Reducing vehicle fuel consumption and exhaust emissions from the application of a green-safety device under real driving

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Abstract

Vehicle emissions have a significantly negative impact on climate change, air quality and human health. Drivers of vehicles are the last major and often overlooked factor that determines vehicle performance. Eco-driving is a relatively low-cost and immediate measure to reduce fuel consumption and emissions significantly. This paper reports investigation of the effects of an on-board green-safety device on fuel consumption and emissions for both experienced and inexperienced drivers. A portable emissions measurement system (PEMS) was installed on a diesel light goods vehicle (LGV) to measure real-driving emissions (RDE), including total hydrocarbons (THC), CO CO_2, NO, NO_2 and particulate matter (PM). In addition, driving parameters (e.g. vehicle speed and acceleration) and environmental parameters (e.g. ambient temperature, humidity and pressure) were recorded in the experiments. The experimental results were evaluated using the Vehicle Specific Power (VSP) methodology to understand the effects of driving behavior on fuel consumption and emissions. The results indicated that driving behavior was improved for both experienced and inexperienced drivers after activation of the on-board green-safety device. In addition, the average time spent was shifted from higher to lower VSP modes by reducing excessive speed, and aggressive accelerations and decelerations. For experienced drivers, the average fuel consumption and NO, NO_2 and soot emissions were reduced by 5%, 56%, 39% and 35%, respectively, with the on-board green-safety device. For inexperienced drivers, the average reductions were 6%, 65%, 50% and 19%, respectively. Moreover, the long-term formed habits of experienced drivers are harder to be changed to accept the assistance of the green-safety device, whereas inexperienced drivers are likely to be more receptive to change and improve their driving behaviors.

***Keywords*:** Green-safety device; Eco-driving; PEMS; VSP; Fuel consumption; Gaseous and particulate emissions

Highlights

- Eco-driving is a cost-effective method for reducing fuel consumption and emissions
- RDE tests were performed with different driver ages, experience and offense points
- Green-safety device increased from 31% to 35% of time spent in lower VSP modes
- Fuel consumption reduced 5%-6% with the green-safety device installed
- Emissions reduced 19%-35% for PM and 56%-65% for NO with the device installed

Abbreviations:

CO: Carbon monoxide

CO_2: Carbon dioxide

DOC: Diesel Oxidation Catalyst

DPF: Diesel Particulate Filter

EGR: Exhaust Gas Recirculation

FID: Flame Ionization Detector

GPS: Global positioning system

HKEPD: Hong Kong Environmental Protection Department

LGV: Light goods vehicle

NO: Nitric oxide

NO_2: Nitrogen dioxide

PEMS: Portable emissions measurement system

PM: Particulate matter

RDE: Real-driving emissions

THC: Total hydrocarbons

VSP: Vehicle Specific Power

1. Introduction

Road transport is a major source of atmospheric pollutants, including hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2) and particulate matter (PM). Greenhouse and pollutant emissions of on-road vehicles have negative impacts on climate change (Sausen, 2010) and human health (Ren et al., 2016; World Health Organization, 2013). According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), the CO_2 emissions from road transport increased by 45% since 1990 (IPCC, 2014). An increasing amount of CO_2 emissions and other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) has received considerable attention from policy makers and environmental groups. In addition, the European Union has set out ambitious targets for 2030, to reduce greenhouse emissions gas by 40% compared to 1990 levels (Rogner, 2007). Although significant progress has been made to limit the pollutant emissions from the transport sector, emissions of diesel vehicles are still one of the main contributors to urban air pollutants as diesel vehicles produce significant percentages (40-60%) of the total NO_x and PM emissions (Pui et al., 2014; Ramlan et al., 2016). In Hong Kong, numerous policies and measures have been adopted by the Hong Kong Environmental Protection Department (HKEPD) to improve roadside air quality and greenhouse gas emissions from motor vehicles (Ning et al., 2012). In order to protect the environment and public health, the Hong Kong SAR Government has carried out air quality impact assessments and published an emissions inventory report of local air pollutant emissions (HKEPD, 2018). It was reported that CO emissions were decreased by 37% between 1997 and 2016 (HKEPD, 2018), which was mainly attributed to a series of vehicle emission control programmes, including the tightening of vehicle emission standards from Euro IV to Euro V in 2012, deploying roadside remote sensing equipment to detect excessive emissions from petrol and LPG vehicles and progressively phasing out some 82,000 pre-Euro IV diesel commercial vehicles by 2019. During the same period, respirable suspended particulates (RSP) and NO_x emissions were greatly reduced by 69% and 39% respectively (HKEPD, 2018).

Air pollution control policies and technologies have been promoted to improve fuel economy and vehicle emissions all over the world, including initiation of the Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 2015), the tightening of automotive emission standards from Euro 5/V to Euro 6/VI (European Parliament and the Council, 2012), electric and hybrid electric vehicles (Huang et al., 2019), better fuel quality and renewable fuels (Zhen and Wang, 2015) and stricter enforcement for high-emitting vehicles (Huang et al., 2018b). Among these typical measures, another important but often overlooked factor to reduce vehicle emissions and to improve fuel economy (hence reducing the negative impact to environment) is eco-driving technology. Eco-driving is a driving behavior based method and is an immediate measure to reduce vehicle emissions and fuel consumption. Although many strategies have been undertaken to improve vehicle fuel economy and roadside air quality (e.g. promoting new vehicle technologies and fuels), the implementation of eco-driving appears to be more cost effective, immediate, relatively simple and can lead to an improvement in fuel efficiency by up to 45% (Sivak and Schoettle, 2012; Xu et al., 2017).

Eco-driving technology was first introduced and discussed in the Driver Energy Conservation Awareness Training (DECAT) program by the United States Department of Energy (U.S. DOE) in 1976 (Alam and McNabola, 2014; Greene, 1986). Eco-driving technology involves a number of factors and strategies to improve the driving behavior hence reducing vehicle emissions and fuel consumption (Huang et al., 2018a; Lee and Son, 2011; Xu et al., 2017). Zhou et al. (2016) identified six groups of eco-driving factors that affected the fuel consumption of a vehicle, including travel-related, weather-related, vehicle-related, roadway-related, traffic-related and driver-related factors. Vahidi and Sciarretta (2018) reported that the connectivity to other vehicles and infrastructure allows better anticipation of upcoming events, such as real-time traffic and signal status information. This can avoid unnecessary acceleration/deceleration and reduce the number of stop and go driving. The results showed that connected and automated vehicles could increase energy efficiency and lead to additional energy savings for neighboring vehicles. Amini et al. (2021) presented the benefits of eco-driving strategies of connected and automated vehicles. The results showed that speed profile optimized by the eco-driving strategy would provide 14.5% average fuel saving for driving on a hybrid electric vehicle. Gao et al. (2019) investigated the sensitivities of fuel economy and exhaust emissions to eco-driving factors using simulation method. The results showed that higher velocity and lower road grade were recommended for eco-driving. The emissions of gaseous nitrogen oxides (NO_x) and soot particles were positively correlated with fuel consumption rate, which was dominated by vehicle acceleration whose effect was aggravated by road grade (Gao et al., 2020). Sivak and Schoettle (2012) defined eco-driving as driver decisions that improved vehicle fuel economy, including strategic decisions (vehicle selection and maintenance), tactical decisions (route planning and weight) and operational decisions (driver behavior). Of those factors identified, changing driving behavior is the most common, useful and effective eco-driving skill that every driver can implement in practice every day (Alam and McNabola, 2014; Huang et al., 2018a). The methods used to positively change driving behavior include eco-driving training programs, in-vehicle eco-driving feedback devices, regulations, incentives and social marketing. Eco-driving training programs are widely used for changing the driver's inefficient driving behaviors. It can achieve immediate and obvious fuel savings, while the main limitation is that the effect is heterogeneous between individuals and can attenuate over time (Andrieu and Pierre, 2012; Strömberg and Karlsson, 2013). On the other hand, in-vehicle eco-driving devices are an important complement to the training programs.

As reviewed above, existing studies on driving behavior only concerned on fuel consumption or specific emissions. In addition, previous studies usually used less accurate methods in the measurements, such as OBD data and simulations. Therefore, the aim of this study is to achieve a thorough understanding of eco-driving technology applied under real driving. To realize this goal, an on-board green-safety device was installed on a diesel light goods vehicle (LGV) to provide real-time feedback to the driver. Real-time warnings were provided to alert the driver so as to improve driving behavior, such as excessive speed, hard acceleration and braking (Alzaman, 2016; Gonder et al., 2012; Vaezipour et al., 2015). A portable emissions measurement system (PEMS) was installed on a diesel vehicle to measure real-driving emissions (RDE), including both gaseous and particulate emissions. In addition, the driving parameters (i.e. vehicle speed and acceleration) and environmental parameters (i.e. ambient temperature, humidity and pressure) were also recorded by an OBD logger. Experimental data was used to evaluate the relationship between driving behavior and fuel consumption for both experienced and inexperienced drivers. The fuel economy and emissions data of diesel LGV were analyzed using the Vehicle Specific Power (VSP) model (Boroujeni and Frey, 2014; Jiménez-Palacios, 1999; Zhang et al., 2014). The current study provides a thorough evaluation of green-safety device effect and supports the development of eco-driving technology in Hong Kong.

2. Experimental setup and analytical methods

To investigate eco-driving technology for reducing emissions and fuel consumption of diesel commercial vehicles in Hong Kong, a Euro 5 diesel 3.3 tonnes LGV (Toyota HiAce) with an on-board green-safety device (Green Safety Advanced Driver Assistant System) was selected to conduct experiments in this study. The device consisted of a driver assistance system, a movement detection sensor, a video camera and a data collection box. Artificial intelligence image processing was used to detect the distance from the object precisely and provides instantaneous auditory warning to the driver when the vehicle acceleration, deceleration and turning speed exceed the safety limit. A total number of 30 drivers were recruited to perform on-road emission tests, including 15 experienced and 15 inexperienced drivers. The on-road emissions experiments were conducted in stage 1 without the green-safety device activated and stage 2 with the green-safety device activated. The hypothesis is that the activation of the green-safety device in stage 2 will positively influence fuel consumption and emission relative to tests in stage 1 without the green-safety activated. Gaseous and particulate emissions measurements were conducted in a real-world driving route by using a PEMS, which integrates an AVL M.O.V.E Gas PEMS 493 and AVL M.O.V.E PM PEMS 494. It was installed on the test vehicle to obtain RDE data, driving parameters and environmental parameters.

2.1 Tested vehicle and driving route

The Toyota HiAce LGV was chosen because it is the dominant diesel vehicle type in Hong Kong. In December 2020, the total number of registered diesel vehicles in Hong Kong increased by 12.3% to around 150,000 vehicles within ten years, including private cars, buses, light buses, LGVs, medium goods vehicles, heavy goods vehicles and special purpose vehicles. In 2020, diesel LGVs account for 50.4% of the total registered diesel vehicles in Hong Kong (Hong Kong Transport Department, 2020). Thus, a diesel LGV representative of the Hong Kong market was selected to perform the on-road emissions measurement. The 3.3 tonnes LGV equips an in-line four cylinder, 3.0 L displacement, turbocharged diesel engine with a combined diesel particulate filter (DPF), exhaust gas recirculation (EGR) and diesel oxidation catalyst (DOC) after treatment system. The installed DPF is a ceramic filter consisting of honeycomb-shaped openings that trap the soot onto the channel walls and prevent the particulate matter from exiting out the tail pipe. The honeycomb substrate is coated with a platinum group metal catalyst and packaged in a stainless steel container. EGR recirculates a controllable proportion of the engine exhaust gas which is mixed with the intake air to reduce NO_x emissions. DOC is a modern catalytic converter consisting of a monolith honeycomb substrate coated with a platinum group metal catalyst and packaged in a stainless steel container. A DOC was used to oxidize CO and HC into CO_2 and H_2O. Furthermore, the DOC was equipped in front of the DPF in the after treatment system. The vehicle was type approved to the Euro 5 standard and was registered in January 2014. It has an automatic four-speed transmission and the mileage was 53,050 km at the beginning of the test. A RDE test route that is representative of daily driving in Hong Kong has been designed, as shown in Figure 1. The testing route has a total distance of 19 kilometers, including 5 kilometers of urban driving, 6 kilometers of rural driving and 8 kilometers of highway driving conditions. One RDE trip took between 25 and 30 minutes to complete. The characteristics of the testing route are described in Table 1. For the environmental conditions during RDE testing, the range of temperature and humidity was between 27.7°C to 29.1°C and 63.2% to 63.9% respectively. The testing days were mainly sunny. It can be noted that the weather conditions were similar in the experiments. In addition, the air-conditioning system was turned on during the experiments to minimize variation of energy consumption between both monitoring stages (Wang et al., 2020).

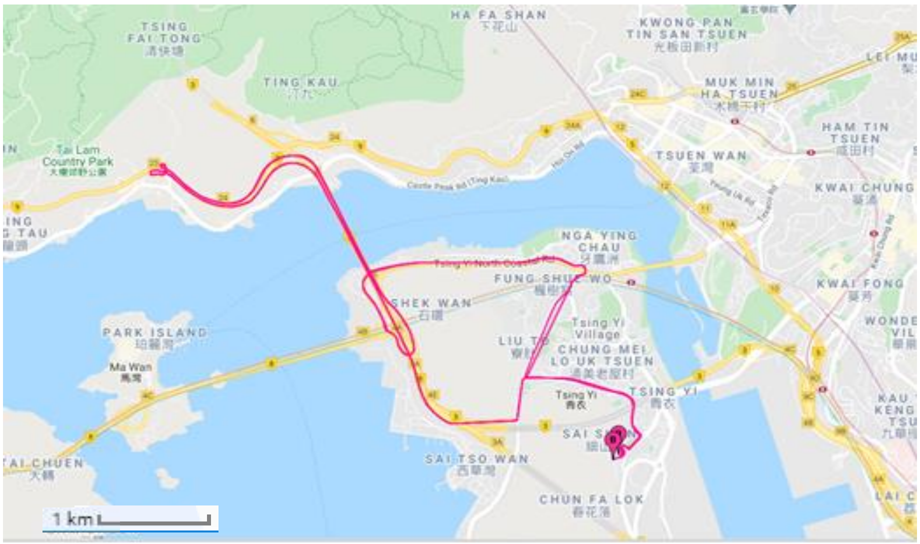


Figure 1: PEMS test routes for on-road data collection.

Table 1: Characteristics of PEMS testing routes.

Road type	Lanes (single direction)	Speed limit (km/h)	Traffic conditions
Urban road	1-2	50	High traffic volume; Traffic lights; Roundabouts; Pedestrian crossings.
Rural road	2-3	70	Moderate traffic volume; Traffic lights; Roundabouts.
Highway	3-4	80	Moderate traffic volume; No traffic light; No pedestrian crossings.

2.2 Test drivers

In this study, a total number of 30 drivers were recruited to conduct the on-road emission experiments, including 15 experienced and 15 inexperienced drivers. As shown in Table 2, the 15 experienced drivers recruited were full time drivers and they had at least 15 years of driving experience, with an age range of 40-72 years old. For the 15 inexperienced drivers, they had 3-5 years of driving experience and were aged between 21-40 years old. The average age of all inexperienced drivers is younger than the experienced drivers. In addition, all drivers recruited to perform on-road emission tests were male to minimize bias attributable to sample heterogeneity. The on-road emission test experiments were conducted in two stages. In the first stage of experiments, the driver was requested to drive along the route normally that follow his own driving style. In the second stage of experiments, an on-board green-safety device was activated to provide the driver with information and guidance on how to improve their driving behavior. In the experiments, each driver is responsible for four trips over the same route. One set of experiments (first stage and second stage) were conducted during 11:00 a.m. to 01:00 p.m. and the second set were repeated during 02:00 p.m. to 04:00 p.m. on the same day, to avoid peak hours and maintain relatively low traffic density which allowed the driver to drive according to their own driving style. The details of on-road emission test experiments are show in Table 3.

Table 2: Details of experienced and inexperienced drivers recruited in the on-road emission tests.

	Gender	Age	Driving experience	Driving Offense points [1]
Driver 1	Male	60-70	More than 25 years	0
Driver 2	Male	>70	More than 25 years	5 - 10 points
Driver 3	Male	60-70	More than 25 years	5 - 10 points
Driver 4	Male	18-30	Less than 5 years	5 - 10 points
Driver 5	Male	30-40	Less than 5 years	0
Driver 6	Male	50-60	More than 25 years	0
Driver 7	Male	>70	More than 25 years	0
Driver 8	Male	30-40	Less than 5 years	0
Driver 9	Male	18-30	Less than 5 years	5 - 10 points
Driver 10	Male	30-40	Less than 5 years	0
Driver 11	Male	30-40	Less than 5 years	0
Driver 12	Male	40-50	15 - 25 years	0
Driver 13	Male	40-50	More than 25 years	0
Driver 14	Male	30-40	Less than 5 years	0
Driver 15	Male	30-40	Less than 5 years	0
Driver 16	Male	30-40	Less than 5 years	5 - 10 points
Driver 17	Male	30-40	Less than 5 years	0
Driver 18	Male	50-60	More than 25 years	0
Driver 19	Male	30-40	Less than 5 years	0
Driver 20	Male	60-70	More than 25 years	0
Driver 21	Male	30-40	Less than 5 years	0
Driver 22	Male	>70	More than 25 years	0
Driver 23	Male	50-60	More than 25 years	0
Driver 24	Male	30-40	Less than 5 years	5 - 10 points
Driver 25	Male	30-40	Less than 5 years	More than 10 points
Driver 26	Male	>70	More than 25 years	0

Driver 27	Male	30-40	Less than 5 years	0
Driver 28	Male	50-60	More than 25 years	0
Driver 29	Male	60-70	More than 25 years	0
Driver 30	Male	50-60	More than 25 years	0

([1] In Hong Kong, if the driver has incurred 15 or more points in respect of offences committed within a period of 2 years, the driver can be disqualified by a Court from holding or obtaining a driving license (Hong Kong Transport Department, 25 August 1984).)

Table 3: The driving pattern of on-road emission test experiments.

Test No.	Testing period	Status of on-board green-safety device
1	11:00 a.m. – 12:00 p.m.	un-activated
2	12:00 p.m. – 01:00 p.m.	Activated
3	02:00 p.m. – 03:00 p.m.	un-activated
4	03:00 p.m. – 04:00 p.m.	Activated

2.3 Portable emissions measurement system

In the on-road emission test experiments, a PEMS was installed on the test vehicle to obtain RDE data, driving parameters and environmental parameters. PEMS integrates advanced gas analysers, a PM measurement device, an exhaust flow meter, a weather station, a wheel speed sensor and a global positioning system (GPS). The on-road emissions experiments were conducted using an AVL M.O.V.E Gas PEMS 493 and AVL M.O.V.E PM PEMS 494. The gas PEMS uses a non-dispersive infra-red (NDIR) analyzer for CO and CO_2 measurement, a non-dispersive ultra-violet (NDUV) analyzer to measure NO and NO_2 separately and simultaneously, a heated flame ionization detector (FID) to analyze total hydrocarbons (THC) and an electrochemical sensor to measure oxygen (O_2). The PM PEMS is a portable soot measurement device by using the micro soot sensor and a particle filter for gravimetric PM measurement. The PM emissions are calculated by using the mass of the particle filter, the time-resolved soot signal and the exhaust mass flow as inputs. The particulate filters were conditioned in an open dish for three hours before the test in an air-conditioned chamber. After this conditioning, the particulate filters weighed and stored until they were used. After the on-road emission test experiments, the particulate filters were taken to the weighing chamber and conditioned for three hours and then weighed. The particulate filters were weighed by the Sartorius air quality microbalance. The microbalance is designed for weighing 47 mm filters specified in the EPA regulation. It is based on gravimetric analysis and provided a resolution from one microgram to six grams.

To assure the accuracy of the test results, the AVL gas PEMS was set to zero with pure nitrogen before each test and was calibrated with standard gases (US EPA Bar 97) before and after the tests on each day. Zero calibration was performed so that the baseline concentration could be established and prevent a drift in measurements. An audit calibration as carried out before and after the road tests by comparing the measured concentrations of mixed gases with the values stated on the gas bottles. A linearity check of the instruments took place approximately once every five weeks to ensure instrument precision. In addition, a 2.5-inch EFM-2 was used to measure instantaneous exhaust mass flow rates and temperature from the test vehicle. A weather station was mounted on the roof of the test vehicle to measure ambient temperature, relative humidity and atmospheric pressure during on-road testing. As shown in Figure 2, the emission gas sample line and exhaust flow measurement system are directly connected to the exhaust pipe. The exhaust emissions flow rate and temperature can be monitored in real-time together with ambient meteorological parameters. A Peiseler MT pulse transducer was employed to measure the wheel speed during the on-road emissions measurement. In addition, a Garmin International Inc. GPS receiver was mounted on the roof of the test vehicle to track the route, elevation and ground speed of the LGV under test. The PEMS was installed in the trunk of the test vehicle and the sampling line was connected to the tailpipe to measure gaseous and PM emissions. The sampling line was heated to a temperature of 190 °C in order to avoid condensation of THC. A Honda EU 30is generator and a battery pack consisting of three lead acid batteries with a capacity of 150 Ah were mounted inside the test vehicle to supply power for the instruments. In the present study, all the data were logged at a sample rate of 10 Hz and sent to the internal storage of a notebook computer using an Ethernet cable. Furthermore, engine control unit (ECU) data were recorded via the OBD system. The data included vehicle speed, engine speed, engine coolant temperature and throttle pedal position.

Figure 2: Diesel 3.3 tonnes LGV connected with the emission gas sample line and exhaust flow measurement system.

2.4 On-board green-safety device

An in-vehicle device is required to provide the driver feedback instantaneously and monitor driving behavior under real traffic conditions. Eco-driving devices can meet the above requirements (Strömberg et al., 2015; Young et al., 2011). They monitor driving performance including speed, acceleration, deceleration, gear shifting, idling time, fuel consumption, road information and traffic conditions. The feedback may be given by a dashboard display, smartphone applications, a GPS navigation system and dedicated aftermarket feedback systems (Jamson et al., 2015). In this study, the on-board green-safety device installed on the test vehicle was used to record the numbers of brake, tailgating and speeding warnings during stage 2 of the on-road emissions experiments. The device is not activated in the first stage of experiments. Figure 3 shows the main components and working principle of the green-safety device used in the present study. As shown in Figure 3, the green-safety device was designed for safety and consisted of a driver assistance system, a movement detection sensor, a video camera and a data collection box. The driver assistance system uses artificial intelligence image processing to identify vehicles, pedestrian and objects with analyses of on-road conditions. In addition, dual cameras detect the distance from the object precisely and the driver assistance system can instantly alert drivers to prevent collisions. The data collection box was used to collect and upload data to the server. Drivers and fleet managers can download and analyze relevant driving performance and driving alert videos via online platforms or mobile phones in real-time. Furthermore, the driver assistance system also provides instantaneous auditory warnings to the driver when the vehicle acceleration, deceleration and turning speed exceeds the safety limit. The warning will not disappear until the drivers make the corresponding changes or the potential hazard disappears. As show in Table 4, those warnings include forward collision warning, lane departure warning, headway monitor warning, speed limit warning and aggressive acceleration, deceleration and turning warning.

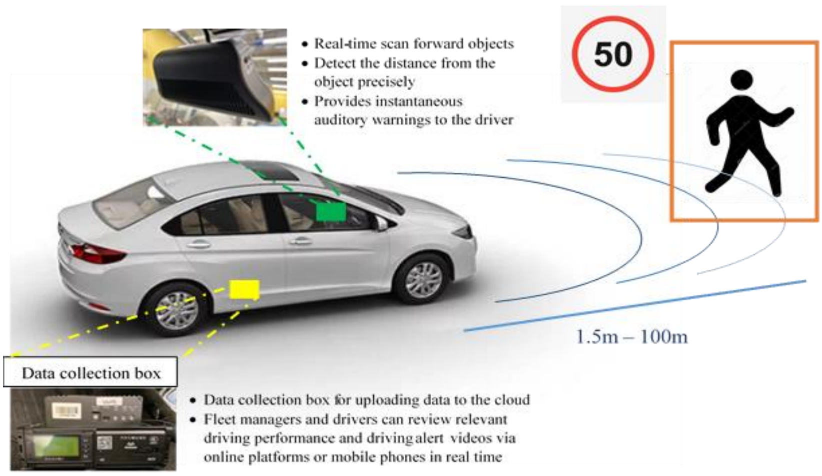


Figure 3: Working principle of on-board green-safety device.

Table 4: Types of warnings provided by the on-board green safety device.

Types of warnings	Alert mechanism
Forward collision warning	When a possible collision will occur with the vehicle

	and other general objects in front.
Lane departure warning	When the vehicle departs from the driving lane.
Headway monitor warning,	When the time gap from the vehicle ahead is less than or equal to 1.0 second.
Aggressive acceleration warning	When the vehicle speed accelerates higher than 10 km/h in one second.
Aggressive deceleration warning	When the vehicle speed decelerates higher than 12 km/h in one second.
Aggressive turning warning	When the turning acceleration of the vehicle is higher than 3.0 m/s^2.

2.5 Data analysis using VSP methodology

VSP is defined as the instantaneous power output of the engine per unit mass of the vehicle (Jiménez-Palacios, 1999). In recent years, emission models have been widely applied to quantify emission rates and fuel consumption over VSP (Jiménez-Palacios, 1999). VSP represents vehicle operating conditions and is calculated with the information of vehicle speed, vehicle acceleration and road grade which are highly correlated with the fuel consumption and gaseous emissions (Song and Yu, 2011; USEPA, 2002). In this study, the VSP methodology was adopted to fulfill the objectives of the present study by calculating the percentage of time spent in different driving patterns, including deceleration, idling, acceleration and hard acceleration. In addition, calculating VSP involves aerodynamic drag and tire rolling resistance of the vehicle. Thus, the formulae were developed for calculating the VSP values of different types of vehicles. Road grade is calculated with the road surface altitude recorded by the GPS. Based on the second-by-second recorded data, the distance traveled along the route is divided into segments of 80 to 100 m. The elevation for each run along the segment is calculated. Thus, the average road grade is calculated for each segment. In this study, equation (1) was applied for calculating the VSP_{LGV} (W/kg) (Jiménez-Palacios, 1999; Zhai et al., 2008).

$$VSP_{LGV} = v \cdot (1.1 \cdot a + g \cdot \sin(\emptyset) \cdot + \varphi_{LGV}) + \delta_{LGV} \cdot v^3 \qquad (1)$$

where v (m/s) is the instantaneous vehicle velocity, a (m^2/s) is the instantaneous vehicle acceleration, g (m/s^2) is the acceleration due to gravity, $\emptyset$ is the road grade, φ is the coefficient of rolling resistance term (0.132 for LGV) (Jiménez-Palacios, 1999; Zhai et al., 2008) and δ_{LGV} is the coefficient of drag term (3.02×10^{-4} for LGVs) (Jiménez-Palacios, 1999; Zhai et al., 2008).

Based on the recorded data, VSP values were calculated and grouped into 14 modes and four driving conditions (Rolim et al., 2014). The negative values of VSP in modes 1 and 2 are grouped into one, as they represent the vehicle's deceleration. Idling is represented in mode 3, including the vehicle's acceleration when it started to move. VSP modes 4-7 and 8-14 are grouped as mild driving and heavy acceleration, respectively. Having a larger number of VSP modes represents the higher power demand of the engine.

3. Results and discussion

Results will be presented and discussed in three sub-sections. Sub-section 3.1 will report the effect of the on-board green-safety device on driving behavior. In 3.2 the driving time distribution for different VSP modes will be analysed. The effect of driving behavior on fuel consumption and exhaust gas emissions will be reported in 3.3.

3.1 Effect of on-board green-safety device on driving performance

To understand the effect of on-board green-safety device on driving performance, driver behavior will be analysed by comparing the driving parameters with and without activation of the green-safety device. Table 5 shows the driving parameters of 30 experienced and inexperienced drivers on a 3.3 tonnes diesel LGV. To understand the effect of the green-safety device on driving performance, the percentages of individual driving parameter will be presented and analysed.

Table 5: Driving parameters of tested 30 drivers on a 3.3 tonnes diesel LGV.

		Experienced driver		Inexperienced driver	
		Stage 1	Stage 2	Stage 1	Stage 2
Vehicle speed (km/h)	Average	44.6 (39 - 54)	41.4 (35 - 46)	46.5 (40 - 53)	42.1 (25 - 48)
	Max	95.9	74.5	85.0	77.4
	Stdev	23.5	20.8	25.6	21.9
Engine speed (rpm)	Average	1,378	1,314	1,432	1,324
	Max	3,789	3,027	3,748	3,333
	Stdev	497	412	542	419
Acceleration (m/s^2)	Max	2.9	1.8	2.2	1.3
	Stdev	0.1	0.1	0.1	0.1
Accelerator pedal position (%)	Average	22.8	21.6	23.4	21.6
	Max	48.0	39.6	53.3	38.3
	Stdev	7.5	5.6	8.4	5.7
Travelling time (minutes)		25	27	24	27

As shown in Table 5, the average vehicle speed of the experienced and inexperienced driver was reduced by 8% and 10% from the first to the second stage respectively. The maximum vehicle speed of the experienced and inexperienced driver was reduced by 22% and 9% from the first to the second stage respectively. The average and maximum engine speed of the experienced driver was reduced by 5% and 20% while that the inexperienced driver was reduced by 8% and 11% from the first to the second stage respectively. In addition, the average accelerator pedal position of the experienced and inexperienced driver was reduced by 5% and 8% from the first to the second stage respectively. The maximum accelerator pedal position of the experienced driver was reduced by 17% while that the inexperienced driver was reduced by 28% from the first to the second stage respectively. From the overall statistics of the driving parameters of 30 drivers, the percentage reduction of average vehicle speed, engine speed and Accelerator pedal position of the inexperienced driver were higher than those of the experienced driver after activation of on-board green-safety device. In contrast, the percentage reduction of maximum vehicle speed and engine speed of the experienced driver were higher than the inexperienced driver from the first stage to the second stage of experiments.

According to the driving performance of 30 drivers, the maximum vehicle speed and engine speed of the experienced drivers were higher than the inexperienced drivers. This can be explained as the rich driving experience for the experienced drivers. Therefore, experienced drivers chose a higher speed on highway. In addition, the percentage reduction of average vehicle speed, engine speed and of accelerator pedal position of the inexperienced driver were higher than those of the experienced driver after activation of the on-board green-safety device. This was mainly due to the long-term formed habits of experienced drivers are harder or less willing to be changed to accept the assistance of the on-board green-safety device, whereas inexperienced drivers are likely to be more receptive to change and improve their driving behaviors.

From a safety point of view, Table 6 compares the total numbers of warning parameters between both monitoring stages. As shown in Table 6, the number of braking events for the experienced and inexperienced driver was greatly reduced by 62% and 72% from the first to the second stage respectively. The number of forward collision, lane departure and headway monitor warnings were reduced more than 50% after activation of on-board green-safety device. For the numbers of aggressive acceleration, aggressive deceleration and aggressive turning warnings, they were greatly reduced by 48%, 100% and 72% for the experienced drivers and 74%, 78% and 60% for the inexperienced driver from the first to the second stage. This indicated a strong impact of on-board green-safety device for both experienced and inexperienced drivers. The number of forward collision, lane departure and headway monitor warning were greatly reduced indicating the green-safety device was effective to improve drivers' understanding of road safety and the reduction of aggressive acceleration, aggressive deceleration and aggressive turning warnings indicating that the green-safety device was also effective to help both experienced and inexperienced drivers to avoid aggressive driving and enhance understanding for eco-driving. In addition, the total numbers of warnings for the experienced and inexperienced driver's group were greatly reduced by 71% and 72% from the first stage to the second stage respectively. This provided an indication that following the instructions from the safety device led to a smoother driving speed than that without the device and yielded a more appropriate vehicle speed when driving.

Table 6: Changes on warning parameters between both monitoring stages.

	Experienced driver		Inexperienced driver	
	Stage 1	Stage 2	Stage 1	Stage 2
Braking number (times)	95	36	177	49
Forward collision warning (times)	10	2	24	5
Lane departure warning (times)	34	15	102	48
Headway monitor warning (times)	109	16	185	28
Aggressive acceleration warning (times)	56	29	57	15
Aggressive deceleration warning (times)	2	0	18	4
Aggressive turning warning (times)	43	12	62	25
Total number of warning (times)	254	74	448	125

3.2 Distribution of travelling time over different VSP mode

Travel time is quite often critical which can affect vehicle emissions and fuel consumption. Shorter travel times are preferred or required. However, when it comes to real-world conditions, travel time can be affected by driving performance including time spent on idling, acceleration and deceleration. Thus, the distributions of VSP modes were calculated to compare the percentage of time spent in different driving patterns, including deceleration, idling, acceleration and strong acceleration. As shown in Table 7, the experiments were conducted on 30 days, including 120 trips with a total of 2,244 km being travelled which was evenly distributed over two stages of experiments both with and without the on-board green-safety device.

Table 7: Driving data between both monitored stages.

	Stage 1	Stage 2
Total travelling time (hours)	24.8	27.3
Total travelling distance (km)	1,122.8	1,121.4
Number of trips	60	60
Number of days	15	15

Figure 3 show the average time spent on different VSP modes without and with the on-board green-safety device for both experienced and inexperienced drivers. As shown in Figure 3, the percentage of time spent in modes 1 and 2 of experienced group's driver is reduced from 50.4%% to 49.6% from stage 1 to 2. This can be explained as the braking time is reduced by the driver. In contrast, the percentage of time spent in modes 1 and 2 of inexperienced group's driver is increased by 0.8% from stage 1 to 2. These findings may relate to the rich driving experience in experienced driver's group, experienced drivers chose a steadier speed than inexperienced drivers (Wu et al., 2018). Furthermore, the on-board green-safety device improved experienced drivers' ability to maintain a more consistent driving behavior to reduce the number of decelerations. There is no significant difference in time spent in two stages of experiments for in both VSP 1-2 and VSP mode 3.

In the medium VSP modes 4 to 7, the percentage of time spent by experienced and inexperienced group's driver is increased by 3.7% and 3.1% from stage 1 to 2 respectively. The increase of average distribution from stage 1 to 2 in modes 4 to 7 can be related to the lower and steady speed of the vehicle as controlled by the on-board green-safety device. It can also be explained that the driver controlled the speed of the vehicle more appropriately. These results can be also supported by the driving parameters for both experienced and inexperienced drivers. After activation of on-board green-safety device, the average vehicle speed and engine speed of experienced driver was lower than inexperienced driver (Stahl et al., 2016).

In the higher VSP modes 8 to 14, the percentage of time spent for experienced and inexperienced driver is reduced by 3.0% and 4.0% from stage 1 to stage 2 respectively. This was due to the reduced time spent on speeding and strong acceleration in the heavy acceleration driving modes in stage 2. The on-board green-safety device was effective to improve drivers' ability to perform eco-driving and reduce the time spent on excess speeding and heavy acceleration. These results can be also supported by the driving parameters for both experienced and inexperienced drivers. The percentage reduction of average vehicle speed and the number of aggressive acceleration warnings of inexperienced drivers was higher than that for experienced drivers.

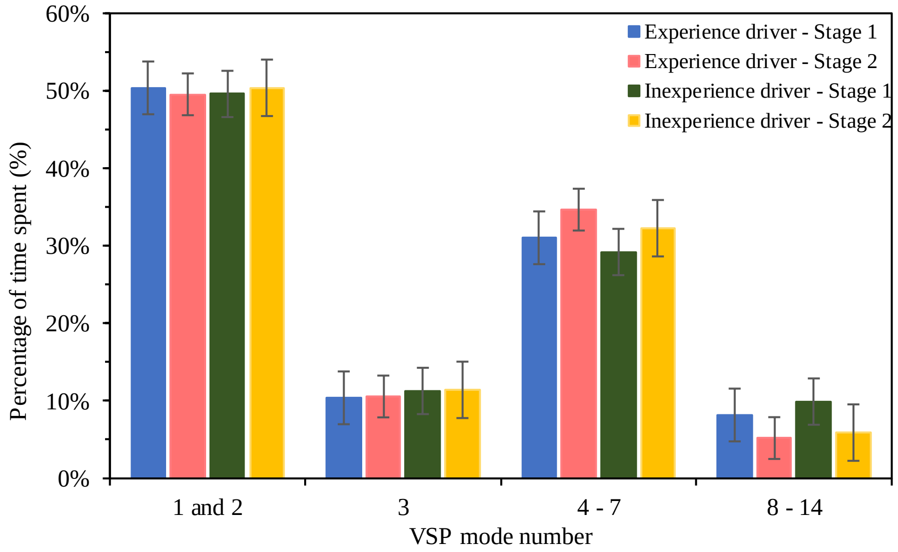


Figure 4: Comparison of average time distribution over VSP modes of experienced driver and inexperienced driver without (stage 1) and with (stage 2) the on-board green-safety device. Error bars are the standard deviation.

3.3 Effect of on-board green-safety device on fuel consumption and exhaust gas emissions

To assess the effect of driving behavior on fuel consumption and gaseous emissions of LGV under real driving conditions, the exhaust gas emissions and fuel economy in each of the

VSP mode were calculated. Table 8 shows the overall fuel consumption and emission rates of the tested diesel 3.3 tonnes LGV for both experienced and inexperienced driver with and without the activation of green-safety device. As shown in Table 8, THC and CO_2 emission rates of the experienced driver were reduced by 3% and 5% respectively from stage 1 to stage 2. The results can be explained as the experienced driver drove the LGV more carefully with the reduction of average vehicle speed and engine speed. In addition, with the reduction of the maximum acceleration and engine speed, the NO emission rates of the experienced driver were greatly reduced by 56% from 0.36 g/km without the activation of device to 0.16 g/km with device, and the NO_2 reduced by 39% from 0.49 g/km to 0.30g/km, demonstrating a strong impact of the on-board green-safety device on NO and NO_2 emissions of experienced driver. However, the CO emission rates of the experienced driver was increased from 0.009 g/km to 0.014 g/km. This result is consistent with the previous study that the driving behavior did not show distinct difference in the CO emissions (Gallus et al., 2017). With the lower acceleration and average vehicle speed of the test vehicle, the soot mass emission rates and fuel consumption were reduced by 35% and 5% from the first stage to second stage of experiment.

For the group of inexperienced drivers, the THC and CO_2 emission rates were reduced by 5% and 6% respectively from stage 1 to stage 2. This results can be explained as the percentage of time spent on lower VSP mode is increased and the driver tends to spend more time on steady speed and acceleration. As shown in Table 8, the CO_2 emissions were reduced from 286.0 g/km without the activation of device to 268.9 g/km with device. Furthermore, the emission rates of NO and NO_2 were greatly reduced by 65% from 0.44 to 0.15 g/s and 50% from 0.55 to 0.27 g/s respectively in the second stage of the on-road emissions experiment, demonstrating a strong impact of the driving behavior on NO and NO_2 emissions of inexperienced driver. The results can be explained as the inexperienced driver drove the LGV more carefully with the reduction of time spent on excessive speeding, strong acceleration and deceleration. In addition, with the lower acceleration and vehicle speed of the test vehicle, the soot mass emission rates and fuel consumption were reduced by 19% and 6% respectively from the first stage to second stage of experiment.

Table 8: Averaged exhaust gas emission rates and fuel consumption of diesel 3.3 tonnes LGV.

	Experienced driver			Inexperienced driver		
	Stage 1	Stage 2	Percentage of change	Stage 1	Stage 2	Percentage of change
THC (g/km)	0.0082	0.0079	-3%	0.0081	0.0077	-5%
CO (g/km)	0.009	0.014	49%	0.016	0.017	4%
CO_2 (g/km)	280.7	266.7	-5%	286.0	268.9	-6%
NO (g/km)	0.36	0.16	-56%	0.44	0.15	-65%
NO_2 (g/km)	0.49	0.30	-39%	0.55	0.27	-50%
Soot mass (g/km)	0.019	0.013	-35%	0.033	0.027	-19%
Fuel economy (l/100km)	10.6	10.1	-5%	10.8	10.2	-6%

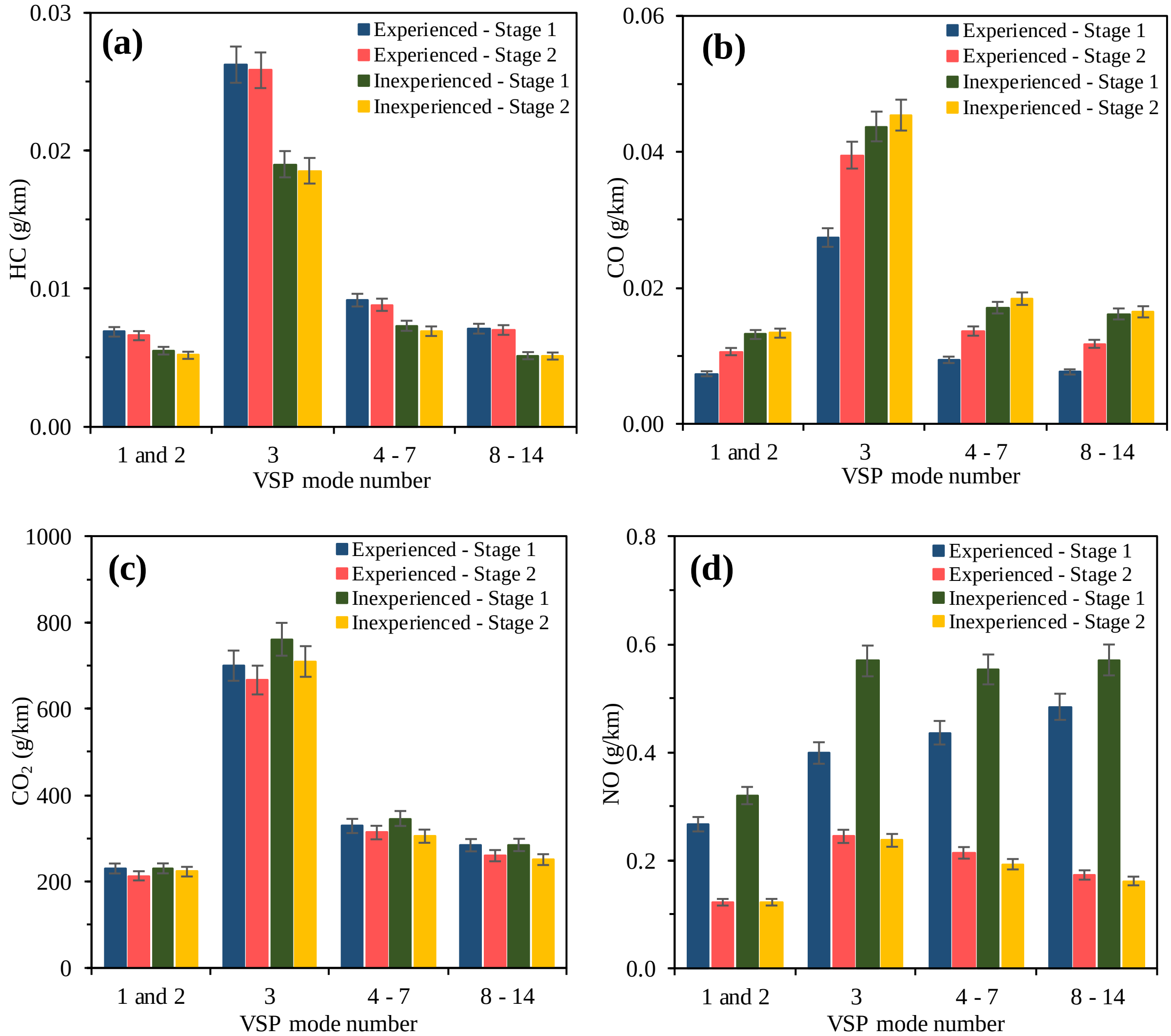
To understand the averaged results shown in Table 8, distributions of the emissions and fuel consumption over the VSP mode will be analysed. Figure 4 shows the distribution of emissions over the VSP modes. As shown in Figure 4, after activation of the on-board green-safety device for experienced driver, the emission rates of THC in VSP modes 1 and 2 was reduced by 4%, CO_2 by 7% NO by 54% and NO_2 by 39%. The results can be explained as the experienced driver reduce the number of braking events and increased the coasting distance. However, the CO emission rates was increased after activation of the on-board green-safety device. It is reasonable to assume that CO emissions were not corresponding to the driving behavior when the LGV was decelerating in VSP modes 1 and 2. Furthermore, the soot mass emission rates were greatly reduced by 20% from the first stage to second stage of experiment.

For the emission rates of inexperienced driver in VSP modes 1 and 2, THC, CO_2, NO and NO_2 emissions were reduced by 6%, 3%, 62% and 46% respectively from stage 1 to stage 2. In addition, the CO emission rates was weakly affected by the driving behavior and remains unchanged in both monitoring stages. The soot mass emission rates were greatly reduced by 28% from the first stage to second stage of experiment. As shown in Figure 5, the fuel consumption of experienced and inexperienced driver in VSP modes 1 and 2 were reduced by 7% and 3% respectively from stage 1 to stage 2. This indicates a strong impact of the driving style such as reduction of braking events and an increase of the coasting distance on fuel economy as shown in the experimental results.

For the emission rates of experienced driver in VSP mode 3 which is the idling condition, THC, CO_2, NO and NO_2 emission rates were reduced by 2%, 5%, 39% and 19% respectively from stage 1 to stage 2. However, the emission rates of CO were increased after activation of the on-board green-safety device. For the emission rates of inexperienced driver in VSP mode 3, THC, CO_2, NO and NO_2 emission rates were reduced by 2%, 7%, 58% and 33% respectively from stage 1 to stage 2. Furthermore, the soot mass emission rates of experienced and inexperienced driver were reduced by 14% and 16% respectively from the first stage to second stage of experiment. As shown in Figure 5, the fuel consumption of experienced in VSP modes 3 was reduced by 5% and inexperienced driver were reduced by 7% from stage 1 to stage 2.

For the emission rates for experienced driver in the medium VSP modes 4 to 7 (which is normal driving condition) (Rolim et al., 2014), the emission rates of THC, CO_2, NO and NO_2 were reduced 4%, 5%, 51% and 37% respectively from stage 1 to stage 2. With the increase of the percentage of time spent in VSP modes 4 to 7, the THC emissions were reduced from 0.0092 g/km without the activation of on-board green-safety device to 0.0088 g/km with the on-board green-safety device. The CO_2 emissions were reduced from 329 g/km to 314 g/km, the NO from 0.44 g/km to 0.21 g/km and the NO_2 from 0.57 g/km to 0.36 g/km. The results indicated that experienced driver controls the speed of the LGV more appropriately and the time spent on steady driving and acceleration was increased in the second stage of experiment. Resulting in the reduction of CO_2, the fuel consumption of experienced driver was reduced by 5% from 12.5 l/100km in stage 1 to 11.9 l/100km in stage 2. In addition, the soot mass emission rates of experienced driver were greatly reduced by 57% from stage 1 to stage 2. This provided indication that the fuel economy and soot mass can be influenced by the travelling speed of the vehicle. For the emission rates of inexperienced driver, the THC emissions were reduced by 5% from 0.0073 g/km to 0.0069 g/km. The CO_2 emissions were reduced by 12% from 346 g/km to 305 g/km, the NO emissions were greatly reduced by 65% from 0.55 g/km to 0.19 g/km and NO_2 emissions by 52% from 0.67 g/km to 0.32 g/km. The reduction of CO_2 was mainly due to the fuel consumption which was reduced by 12% from 13.1 l/100km without the activation of device to 11.6 l/100km with the device. These results indicated that inexperienced driver controlled the speed of the LGV more appropriately so that more time was spent on driving slowly and steadily in stage 2 of the on-road experiment. Furthermore, the soot mass emission rates of inexperienced driver were reduced by 35% from stage 1 to stage 2.

In higher VSP modes 8 to 14 with heavy acceleration, the emission rates THC, CO_2, NO and NO_2 of the experienced driver were reduced by 1%, 9%, 64% and 43% respectively from stage 1 to stage 2. In the second stage of the experiment, the maximum acceleration of the experienced driver was decreased by 61% from 2.9 m/s^2 to 1.8 m/s^2. This indicates a strong impact of the driving style such as reduction of excess speeding and strong acceleration on emission rates of experienced driver as shown in the experimental results. With the lower and steady speeds of the test vehicle, the fuel consumption of experienced driver was reduced by 9% from the first stage to the second stage of experiment. In addition, the soot mass emission rates for experienced drivers were greatly reduced by 52% from stage 1 to stage 2. For the emission rates of the inexperienced driver, the emission rates THC, CO_2, NO and NO_2 of the experienced driver were reduced by 1%, 12%, 72% and 58% respectively from stage 1 to stage 2. After the activation of the on-board green-safety device, the maximum acceleration and speed of the inexperienced driver was decreased by 69% and 17% respectively. This indicates a strong impact of the driving style such as reduction of excess speeding and strong acceleration on emission rates of inexperienced driver as shown in the experimental results. With the lower and steady speeds of the test vehicle, the fuel consumption and soot mass emission rates were reduced by 12% and 6% respectively from stage 1 to stage 2.



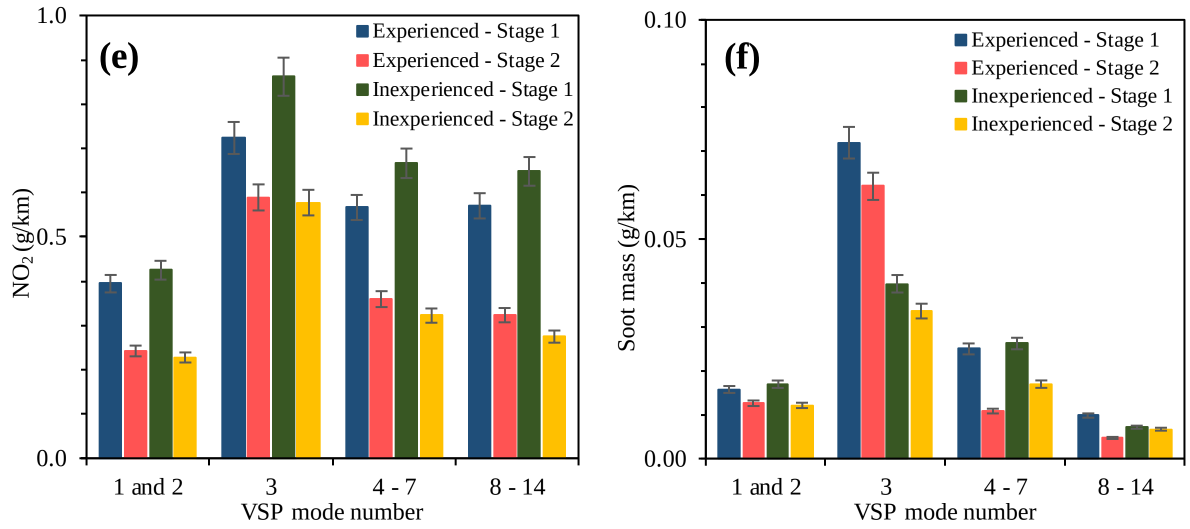


Figure 5: The THC (a), CO (b), CO_2 (c), NO (d), NO_2 (e) and soot (f) emissions of the LGV for experienced and inexperienced drivers in each group of the VSP modes in both monitoring stages

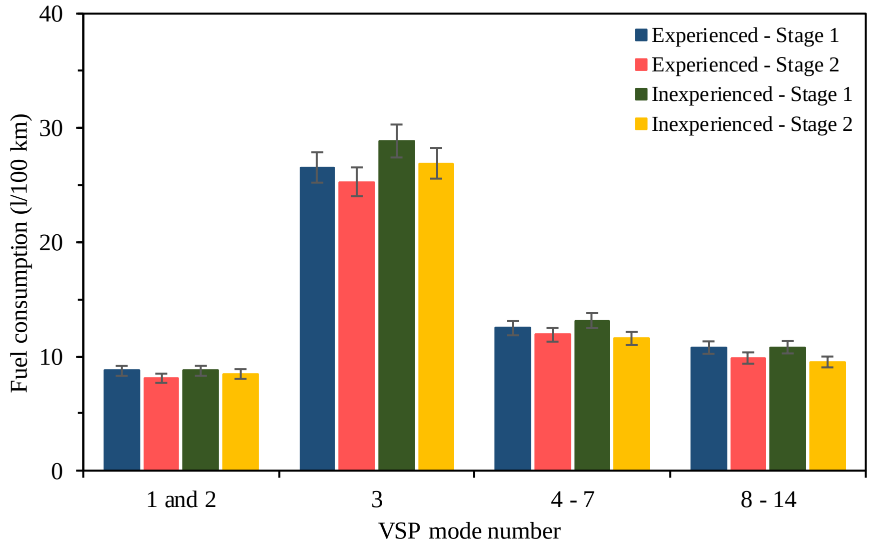


Figure 6: The fuel consumption of the LGV for experienced and inexperienced driver in each group of the VSP modes in both monitoring stages.

4. Conclusions

On-road emissions experiments have been conducted to investigate the effects of driving behavior on fuel consumption and gaseous and particulate emissions of a diesel 3.3 tonnes LGV. A PEMS was used to measure the emissions data, driving parameters and environmental parameters from a diesel LGV under real-world conditions. A representative driving route that covered urban and highway driving was designed for the experiments. The effectiveness of on-board green-safety device for both experienced and inexperienced drivers and the effect of driving behavior on fuel consumption and emissions were examined. The VSP model was applied to analyse the experimental data. The major results can be summarised as follows.

1) The on-board green-safety device improved driving behavior obviously for both experienced and inexperienced drivers. The total number of warnings for the experienced and inexperienced driver was greatly reduced by 71% and 72% respectively.

2) The maximum vehicle and engine speeds for the experienced driver (22% and 20%) were reduced more than the inexperienced driver (9% and 11%) by the green-safety device. In contrast, the average vehicle and engine speeds for the inexperienced driver (10% and 8%) were reduced more than the experienced driver (8% and 5%) after activation of on-board green-safety device.

3) The VSP results of both experienced and inexperienced drivers showed that the percentage of time spent on lower VSP mode was increased and the time spent on higher VSP mode was decreased after the green-safety device was activated. This was due to the driver's more adequate use of the engine as well as to spend more time on cruising.

4) By following the instructions from the on-board green-safety device, the driving behavior had a positive effect on fuel consumption and gaseous emissions of both experienced and inexperienced drivers. For the experienced driver, the average THC was reduced by 3%, CO_2 by 5%, NO by 56%, NO_2 by 39%, soot mass by 35% and fuel consumption by 5% with the on-board green-safety device. For the inexperienced driver, the average reduction was 5% for THC, 6% for CO_2, 65% for NO, 50% for NO_2, 19% for soot mass and 6% for fuel

consumption. The experimental results can be explained as the driving behavior improved and the time spent on excessive speeding, strong acceleration and deceleration was reduced.

5) Overall, our RDE testing results indicate that the on-board green-safety device can be deployed in vehicles not only to positively influence driving behavior but also to successfully reduce real driving fuel consumption and emissions. In order to further investigate the effects of driving behavior on fuel consumption and emissions, future research should extend to passenger cars and trucks which may show similar or different results from the change of driving behavior.

References

Alam MS, McNabola A. A critical review and assessment of Eco-Driving policy & technology: Benefits & limitations. Transport Policy 2014; 35: 42-49.

Alzaman C. Impact of optimisation on idle time's fuel consumption and CO2 emissions in urban transportation. International Journal of Business Performance and Supply Chain Modelling 2016; Vol. 8, No. 2, : 157-179.

Amini MR, Qiuhao H, Wang H, Feng Y, Kolmanovsky I, Sun J. Experimental Validation of Eco-Driving and Eco-Heating Strategies for Connected and Automated HEVs, 2021.

Andrieu C, Pierre GS. Comparing Effects of Eco-driving Training and Simple Advices on Driving Behavior. Procedia - Social and Behavioral Sciences 2012; 54: 211-220.

Boroujeni BY, Frey HC. Road grade quantification based on global positioning system data obtained from real-world vehicle fuel use and emissions measurements. Atmospheric Environment 2014; 85: 179-186.

European Parliament and the Council. amending Regulation (EC) No 715/2007 of the European Parliament and of the Council and Commission Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6). Official Journal of the European Union 2012; COMMISSION REGULATION (EU) No 459/2012.

Gallus J, Kirchner U, Vogt R, Benter T. Impact of driving style and road grade on gaseous exhaust emissions of passenger vehicles measured by a Portable Emission Measurement System (PEMS). Transportation Research Part D: Transport and Environment 2017; 52, Part A: 215-226.

Gao J, Chen H, Dave K, Chen J, Jia D. Fuel economy and exhaust emissions of a diesel vehicle under real traffic conditions. Energy Science & Engineering 2020; 8: 1781-1792.

Gao J, Chen H, Li Y, Chen J, Zhang Y, Dave K, et al. Fuel consumption and exhaust emissions of diesel vehicles in worldwide harmonized light vehicles test cycles and their sensitivities to eco-driving factors. Energy Conversion and Management 2019; 196: 605-613.

Gonder J, Earleywine M, Sparks W. Analyzing Vehicle Fuel Saving Opportunities through Intelligent Driver Feedback. SAE International Journal of Passenger Cars - Electronic and Electrical Systems 2012; 5: 450-461.

Greene DL. Driver Energy Conservation Awareness Training: Review and Recommendations. Department of Energy (United States) 1986.

HKEPD. Hong Kong Air Pollutant Emission Inventory Report. 2018; EPD/TR/1/18.

Hong Kong Transport Department. Road Traffic (Driving-offence Points) Ordinance, Chapter 375., 25 August 1984.

Hong Kong Transport Department. Table 4.4: Registration and Licensing of Vehicles by Fuel Type, 2020.

Huang Y, Ng ECY, Zhou JL, Surawski NC, Chan EFC, Hong G. Eco-driving technology for sustainable road transport: A review. Renewable and Sustainable Energy Reviews 2018a; 93: 596-609.

Huang Y, Organ B, Zhou JL, Surawski NC, Hong G, Chan EFC, et al. Emission measurement of diesel vehicles in Hong Kong through on-road remote sensing: Performance review and identification of high-emitters. Environmental Pollution 2018b; 237: 133-142.

Huang Y, Surawski NC, Organ B, Zhou JL, Tang OHH, Chan EFC. Fuel consumption and emissions performance under real driving: Comparison between hybrid and conventional vehicles. Science of The Total Environment 2019; 659: 275-282.

IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Edenhofer O, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.), editor, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2014.

Jamson AH, Hibberd DL, Merat N. Interface design considerations for an in-vehicle eco-driving assistance system. Transportation Research Part C: Emerging Technologies 2015; 58, Part D: 642-656.

Jiménez-Palacios JL. Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing. Thesis (Ph.D.)--Massachusetts Institute of Technology, Dept. of Mechanical Engineering 1999: p. 345-361.

Lee T, Son J. Relationships between Driving Style and Fuel Consumption in Highway Driving. SAE Technical Paper 2011-28-0051, 2011.

Ning Z, Wubulihairen M, Yang F. PM, NOx and butane emissions from on-road vehicle fleets in Hong Kong and their implications on emission control policy. Atmospheric Environment 2012; 61: 265-274.

Pui DYH, Chen S-C, Zuo Z. PM2.5 in China: Measurements, sources, visibility and health effects, and mitigation. Particuology 2014; 13: 1-26.

Ramlan NA, Yahya WJ, Ithnin AM, Hasannuddin AK, Norazni SA, Mazlan NA, et al. Performance and emissions of light-duty diesel vehicle fuelled with non-surfactant low grade diesel emulsion compared with a high grade diesel in Malaysia. Energy Conversion and Management 2016; 130: 192-199.

Ren W, Xue B, Geng Y, Lu C, Zhang Y, Zhang L, et al. Inter-city passenger transport in larger urban agglomeration area: emissions and health impacts. Journal of Cleaner Production 2016; 114: 412-419.

Rogner H-H, D. Zhou, R. Bradley. P. Crabbé, O. Edenhofer, B.Hare (Australia), L. Kuijpers, M. Yamaguchi. Introduction. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: [B. Metz ORD, P.R. Bosch, R. Dave, L.A. Meyer (eds)], editor, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. , 2007.

Rolim CC, Baptista PC, Duarte GO, Farias TL. Impacts of On-board Devices and Training on Light Duty Vehicle Driving Behavior. Procedia - Social and Behavioral Sciences 2014; 111: 711-720.

Sausen R. Transport impacts on atmosphere and climate. Atmospheric Environment 2010; 44: 4646-4647.

Sivak M, Schoettle B. Eco-driving: Strategic, tactical, and operational decisions of the driver that influence vehicle fuel economy. Transport Policy 2012; 22: 96-99.

Song G, Yu L. Characteristics of Low-Speed Vehicle-Specific Power Distributions on Urban Restricted-Access Roadways in Beijing. Transportation Research Record: Journal of the Transportation Research Board 2011; 2233: 90-98.

Stahl P, Donmez B, Jamieson GA. Supporting anticipation in driving through attentional and interpretational in-vehicle displays. Accid Anal Prev 2016; 91: 103-13.

Strömberg H, Karlsson ICM, Rexfelt O. Eco-driving: Drivers' understanding of the concept and implications for future interventions. Transport Policy 2015; 39: 48-54.

Strömberg HK, Karlsson ICM. Comparative effects of eco-driving initiatives aimed at urban bus drivers – Results from a field trial. Transportation Research Part D: Transport and Environment 2013; 22: 28-33.

United Nations. Paris Agreement. 2015.

USEPA. Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission System. 2002.

Vaezipour A, Rakotonirainy A, Haworth N. Reviewing In-vehicle Systems to Improve Fuel Efficiency and Road Safety. Procedia Manufacturing 2015; 3: 3192-3199.

Vahidi A, Sciarretta A. Energy saving potentials of connected and automated vehicles. Transportation Research Part C: Emerging Technologies 2018; 95: 822-843.

Wang H, Amini MR, Hu Q, Kolmanovsky I, Sun J. Eco-Cooling Control Strategy for Automotive Air-Conditioning System: Design and Experimental Validation. IEEE Transactions on Control Systems Technology 2020: 1-12.

World Health Organization. Review of evidence on health aspects of air pollution - REVIHAAP Project. 2013.

Wu Y, Zhao X, Rong J, Zhang Y. The effectiveness of eco-driving training for male professional and non-professional drivers. Transportation Research Part D: Transport and Environment 2018; 59: 121-133.

Xu Y, Li H, Liu H, Rodgers MO, Guensler RL. Eco-driving for transit: An effective strategy to conserve fuel and emissions. Applied Energy 2017; 194: 784-797.

Young MS, Birrell SA, Stanton NA. Safe driving in a green world: A review of driver performance benchmarks and technologies to support 'smart' driving. Applied Ergonomics 2011; 42: 533-539.

Zhai H, Frey HC, Rouphail NM. A Vehicle-Specific Power Approach to Speed- and Facility-Specific Emissions Estimates for Diesel Transit Buses. Environmental Science & Technology 2008; 42: 7985-7991.

Zhang S, Wu Y, Liu H, Huang R, Un P, Zhou Y, et al. Real-world fuel consumption and CO2 (carbon dioxide) emissions by driving conditions for light-duty passenger vehicles in China. Energy 2014; 69: 247-257.

Zhen X, Wang Y. An overview of methanol as an internal combustion engine fuel. Renewable and Sustainable Energy Reviews 2015; 52: 477-493.

Zhou M, Jin H, Wang W. A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing. Transportation Research Part D: Transport and Environment 2016; 49: 203-218.

Supplementary Material

Table S1: The specifications of the AVL M.O.V.E Gas PEMS 493 and PM PEMS 494.

Gas	Measurement Range	Zero Drift	Analyzer
THC	0-30,000 ppmC1	< 1.5 ppmC1/8h	FID
NO	0-5000 ppm	2 ppm/8h	NDUV
NO_2	0-2500 ppm	2 ppm/8h	NDUV
CO	0-5 vol%	20 ppm/8h	NDIR
CO_2	0-20 vol%	0.1 vol%/8h	NDIR
Dilution ratio		DR=2 to 100 (proportional)	
Filter holder		47 mm, measurement filter	
Soot measuring range		up to 1000 mg/m^3 (at DR=20)	
Soot detection limit		~ 5 µg/m^3	

Table S2: Key parameters measured and recorded by PEMS.

Parameter	Unit
Total hydrocarbons	ppm
Carbon monoxide	ppm
Carbon dioxide	%
Nitric oxide	ppm
Nitrogen dioxide	ppm
Soot mass	µg
Ambient temperature	°C
Ambient humidity	%
Ambient pressure	mbar
Exhaust flow rate	l/h
Exhaust flow temperature	°C
Vehicle speed	km/h
Vehicle position	Latitude and longitude
Vehicle altitude	m
Throttle pedal position	%
Engine speed	rpm
Engine coolant temperature	°C

Table S3: The specifications of the on-board green-safety device.

Sensor unit		
Electrical characteristics	Input voltage	9 – 32 volt
	Input current	540 mA @ 12 volt, 270 mA @ 24 volt
	Max power consumption	6.5 W
Movement detection sensor	Sensor model	Foresight binocular camera
	Resolution	720 p
	Scan distance	1.5 m to 100 m
	Horizontal field angle	~ 42 degree
	Time delay	< 3 ms
Driving user interface unit		
Types of warnings	Forward collision warning, lane departure warning, headway monitor warning, aggressive acceleration warning, aggressive deceleration warning, aggressive turning warning	