intersection, advice information was displayed at 30 m in front of the intersection stop line and feedback information was displayed when drivers reached the stop line.

2.4. Participants

53 participants in total were recruited for the study while only 36 (18 females, 18 males) completed the whole experiment with valid eye-movement data and without motion sickness. The participants aged between 18–65 years old (M = 31.44, SD = 12.12) and all of them held a valid driver licence with 61.3% of them reporting driving mileage over 10, 000 km in the previous year. They were recruited through social media posts, university webpage advertisement and snowball sampling. All participants signed a consent form to participate and were informed that their participation was entirely voluntary and that data would remain anonymous and reported in an aggregate manner only.

The study was conducted in accordance with the Australian Code for the Responsible Conduct of Research (QUT Ethic approval number 1600000651).

2.5. Procedures

Upon arrival, participants were introduced to the experimental procedure and advised to drive as they normally would and to adhere to traffic laws as in real-life situations. The participants were also notified that they could quit the experiment at any time in case of motion sickness or any kind of discomfort. Before the formal experiment, each participant completed a practice drive for about 5 min to get familiar with the driving simulator operation followed by an explanation of the in-vehicle eco-safe driving system on an iPad.

The formal experiment included four times of drive on the same route under four different eco-safe information display conditions respectively, which were (1) no information as baseline (BL), (2) advice information only (AO), (3) feedback information only (FO), and (4) both advice and feedback information (AF).

As this was a within-subjects experiment design, each participant was administered to all four eco-safe information conditions. In order to eliminate the learning effect and experiment order effect, the starting road location of each drive was arranged randomly. Traffic flow was also varied among different traffic situations, and the order of four conditions' driving was also counter-balanced among participants. Each drive took about 10 min to complete and the total experiment took about 2 h for each participant. After completing the experiment, participants received an AUD70 gift voucher as a reimbursement of their participation.

2.6. Data collection and analysis

The study focused on drivers' glance behaviour when using an in-vehicle eco-safe driving system, thus only the eye-movement data collected by the faceLAB™ were analysed in the paper. The eye-movement data were sampled at 60 Hz. Key variables during each traffic situation were extracted from the raw data. The duration of car-following section was 250 m starting from the location where the simulator triggered the leading vehicle to move. The durations of signalized and stop-sign intersection sections were both from 30 m in front of the intersection stop line to 80 m after it.

According to ISO 15007-1 (2014), a saccade was defined as brief, fast movement of the eyes that changes the point of fixation and a glance was defined as the maintaining of visual gaze within an area of interest. In this study, both details of saccade and glance were extracted by Matlab coding, which included total saccade duration (TSD), average saccade duration (ASD), saccade frequency (SF), total glance duration (TGD), average glance duration (AGD) and glance frequency (GF). More specifically, (1) the total saccade (glance) duration was defined as the total time of all the saccades (glances) within a traffic situation duration, in s; (2) the average saccade (glance) duration referred to the average time of each saccade (glance) within a traffic situation duration, in s; and (3) the saccade (glance) frequency represented the number of saccades (glances) per second within a traffic situation duration, in /s. Areas of interest (AOI) in the study included the front roadway, the HMI and the speedo within which the glance details were extracted.

To address the research questions raised above, the saccade and glance variables were analysed among different eco-safe information conditions (i.e., BL, AO, FO and AF) as well as among different traffic situations (i.e., CF, SLI and SSI). Since the distributions of the majority variables did not fulfil the normality assumption required for the analysis of variance, Friedman test was then adopted as a non-parametric alternative to the repeated-measures ANOVA in the study (Friedman, 1939). Post-hoc test (Wilcoxon type) for pairwise comparison was conducted accordingly by using Bonferroni adjustment. It should be clarified that in the car-following situation, drivers received feedback information only when the headway time was less than 2.5 s, and the proportion turned out to be no more than one third of the total drivers. Therefore in the car-following situation, only effect of advice information was tested in comparison to the baseline.

3. Results

3.1. Comparison among different traffic situations

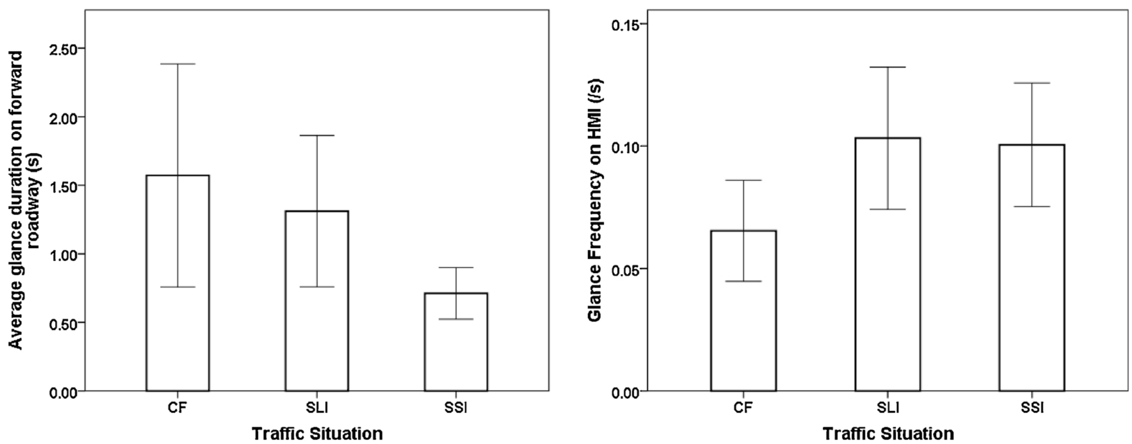
When drivers conducted multi tasks during driving, it was quite possible that their visual scanning strategy might change according to the cognitive demand of different environmental situations (Li et al., 2018). As all drivers received AO information in three traffic situations, the saccade and glance variables in AO condition were then analysed to identify the change of visual scanning strategy when interacting with the HMI among different traffic situations. Table 1 listed the descriptive statistic results and Friedman test results of saccade and glance variables in three situations, among which the total saccade and total glance durations were excluded, as they were highly dependent on the situation duration.

The results showed that drivers' average glance duration on front roadway and glance frequency on HMI changed significantly among three traffic situations. Pairwise comparison further indicated that the

Table 1
Descriptive statistic and Friedman test results of variables in three traffic situations.

Area of Interest	Variables	Traffic situations						Friedman test		
		CF		SLI		SSI				
		Mean	S.D.	Mean	S.D.	Mean	S.D.	N	df	χ^2
–	ASD	.051	.009	.055	.007	.055	.008	34	2	4.941
	SF	.672	.315	.756	.360	.681	.228	34	2	1.647
Forward roadway	AGD	1.571	2.331	1.310	1.556	.711	.539	33	2	12.182**
	GF	.526	.273	.530	.292	.575	.232	34	2	3.588
Speedo	AGD	1.068	1.860	1.039	1.095	1.035	.993	34	2	2.882
	GF	.489	.234	.446	.249	.417	.181	34	2	0.117
HMI	AGD	.223	.189	.322	.359	.264	.257	32	2	3.254
	GF	.065	.059	.103	.083	.101	.072	34	2	12.444**

** Significant at the 0.01 level.



(a) Average glance duration on forward roadway (b) Glance frequency on HMI

Fig. 4. Differences of variables among three traffic situations.

average glance duration on front roadway was longer in CF and SLI situations compared to the SSI situation (CF/SSI: $z = -3.821$, $p < 0.01$; SLI/SSI: $z = -2.886$, $p < 0.01$)(see Fig. 4a), while the glance frequency on HMI was higher in SLI and SSI situations than in CF situation (SLI/CF: $z = -2.972$, $p < 0.01$; SSI/CF: $z = -2.936$, $p < 0.01$)(see Fig. 4b).

3.2. Comparison among different eco-safe information conditions

3.2.1. Car-following situation

For the car-following situation, Wilcoxon signed ranks test was conducted between BL and AO conditions on saccade and glance variables. The descriptive statistic and test results were listed in Table 2. It showed that the total saccade duration, saccade frequency, total glance duration on forward roadway, average glance duration on speedo, total and average glance duration as well as the glance frequency on HMI had significant differences between BL and AO conditions. Compared to BL condition, drivers in AO condition had more frequent saccadic eye-movement, longer total glance duration on forward roadway, shorter average glance duration on speedo, as well as longer and more frequent glance on HMI (see Fig. 5).

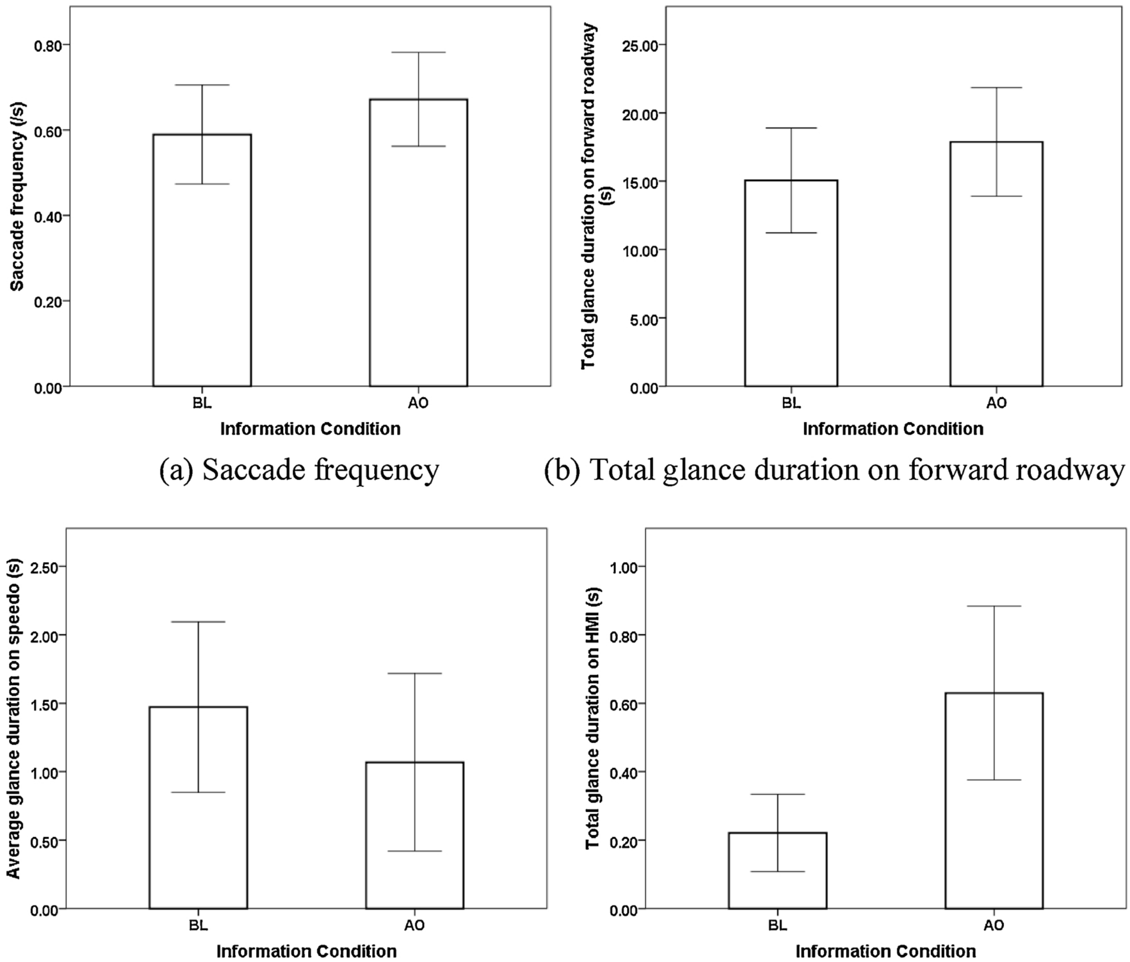
3.2.2. Signalized intersection situation

Table 3 listed the descriptive statistic results of all the variables and the Friedman test results of variables among four eco-safe information conditions in signalized intersection situation. The results showed that the eco-safe information conditions had significant effect on drivers' total saccade duration, total glance duration, average glance duration as well as glance frequency on HMI. Post-hoc test further showed that (1) the total saccade duration in AF condition was significantly larger than that in BL condition ($z = -3.129$, $p < 0.01$), see Fig. 6a; (2) the total glance duration on HMI was significantly larger in AO, FO and AF conditions than in BL condition (AO/BL: $z = -2.979$, $p < 0.01$; FO/BL: $z = -3.557$, $p < 0.01$; AF/BL: $z = -4.244$, $p < 0.01$), see Fig. 6b; (3) compared to BL condition, the average glance duration ($z = -3.328$, $p < 0.01$) and glance frequency on HMI ($z = -3.600$, $p < 0.01$) were

Table 2
Descriptive statistic and Wilcoxon signed ranks test results of variables in CF situation.

Area of Interest	Variables	Eco-safe information conditions				Wilcoxon signed ranks test	
		BL		AO			
		Mean	SD	Mean	SD	N	Z (BL/AO)
	TSD	.870	.529	1.149	.655	33	−2.314*
	ASD	.048	.008	.051	.009	33	−1.796
	SF	.589	.337	.672	.315	33	−1.957*
Forward roadway	TGD	15.059	11.174	17.871	11.378	33	−2.117*
	AGD	1.482	1.893	1.571	2.331	33	−0.027
	GF	.509	.398	.526	.273	33	−1.367
Speedo	TGD	14.275	11.904	12.850	11.977	33	−0.652
	AGD	1.472	1.814	1.068	1.860	33	−2.207*
	GF	.446	.327	.489	.234	33	−1.760
HMI	TGD	.221	.329	.630	.727	33	−2.757**
	AGD	.113	.147	.223	.189	33	−2.070*
	GF	.043	.074	.065	.059	33	−2.238*

* Significant at the 0.05 level.
** Significant at the 0.01 level.



(a) Saccade frequency (b) Total glance duration on forward roadway

(c) Average glance duration on speedo (d) Total glance duration on HMI

Fig. 5. Differences of variables between AO and BL conditions in CF situation.

significantly larger in AF condition, see Fig. 6c and d.

3.2.3. *Stop-sign intersection situation*

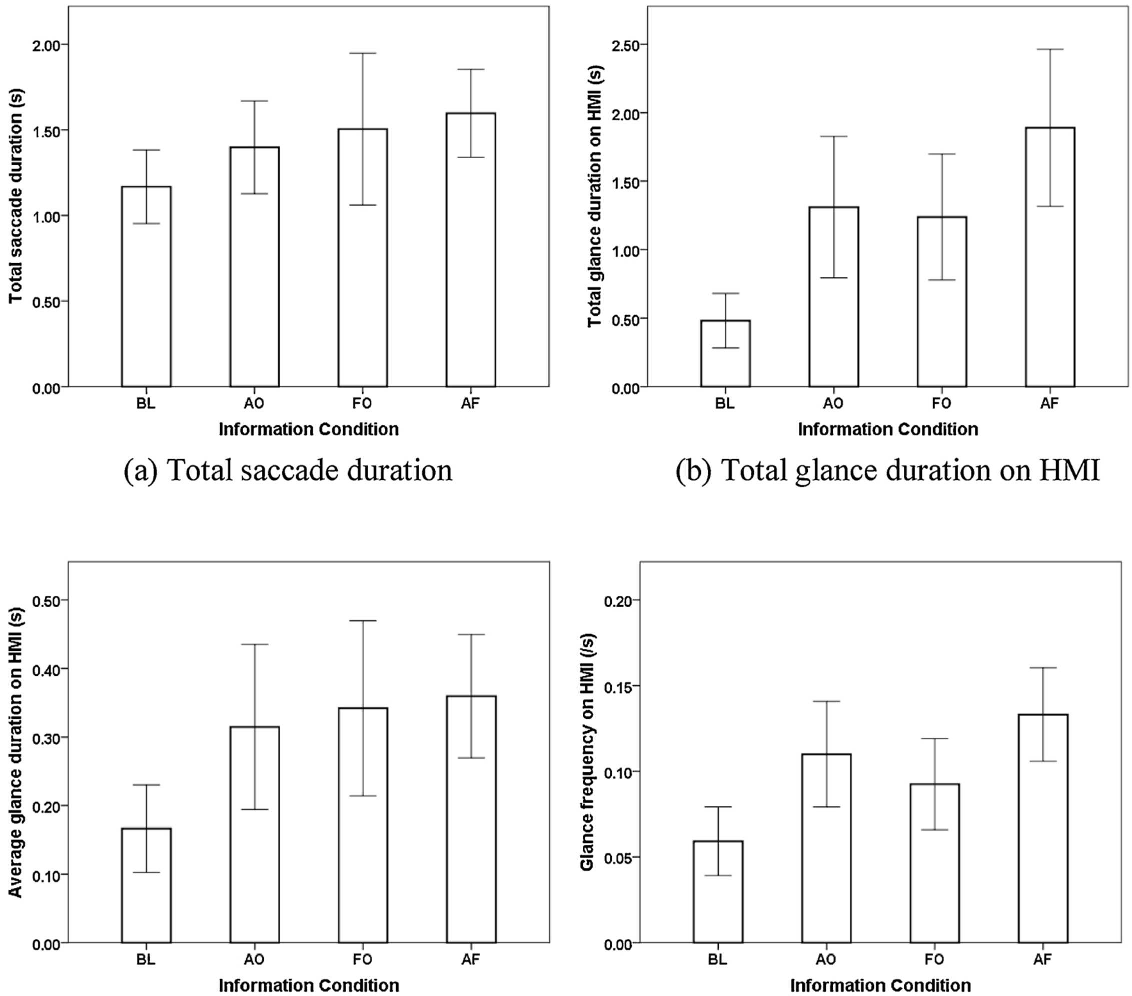
According to the Friedman test results of variables in stop-sign intersection situation (see Table 4), the variables that had significant difference among four information conditions included saccade duration, saccade frequency, total glance duration on forward roadway, total glance duration on speedo, total/average glance duration as well as glance frequency on HMI.

Specifically, post-hoc test results indicated that (1) the total saccade duration in AO, FO and AF conditions was significantly larger than that in BL condition (AO/BL: z = -4.583, $p < 0.01$; FO/BL: z = -4.060,

Table 3
Descriptive statistic and Friedman test results of variables in SLI situation.

Area of Interest	Variables	Eco-safe information conditions								Friedman test		
		BL		AO		FO		AF				
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	N	df	χ^2
	TSD	1.167	.644	1.398	.804	1.505	1.329	1.596	.762	31	3	13.816**
	ASD	.052	.007	.055	.007	.055	.008	.057	.007	31	3	8.458
	SF	.681	.254	.757	.362	.700	.298	.779	.279	31	3	5.052
Forward roadway	TGD	14.400	10.200	16.528	11.077	19.517	18.319	16.115	11.009	31	3	7.252
	AGD	1.210	1.464	1.284	1.522	1.194	1.278	1.008	1.003	31	3	2.640
	GF	.530	.391	.584	.421	.541	.304	.579	.348	31	3	1.568
speedo	TGD	14.666	11.599	13.787	12.000	13.416	11.315	15.301	12.057	31	3	6.406
	AGD	1.156	1.051	.990	1.083	1.000	1.075	.873	.687	31	3	3.426
	GF	.448	.266	.474	.309	.425	.241	.481	.257	31	3	1.606
HMI	TGD	.481	.598	1.311	1.526	1.239	1.377	1.890	1.694	31	3	23.394**
	AGD	.166	.191	.315	.350	.342	.377	.360	.258	31	3	9.713*
	GF	.059	.060	.110	.091	.092	.080	.133	.081	31	3	15.771**

* Significant at the 0.05 level.
** Significant at the 0.01 level.



(a) Total saccade duration
(b) Total glance duration on HMI
(c) Average glance duration on HMI
(d) Glance frequency on HMI

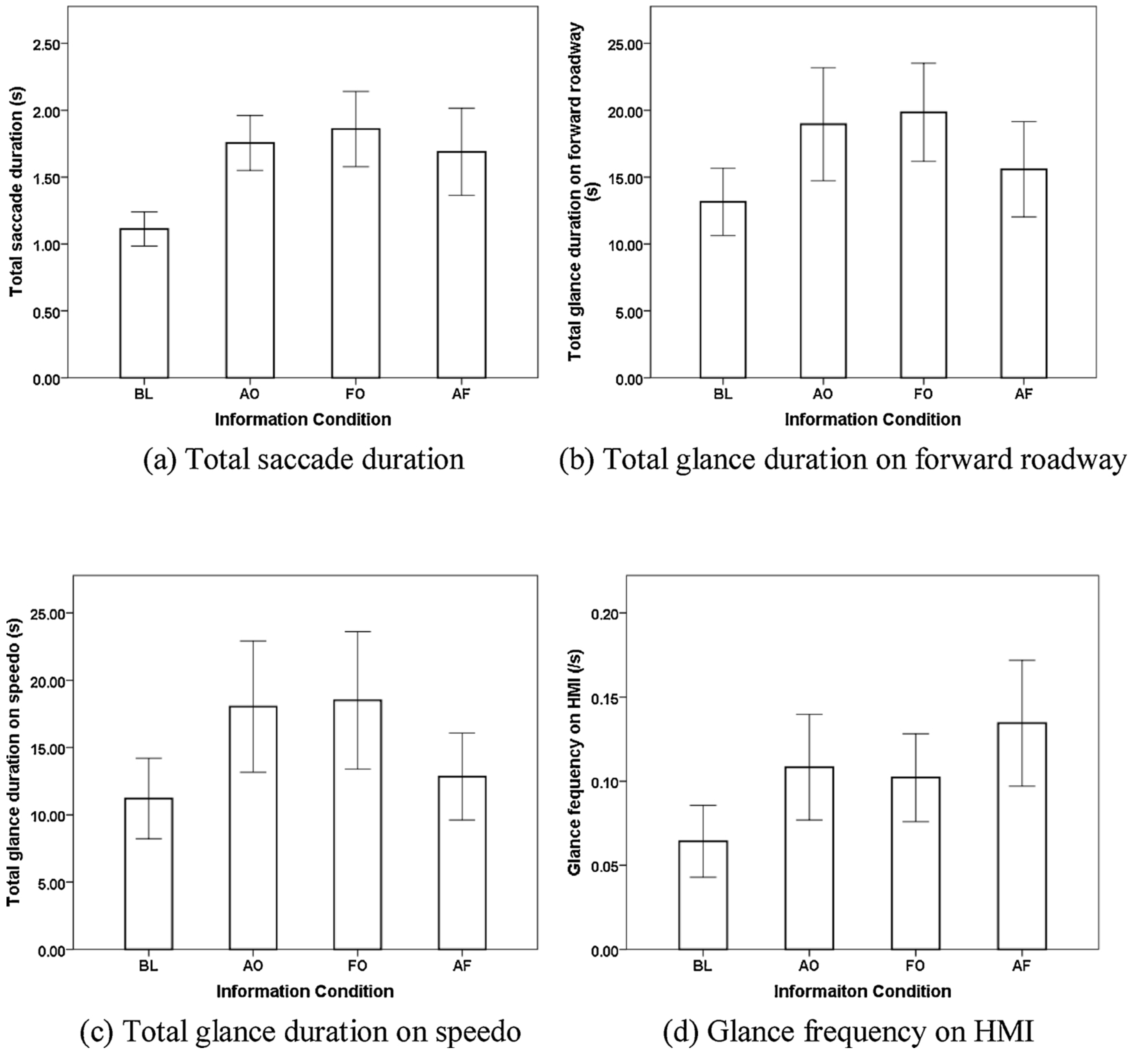
Fig. 6. Differences of variables among four eco-safe information conditions in SLI situation.

$p < 0.01$; AF/BL: $z = -4.172$, $p < 0.01$), see Fig. 7a; (2) the saccade frequency in AF condition was significantly larger than that in BL condition (AF/BL: $z = -3.046$, $p < 0.01$); (3) the total glance duration on front roadway in AO and FO conditions was significantly larger than that in BL condition (AO/BL: $z = -3.725$, $p < 0.01$; FO/BL: $z = -3.787$, $p < 0.01$), see Fig. 7b; (4) the total glance duration on speedo in AO and FO conditions was significantly larger than that in BL and AF conditions (AO/BL: $z = -4.458$, $p < 0.01$; FO/BL: -4.129, $p < 0.01$; AO/AF: $z = -3.118$, $p < 0.01$; FO/AF: $z = -2.761$, $p < 0.01$), see Fig. 7c; (5) the total glance duration on HMI (AO/BL: $z = -3.815$,

Table 4
Descriptive statistic and Friedman test results of variables in SSI situation.

Area of Interest	Variables	Eco-safe information conditions								Friedman test		
		BL		AO		FO		AF				
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	N	df	χ^2
	TSD	1.112	.377	1.755	.607	1.860	.855	1.690	.963	31	3	28.897**
	ASD	.052	.010	.055	.007	.053	.008	.055	.010	31	3	9.039
	SF	.649	.166	.689	.229	.706	.264	.754	.246	31	3	8.381*
Forward roadway	TGD	13.147	7.449	18.957	12.492	19.856	11.175	15.593	10.530	31	3	18.329**
	AGD	.770	.600	.728	.561	.796	.701	.716	.643	31	3	4.587
	GF	.618	.333	.599	.298	.634	.355	.620	.238	31	3	3.426
Speedo	TGD	11.212	8.824	18.039	14.428	18.507	15.539	12.841	9.550	31	3	30.406**
	AGD	.772	.639	1.020	.977	.847	.724	.718	.539	31	3	2.961
	GF	.473	.263	.434	.231	.476	.282	.480	.211	31	3	2.961
HMI	TGD	.363	.510	1.587	1.932	1.433	1.338	1.414	1.579	31	3	23.388**
	AGD	.104	.131	.256	.252	.333	.376	.230	.242	31	3	20.495**
	GF	.064	.063	.108	.093	.102	.080	.134	.111	31	3	12.974**

* Significant at the 0.05 level.
** Significant at the 0.01 level.



(a) Total saccade duration (b) Total glance duration on forward roadway

(c) Total glance duration on speedo (d) Glance frequency on HMI

Fig. 7. Differences of variables among four eco-safe information conditions in SSI situation.

$p < 0.01$; FO/BL: $z = -4.488$, $p < 0.01$; AF/BL: $z = -3.815$, $p < 0.01$) and average glance duration on HMI (AO/BL: $z = -3.429$, $p < 0.01$; FO/BL: $z = -3.852$, $p < 0.01$; AF/BL: $z = -3.137$, $p < 0.01$) were significantly larger in AO, FO and AF conditions compared to BL condition; (7) the glance frequency on HMI was significantly higher in AF condition than in BL condition ($z = -3.347$; $p < 0.01$), see Fig. 7d.

4. Discussion

When it comes to designing or employing an in-vehicle HMI information system, the trade-off between providing sufficient information and minimising driver's distraction is always deemed as a major challenge (Kraft et al., 2018; Rouzikhah et al., 2013). However, an ergonomically designed HMI can not only avoid distraction problems, but also has the potential to enhance drivers' attention allocation on road. Given that our previous study has identified the positive outcomes of the eco-safe driving system in improving drivers' fuel-saving and safety-related performances (Vaezipour et al., 2018, submitted for publication), this study mainly focused on drivers' glance behaviours as indicators of visual distraction when using the eco-safe driving system. Questions of whether different types of eco-safe information conditions led to differences in glance behaviours and whether drivers adopted different visual attention allocation strategies in different traffic situations were also addressed.

First of all, drivers' glance behaviours changed significantly in different traffic situations as expected. In the present study, the car-following situation was comparatively more task-demanding compared to the intersections as the leading vehicle's movement was hard to predict. Drivers need to pay high attention to the speed changes of the leading vehicle to maintain a safety margin. This could explain the result showed in the study that drivers in car-following situation had longer glance duration on the forward roadway compared to the intersection situation. In addition, drivers directed their glances more frequently to the HMI display in intersection situations compared to the car-following situation. This implied that in simple situation, drivers adapted and spent more time to check the HMI and try to understand the information showed on it while in complex situation drivers would shift their attention to more important targets. The results showed clearly that drivers adapted their eye movement behaviour to the driving task complexity and the finding was consistent with many previous studies (Victor et al., 2006; Rommerskirchen et al., 2014). In a study testing the sensitivity of eye-movement measures to in-vehicle task difficulty and driving task demands, Victor et al. (2005) found that as driving task complexity increased, drivers increased their road viewing time and spatially concentrated their gaze on the road centre area. Rommerskirchen et al. (2014) investigated drivers' visual behaviour when using an anticipatory eco-driving assistant system in different situations, and results showed that the percentage of gaze time on the HMI was significantly reduced in more complex situations.

Among all three traffic situations in the study, drivers had significantly more saccadic eye-movement when provided with eco-safe information compared to the baseline condition. As a saccade serves as rapid shift of gaze direction from one object in the visual field to another (Fuchs, 1976), the increased saccade activities implied that drivers were locating different interesting parts in their field of view actively. Although the visual information collection process was impaired during the saccadic trajectory, the frequent saccades still showed that drivers' gaze shifted quickly between different stimuli of interest. Thus, it can be inferred from the results that after the eco-safe information was provided, drivers' demand and their effort in collecting visual information from different targets in the scene both increased.

The forward roadway is a vital area that needs intensive focus to keep on-road safety during driving. When comparing the amount of visual attention on forward roadway before and after placing a visual-display information source in vehicle, most research reported a significant reduction while some others found no significant change. Research of Birrell and Fowkes (2014) reported no reduction of glances to the centre of road after introducing an in-vehicle smart driving aid in comparison to a control condition. Victor et al. (2005) found that when subjects completing a visual in-vehicle task, the percentage of gaze within road centre area dropped significantly as compared to baseline driving. Interestingly, in the current study, when drivers were in a car-following situation or drove across a stop-sign intersection, they had significantly longer glance duration on the forward roadway in eco-safe driving conditions compared to the baseline condition. The tendency was similar in signalized intersection although the difference was not significant. The result indicated an obviously positive outcome from the introduction of eco-safe information display that it prompted drivers to pay more visual attention to the safety-related area.

Previous research has suggested that in many situations, drivers have time to look at targets that are not traffic relevant, which is known as the "visual spare capacity" (Birrell and Fowkes, 2014). The proportion of "spare" attentional capacity that drivers allocated on non-driving tasks could be up to 30%–50% in terms of different driving situations (Hughes and Cole, 1986; Antin et al., 1990; Green and Shah, 2004). The presence of visual spare capacity ensured that drivers can execute additional tasks, such as interacting with a driver support system, while still being sufficiently attentive to the driving task (Ahlstrom and Kircher, 2017). Therefore, it is not surprising that in the present study the glance duration on the forward roadway increased even after the eco-safe driving system was introduced, probably because the drivers made use of the visual spare capacity.

Another key finding from the study is that by comparing the three eco-safe information conditions, drivers seemed to have better visual allocation in AO and FO conditions than in AF condition. This could be demonstrated from two aspects: firstly, when driving across the stop-sign intersection, drivers had significantly longer total glance duration on the forward roadway and speedo in AO and FO conditions in comparison to the baseline condition while the difference between AF and baseline conditions was not significant; secondly, the glance frequency on HMI display was significantly higher in AF condition compared to the BL condition in both stop-sign intersection and signalized intersection. In another word, drivers focused more on the safety-related area in AO and FO conditions but they looked at the HMI display more frequently in AF condition. This is probably because in AF condition both the advice and feedback information about eco-safe driving was displayed continuously without interruption, and thus it attracted drivers more. Similarly, Kircher et al. (2014) compared the effects of intermittent versus continuous visual eco-driving system on glance behaviour and reported that the continuous system led to more glances and longer dwell time on the display compared to the intermittent system.

In terms of the major safety concern-driver distraction regarding the use of HMI display, NHTSA guidelines on in-vehicle devices suggest that the use of in-vehicle systems should not lead to drivers' glances away from the roadway for greater than 2 s at a time, otherwise the risk of a crash or near crash would increase accordingly (NHTSA, 2012). Results from the current study showed that when using the eco-safe driving system, the average glance duration on the system was around 0.2-0.4 s regarding all situations with information display, and no single glance made to the system was longer than 2 s by any of the 36 participants. Additionally, a comparison of the glance duration on different types of eco-driving information display could be conducted between previous studies. Ahlstrom and Kircher (2017) reported that drivers looked at a visual eco-driving system with mean glance duration of about 0.5–0.6 s depending on road type and the value was around 1 s in the study of Kircher et al. (2014). Hallihan et al. (2011) designed a hybrid interface that had the potential to improve drivers' eco-driving behaviours, and the mean glance duration on the interface while driving with it was 0.56 s. Comparatively, the glance duration on the HMI display was shorter in the present study. One possible reason might be that the information conveyed to drivers was not only related to eco-driving, but also strengthened the safety aspect, which enhanced the drivers to allocate more attention to the safety-related areas. Another reason could be due to the design of the interface, which tended to use more intuitive pictures instead of numbers or text to convey information. Short glance on the visualized interface was advisable as it ensured drivers to obtain sufficient information quickly and meanwhile avoid an excess of workload in information processing. Based on the comparison with other studies, it could be inferred that driving with a simplified designed HMI and graphically presented eco-safe driving information had the potential to reduce glance duration on it and thus avoid visual distraction of the in-vehicle display.

Finally, some limitations of the study should be noted. In order to increase the diversity of the driving scenario and the realism of driving experience, various traffic situations were included but the complexity of traffic situations was not strictly controlled, and it was hard to identify how each driver perceived the difficulties in these situations. A strictly controlled traffic situation should involve the same event with varied environmental elements, for example, a stop-sign intersection with vs. without crossing traffic. Furthermore, the study only chose the areas of interest which were most distraction-related (the HMI display), safety-related (the forward roadway) and fuel-efficiency-related (the speedo). More detailed areas such as left/right side windows and mirrors were suggested to be involved for a complete driver visual attention allocation analysis. Additionally, the present study only focused on drivers' glance behaviour. To achieve a comprehensive evaluation of the safety outcomes associated with the eco-safe driving HMI, more visual metrics should be taken into consideration. For instance, drivers' blink details and pupil size could be involved to evaluate the change of drivers' mental workload when they interacted with the HMI.

5. Conclusion

By using a driving simulator experiment, the study was the first one that tested the effectiveness of an in-vehicle eco-safe HMI. Drivers' glance behaviours were compared among different traffic situations and under different conditions of eco-safe information display. The study demonstrated that drivers could adapt their visual scanning strategies to different traffic situations. In the more complex car-following situation, they paid longer glances to the forward roadway, while in the less complex intersection situations they spared more time to look at the HMI system. The presenting of eco-safe driving information facilitated more active saccadic eye-movement, more visual attention on the forward roadway and on the HMI system. Specifically, the AO and FO conditions seemed to create more safety benefit compared to the AF condition, as drivers paid more visual attention on the forward roadway in former conditions but they directed more frequent glance to the HIM in the latter condition, although no evidence of visual distraction was established by the three types of information display. As this is a simulator-based study, it is suggested that real-world driving test of the eco-safe driving system should be conducted in the future to compare and validate results of the present study before its application in reality. Future study could also integrate various modalities of information display (i.e. audio and visual information) in the eco-safe driving system to explore whether it can further improve drivers' behavioural and visual performance in eco-safe driving.

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