Investigating eco-driving technology to reduce fuel consumption and emissions by using an on-board safety device in diesel commercial vehicles in Hong Kong

by Ng Cheuk Yin, Elvin
Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy

under the supervision of Dr Nic Surawski, Professor Guang Hong and Professor John Zhou.

University of Technology Sydney
Faculty of Engineering and Information Technology

Oct 2022

Certificate of Original Authorship

I, Ng Cheuk Yin, Elvin, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering of Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature: Production Note: Signature removed prior to publication.

Date: 24 October 2022

Acknowledgements

To pursue a doctoral degree could be a long and challenging journey. This journey becomes a reality with the kind support and help of many individuals. I would like to extend my sincere thanks to the following wonderful people who made this journey fruitful and enjoyable.

First of all, I would like to express my deep gratitude to my principal supervisor, Dr. Nic Surawski. I have learned many things since I became Dr Surawski's student. He invested numerous efforts in supervising me and spends vary much time instructing me how to prepare a paper, search literature and perform data analysis. Without his guidance and persistent help this dissertation would not have been possible. I am also grateful to my co-supervisors Professor Guang Hong and Professor John Zhou who giving me opportunity to do research and providing invaluable guidance throughout this research. Their vision, sincerity and motivation have deeply inspired me. They have taught me the methodology to carry out the research. It was a great honor to work and study under their guidance.

I really appreciate Dr. Yuhan Huang for your time and assistance in the experiments. I would like to thank him for helping and supporting me and specially for being always available when I needed something.

This study was sponsored by the industry doctorate degree program between UTS and VTC. The funding provided by the Vocational Training Council of Hong Kong is gratefully appreciated.

Contents

List of Publications

Journal articles

[1] **Elvin C.Y. Ng**, Y. Huang, G. Hong, et al. Reducing vehicle fuel consumption and exhaust emissions from the application of a green-safety device under real driving. Science of the Total Environment 2021; 793: 148602. (IF=7.963, SJR Q1)

[2] Y. Huang, **Elvin C.Y. Ng**, Nic C. Surawski, et al. Effect of diesel particulate filter regeneration on fuel consumption and emissions performance under real-driving conditions. Fuel 2022; 320: 123937. (IF=6.609, SJR Q1)

[3] Y. Huang, **Elvin C.Y. Ng**, J. Zhou, et al. Impact of drivers on real-driving fuel consumption and emissions performance. Science of the Total Environment 2021; 798: 149297. (IF=7.963, SJR Q1)

[4] Y. Huang, **Elvin C.Y. Ng**, J. Zhou, et al. Eco-driving technology for sustainable road transport: A review. Renewable & Sustainable Energy Reviews 2018; 93: 596-609. (IF=14.982, SJR Q1)

Conference proceedings

[5] **Elvin C.Y. Ng**, Y. Huang, G. Hong, et al. Effects of an on-board safety device on the emissions and fuel consumption of a light duty vehicle. SAE conference paper - International Powertrains, Fuels & Lubricants Meeting 2018; 2018-01-1821. (SIR Q2)

[6] **Elvin C.Y. Ng**, Eco-driving - Fuel Saving Techniques, Eco-driving Seminar (Hong Kong SAR Environmental Protection Department), Invited talk, 19th of Jan 2018.

Other publications arising from this thesis

[7] Y. Huang, **Elvin C.Y. Ng**, Nic C. Surawski, et al. Large eddy simulation of vehicle emissions dispersion: Implications for on-road remote sensing measurements. Environmental Pollution 2020; 259: 113974. (IF=8.071, SJR Q1)

[8] Y. Huang, **Elvin C.Y. Ng**, Y.S. Yam, et al. Impact of potential engine malfunctions on fuel consumption and gaseous emissions of a Euro VI diesel truck. Energy Conversion and Management 2019; 184: 521-529. (IF=9.709, SJR Q1)

Successful grants

[9] **Elvin C.Y. Ng (Principal Investigator)**, Y. Huang and Eddy F.C. Chan. Evaluation of eco-driving technology for reducing fuel consumption and emissions. Environment and Conservation Fund (Project No.: ECF Project 56/2018), HK$496,193, (Completed in 2021).

List of Tables

List of Figures

Definitions and Abbreviations

Acronyms

CAN	Control Area Network
CMOS	Complementary Metal-Oxide-Semiconductor
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DCV	Diesel Commercial Vehicle
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EEA	European Environment Agency
EGR	Exhaust Gas Recirculation
FID	Flame Ionization Detector
GHG	Greenhouse Gas
GPS	Global Positioning System
HC	Hydrocarbons
HGV	Heavy Goods Vehicle

HKEPD	Hong Kong Environmental Protection Department
HKSAR	Hong Kong Special Administrative Region
ICE	Internal Combustion Engine
JCEC	Jockey Club Heavy Vehicle Emissions Testing and Research Centre
LGV	Light Goods Vehicle
LPG	Liquefied Petroleum Gas
MGV	Medium Goods Vehicle
MPA	Mean Positive Acceleration
MANOVA	Multivariate Analysis of Variance
NDIR	Non-dispersive Infra-red
NDUV	Non-dispersive Ultra-violet
NEDC	New European Driving Cycle
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
O_2	Oxygen
OBD	On-Board Diagnostics

PEMS	Portable Emissions Measurement System
PM	Particulate Matter
UNFCCC	United Nations Framework Convention on Climate Change
USDoE	United States Department of Energy
RDE	Real-Driving Emissions
RPA	Relative Positive Acceleration
RSP	Respirable Suspended Particulates
SCR	Selective Catalytic Reduction
THC	Total Hydrocarbons
VSP	Vehicle Specific Power
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

Symbols

VSP_{LGV}	Vehicle specific power of LGVs
VSP_{MGV}	Vehicle specific power of MGVs
v	Vehicle velocity
a	Instantaneous vehicle acceleration
g	Gravity
$\emptyset$	Road grade
φ_{LGV}	Coefficient of rolling resistance term for LGV
φ_{MGV}	Coefficient of rolling resistance term for MGV

Abstract

Vehicle emissions have negative impacts on climate change, air quality and human health. The driver is the last major and often overlooked factor that determines vehicle performance. Eco-driving is a relatively low cost and driving-behavior-based method aimed to reduce vehicle fuel consumption and emissions. In this thesis, a safety device was installed on a suite of diesel commercial vehicles to assess its eco-driving capabilities. Because the on-board safety device provided real-time feedback to the driver on their driving performance, actioning of the warnings provided from the safety device could enable not only safety benefits to be achieved but potentially reductions in fuel consumption and emissions as well. Exploring the hypothesis that a safety device can simultaneously facilitate the reduction of fuel consumption and emissions is the principal contribution of this thesis.

To investigate the effects of driving behavior on fuel consumption and gaseous emissions of diesel goods vehicles, a portable emissions measurement system was installed on three target vehicles to measure real-driving emissions. In addition, driving and environmental parameters were recorded in the experiments. The on-board safety device installed on the test vehicle was used to record the number of warnings in two separate stages of testing. In the first stage, the number of warnings were recorded while the driver implemented their natural driving style. In the second stage, the number of warnings were recorded but real-time warnings were issued to the driver to improve their driving behavior. The experimental results were evaluated using the Vehicle Specific Power methodology to understand the effects of driving behavior on fuel consumption and gaseous emissions. In this thesis, two studies (three vehicles in total) were conducted to investigate the effects of driving behavior on fuel consumption and emissions of diesel goods vehicles. The first study was conducted to evaluate the effects of an on-board safety device on driving behavior (and fuel consumption and emissions) of two diesel commercial vehicles, including a 5.5 tonnes light goods vehicle and a 16 tonnes medium goods vehicle. In the second study, the effectiveness of the safety device was investigated using a diesel 3.3 tonnes light goods vehicle and 30 drivers with different levels of driving experience were recruited to conduct the on-road emissions experiments. Altogether, the results from this thesis demonstrate that the on-board safety device has a positive impact on fuel consumption and emissions from vehicles through issuing real-time warnings that improve driving behavior.

Chapter One

1. Introduction

1.1 Research background and its contribution to knowledge

Worldwide concerns regarding global warming and fossil fuel depletion have driven many countries to take more serious actions in energy saving and CO_2 emissions reduction initiatives. According to the European Commission, passenger cars and light goods vehicles comprise 12% and 2.5%, respectively, of total European Union CO_2 emissions [1, 2]. In addition, the share of road transport CO_2 emissions from heavy-duty vehicles is projected to increase to 32% of total transport CO_2 emissions in 2030 [3]. According to the 2030 Climate Target Plan, the European Commission also suggested that greenhouse gas emissions should be reduced by 55% compared to 1990 levels to meet the 2030 target of 48 g/km and 60 g/km for passenger cars and light-duty vehicles respectively [4, 5]. Apart from CO_2 emissions, on-road vehicle emissions are one of the major sources of atmospheric pollutants, including HC, CO, NO_x and Particulate Matter (PM). Greenhouse and pollutant emissions of on-road vehicles have negative impacts on climate change [6] and human health [7, 8]. According to the International Energy Agency [9], road transport has a more significant contribution to climate change as compared to other sectors in the transportation industry (e.g. rail, marine and air transport). As a result, development of innovative technology for emissions reduction in the transport sector is a key priority.

Road transport emissions are a major source of air pollution that Hong Kong has been facing for many decades [10, 11], with numerous policies having been adopted by the Hong Kong Environmental Protection Department (HKEPD) to improve roadside air quality and greenhouse gas emissions from motor vehicles [12, 13]. In order to protect the environment and public health, the Government of the Hong Kong Special Administrative Region (HKSAR) has carried out air quality impact assessments and published an emissions inventory report to improve the quality of local air pollutant emission [14]. It was reported that CO emissions were decreased by 37% between 1997 and 2016 [14], which was mainly caused by a decline in emissions from the road transport sector. During the same period, respirable suspended particulates (RSP) and NO_x emissions were greatly reduced by 69% and 39% respectively [14].

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) [15], better fuel quality and renewable fuels [16] and stricter enforcement for high-emitting vehicles [17]. However, another important but often overlooked factor to reduce vehicle emissions and to improve fuel economy (hence reducing the negative impact to the 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. The scope of eco-driving is to avoid aggressive accelerations and decelerations and also to increase passive driving strategies (e.g.

maintaining a constant driving speed and reducing maximum speeds). Although many strategies have been undertaken to improve 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 improvements in fuel efficiency up to 45% can be achieved [18, 19]. Therefore, this thesis is dedicated to understanding how eco-driving technology can positively influence the fuel consumption and emissions performance of on-road vehicles.

Eco-driving has gained significant attraction in air pollution and climate change policy in many countries [20, 21], as well as being the focus of a number of recent investigations [19, 22-24]. In addition, an individual's driving behavior and network-wide impacts of eco-driving were also investigated in previous studies. The implementation of eco-driving by changing an individual's driving behavior could reduce fuel consumption by 5 - 45% [18, 25]. However, a high percentage of eco-drivers could have negative effects on global emissions under high traffic demand conditions because higher headways and smooth acceleration/deceleration profiles increased congestion [26]. The negative effects on the environment depend on the traffic volumes of the road network. At low traffic flow, the negative impact is small and the level of impact is related to the road network configuration. However, large negative impacts were observed for high traffic volume scenarios with an increase in the percentage of eco-drivers. Therefore, one of the eco-driving skills - route choice is an important factor in high traffic flow. Normally, several routes will be provided to the drivers for a given origin-destination trip including the shortest travel distance and the fastest travel time. However, the shortest or fastest route is not always the best choice in terms of fuel consumption and emissions. More details of route choice will be discussed in section 2.3.4.

At present, aftermarket devices are available to monitor driver safety under real-driving conditions. The hypothesis tested by this thesis is that real-time feedback on driving safety could yield positive benefits for fuel consumption and emissions. This outcome could be achieved by a driver actioning a warning issued by the safety device which positively changes driving behavior (e.g. by reducing aggressive accelerations). Through the deployment of an on-board safety device that monitors driving behavior, this thesis experimentally investigates the effects of a change in driving behavior on vehicle emissions and fuel consumption and to further develop eco-driving technology for vehicles to reduce their fuel consumption and gaseous emissions. Current eco-driving studies [27, 28] mainly focus on fuel savings and CO_2 reduction of individual vehicles but ignore the pollutant emissions from other chemical species and impacts on the traffic network. In addition, a deep and comprehensive understanding of eco-driving factors is important to improve on-road vehicle fuel economy and to reduce pollutant emissions. This will encourage the promotion of eco-driving behavior to the public which will help to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future.

1.2 Research objectives and methodology

This PhD project aims to investigate the application of an on-board safety device to improve a driver's driving behavior and thus reduce vehicle fuel consumption and gaseous emissions. To realize this goal, an on-board safety device was installed on test vehicles to provide real-time feedback to the driver. Real-time warnings were provided to alert the driver so as to improve driving behavior related to excessive speeding, engine idling time and hard acceleration and braking events [29-31]. The on-board device was designed for safety, and it could provide real-time feedback information to the driver for improving the safety features of their driving. This feedback information could influence driving behavior in a positive way leading to a significant reduction in fuel consumption and vehicle emissions. The driving user interface provides instantaneous visual and auditory warnings to alert the driver to prevent speeding, aggressive accelerations and decelerations. A portable emissions measurement system (PEMS) was installed on three different types of diesel vehicles to measure real-driving emissions (RDE), including total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NO_x) and particulate matter (PM). The driving parameters (i.e. engine speed, vehicle speed and acceleration) and environmental parameters (i.e. ambient temperature, humidity and pressure) were also recorded during on-road emissions measurements. Furthermore, a 3.3 tonnes diesel light goods vehicle (LGV), a 5.5 tonnes diesel LGV and a 16 tonnes diesel medium goods vehicle (MGV) were selected to conduct experiments in this study. The LGVs and MGV were chosen because they are the dominant vehicle types in Hong Kong. In order to understand the effects of driving behavior on vehicle emissions and fuel consumption, on-road emissions experiments were performed on a typical driving route in Hong Kong, including urban, rural and highway conditions.

Overall, five thesis objectives are required to achieve the overall aim; namely,

1) to investigate the effects of driving behavior on emissions and fuel consumption of diesel goods vehicles,
2) to explore the role of an on-board safety device in improving fuel consumption and

emissions from LGVs and MGVs under real-driving conditions,

3) to deeply understand fuel economy and emissions dynamics by implementing a Vehicle Specific Power (VSP)-based model based off RDE experimental data,
4) to develop statistical models that investigate the effects of driving behavior on emissions and fuel consumption of diesel goods vehicles,
5) to recommend new control functions aimed for eco-driving applications. The newly developed control functions can be implemented into future versions of the safety device that enables the driver to improve their driving behavior.

1.3 Thesis outline

To achieve the overall thesis aim, the contents of the following six chapters of this thesis are outlined as follows.

Chapter Two reviews the background information regarding exhaust emissions and fuel consumption of vehicles, factors of eco-driving technology and experimental methods for exhaust emissions measurement from published works.

Chapter Three establishes the methodology to investigate fuel consumption and emissions from the diesel LGVs and MGV equipped with a safety device.

Chapter Four explores and investigates the role of the deployment of an on-board safety device on driving behavior and consequently on fuel economy and gaseous emissions of diesel LGV and MGV using a PEMS. Chapter Four also presents and discusses the statistical analysis results of the safety device on driving behavior, emissions and fuel consumption of diesel goods vehicles.

Chapter Five explores and investigates the effects of an on-board safety device on driving behavior of experienced and less-experienced drivers on fuel consumption and emissions of diesel LGV. Chapter Five also investigates the significant effects of the safety device on driving behavior for drivers with different levels of driving experience.

Chapter Six concludes this thesis by summarizing the outcomes of each chapter, recommending new control functions and future research work.

Chapter Two

2. Literature review

2.1 Fuel consumption and air pollution from vehicles

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 [15], the tightening of automotive emission standards from Euro V to Euro VI [32], better fuel quality and renewable fuels [16] and stricter enforcement for high-emitting vehicles [17]. On 12th December 2015, Parties to the UNFCCC reached a landmark agreement – the Paris Agreement – to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future. The Paris Agreement's aim is to keep global temperature rises well below 2 °C relative to pre-industrial levels and to pursue further efforts to limit the temperature increase to 1.5 °C. Additionally, the agreement aims to increase the ability of countries to deal with the impacts of climate change and at making finance flows consistent with low greenhouse gas (GHG) emissions and climate-resilient pathways [20, 33, 34]. The governments that have ratified the UNFCCC have met annually as the Conference of the Parties to take stock of their progress, monitor the implementation of their obligations and continue to work on the best way to tackle climate change.

Currently, there are 196 Parties that have ratified the convention [35]. According to the Leaders Summit on Climate in April 2021, the president of the United States has proposed to reduce greenhouse emissions by 50% to 52% in 2030 compared to 2005 levels [36]. The transport sector consumes about 20% of global energy and is responsible for nearly 25% of global energy related CO_2 emissions, 75% of which are emitted by road transport [2]. In addition, it is estimated that the energy consumption and CO_2 emissions of world transport in 2030 will increase by more than 50% due to increasing population and economic growth [2, 37]. In order to achieve this goal, the road transport sector must take an important role to make a significant contribution to sustainability outcomes.

In Hong Kong, road transport emissions are a major source of air pollution. In order to protect the environment and public health, the Hong Kong SAR government has implemented a series of policies and motor vehicle emission control program to improve ambient and roadside air quality including phasing out 80,000 pre-Euro IV diesel commercial vehicles (DCVs), replacement of catalytic converters and oxygen sensors of liquefied petroleum gas taxis and light buses and retrofitting light- and heavy-duty vehicles with diesel particulate filters (DPF) and diesel oxidation catalysts (DOC) [12]. In addition, the Hong Kong government is preparing new initiatives to further reduce air pollutant emissions of on-road vehicles to improve roadside air quality, including progressively phasing out about 40,000 Euro IV DCVs, tightening the automotive emission standards of first registered motorcycles to Euro 4, as well as the emissions standards of first registered light buses and buses to Euro VI, and retrofitting Euro IV and V diesel double-deck franchised buses with enhanced selective catalytic reduction (SCR) systems to reduce the emissions of NO_x [38].

An important factor which is often overlooked that may reduce vehicle emissions and fuel consumption significantly is eco-driving technology. The investment for new vehicle technologies and fuels is usually significant and long-term, and an improvement of only a few percent may be considered significant. It has been estimated that the potential efficiency improvements of advanced engine and vehicle technologies were only about 4 - 10% and 2 - 8% respectively [39]. However, the implementation of eco-driving appears to be more cost-effective, immediate, relatively simple and an improvement in fuel efficiency up to 45% can be achieved [18]. Eco-driving is also more cost-effective than fleet retrofit programmes (e.g. replacing existing diesel buses with new compressed natural gas ones) [19]. Eco-driving is an initiative which has seen worldwide adoption and investigation in the past decade [40] although great efforts are needed to convert the claimed benefits of eco-driving into real-driving with lasting and uniform effects [41].

2.2 Safe driving and eco-driving behaviors

Safe driving has been studied extensively and league tables are produced regularly to monitor the global impacts of road deaths. According to the World Health Organization, the Global Status Report on Road Safety serves as a baseline for the Decade of Action for Road Safety 2011 - 2020, declared by the United Nations General Assembly. In addition, the number of road traffic deaths has not increased but remains unacceptably high at 1.24 million per year [42]. Safety is the most important concern in a driving task. Throughout the literature, safe driving recommends appropriate driving speed for the specific road and/or conditions, smooth acceleration/deceleration driving behavior and looking ahead at the traffic flow, signals and road grade [43]. Researchers also found that the principal causes of traffic accidents are biases in risk perception, self-regulation, inexperience and self-confidence when driving [44]. The Department for Transport of United Kingdom (UK) reported that exceeding the speed limit or driving too fast for the conditions were identified as contributory factors and caused 115,584 casualties on UK roads in 2020, including 1,460 deaths, 22,069 serious injuries and 92,055 slight injuries [45]. In addition, Taylor et al. [46] investigated that a 10% increase in average driving speed would result in a 26% increase in the frequency of all accidents causing injury. Other than the driving speed factors, related measures such as acceleration/deceleration rate [47], driver headway behavior [48], various kinds of driver fatigue [49] and alcohol driving [50] have also been used when considering safe-driving behavior and accident frequency or prediction. Furthermore, the American Automobile Association Foundation for Traffic Safety suggested that 56% of fatal accidents involved one or more actions typically associated with aggressive driving behavior, with excessive driving speed being the number one factor [51].

Generally, driver behaviors for eco-driving largely overlaps with safe driving. Eco-driving recommends avoiding excessive speed and aggressive driving which are highly linked with crash risk and severity. When drivers are asked to drive more efficiently, they generally interpret this as to drive more slowly. Wahlberg [47] found that the acceleration/deceleration rate is perhaps more related to green driving, although it is still a factor in safe driving. Young et al. [43] suggested that changing driving behavior can improve road safety but also reduce fuel consumption and emissions. Haworth and Symmons [52] analysed that accident rates were decreased around 35% after eco-driving training, in addition to an observed reduction in fuel consumption (11%) and emissions (23 - 50%). On the other hand, some eco-driving behavior that improve fuel consumption and emissions may have detrimental effects on safety. For example, it may compromise achieving a headway when maintaining a constant speed through the avoidance of braking. Also, it may adversely affect vehicle control when travelling in the highest possible gear. Haworth and Symmons [52] investigated that in-vehicle fuel consumption feedback devices may be detrimental to safety if they cause a distraction to the driver. In addition, different types of in-vehicle eco-driving devices would cause different distraction for drivers (e.g. visual, manual and cognitive). Staubach et al. [53] found that the distraction was initially very high (with glance duration >2 s) but reduced over time when introducing a new in-vehicle device. The experimental results also indicated that fuel consumption or CO_2 emissions can be reduced up to 18%.

2.3 Factors of eco-driving technology

Eco-driving involves a number of factors and has different definitions or scopes in the literature. Sanguinetti et al. [54] identified six classes of eco-driving including driving, cabin comfort, trip planning, load management, fuelling and maintenance. Sivak and Schoettle [18] reported that the decisions made by a driver significantly affected the fuel economy of light-duty vehicles. The effects of drivers' decisions could be grouped into three categories, including strategic decisions (selection of vehicle and vehicle maintenance), tactical decisions (optimization of route choice and vehicle loading) and operational decisions (driving behavior). It was found that aggressive driving behavior resulted in high emissions and fuel consumption and that maintaining an eco-driving style could reduce fuel consumption by 5 - 30%. Zhou et al. [39] identified six groups of factors affecting fuel consumption, namely travel-, weather-, vehicle-, roadway-, traffic- and driver-related factors. A broader scope of eco-driving also involved public education, driving feedback devices, regulation, fiscal incentives and social norm reinforcement. The driving behavior was further divided into vehicle speed, acceleration, deceleration, idling, route selection and vehicle accessories (other factors). These are the most common driving factors (or parameters) and useful eco-driving skills that every driver can manually control in driving practice, rather than purchasing a new fuel-efficient car. In addition, changes in these driving behaviors could lead to significantly higher reductions in fuel consumption and emissions than other behaviors such as better maintenance practices [40]. The following sub-sections will discuss and analyse the main eco-driving factors.

2.3.1 Driving speed

Maintaining a constant speed is an important factor in fuel consumption under different road conditions [55, 56]. Optimal fuel efficiency can be achieved while cruising at a steady speed. Therefore using cruise control when possible is commonly recommended for eco-driving [18, 57]. Fuel economy varies with the type of vehicle and also varies with the cruising speed [58, 59]. This is because each internal combustion engine (ICE) has a unique speed for optimal fuel economy. The fuel consumption rate firstly decreases with the increase of engine speed due to reduced heat losses, reaches the optimal point and then increases at high speeds due to increased friction losses [60]. Therefore, the fuel consumption and driving speed curve shows a U-shape. El-Shawarby et al. [61] investigated the effects of constant cruise speed on emissions and fuel consumption based on a sequence of 10 one-kilometer trips. The results showed that the optimal emissions and fuel consumption rates per unit distance (L/100km) were in the range of 60 – 90 km/h, with considerable increases demonstrated outside this range. Wang and Rakha [62] reported that the optimal cruising speed of diesel buses were in the range of 40 – 50 km/h, which was lower than that of the range of 60 – 80 km/h for light-duty gasoline vehicles. Wang et al. [63] also found that the fuel consumption per unit time (L/h) was positively correlated with the cruise speed. In addition, the fuel consumption per unit distance (L/100km) was optimum at speeds between 50 – 70 km/h and the fuel consumption of passenger cars increase significantly with acceleration. The European Environment Agency (EEA) suggested that reducing motorway speed limits from 120 to 110 km/h could reduce fuel consumption significantly by 12% for diesel cars and 18% for gasoline cars, assuming smooth driving and 100% compliance with speed limits. Moreover, heavy goods vehicles speed limits in Europe motorways are in line with the optimal speed in terms of fuel consumption and CO_2 reductions per vehicle-km (80 – 90 km/h) [64]. In addition, fuel efficiency is highly affected by aerodynamic drag. Barnard et al. [65] investigated that about 30 % to 50 % of fuel energy was lost due to aerodynamic drag. The United States Department of Energy (USDoE), Office of Energy Efficiency and Renewable Energy proposed that fuel economy usually decreased rapidly at speeds above 80 km/h although each vehicle reached its optimal fuel economy at a different speed [57]. It can be seen that the above suggested optimal cruising speeds are usually below the speed limits on motorways (e.g. 110 km/h in Hong Kong and NSW Australia, 120 km/h in China and 130 km/h in Germany). Therefore, reducing motorway speed limits may help to reduce emissions and fuel consumption.

As a matter of fact, when it comes to real-world conditions, driving speed cannot be maintained ideally constant and must take the speed limit, travel time, road grade, traffic flow and traffic signals into account [66]. Therefore, the optimal speed for eco-driving is usually recommended at or slightly below the speed limit [54, 67]. Many studies have been carried out to estimate the optimal driving speed profile under real-world traffic conditions. Wang et al. [68] investigated the impacts an Ecological Adaptive Cruise Control algorithm on CO_2 emissions, travel efficiency and driving comfort of vehicles in free and moderately congested conditions. D'Amato et al. [69] proposed a fuel economy based cruise controller that adapted cruising speed and gear shifting to the local road grade. Li et al. [70] proposed a periodic servo-loop longitudinal control algorithm for an adaptive cruise control system to minimise fuel consumption in car-following scenarios.

2.3.2 Acceleration and deceleration

Maintaining a constant driving speed, avoiding unnecessary acceleration and deceleration are an important part of the eco-driving strategies to enhance fuel efficiency and reduce vehicle emissions. The function of acceleration/deceleration is to increase/reduce the driving speed or to start/stop the vehicle. However, there are always more or less efficient ways to do that, and the strategies vary significantly and have no consensus [54, 71]. Ahn et al. [72] identified that maintaining a constant velocity and avoiding unnecessary acceleration and deceleration are the key principles of eco-driving. The US Department of Energy [57] suggested that aggressive driving (speeding, rapid acceleration and hard braking) could lower fuel economy by roughly 15 - 30% at highway speeds and 10 - 40% in stop-and-go traffic. The Australian Department of the Environment [73] suggested drivers use the accelerator gently since aggressive acceleration/deceleration to the target speed would involve more use of petrol. Drivers could avoid unnecessary acceleration and deceleration by driving at a good distance from the car in front, so drivers can anticipate and travel with the traffic flow.

Eco-driving usually encourages drivers to minimise the use of the accelerator and brake pedals by looking ahead at the traffic flow, signals and road grade. This kind of anticipation can help shift the gears more efficiently and avoid unnecessary accelerating, braking, excessive speeding and idling. A number of studies have been carried out to investigate the effects of acceleration and deceleration on fuel consumption and emissions. Yang et al. [74] summarized that frequent acceleration associated with stop-and-go waves, excessive speeds, slow movement on congested roads, and extra idling times are major causes of increased fuel consumption and emissions. Pelkmans et al. [75] investigated the influence of test cycle characteristics on fuel consumption and emissions of city buses. The results showed that acceleration was the dominant factor, which shared 35% of the driving time but was responsible for 70% of fuel consumption and 60 - 80% of CO, HC and NO_x emissions of the entire drive cycle. Gallus et al. [76] used several acceleration-based parameters to characterize the aggressiveness of driving style, including mean positive acceleration (MPA), relative positive acceleration (RPA) and 95th percentile of velocity multiplied by positive acceleration ($v \times a_{pos}95\%$). The results showed that CO_2 and NO_x emissions of aggressive driving (larger MPA, RPA and $v \times a_{pos}95\%$ values) were 20 - 40% and 50 - 255% higher than those of normal driving, respectively. However, CO and HC emissions did not show distinct differences between driving styles. Chen et al. [77] analysed the on-road emissions and fuel consumption of heavy-duty diesel vehicles in Shanghai. The results showed that low-speed conditions with frequent acceleration and deceleration, particularly in congested conditions, were the main factors resulting in high CO and HC emissions. Alleviating congestion would significantly improve vehicle fuel economy and reduce CO and HC emissions.

As reviewed above, a smooth driving style saves fuel and produces less emissions compared to aggressive driving. Therefore, acceleration and deceleration are key factors that influence fuel economy and emissions. Experiments have been carried out to find the optimum acceleration and deceleration values or strategies under various road conditions. Choi and Kim [78] investigated the critical aggressive acceleration values that caused an abrupt increase in fuel consumption and CO_2 emissions for a Liquefied Petroleum Gas (LPG) passenger car. Classification and Regression Tree analysis was used to find the critical aggressive accelerations at which the increments of fuel consumption change abruptly. The results showed that the critical values for aggressive accelerations (causing an abrupt change of fuel consumption) were 2.598 m/s^2 for starting of the vehicle and 1.4705 m/s^2 during driving. The most efficient use of gears and acceleration strategy was low engine speed (between 2,000 and 2,500 rpm) and moderate throttle position (50%) for both petrol and diesel cars [79]. Birrell et al. [67] recommended using smooth and positive acceleration to reach high gears and to reach the desired cruising speed sooner, and using a uniform throttle operating at no more than 50%. Regarding deceleration, they recommended using the engine brake (without changing down through the gears) for smooth deceleration and minimising the use of the foot brake where appropriate.

2.3.3 Idling

Idling is common in traffic conditions, especially during urban driving, such as at traffic lights or in stop-and-go driving during traffic congestion. However, idling periods in traffic are relatively short. There is more concern over long periods of idling of diesel heavy-duty vehicles while the engine is running and the vehicle is not driving. Idling should be minimised because every vehicle achieves zero fuel efficiency (0 km/L) when idling [54]. An idling vehicle consumes about 0.6 - 5.7 L/h fuel depending on the vehicle type, engine size, fuel type and loading [80]. According to the USDoE, idling from light-duty and heavy-duty vehicles combined consumed about 22.7 billion litres of fuel annually. About half of that is attributable to personal vehicles, which generate around 30 million tons of CO_2 every year just by idling [57]. Eliminating unnecessary idling of personal vehicles would be the same as taking 5 million vehicles off the road in terms of saving fuel and reducing emissions [81].

There are many strategies that can help to reduce idling time. Firstly, it is needed to update people's understanding and knowledge on idling. Modern cars do not need to idle to warm up the engine or catalytic converter [81]. Reaching the ideal operating temperature is achieved more quickly by driving than idling. Even on the coldest days, most manufacturers recommend avoiding idling and driving off gently for about 30 s to warm up the engine. Similarly, modern cars do not suffer damage by being turned on and off, and 10 s idling has more fuel consumption and emissions than stop-and-restart does [73, 81]. However, a survey showed that the average total idling time of American drivers was 16.1 min per day [57]. At least 80% of the respondents thought that idling a vehicle for more than 30 s was better than stop-and-restart. The average respondent believed that a vehicle should be idled for at least two minutes before driving in mild weather and even longer in cool or cold weather. Consequently, a large amount of fuel was wasted in idling due to inaccurate or outdated knowledge [82]. In addition, idling also produces high pollutant emissions of HC, CO, NO_x and PM [83].

The above knowledge mainly targets idling off-road, such as avoiding long idling periods before driving or stopping and turning the engine off in drive-through queues or while waiting for passengers. However, drivers usually have less control over idling in traffic and it may be inconvenient or even unsafe to turn off the engine. This kind of idling can be reduced or avoided by more efficient speed, accelerating, decelerating and routing behaviors. Li et al. [84] proposed an advanced driving alert system to alert drivers to release the throttle earlier and brake gently in response to changes of traffic signals. The results showed 8% of fuel savings in medium congested traffic. Idling times at intersections, during congestion and accidents could be reduced or avoided by eco-routing devices [85, 86]. Nowadays, many new vehicles are now equipped with stop-start technology which turns off the engine whenever idling and restarts the engine when drivers release the brake pedal. Engine stop-start technologies are increasingly in use to improve fuel consumption and reduce emissions of internal combustion engines [87, 88]. Fonseca et al. [89] investigated the efficiency of stop-start technology on two Euro 4 diesel vehicles in urban traffic. The experimental results showed that the vehicle with a stop-start system installed had more than 20% CO_2 emissions reduction partly due to zero idling emissions.

2.3.4 Route choice

Route choice selection is another major factor that affects the total fuel consumption and emissions for a vehicle's trip. Route choosing involves a number of factors including travel time and distance, speed limits, and road and traffic conditions. Normally, there are several routes provided to the drivers for a given origin-destination trip. Once the route is chosen, the aforementioned eco-driving factors will be largely limited by the route characteristics. Mostly, a driver would choose a route with either the shortest travel distance or the fastest travel time. However, Ericsson et al. [90, 91] investigated the route with shortest distance is not always the best choice in terms of fuel consumption and emissions. Ahn et al. [92] investigated the impacts of route choice selection on fuel consumption and emission rates for different vehicle types using microscopic and macroscopic emission estimation tools. The results showed that the faster highway route choice is not always the best from an environmental and fuel consumption perspective. This is because the fastest route may be longer and include highways that the vehicles are not allowed to run at the eco-driving speed (50 - 90 km/h, as discussed in Section 2.3.1), thus resulting in higher fuel consumption and emissions. While the shortest route may contain congested traffic, leading to higher fuel consumption and longer travel time. A trade-off is needed between the travel time, distance and fuel consumption. Zeng et al. [28] developed an eco-routing approach combining the weighting method and k-shortest path algorithm to determine the optimal path with minimum CO_2 emissions while satisfying time constrains. The vehicle CO_2 emission model and eco-routing approach are validated in a large-scale transportation network in Japan. They found that the average reduction of CO_2 emissions could reach 11% when the travel time buffer was around 10%. Kuo [93] proposed a simulated annealing algorithm to calculate the fuel consumption for a time-dependent routing problem. The results show that the proposed method could have 25% improvement in fuel economy over the fastest-route and 23% over the shortest-route method.

Fuel economy and emissions is influenced by the type of road, road grade and by the traffic conditions significantly. Road type determines the average driving speed and the acceleration and deceleration profiles, and consequently fuel economy. The Canada Office of Energy Efficiency [94] reported that the average fuel economy of highways with an 80 km/h speed limit or higher is about 9% better than other roads. Choosing a flat and constant speed limit road is not only safer, but also saves fuel. Large road grade also has strong effects on fuel economy. Boriboonsomsin and Barth [95] found that, in a particular scenario with the same origin and destination but two alternative routes, fuel economy of flat routes would be 15 - 20% better than that of hilly roads. Jin et al. [96] reported that, for a 250-metre freeway segment with the same initial speed, final speed and trip time, the fuel consumption of a 6% grade route was 86% and 170% higher than those of 0 and -6% grade routes, respectively. Higher grade profiles required the vehicle to run at high engine load condition more frequently, causing higher fuel consumption and emissions. A small proportion of the entire trip with high engine load condition was responsible for a significant amount of trip emissions and fuel consumption [92]. Traffic conditions clearly influence fuel consumption and emissions. The traffic flow process including volume of traffic, phasing of traffic lights and regulation strategies should also be considered when choosing the route. A fuel-efficient route should avoid congested roads and minimise the idling time at intersections or traffic lights. Several studies had been performed regarding this aspect. Boriboonsomsin et al. [97] developed an eco-routing navigation system that determined the most fuel-efficient and most environmentally friendly route based on the historical and real-time traffic information. The results showed that, compared with the fastest route, an eco-route could provide an average reduction of fuel consumption reaching 12% but incurring a 22% longer travel time for a short trip less than 24 km, a reduction of 13% fuel consumption but a 22% longer travel time for a medium trip (24

- 48 km), and 14% fuel savings but a 16% longer travel time for a long-distance trip more than 48 km. Yao and Song [85] proposed an eco-route planning algorithm based on locally collected vehicle operation and emission data and a dynamic traffic information database. The eco-route planning algorithm is consistent with the road network characteristics of Chinese cities. Compared with the fastest route, the eco-route could reduce 2.2 - 7.4% of fuel consumption depending on the vehicle type, travel distance and traffic flow. The maximum fuel savings and average effectiveness values of CO_2 emission reduction could be achieved under heavy congestion and 10 - 15 km travel distance conditions.

The network-wide impacts of eco-routing strategies are a commonly ignored factor in eco-routing studies. The above studies mostly investigated the effectiveness of eco-routing system for individual vehicles. Rakha and Ahn [98, 99] presented an eco-routing model to evaluate how individual vehicle's route choice would affect others on network levels. An INTEGRATION microscopic traffic assignment and simulation framework was used for modeling eco-routing strategies. The results showed that the system-wide benefits of eco-routing generally increased with the increase of system market penetration rate and 15% reduction in fuel consumption can be observed. Jiang et al. [100] proposed an eco-driving system to prioritize mobility before improving fuel efficiency that optimizes the entire traffic flow by optimizing speed profiles of connected and automated vehicles. The benefits of eco-driving increased with the market penetration rate of connected and automated vehicles until leveling off at a 40% penetration rate.

2.3.5 Other factors (vehicle accessories)

Vehicle accessories are grouped into other factors of eco-driving technology. Other factors influencing fuel consumption and emissions include vehicle weight, axle distribution, tyre pressure, vehicle maintenance and aerodynamic drag [18, 54, 57, 101]. Numerous investigations have reported that minimising vehicle weight can reduce fuel consumption and CO_2 emissions, for example, it is estimated that a 2% increase in fuel consumption occurs by adding an extra 45 kg of vehicle weight. This increase in fuel consumption is also dependent on the size of the vehicle, the travelling time and the driving style of the driver. It has been noted that the impact is more significant for small vehicles [40, 57]. It is estimated that each additional pound of average passenger weight would increase US petrol consumption by more than 148 million litres per year [102]. Maintaining optimal tyre pressure and maintenance of the emission control system are the two key features among maintenance techniques. The US Transportation Research Board [103] reported that under-inflated tyres with increased rolling resistance can increase fuel consumption by 1 - 2%. According to the US Environmental Protection Agency, driving with under-inflated tyres could increase fuel consumption by 1% for every 5 psi drop in tyre pressure. Proper maintenance can reduce fuel consumption. Fuel consumption could increase by 4% with a poorly tuned engine and by as much as 40% with a faulty oxygen sensor [104]. Aerodynamic drag should be minimised. Additional parts on the exterior of a vehicle or having the windows open could increase air resistance and fuel consumption by over 20% at high driving speeds [73]. Large roof racks and blunt roof cargo boxes can reduce fuel economy by around 2 - 8% in city driving, 6 - 17% on highways, and 10 - 25% at interstate speeds (105 - 120 km/h) [57]. Rear-mount cargo boxes or trays reduce fuel economy by much less, only 1 - 2%

in city driving and 1 - 5% on highways [57]. Therefore, it is recommended to remove all external cargo containers when they are not in use, to use rear racks rather than roof racks, and to use aerodynamic racks and to pack cargo tight and low if roof cargo cannot be avoided [54]. However, drivers usually do not have much control over these factors during a trip and the chance of implementing these countermeasures is relatively low.

2.3.6 Comparison of eco-driving factors

As reviewed above, eco-driving consists of a number of factors including driving speed, acceleration/deceleration, idling, route selection and vehicle accessories (other factors). These are the most common driving factors (or parameters) and useful eco-driving measures for fuel savings and CO_2 reduction. In addition, it should be noticed that eco-driving factors are not independent and mostly overlap with each other, as shown in Table 1. Figure 1 compares the ranges of percentages of fuel savings and CO_2 reduction contributed by each eco-driving factor. Savings in fuel consumption are taken from experimental or numerical studies for a given origin-destination trip. Some data indicating the potential benefits of a single factor in ideal or extreme conditions are not comparable and thus excluded. For example, although fuel consumption of a 6% grade 250-meter road is 86% and 170% higher than those of 0% and -6% grade roads [96], there are no three such routes containing only uphill, flat or downhill roads for a given origin-destination trip. As shown in Figure 1, the eco-driving factor contributing the highest percentage of fuel saving and CO_2 reduction is acceleration/deceleration, contributing to 3.5 - 40% fuel savings and CO_2 reduction. This provides evidence of the effectiveness of avoiding aggressive driving behaviors that are commonly recommended in eco-driving programs. It is followed by driving speed reduction behaviors (2 - 29%). Route choice and idling could contribute 2.2 - 25% and 6 - 20% fuel savings, respectively. Other factors (vehicle accessories) contributing to 0.3 - 25% fuel savings and CO_2 reduction. Factors that drivers have control over during a trip, such as weight management and tyre pressure, have an insignificant effect on fuel consumption (< 3%). Although a faulty oxygen sensor can cause up to 40% more fuel consumption, such a factor is not frequent and drivers have no control over it during a trip. Therefore, the majority of eco-driving studies focused on the driving behaviors of driving speed, acceleration, deceleration, idling and route choice.

Table 1: Driving parameters included in each eco-driving factor.

Eco-driving factors	**Parameters considered**	**References**
Driving speed	Vehicle speed, engine speed, speed limit, cruise control, travel time, traffic conditions, gear shift and road grade.	[33, 36 - 48]
Acceleration/ deceleration	Aggressiveness (speeding, rapid acceleration and hard braking), accelerator control, anticipation, traffic conditions, gear selection and engine/foot brake.	[36, 45, 50 - 52, 55 - 57]
Idling	Driver's knowledge on idling, anticipation, headways, throttle control, traffic flow, traffic signal, route choice and stop-start technology.	[51, 59, 62 - 67]
Route choice	Travel time, travel distance, speed limit, road conditions, traffic conditions, road grade, road type, vehicle speed, vehicle type, network-	[63, 68 - 70, 72 - 79]

	wide impacts and market penetration rate.	
Other factors (vehicle accessories)	Vehicle weight, axle distribution, tyres pressure, vehicle maintenance and aero dynamic drag.	[32, 33, 36, 53, 81 - 83]

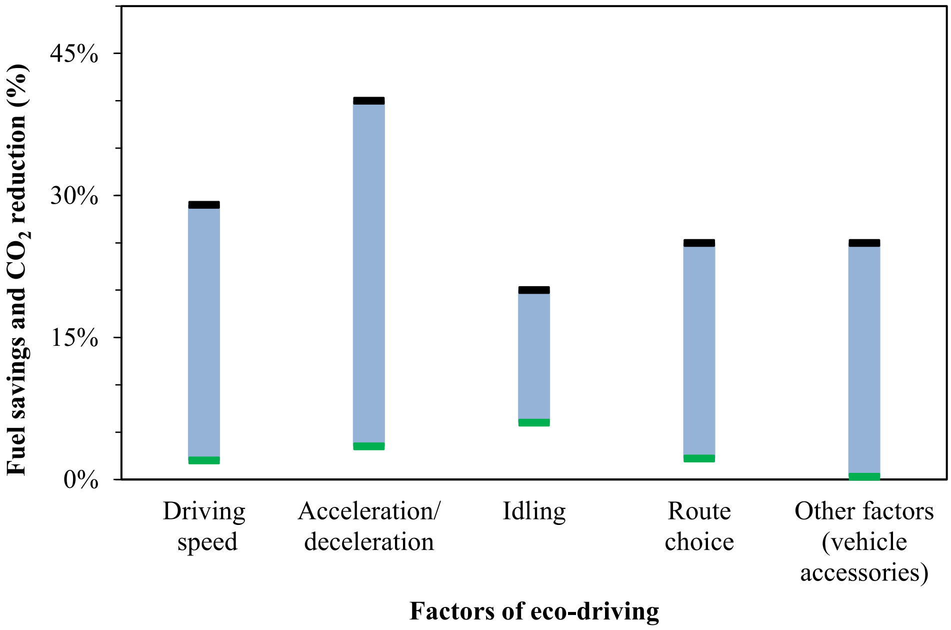


Figure 1: Ranges of percentages of fuel savings and CO_2 reduction contributed by each eco-driving factor* (Green bars show the minimum change and black bars show the maximum change).

*Data are derived from [33, 36 - 48] for driving speed, [36, 45, 50 - 52, 55 - 57] for acceleration/deceleration, [51, 59, 62 - 67] for idling, [63, 68 - 70, 72 - 79] for route choice and [32, 33, 36, 53, 81 - 83] for other factors (vehicle accessories).

2.3.7 The limitations of eco-driving

Current eco-driving studies mostly investigate and focus on the advantages of eco-driving, but lacks consideration on potential limitations. The changes in behavior of a single eco-driver may cause unusual driving behavior (e.g. increased overtaking and annoyance) from some drivers in traffic. In addition, using driver assistance devices to facilitate eco-driving may increase the risk of accidents by causing distraction. Liu and Lee [105] examined the effects of cellular phone communication on driving performance and found that driving with phone use in different traffic environments induced measurable variations in driver workload. Rouzikhah et al. [106] reported that navigation devices and online eco-driving messages can put a significant workload on drivers thus increasing the risk of accidents. Similar to these influencing factors, the potential limitations of eco-driving depends strongly on the design of the system, such as the type, content, complexity and presentation of information and the location of the devices in the vehicle.

The major advantages of eco-driving are that it can improve fuel economy and emissions of on-road vehicles by changing the driver's driving behavior without significant investment and long-term investigation. However, another limitation of eco-driving is public acceptability. A number of investigations have examined the response of drivers to eco-driving through the analysis of awareness and training programs. The results indicated that the drivers showed little motivation for eco-driving in general [107]. Furthermore, the drivers had a tendency to forget eco-driving training in the long-term. Although drivers were found to have an immediate improvement in fuel consumption after taking the eco-driving training, thereafter some drivers tended to regress back to original driving habits [108]. Therefore, it is clear the on-board eco-driving devices are an important complement to training programmes whose impact may attenuate over time.

A commonly ignored factor in eco-driving studies was how individual vehicle's route choice would affect others on network levels. The above studies mostly investigated the effectiveness of eco-driving for individual vehicles. However, some research investigations have reported potentially negative issues that lower the credibility of eco-driving initiatives. Wang et al. [109] reported that higher concentrations of CO_2 are emitted when considering a single lane, as a result of eco-driving during moderate congestion. Alam and McNabola [110] simulated the impacts of eco-driving on network-wide traffic and environmental performance at a number of speed-restricted (30 km/h) road networks. The results showed that increasing levels of eco-driving in certain road networks would have negative effects on CO_2 emissions and traffic congestion detriments at the road network level in the presence of heavy traffic. Moreover, it is possible that if too many drivers are directed into the same route, then the initially calculated eco-route may become congested and thus not fuel efficient [97].

2.4 Experimental testing methods for eco-driving (light, medium & heavy goods vehicles)

The benefits of eco-driving technology have received significant attention in the literature. Numerous research investigations have highlighted the benefits of eco-driving technology in terms of fuel consumption and emissions. This section reviews the experimental testing methods used to investigate eco-driving technology, including laboratory testing, on-road emissions measurement experiments and numerical modelling. Their mechanisms, advantages/disadvantages and applications are discussed and compared.

2.4.1 Laboratory experiments

Fuel consumption and emissions for different driving styles can be measured in the laboratory using an engine dynamometer, chassis dynamometer and driving simulators. Laboratory experiments are performed under controlled environmental conditions (e.g. ambient temperature and humidity). The accuracy and repeatability of laboratory experiments are typically higher than those of on-road experiments as the on-road results are affected by road or climatic conditions.

2.4.1.1 Engine dynamometer

Engine dynamometers are commonly used to investigate the engine power/torque characteristics, fuel consumption and emissions level of an engine by providing simulated road loading. In an engine dynamometer test cell (Figure 2 and Figure 3), the engine driveshaft is directly coupled to the dynamometer shaft. An absorption unit is used to absorb any specific load and measure the engine power, torque and speed. The absorption unit can be classified into different types by the power sources, such as eddy current, alternating current, direct current hydraulic brake and water brake. In a fully instrumented engine dynamometer test cell environment, various engine operating parameters can be measured, including the engine oil temperature, coolant temperature, intake air flow rate, fuel flow rate, torque, engine speed, in-cylinder pressure, exhaust emissions and fuel consumption.

Figure 2: Heavy-duty transient engine dynamometer test cell with a Euro V diesel bus engine in Hong Kong Jockey Club Heavy Vehicle Emissions Testing and Research Centre (JCEC).

Figure 3: Light-duty eddy current engine dynamometer test cell with a Euro 3 diesel engine in Hong Kong JCEC.

In an engine dynamometer testing, the engine and exhaust after-treatment system are required to be removed from the vehicle and the tests must follow the procedures specified in the regulation [111]. Load is applied to the engine via the dynamometer shaft which is controlled by the operators to simulate the road resistance in different experiments. Heated sample lines are directly connected to the engine exhaust. Exhaust emissions gas and fuel consumption can be monitored in real-time together with the engine power, torque, speed and other operating parameters. In addition, PM can be also measured from the exhaust gases in the engine dynamometer experiments. The major advantage of engine dynamometers is that the test cell can be climatically controlled. The ambient temperature and humidity can be controlled to simulate driving under a wide range of climatic conditions. In addition, the engine parameters (e.g. injection timing, fuel injection pressure, intake air temperature) can be controlled in a test cell environment. The operator has full control of all the engine parameters. Thus, engine dynamometer experiments can be conducted to investigate the impacts of driving styles and ambient conditions on emissions and fuel consumption. Furthermore, the engine driveshaft is directly connected to the dynamometer to measure power of the engine. The results are not affected by transmission and driveline power losses. Therefore, the accuracy and reliability of the engine dynamometer test are relatively high. The limitation of engine dynamometers are that they may not fully represent the fuel consumption and emissions of a complete vehicle and the range of test conditions is limited although real-world engine load test cycles can be run on modern engine test benches by simulating the vehicle dynamics [112]. Furthermore, the fuel consumption and emissions of entire vehicle fleets cannot be represented by engine dynamometer testing as usually only a few engines in each vehicle type are tested.

2.4.1.2 Chassis dynamometer

Chassis dynamometers enable an operator to simulate the resistive load on vehicle wheels. It consists of three main components, namely the load cell (absorption unit), the roller set and the power and torque indication system. As shown in Figure 4 and Figure 5, chassis dynamometer roller sets have a variety of diameters that depend on the application. Chassis dynamometer testing of passenger car or light-duty vehicles is performed on a light-duty transient chassis dynamometer. Medium to heavy-duty vehicles including minibus to double decker buses can be tested on a heavy-duty transient chassis dynamometer.

Figure 4: Light-duty transient chassis dynamometer in Hong Kong JCEC.

Figure 5: Heavy-duty transient chassis dynamometer in Hong Kong JCEC.

During chassis dynamometer testing, the vehicle is tied down and placed on a set of rollers which are directly coupled to the dynamometer load cell or a belt drive system. The resistive load can be applied to the vehicle to simulate real-world driving resistance. The driving cycles and load can be controlled by an operator, which are mainly transient cycles such as the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) and New European Driving Cycle (NEDC) [113]. These cycles are pre-defined driving profiles that the operator has to attempt to emulate during different stages of a test cycle. The operator must anticipate and follow the speed within ± 2 km/h and time ± 1 s in the pre-defined test cycle [114]. Fuel consumption, exhaust emissions and vehicle driving parameters of the testing vehicle are continuously measured and recorded. As chassis dynamometers are designed to meet regulatory standards, the experimental results are highly precise and reliable. Moreover, ambient temperature and humidity in the laboratory can be controlled to simulate real-driving under a wide range of climate conditions. The test cycles, climate condition and simulation of road and aerodynamic resistance can be fully controlled by the operators, thus the test results are not affected by the real-world driving factor and the test repeatability is relatively high. Therefore, chassis dynamometer testing can evaluate the impacts of driving behavior and ambient conditions on emissions and fuel economy, which will be analysed for further development of eco-driving technology. On the other hand, driving resistance that simulates road load is generated from vehicle coast down tests under artificial conditions. Thus, vehicle emissions and fuel consumption results performed by chassis dynamometer testing are lower when compared to real-driving results [115]. Furthermore, the ranges of test conditions such as steep road gradients are limited in chassis dynamometer testing. Thus, chassis dynamometer testing may not fully represent real-driving.

2.4.1.3 Driving simulator

Driving simulators are mainly built in the laboratory to evaluate the impact of driving behavior on fuel consumption and emissions, to provide eco-driving training to the drivers, and to evaluate new eco-driving training programs and in-vehicle devices. The driving simulator shown in Figure 6 consists of a fixed base or motion based car mock-up with driving panel, steering wheel, acceleration and brake pedal and indicators. The road scenarios are displayed on the screen, which provide road environment and traffic information to the driver. Vehicle driving parameters such as driving speed, acceleration and deceleration rates, gear shifting time, idling time and vehicle emissions are measured and recorded during driving [116].

Figure 6: Driving simulator in Beijing University of Technology [116].

The major advantage of driving simulators is that they offer a safe and effective method for examining various factors on driver performance. Safety issues and traffic accidents are not a concern in a laboratory driving simulator study [117]. Real-time driving behavior and emission information can be displayed on the screen to the driver. The driver can understand well the impacts of their real-time action on emissions and fuel consumption during the whole process of the experiment. Furthermore, the driving behaviors can be recorded and used to develop an eco-driving database, which can be used to improve the driving performance of individual drivers. The limitation of driving simulators is that road and traffic conditions are pre-defined and fixed. The real-time traffic and road conditions are not included. As a result, calculations of emissions and fuel consumption corresponding to different vehicle operation conditions are highly dependent on the simulator program. The use of driving simulators may also cause simulator sickness mostly due to an incongruity of sensory input with conflicting signals from simulated and actual motion [118].

2.4.2 On-road experiments

Emissions and fuel consumption measurements under on-road conditions provide valuable data regarding the impact of driver behavior on emissions. However, on-road experimental results are typically less accurate and repeatable than those from laboratory testing as they operate outside the boundaries of the emissions laboratory. In addition, on-road experiments are highly affected by the uncertainties in environmental or traffic conditions, driver behavior and transient operation due to the absence of standard testing cycles [112]. The commonly used on-road research methods for eco-driving include on-board measurements, data loggers, odometer readings and fuel use, and surveys.

2.4.2.1 On-board measurement - PEMS

PEMS is a mobile emission measurement instrument that is used on-board the vehicle to test under real-driving conditions. PEMS can provide instantaneous emissions measurement with satisfactory levels of accuracy. As shown in Figure 7, a PEMS unit integrates advanced gas analysers, a PM measurement device, an exhaust flow meter, a weather station, a global positioning system (GPS) and connects with the on-board diagnostics (OBD) port of the vehicle to provide data such as vehicle speed, engine speed, accelerator pedal position, fuel injection rate, coolant temperature and total fuel consumption. PEMS are installed either in the cabin or in the trunk of the test vehicle. As shown in Figure 8, heated sample lines and exhaust flow measurement systems are directly connected to the tailpipe. The sampling line is pre-heated to 190 °C to avoid the condensation of HC. Exhaust emissions, flow rate and temperature can be measured and recorded in real-time together with the engine, vehicle and ambient parameters. In on-road experiments, PEMS typically measures instantaneous CO, CO_2, HC, NO_x and PM emissions from the tailpipe. A weather station is mounted on the roof of the test vehicle to measure ambient temperature and relative humidity during on-road testing. In addition, a power generator and a battery pack are used to supply power for the instruments. Two bottles of synthetic air and Flame Ionization Detector (FID) fuel are also mounted in the test vehicle for calibration and operational purposes. PEMS is well utilised and developed because the Euro-6c regulation includes RDE as a new and additional type approval test for new vehicles [119].

7

Figure 7: PEMS unit in Hong Kong JCEC.

Figure 8: A coach bus instrumented with PEMS.

The major advantage of PEMS is that it can provide a detailed series of second-by-second real-time emissions data together with the engine, vehicle and ambient parameters during an on-road driving. PEMS can be installed into different categories of vehicles to build up a large database of emissions data under different driving conditions. The data includes a wide range of driving behaviors, traffic conditions, ambient conditions and vehicle conditions for further development of eco-driving technology. The effects of driving style on fuel consumption and emissions can be analysed [56]. In addition, the impacts of road grade can be also investigated, which would be difficult to replicate in laboratory testing [76]. On the other hand, PEMS only measures a limited range of pollutants which are less comprehensive than what laboratory testing achieves. The total weight of PEMS equipment including accessories is about 200 - 300 kg which may affect the measurement results, especially for light weight vehicles. It was estimated that 45 kg of extra weight could increase fuel consumption by 1 - 2% [40, 57]. Moreover, the repeatability and accuracy of PEMS measurements are lower than laboratory testing due to the sensors from the PEMS are not as accurate as laboratory-grade analysers and variability in driving behavior, traffic conditions, ambient conditions and vehicle conditions in real-driving.

2.4.2.2 On-board data logger

On-board data loggers are designed to collect vehicle state information and monitor driver operation data from a vehicle under real-driving conditions. Data loggers are plugged into the OBD II or control area network (CAN) of the vehicle to monitor engine, vehicle and ambient parameters. As shown in Figure 9, an on-board data logger installed in the vehicle, the vehicle speed, engine speed, positions of accelerator and brake pedals, fuel consumption, GPS and emissions data can be measured and recorded in real-time during on-road driving. OBD II is a standard protocol to provide real-time data of driving parameters and has been adopted by the US EPA from 1996 [120]. OBD II and CAN can be simply connected with a data logger and collect driving parameters during normal driving. Instead of installation of a set of PEMS equipment in the test vehicle, gas bottles and accessories in the test vehicle, a data logger is simply a plug-in to record all the driving parameters. It can minimise the effects of the added device mass on the measured results compared to PEMS, especially for light weight vehicles. Most of the vehicles built after 1996 should have OBD II ports and older vehicles generally do not. The data collected from data loggers can be used to investigate the impacts of driving behaviors, road and ambient conditions on emissions and fuel consumption. Moreover, data loggers can be used in a large number of vehicles and can collect long-term experimental data during normal daily driving at a low cost. The major disadvantage of data loggers is that the data available from the OBD II and CAN differs by manufacturer, vehicle model and type. Not all engine parameters are available for different types of vehicles as they may not be found within the data stream or may not show on the OBD II and CAN. Furthermore, collection of data from the engine control unit by the OBD II connector relies on various tools and specific software, such as data loggers, hand-held scan tools, mobile device-based tools and computer-based scan tools. Data cannot be extracted and recorded if those tools are not provided.

Figure 9: An on-board data logger with the vehicle state information.

2.4.2.3 Odometer reading and fuel use

The application of eco-driving has been extensively implemented in normal daily driving. To evaluate the effectiveness of eco-driving, fuel consumption can be manually logged by paper forms, fuel cards and company records (i.e. how frequently and how much fuel is refilled) and the vehicle usage can be recorded via the odometer reading [24, 121]. The major advantage of this recording method is that it is relatively simple and inexpensive. It can be applied to a large number and different types of vehicles which is feasible for long-term studies. Furthermore, this method does not have any impact on driving behavior. On the other hand, human errors may occur in recording the mileage and fuel use, such as drivers may forget to record the data at gas stations. Missing mileage records and the amount of fuelling records may lead to the data being unusable and unavailable for further analysis. Another limitation is that the data available are very limited, mainly the mileage and fuel use. The collected data are only mean values in certain periods.

2.4.2.4 Surveys

Surveys are assigned to the drivers after they are involved in training programs or testing with the on-board eco-driving device to adopt eco-driving knowledge and skills. General eco-driving training programs are structured to help drivers understand traffic conditions and improve their driving behaviors by adopting an eco-driving style with the principal aim of reducing fuel consumption and emissions, such as avoiding heavy acceleration and braking, reducing idling time, shifting up through the gears as soon as possible and maintaining a steady speed, for example [122]. The levels of fuel savings and emissions reduction are mainly dependent on the driver's motivation, attitude, acceptance, knowledge and behavioral change. Thus, the surveys are used to understand the driver's behavioral change and acceptance of eco-driving training programs [123]. The advantages of surveys that they are relatively simple and inexpensive. Furthermore, the feedback of a driver's experience can be investigated after the training and used to improve the effectiveness of the eco-driving training program and in-vehicle devices. The major limitation of surveys is that the information collected is very limited and no quantitative data on fuel consumption and emissions is available. Högberg [124] found that there is a limit to how much information respondents can handle while making a decision. Random errors will be increased simultaneously when the number of choices set increases. In addition, too many attributes and levels included can result in a survey that is very difficult for the respondents to comprehend. Martin et al. [125] categorised eco-driving interventions into two groups, namely static interventions (survey, brochure and website) and dynamic interventions (in-vehicle device). Among all these interventions, the effects of static interventions were less effective than dynamic interventions. In addition, the experimental results showed that only few drivers modified their driving behavior and a large percentage of drivers would exhibit no change after receiving the static information. Furthermore, surveys are assigned to the drivers to assess the effectiveness immediately after training and generally demonstrated obvious improvements in fuel consumption, emissions and driving behaviors. However, long-term studies showed that the improvement faded over time, drivers forgot the eco-driving behaviors and regressed back to their own developed driving habits.

2.4.3 Numerical modelling and data analysis

Numerical modelling for applications in eco-driving is mainly developed by engine parameters and vehicle state information. Modelling is widely used to evaluate the fuel consumption and emissions of new eco-driving and eco-routing algorithms of in-vehicle devices. Numerical models are used to predict the quantity and analyse the level of fuel consumption and emissions as a result of different driving behaviors, such as engine and driving speeds, acceleration/deceleration, idling, traffic flow and signals, and route choice. Smit et al. [126] analysed that five major categories are required as input data for models. They include average driving speed, traffic conditions, driving conditions, second by second engine parameters and vehicle state data. Parameters in each category can provide different information such as emission, fuel consumption or energy consumption. Rolim et al. [127] investigated the vehicle specific power model to estimate the power per unit mass of the vehicle. According to the vehicle specific power model, the parameters of road gradient, instantaneous vehicle speed and acceleration are used to define the amount of fuel used, the concentrations of CO_2 emission and pollutant emissions according to the driving power demand. Zhou et al. [39] classified fuel consumption models into white-box, grey-box and black-box models, with ascending simplicity and descending accuracy. The eco-driving model should be high prediction accuracy to predict fuel consumption. In addition, to quantify pollutant emissions and fuel consumption from road transport, a number of analytical approaches for modelling of eco-driving impacts have been developed for the micro and the macro simulation scales. Their distinction is made according to the temporal and spatial horizons. Samaras et al. [128] proposed a division of the methods into the macro and micro scales. Linton et al. [129] proposed to include each model into one of six main groups, namely: traffic network models, behavioral models, agent-based modelling, system dynamics modelling, techno-economic and integrated assessment models. They are ordered ascending from the micro to the macro scale and descending according to the degree of accuracy. Silvio Nocera et al [130] analysed the effectiveness of the micro and macro modelling approaches in evaluating the CO_2 emissions in different transport conditions. They found that the adoption of the micro approach is accurately determine transport demand and CO_2 emissions at the urban level. The major advantage of numerical modelling is that it can investigate the effectiveness of new eco-driving strategies or algorithms (e.g. adaptive eco-cruising speed control and eco-routing) without conducting field experiments, saving greatly in both research time and cost. The limitation of numerical modelling is that the results are less accurate and reliable than those of laboratory and on-road experiments. A model may only consider a few driving parameters (input variables) and ignore others that also have significant impacts on driver performance. Moreover, repetition of emissions test with the same driving condition is required and the output results are limited as well. Thus, the cost for developing a numerical modelling for a large number and different types of vehicles is relatively high.

2.5 Comparison of research methods and their applications

The mechanisms, advantages and limitations of the research methods used for eco-driving are summarized in Table 2. As shown in Table 2, each research method has its own advantages and disadvantages, which determine their applications in eco-driving research. Engine and chassis dynamometers are commonly used for testing the vehicle fuel consumption and emission levels for type-approval or regular inspection and maintenance (I/M) programs. They are highly accurate and repeatable. The testing results of engine and chassis dynamometer are also valuable for developing numerical models. Driving simulators are a safe and effective method to design and evaluate new eco-driving training strategies and in-vehicle devices. PEMS can measure second-by-second emissions and fuel consumption data, along with the road, traffic, driving and weather parameters under real-world driving. The resulting dataset enables us to perform detailed analysis on the effects of each driving parameter on driver performance, thus to identify low-emission and fuel-efficient behaviors for developing more effective eco-driving strategies. Data loggers are suitable for evaluating the effectiveness of eco-driving training programs or in-vehicle devices during actual driving both at large-scale and long-term. They are low-cost, fast and simple to setup. Odometer readings and fuel records are commonly used for long-term and large-scale studies. The cost is even lower while the data collected is much less compared to data loggers. Surveys are mainly used to understand drivers' attitude, knowledge, motivation and acceptance of eco-driving training programs and in-vehicle devices, which cannot be acquired by other methods. Numerical modelling is usually used to evaluate the new eco-driving algorithms and predict the effects of driving behaviors on emissions and fuel consumption, which can help to reduce both the research cycle and cost.

Table 2: Comparison of eco-driving research methods.

Method	**Mechanism**	**Advantages**	**Disadvantages**
Engine dynamometer	Simulated load can be applied via dynamometer to measure engine operation parameters	High accuracy and repeatability Climatically controlled Full control on engine	Not real-world data High cost Not a complete vehicle Small scale studies
Chassis dynamometer	Simulated resistive load can be applied via chassis roller to measure vehicle operation parameters	High accuracy and repeatability Climatically controlled	Not real-world data High cost Small scale studies

Driving simulator	Driving simulator system can record driver’s driving behaviors and performance data	No safety issue or traffic accident Low cost	Not real-world data Driving conditions are pre-defined Simulator sickness Short-term studies
PEMS	Vehicle emissions testing instrument can be installed on-board in the target vehicle to measure vehicle operation parameters	Moderately high accuracy Real-world data Wide driving and ambient conditions	Repeatability is limited Added weight may basis results Small-scale and short-term studies
Data logger	Vehicle and engine operation parameters can be read and recoded from OBD II and CAN	Low cost, fast and easy to setup Real-world data Long-term and large-scale studies No impact on driver performance	Repeatability is limited Low accuracy Available data is limited and differs by vehicle model
Odometer reading and fuel record	Odometer reading and fuelling frequency can be recorded by drivers or company	Low cost and simple Real-world data Long-term and large-scale studies No impact on driver performance	Low accuracy and repeatability May miss some records (human factors)
Surveys	Feedback can be received from drivers after eco-driving training/programs	Low cost and simple Large scale studies Understand drivers’ attitude, motivation and acceptance	No quantitative data on fuel consumption and emissions

Numerical modelling	The effects of driving behaviors on emissions and fuel consumption can be predicted and evaluated by numerical modelling	Low cost Shorten research cycle	Not real-world data Limited factors considered Limited output data

2.6 Knowledge gaps

Research methods used for eco-driving are reviewed above, including laboratory testing, on-road experiments and numerical modelling. In addition, factors of eco-driving technology are discussed and analysed. However, another important but overlooked factor to improve driving behavior hence reducing vehicle emissions and improve fuel economy is the application of on-board safety devices. On-board safety devices collect real-time safety-specific information which is provided to drivers to improve their on-road driving behavior and performance. This feedback information can be presented in the form of an auditory, visual or tactile alert via the on-board safety device [71, 131-133]. Different studies have been carried out to explore the effects of on-board safety devices on improving driver's driving behavior and evaluate the on-board systems using for instance sounds, lights or visual displays and haptic feedback as carriers of the information. Wang et al. [134] investigated the effects of visual and auditory feedbacks on driver performance. In the experiment, visual and auditory feedbacks were used to provide the advisory traffic information under the same circumstances. The results indicated that the visual feedback supported efficient driving whereas the auditory feedback supported safe driving via faster reactions. Lindgren et al. [135] compared the integrated advisory warning information display with a display providing only critical warnings. The results showed that drivers keep a longer and thus safer distance to cars in front of them when given advisory information rather than critical warnings only. Gaffary and Lécuyer [136] presented a survey on the use of haptic feedback in vehicles to enhance drivers' safety performance. The results indicated that haptic feedback appears to be an effective way to reduce the visual workload and convey information, such as for preventing hazards. However, current on-board safety device studies [23, 137-140] mainly focus on the effectiveness for improving driver's driving behavior and also the road safety implications of these systems but lack consideration of the relationship between on-board safety device implementation and gaseous emissions and fuel consumption under real-world driving conditions. In addition, researchers found that different drivers have different driving behaviors and attitudes towards eco-driving. The driving skills, habits and the risk perception abilities between professional and non-professional drivers were not always the same [22, 141, 142]. Therefore, this study aims to investigate the application of an on-board safety device to improve a driver's driving behavior thus reducing vehicle fuel consumption and gaseous emissions.

In this study, an on-board safety device was installed to provide the driver feedback instantaneously and monitor driving behavior under real traffic conditions. The device consists of a driver assistance system, movement detection sensor, video camera and a data collection box to monitor and record driving performance. The driver assistance system provides instantaneous auditory warnings to the driver when the vehicle acceleration, deceleration and turning speed exceeds the safety limit. In addition, the driver assistance system also provides instantaneous auditory warnings to alert the driver when a collision is imminent with an object (e.g. vehicle, pedestrian and cyclist). The hypothesis tested by this thesis is that real-time feedback on driving safety will yield positive benefits for fuel consumption and emissions. The experiments were conducted to investigate the effects of eco-driving and the majority of eco-driving studies focused on an individual's driving behavior. Furthermore, experiments were conducted with a driver-assistance system to overcome the known limitations with individual driving behavior that quite often relies on an eco-driving training program without driver assistance for achieving the desired benefit in fuel consumption and emissions. This thesis aims to achieve a thorough understanding of eco-driving technology, to investigate the effects of driving behavior on vehicle emissions and fuel consumption and to further investigate the application of an on-board safety device as an eco-driving technology for vehicles to reduce their fuel consumption and gaseous emissions. Finally, new control functions can be suggested and implemented into the safety device for different types of vehicles instead of only diesel goods vehicles to obtain a more significant effect on safe and green driving.

Chapter Three

3 Experimental setup of on-road emissions experiment

To investigate the effects of driving behavior on fuel consumption and gaseous emissions, a PEMS was installed on the test vehicles to measure RDE. In addition, the driving and environment parameters were recorded in the experiments. The experimental results were evaluated by the VSP methodology to understand the effects of driving behavior on fuel consumption and gaseous emissions. Sections 3.1 and 3.2 present the methodology for investigating the effectiveness of an on-board safety device on driving behavior of diesel goods vehicles and the effects of the safety device for experienced and less-experienced drivers.

3.1 Test rig for investigating of the effectiveness of on-board safety device on driving behavior

The objective of chapter 3.1 is to describe the methodology for installing an on-board safety device onto two diesel goods vehicles (one LGV and one MGV) to explore the effects on driving behavior and consequently on fuel economy and gaseous emissions using a PEMS. This section introduces the experimental setup, procedures, test conditions and the analytical method.

3.1.1 Test vehicles and driving route

In the first study, two diesel vehicles were selected to conduct the on-road emissions experiments; namely, a 5.5 tonnes LGV as shown in Figure 10 and a 16 tonnes MGV as shown in Figure 11. Each of them was installed with a safety device and a PEMS. The experiments were conducted in stage 1 without the safety device activated and stage 2 with the safety device activated, whereby activation of the safety system involved real-time warnings being issued to the driver of a vehicle. Real-time warnings were issued to the driver when speeding and potentially dangerous situations were detected. For example, the speed limit indicator scans for speed limits signs along the road to recognize the speed limit. Then the safety system provides instantaneous visual and auditory warnings to the driver when the vehicle exceeds the posted limit. In addition, the system sensor unit detects the moving objects in front of the vehicles and identifies an imminent collision. The forward collision warning indicates that under the current dynamics relative to the vehicle ahead, a collision is imminent and a lane departure warning alerts the driver of unintended or unindicated lane departure. The 5.5 tonnes LGV and the 16 tonnes MGV were chosen because they are the dominant diesel commercial vehicle types in Hong Kong. In May 2020, the total number of registered diesel vehicles in Hong Kong increased by 8.2% up to around 150,000 vehicles within five years, including private cars, buses, light buses, LGVs, MGVs, heavy goods vehicles (HGVs) and special purpose vehicles. As shown in Table 3, light and medium goods vehicles accounted for 50% and 25% of the total registered diesel vehicles in Hong Kong, respectively. For the tested LGV, it was an in-use diesel vehicle in Hong Kong equipped with two after treatment systems including exhaust gas recirculation (EGR) and a diesel oxidation catalyst (DOC). For the tested MGV, it was a Euro VI diesel vehicle and installed with emissions reduction devices including EGR, DOC, selective catalytic reduction (SCR) and a diesel particulate filter (DPF). The technical parameters of the two diesel goods vehicles are shown in Table 4.

Figure 10: The LGV used for on-road emissions measurement.

Figure 11: The MGV used for on-road emissions measurement.

Table 3: Registered diesel vehicles in Hong Kong for 2015 and 2020 [143, 144].

Type of vehicle	**Number of registered vehicles in 2015**	**Number of registered vehicles in 2020**
Private car	5,655	11,974
Buses	13,570	14,184
Light buses	3,624	3,166
Light goods vehicles	70,969	74,333
Medium goods vehicles	36,710	36,567
Heavy goods vehicles	5,485	6,714
Special purpose vehicles	1,368	1,691
Total	137,381	148,629

Table 4: The specifications of the test vehicles.

	LGV	**MGV**
Manufacturer	Isuzu	Scania
Model	NPR70	G280
Year	2003	2013
Engine size (c.c.)	4,751	9,291
Gearbox	Manual	Manual
Gross vehicle weight (kg)	5,500	16,000
Odometer	474,451	84,055
After-treatment system	EGR and DOC	EGR, DOC, SCR and DPF

The on-road emissions tests were conducted using a test route that was designed to reflect the characteristics of a typical Hong Kong real-world driving task. To design the test route, a typical and popular test route was selected for the on-road emissions tests. In order to reflect the diversity of normal on-road driving, a test route was constructed with around 6 kilometers of urban roadway driving and 28 kilometers of rural driving with a targeted total test duration of 45 minutes. The characteristics of the testing route are described in Table 5. The on-road emissions experiments were conducted in two stages. In the first stage of the experiments, the driver was requested to drive along the route normally. In the second stage of experiments, an on-board safety device was installed (and operational) on the test vehicles to provide the driver with real-time information and guidance on how to improve their driving behavior. In the experiments, one driver is responsible for each vehicle and each vehicle was tested for two trips over the same route (i.e. two trips without the safety device and two trips with the safety device activated). Due to a limitation of resources, only two drivers (driver A and driver B) were recruited to conduct the on-road emissions experiments. In the on-road emissions experiments, the LGV was driven by driver A and the MGV was driven by driver B. Both drivers were full-time drivers with at least 20 years of driving experience. The drivers were male and their age range are 50 - 58 years old. Based on the test order described above, the drivers were asked to conduct practice driving in a car park for 10 to 15 minutes to become familiar with the vehicles and the on-board device before performing the on-road emissions experiments. The test route used for on-road emissions measurement is shown in Figure 12. The experiments were conducted during 11:30 a.m. to 12:30 p.m. and repeated during 03:30 p.m. to 04:30 p.m. on the same day, to avoid peak hours and to maintain a relatively low traffic density which allowed the driver to drive according to their own driving style in stage 1. Table 6 shows the environmental conditions in the experiments. It can be noted that weather conditions were similar in the experiments. For the environmental conditions during the on-road emissions testing, the ranges of temperature and humidity were 25.1 - 26.3 °C and 72.1% - 83.3% respectively. There were mainly sunny days for the emissions testing.

Table 5: Characteristics of road types tested.

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

Remarks: No highway driving was done with > 90 km/h due to the sorts of roads planned in the experiment.

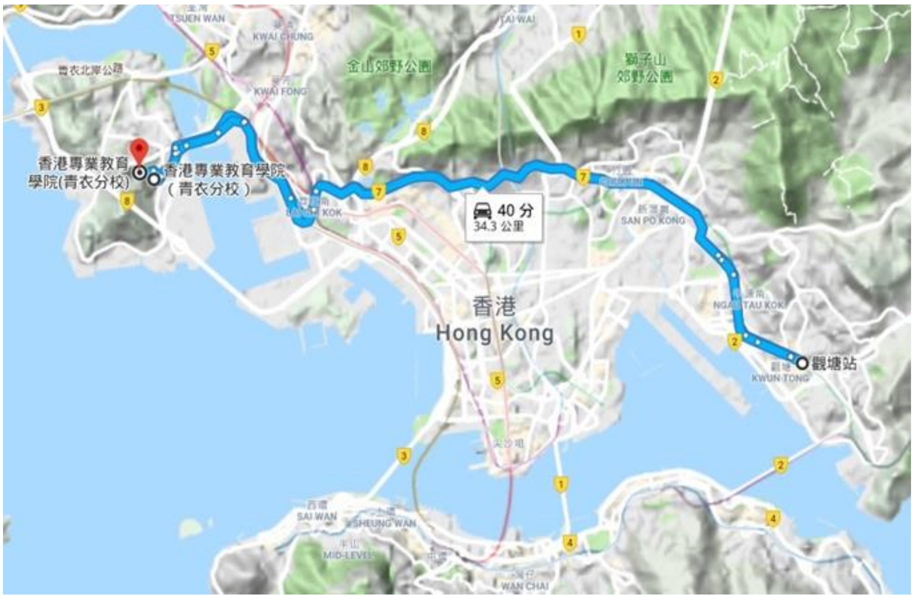


Figure 12: Experimental test route for on-road data collection (map sourced from Google Maps).

Table 6: Environmental conditions during the experiments.

Temperature (°C)	25.1 - 26.3
Humidity (%)	72.1 - 83.3
Weather	Sunny

3.1.2 On-board safety device

Fuel consumption and vehicle emissions are strongly affected by driving behavior [18, 76]. Eco-driving training programs are able to provide drivers with the knowledge and skills to drive more efficiently and in a more environmentally friendly fashion. However, the training effects of eco-driving programs can be short-lived as drivers tend to revert back to their previous driving behaviors. On the other hand, on-board devices can continuously monitor driving and provide drivers with feedback. Feedback on driving performance and advice on improving it are provided to drivers based on the monitoring. Furthermore, they can provide the driver feedback instantaneously and monitor driving behavior under real traffic conditions. Safety devices can meet the above requirements [43, 145]. They monitor driving performance, including vehicle speed, acceleration, deceleration, gear shifting, idling time, fuel consumption, road information and traffic conditions. The feedback may be given by dashboard displays, smartphone applications, GPS navigation systems and dedicated aftermarket feedback systems [146]. Although drivers are willing to adopt on-board devices, acceptance depends strongly on the design of the system, such as the type, content, complexity and presentation of information, which should be considered seriously from an ergonomics perspective [147]. It has been clearly shown that different drivers have very different preferences on the type of information and the majority preferred simple and clear information [148]. Personalised feedback could increase drivers' acceptance and the effectiveness of on-board safety devices [149, 150].

In this study, an on-board safety device was installed on the test vehicles to record the number of tailgating and brake warnings in stage 1 and the real-time warnings were issued to the driver in the second stage of the experiments. Table 7 shows the model and specifications of the sensor and driving user interface unit of the on-board safety device. The on-board safety device was manufactured in Israel and consisted of a Mobileye Advanced Driver Assistance Systems and a Mobileye EyeWatch in-car feedback system. They were developed to provide feedback and collect raw driver operation data under real traffic condition, including driver operation data and a driving video. All acquired data were recorded in the internal SD card and transmitted to a server. The sensor unit had an input voltage of 12 to 28 volts and an input current of 120 to 220 mA. It was equipped with an Aptina MT9V024 RCC vision sensor. The camera was a compact high dynamic range complementary metal-oxide-semiconductor (CMOS) and the pixel size was 6.0 μm × 6.0 μm. For the physical characteristics of the driving user interface unit, the diameter and the depth were 49 mm and 24 mm, respectively. The input voltage was 5 volts and the input current was 500 mA. In order to provide precise visual and auditory warning to the driver, the unit was equipped with a high-quality audio alert buzzer and a high–intensity visual indication on an LED display unit. Figure 13 shows the main components and signal flows of the safety device used in the present study. As shown in Figure 13, the device consists of a driving user interface, a movement detection sensor and a video camera which provide warnings to the driver when speeding and potentially dangerous situations were detected. The movement detection sensor and video camera were mounted on the windshield. The driving user interface was installed on the front panel of the test vehicles. The movement detection sensor detects the moving objects in front of the vehicles and identifies an imminent collision. The driving user interface (as shown below) will provide instantaneous visual and auditory warnings to alert the driver when a collision is imminent with an object (e.g. pedestrian, cyclist, motorcycle, truck). In addition, the speed limit indicator scans for speed limits signs along the road to recognize the speed limit. The driving user interface (Figure 14) also provides instantaneous visual and auditory warnings to the driver when the vehicle exceeds the posted limit. The warnings will not disappear until the driver makes the corresponding changes or the potential hazard disappears. As shown in Figure 14, those warnings include a headway monitoring warning, lane departure warning, forward collision warning, pedestrian collision warning and speed limit warning. Driving behavior can potentially be improved after the driver receives feedback from the device by correcting the problems indicated by the warning. The device can also be used to monitor driving performance and to record road information and traffic conditions which involve storing the data on the internal SD card and uploading the data to a server. This last feature is important in this study as extra hardware and software are not required to be purchased and installed to access and analyse the recorded data. In addition, the experimental data is available online for drivers/users to review their driving behavior during or after on-road driving. For example, the barriers to use a smart phone application as an in-vehicle feedback device are significant, requiring availability of a smart phone, acquisition of software, purchase and installation of a phone holder or car mounting base. On the other hand, the limitation of the on-board safety device is that it may cause distraction to drivers. The introduction of visual feedback will inevitably draw some attention away from the driving task and increase cognitive workload. Furthermore, the on-board safety devices are relatively expensive (around HK$12,000 per device), which will tend to limit their overall market penetration and impact.

Table 7: Specifications of the on-board safety device.

Sensor unit		
Electrical characteristics	Input voltage	12 - 28 volts
	Input current	220 mA @ 12 volts / 120 mA @ 24 volts
Vision sensor	Sensor model	Aptina MT9V024 RCC
	Optical Format	1/3”
	Pixel Size	6.0 µm × 6.0 µm
Driving user interface unit		
Electrical characteristics	Input voltage	5 volts
	Input current	500 mA
Physical characteristics	Diameter	49 mm
	Depth	24 mm
Display characteristics	Viewing Angle	120 degree
	Display colours	Red, White, Green, Blue
Types of warnings	Headway monitoring warning, lane departure warning, forward collision warning, pedestrian collision warning and speed limit warning.	

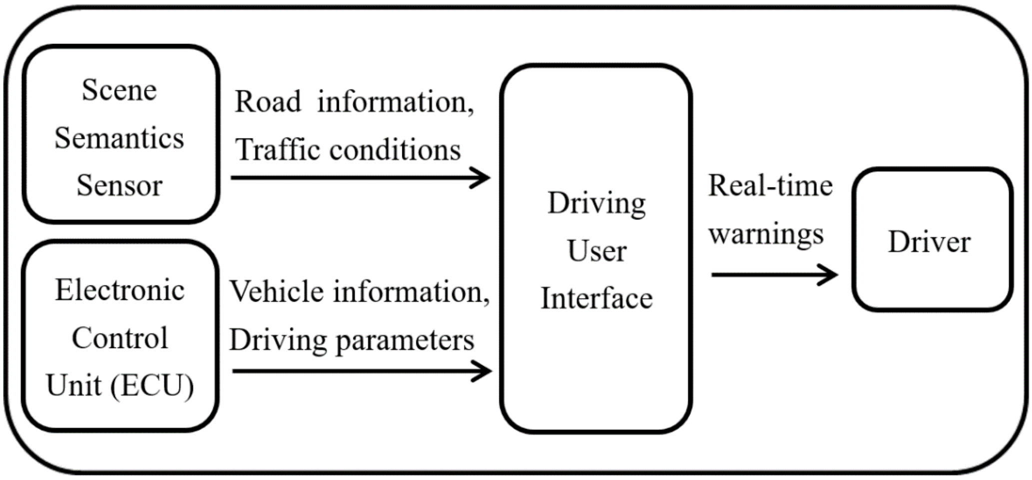


Figure 13: Block diagram of the on-board safety device.

(a). Forward collision warning

(b). Headway monitoring warning

(c). Speed limit warning

(d). Pedestrian & Cyclist Collision Warning

(e). Lane departure warning

Figure 14: Types of warnings provided by the on-board safety device.

3.1.3 Portable emissions measurement system

PEMS is a set of emissions measurement systems that can be installed on the vehicle under study [151, 152]. PEMS has become an important method for RDE research because it can provide instantaneous emissions of different pollutants with satisfactory levels of accuracy in a dynamic on-road environment from real-driving. In the on-road emissions experiments, a PEMS [153] was installed on the test vehicles including a 5.5 tonnes LGV (Figure 10) and a 16 tonnes MGV (Figure 11) to obtain real-world emission data, driving parameters and environmental parameters. As shown in Figure 15, an EMS 5003 emissions gas analyzer was integrated into the system to measure vehicle emission concentrations from the tailpipe, including HC, CO, CO_2 and NO. The EMS 5003 employs a Non-dispersive Infra-red (NDIR) detector with a reading accuracy of ± 3% to measure HC, CO and CO_2. NO and O_2 sensors are measured by electrochemical cells with a reading accuracy of ± 4% and ± 0.1% respectively. The technical parameters of the EMS 5003 emissions gas analyzer are shown in Table 8. To assure the accuracy of the test measurements, the EMS 5003 was zeroed before each test and was calibrated with standard gases (US EPA Bar 97) before the first test on each day [154]. In addition, a Sensors EFM-2, an exhaust flow measurement system, was directly connected to the tailpipe to measure instantaneous exhaust mass flow rate and temperature from the vehicles. A weather station and a GPS module were mounted on the roof of the test vehicles to measure and record environmental and driving parameters. A Vaisala HMP155 humidity and temperature probe was employed to measure ambient temperature, relative humidity and atmospheric pressure during on-road testing. At the same time, a VBOX Mini (which is a GPS module) was used to track the route, elevation and ground speed during tests. In addition, a battery pack consisting of three lead acid batteries with a capacity of 285 Ah was mounted inside the trunk to supply power for the instruments. In the present study, gaseous emissions data, driving and environmental parameters were logged at a sample rate of 1 Hz and sent to the internal storage of a notebook computer using an Ethernet cable. The key recorded parameters are shown in Table 9. During experiments on four days, data of real-world driving in excess of 270 km were collected from the test vehicles. Around 20,000 data points, including emissions data, driving parameters and environmental parameters were analysed.

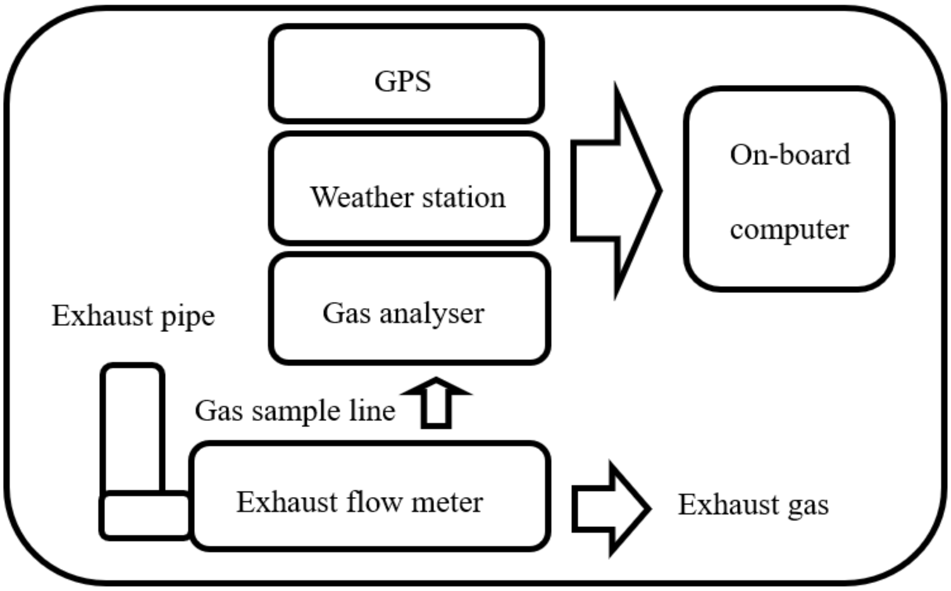


Figure 15: Block diagram of a PEMS.

Table 8: The specifications of the EMS 5003 emissions gas analyzer.

Gas	Standard Range	Resolution	Accuracy
HC	Propane: 0 - 4000 ppm	1 ppm	± 4 ppm or 3% reading
CO	0 - 15%	0.01%	± 0.02% ppm or 3% reading
CO_2	0 - 20%	0.1%	± 0.3% ppm or 3% reading
NO	0 - 5000 ppm	1 ppm	± 25 ppm or 4% reading in 0 - 4000 ppm ± 25 ppm or 8% reading in 4001 - 5000 ppm

Table 9: Key parameters collected by the PEMS.

Equipment	Parameter	Unit
EMS 5003 emissions gas analyser	Hydrocarbons	ppm
	Carbon monoxide	%
	Carbon dioxide	%
	Nitric oxide	ppm
Vaisala HMP155 humidity and temperature probe	Ambient temperature	° C
	Ambient humidity	%
	Ambient pressure	mbar
EFM-2 exhaust flow measurement device	Exhaust flow rate	kg/hr
	Exhaust flow temperature	° C
VBOX Mini GPS module	Vehicle speed	km/h
	Vehicle position	Latitude, longitude and elevation
	Vehicle altitude	m

3.1.4 Data analysis using VSP methodology

VSP is defined as the instantaneous power output of the engine per unit mass of the vehicle [155]. In recent years, emission models have been widely applied to quantify emission rates and fuel consumption using VSP analysis [154, 156, 157]. VSP represents vehicle operating conditions and is calculated using information regarding vehicle speed, vehicle acceleration and road grade all of which are highly correlated with fuel consumption and gaseous emissions [158, 159]. 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, VSP calculations involve aerodynamic drag and tire rolling resistance of the vehicle. Thus, the formulae were developed for calculating the VSP values for different types of vehicles. In the present study, equations (1) and (2) are applied for calculating the VSP of LGVs and MGVs respectively [155, 160].

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

$$VSP_{MGV} = v \cdot (a + g \cdot \sin(\emptyset) + \varphi_{MGV}) + \delta_{MGV} \cdot v^3$$

where VSP_{LGV} (W/kg) and VSP_{MGV} (W/kg) are the calculated vehicle specific powers of LGVs and MGVs, 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_{LGV} or φ_{MGV} is the coefficient of rolling resistance term (0.132 and 0.092 for LGVs and MGVs, respectively [127, 160]), and δ_{LGV} or δ_{MGV} is the coefficient of drag term (3.02×10^{-4} and 2.1×10^{-4} for LGVs and MGVs, respectively [127, 160]).

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 0.1 km. The elevation for each run along the segment is averaged and calculated. Thus, the average road grade is calculated for each segment.

Based on the recorded data, VSP values were calculated and grouped into 14 modes and four driving conditions as shown in Table 10. 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.

Table 10: Vehicle specific power modal range [127].

Vehicle specific power (W/kg)	**VSP Mode**	**Driving condition**
$VSP < -2$	1	Deceleration
$-2 \leq VSP < 0$	2	
$0 \leq VSP < 1$	3	Idling
$1 \leq VSP < 4$	4	Mild driving
$4 \leq VSP < 7$	5	
$7 \leq VSP < 10$	6	
$10 \leq VSP < 13$	7	

$13 \leq VSP < 16$	8	
$16 \leq VSP < 19$	9	
$19 \leq VSP < 23$	10	
$23 \leq VSP < 28$	11	Heavy acceleration
$28 \leq VSP < 33$	12	
$33 \leq VSP < 39$	13	
$VSP \geq 39$	14	

3.2 Test rig for investigating the effectiveness of safety device for experienced and less-experienced drivers

In the second study, eco-driving technology for reducing emissions and fuel consumption of diesel commercial vehicles in Hong Kong was investigated. An on-board safety device was installed on a Euro 5 diesel light goods vehicle. 30 drivers with different levels of driving experience were recruited to perform on-road emission tests, including 15 experienced and 15 less-experienced drivers. Gaseous and particulate emissions measurements were conducted on a real-world driving route by using PEMS. This section introduces the experimental setup, procedures, test conditions and the analytical method.

3.2.1 Test vehicle and driving route

In Hong Kong, there were a total number of 150,000 registered goods vehicles in 2020, including light, medium and heavy goods vehicles. Around 75,000 light goods vehicles were registered and travelling on road [143]. Thus, a diesel light goods vehicle representative of the Hong Kong market was selected to perform the on-road emissions measurement, as shown in Figure 16. The 3.3 tonnes LGV is equipped with an in-line four-cylinder, 3.0 L displacement, turbocharged diesel engine with a combined DPF, EGR and DOC after treatment system. The DPF is a ceramic filter consisting of thousands 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. 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 at the beginning of the test had covered 53,050 kilometers. The technical parameters of the 3.3 tonnes LGV are shown in Table 11.

Figure 16: The 3.3 tonnes light goods vehicle used for on-road emissions experiment.

Table 11: The specifications of the test vehicle.

Manufacturer	Toyota
Model	HIACE
Year	2014
Engine size (c.c.)	2,982
Gearbox	Automatic
Gross vehicle weight (kg)	2,800
Odometer (km)	53,050
After treatment system	EGR, DOC and DPF

The on-road emissions tests were conducted in Hong Kong, along the route shown in Figure 17. The testing routes in the New Territories consisted of urban (< 50 km/h), fast urban (50 - 70 km/h) and highway (> 70 km/h) driving conditions [161]. The test route was constructed around 5 kilometers of urban roadway driving, 6 kilometers of fast urban driving and 8 kilometers of highway driving with a total distance of 19 kilometers. One complete PEMS trip duration was targeted between 25 and 30 minutes. The fuel consumption rate firstly decreases with the increase of engine speed due to reduced heat losses, reaches the optimal point and then increases at high speeds due to increased friction losses [162]. As a result, the fuel consumption-driving speed curve shows a U-shape. Therefore, highway driving condition was included in the on-road emissions tests to cover a wide range of driving speed, to improve understanding of the driving behavior on fuel economy. All on-road emissions tests were started with the coolant temperature in a range of 75 to 90 °C. Figure 18 shows the vehicle speed profile of the PEMS test route compared to the NEDC and WLTC cycles (Figure 19). As it can be seen, the total time of the PEMS test is similar to the NEDC and WLTC, respectively. Also, the PEMS test route had more balanced shares for rural, urban and highway driving conditions. The characteristics of the PEMS testing route are described in Table 12.

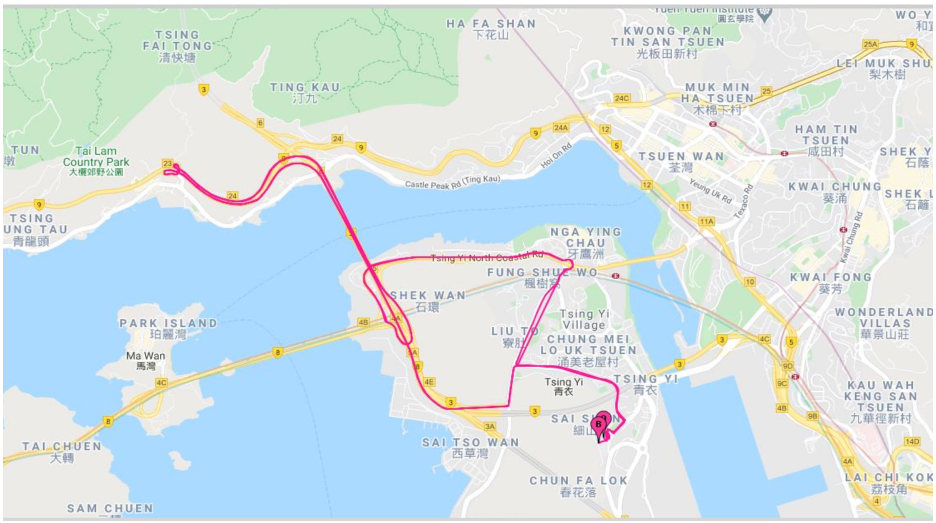


Figure 17: PEMS test route for on-road data collection (map sourced from Google Maps).

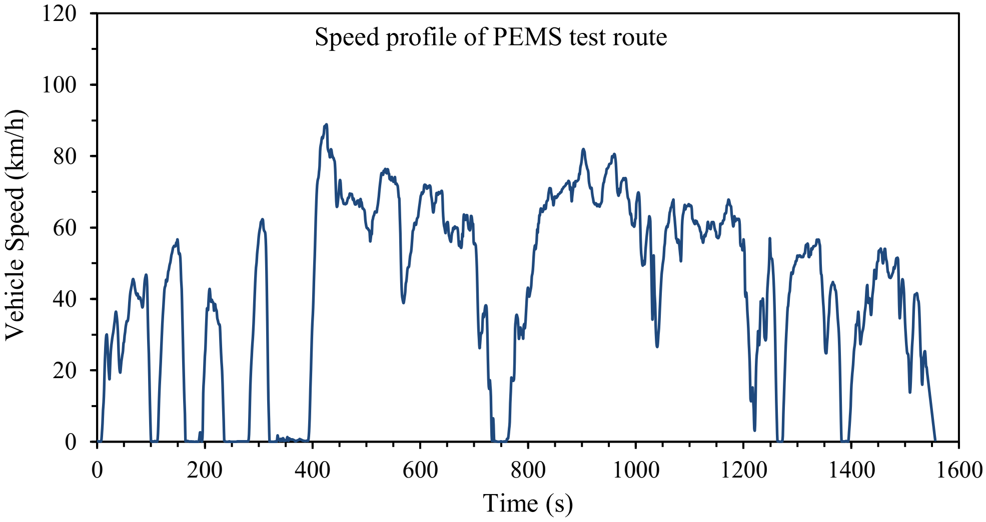


Figure 18: Vehicle speed profile of the PEMS test route.

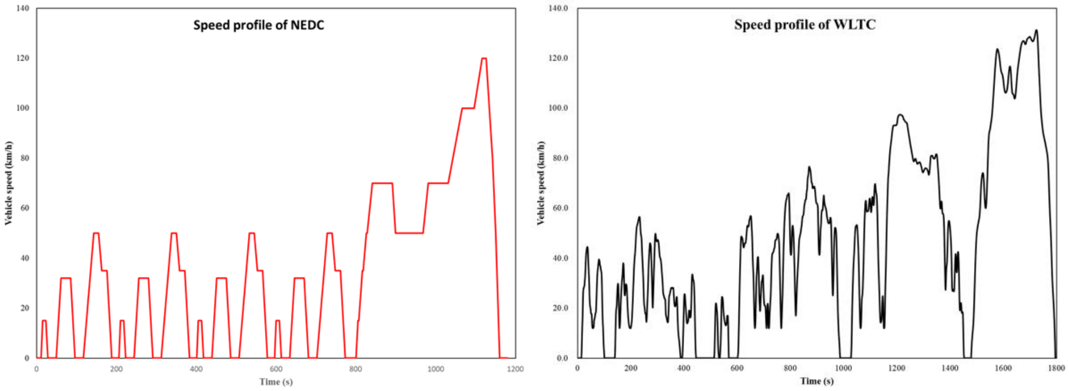


Figure 19: Vehicle speed profile of the NEDC and WLTC.

Table 12: Characteristics of PEMS testing route.

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.

3.2.2 Test drivers

As reviewed above, different drivers have different driving behaviors and attitudes towards eco-driving. Researchers found that the driving skills, habits and the risk perception abilities between professional and non-professional drivers were not always the same [22, 141, 142]. Therefore, to discover the possible distinct effects of eco-driving on different driver groups and understand the effectiveness of on-board safety device comprehensively, 30 drivers were recruited to conduct the on-road emission tests in the second study, including 15 experienced and 15 less-experienced drivers. The 15 experienced drivers recruited were professional drivers and they are full-time taxi or truck drivers. In addition, the experienced drivers had at least 15 years of driving experience, with an age range of 40 - 72 years old and they are holding a valid passenger car, taxi and LGV driving license. For the 15 less-experienced drivers, they had 3 - 5 years of driving experience and were aged between 21 - 40 years old. The average age of all less-experienced drivers is younger than that of the experienced drivers and the less-experienced drivers are holding a valid passenger car and LGV driving license. In addition, all 30 experienced and less-experienced drivers recruited to perform on-road emission tests were male to minimise bias attributable to sample heterogeneity. Details of test drivers recruited in the on-road emission tests are shown in Table 13. Before the first stage of the on-road emissions experiments, 10 to 15 minutes of practice driving was conducted in the car park. Drivers can become familiar with the vehicles and on-board device to minimise the confounding of learning on the experimental results. 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 followed his own driving style. In the second stage of experiments, the on-board safety device was activated to provide the driver with real-time information and guidance on how to improve their driving behavior. In the experiments, each driver was 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 drivers to drive according to his own driving style. The details of on-road emissions experiments are shown in Table 14.

Table 13: Details of test drivers (experienced and less-experienced 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	Less than 3 points
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	Less than 3 points
Driver 6	Male	50 - 60	More than 25 years	Less than 3 points
Driver 7	Male	> 70	More than 25 years	Less than 3 points
Driver 8	Male	30 - 40	Less than 5 years	Less than 3 points
Driver 9	Male	18 - 30	Less than 5 years	5 - 10 points
Driver 10	Male	30 - 40	Less than 5 years	Less than 3 points
Driver 11	Male	30 - 40	Less than 5 years	Less than 3 points
Driver 12	Male	40 - 50	15 - 25 years	Less than 3 points
Driver 13	Male	40 - 50	More than 25 years	Less than 3 points
Driver 14	Male	30 - 40	Less than 5 years	Less than 3 points
Driver 15	Male	30 - 40	Less than 5 years	Less than 3 points

Driver 16	Male	30 - 40	Less than 5 years	5 - 10 points
Driver 17	Male	30 - 40	Less than 5 years	Less than 3 points
Driver 18	Male	50 - 60	More than 25 years	Less than 3 points
Driver 19	Male	30 - 40	Less than 5 years	Less than 3 points
Driver 20	Male	60 - 70	More than 25 years	Less than 3 points
Driver 21	Male	30 - 40	Less than 5 years	Less than 3 points
Driver 22	Male	> 70	More than 25 years	Less than 3 points
Driver 23	Male	50 - 60	More than 25 years	Less than 3 points
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	Less than 3 points
Driver 27	Male	30 - 40	Less than 5 years	Less than 3 points
Driver 28	Male	50 - 60	More than 25 years	Less than 3 points
Driver 29	Male	60 - 70	More than 25 years	Less than 3 points
Driver 30	Male	50 - 60	More than 25 years	Less than 3 points

[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 [163].

Table 14: The driving pattern of on-road emission test experiments.

Test No.	Testing period	Status of on-board 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

3.2.3 Portable emissions measurement system

A PEMS installed on the test vehicle was used to record real-world emissions data. PEMS is a mobile instrument that is used on-board to measure vehicle emissions under real-driving conditions. PEMS integrates advanced gas analysers, a PM measurement device, an exhaust flow meter, a weather station, a wheel speed sensor and a GPS. In order to assure data quality, the on-road emissions experiments were conducted using AVL M.O.V.E Gas PEMS 493 and AVL M.O.V.E PM PEMS 494. In addition, the AVL M.O.V.E Gas PEMS 493 and PM PEMS 494 were not set up and commissioned in time for the first study. Therefore, the emissions data were measured and recorded by an EMS 5003 emissions gas analyzer in the first study. The gas PEMS uses a NDIR sensor for CO and CO_2 measurements, a non-dispersive ultra-violet (NDUV) analyzer to measure NO and NO_2 separately and simultaneously, a heated FID to analyze total hydrocarbons (THC) and an electrochemical sensor to measure oxygen (O_2). For the AVL M.O.V.E Gas PEMS 493, the analyzer used for emissions gases measurement were especially optimized for a high accuracy and resolution with a reading accuracy of ± 2% which was higher than the EMS 5003 emissions gas analyzer. The technical parameters of gas PEMS are shown in Table 15. 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. In addition, the filter conditioning and weighing environment is maintained in a mean temperature of 20 - 23 °C and a mean relative humidity of 45 - 55% over 24 hours. 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 was designed for weighing 47 mm filters specified in the EPA regulation [164]. It was based on gravimetric analysis and provided a resolution from one microgram to six grams. The technical parameters of PM PEMS are shown in Table 16.

To assure the accuracy of the test results, the AVL gas PEMS was zeroed with pure nitrogen before each test and was calibrated with standard gases (US EPA Bar 97) before and after the tests on each day. A zero calibration was performed so that the baseline concentration could be established to prevent a drift in measurements. An audit calibration was 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. The test vehicle with the AVL gas and PM PEMS installed and the zero-calibration gas bottle are shown in Figure 20 and 21. In addition, a Sensors EFM-2, a 2.5-inch exhaust flow measurement device was used in this study to measure instantaneous exhaust mass flow rate and exhaust temperature from the test vehicle. A weather station was mounted on the roof of the test vehicle to measure the ambient temperature, relative humidity and atmospheric pressure during the on-road testing. As shown in Figure 22, 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. global positioning system 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 HC. A Honda EU 30is generator and a battery pack consisting of three lead acid batteries with a capacity of 150 Ah was mounted inside the test vehicle to supply power for the instruments. In the present study, gaseous emissions data, PM emissions data, driving and environmental parameters 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. The key recorded parameters are shown in Table 17.

Table 15: The specifications of the AVL M.O.V.E Gas PEMS 493.

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

Table 16: The specifications of the AVL M.O.V.E PM PEMS 494.

Specifications	
Dilution ratio	up to DR = 20 (constant)
	DR = 2 to 100 (proportional)
Sample flow over filter	6 L/min
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

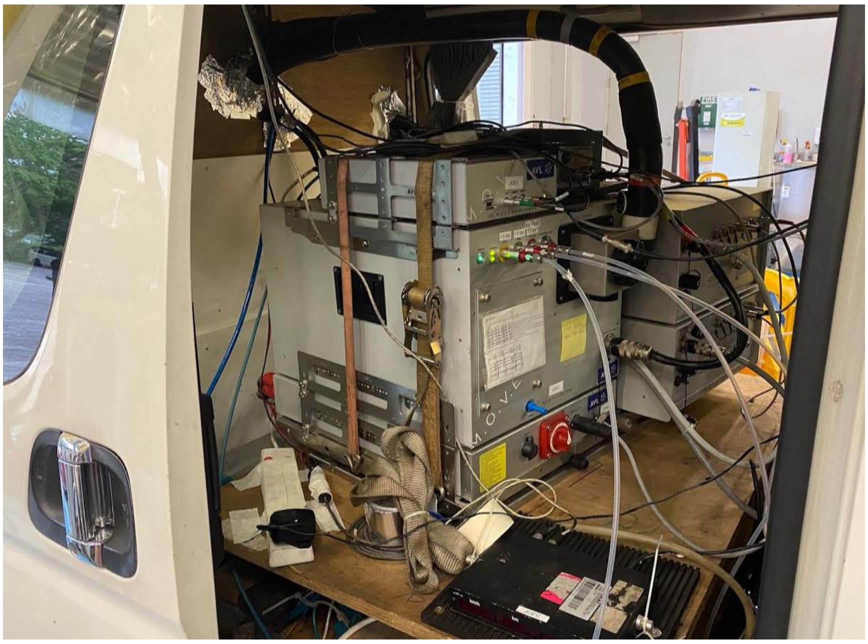


Figure 20: AVL gas PEMS installed on the test vehicle.

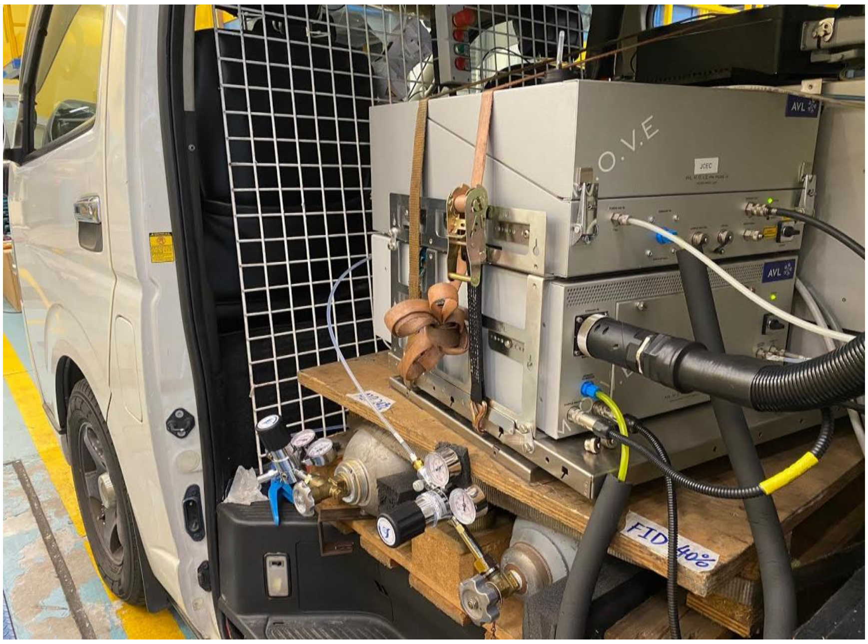


Figure 21: AVL PM PEMS installed on the test vehicle.

Table 17: 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

Figure 22: Test vehicle exhaust connected with the emissions gas sample line and exhaust flow measurement system.

3.2.4 On-board safety device

In this study, the on-board safety device installed on the test vehicle was used to record the number of braking events, and tailgating and speeding warnings in stage 1 and stage 2 of the on-road emissions experiments. The device was not activated until the second stage of the experiments. Figure 23 shows the main components and working principle of the safety device used in the present study. As shown in Figure 23, the safety device was designed to maintain safe driving conditions and consisted of a driver assistance system, movement detection sensor, video camera and a data collection box. In addition, the safety device used in this study has been further developed and upgraded to second generation by the relevant OEM. The movement detection system and driver assistance system were both upgraded to provide higher precision in the perception of potentially dangerous situations and to also provide comprehensive information to the driver. However, the details of system upgrade cannot be provided as they are proprietary and confidential information owned by Mobileye. The driver assistance system uses artificial intelligence image processing to analyse road conditions and to identify vehicles, pedestrians and other objects. 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 the data to the server. Drivers and fleet managers can download and analyse the relevant driving performance and driving alert videos via online platforms or mobile phones instantly. Table 18 shows the model and specifications of the driver assistance system and movement detection sensor. The driver assistance unit had an input voltage of 9 to 32 volts and an input current of 270 to 540 mA. It was equipped with a Foresight binocular camera. The resolution of the camera was 720 p and the scan distance was 1.5 to 100 m. During the on-road emission experiments, the driver assistance system was installed on the front panel of the test vehicle. The dual cameras were mounted on the windshield to detect and scan the moving objects in front of the vehicles and to identify the distance from the object precisely. The driver assistance system provides instantaneous auditory warnings to alert the driver when a collision is imminent with an object (e.g. vehicle, pedestrian or cyclist). 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 does not disappear until the drivers make the corresponding changes or the potential hazard disappears. As show in table 19, those warnings include forward collision warnings, lane departure warnings, headway monitor warnings, speed limit warnings as well as aggressive acceleration, deceleration and turning warnings. Driving behavior can be improved after the driver receives feedback from the device and avoids the problems indicated in the warning. The device can also be used to monitor driving performance and record the road information and traffic conditions and store the data in the internal SD card to be uploaded to a server. The major advantage of the upgraded on-board safety device is that it can provide instantaneous auditory warnings (without any visual feedback information and warnings) to the drivers when speeding and a potentially dangerous situation is detected. Researchers found that different types of feedback information would cause different distraction for drivers (e.g. visual, manual and cognitive). In addition, investigations showed that a driver would spend 4 - 8% of the time looking at the eco-driving displays when the visual feedback and information is presented [165]. The auditory feedback only had little effects on workload, it will not reduce driver’s attention to the forward view and increase their subjective workload. Gonder et al. [30] also suggested that auditory feedback might be preferable from a driver distraction point of view and the information provided should be made as simple as possible to understand to minimise the cognitive effort required to process it.

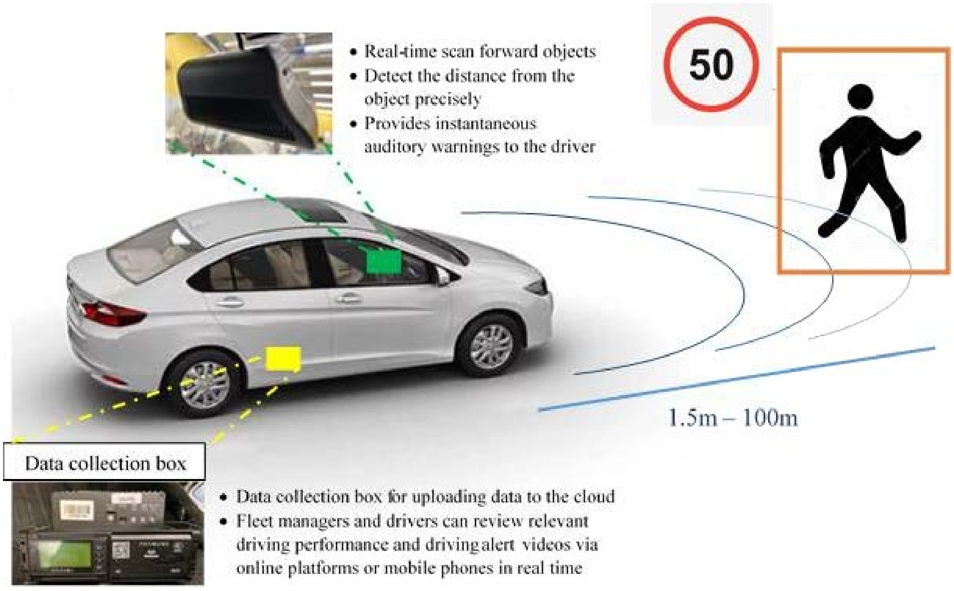


Figure 23: Working principle of the on-board safety device.

Table 18: Specifications of the on-board safety device.

Sensor unit		
Electrical characteristics	Input voltage	9 - 32 volts
	Input current	540 mA @ 12 volts, 270 mA @ 24 volts
Movement detection sensor	Sensor model	Foresight binocular camera
	Resolution	720 p
	Scan distance	1.5 m to 100 m

Table 19: Types of warnings provided by the on-board safety device.

Types of warnings	Alert mechanism
Forward collision warning	When a possible collision can occur between the vehicle and other general objects in front.
Lane departure warning	When the vehicle departs from the original driving lane without using the turn signal.
Headway monitor warning	When the distance from the vehicle ahead is equal or less than 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.

3.2.5 Data analysis using VSP methodology

Real-world emissions data and driving parameters were collected using a PEMS. Various models have been developed recently to analyse a vehicle's environmental performance. In this study, the VSP methodology was adopted by calculating the percentage of time spent in different driving patterns, including deceleration, idling, acceleration and hard acceleration. VSP is defined as the engine power output per unit mass of the vehicle. It is expressed as a function of vehicle speed, vehicle acceleration and road grade [166]. The main advantage of the VSP methodology is that the vehicle's specific power can be directly calculated from the data acquired in the experiments. Details of VSP calculations were defined and discussed in Section 3.1.4.

Chapter Four

4 Effects of an on-board safety device on driving behavior (and fuel consumption and emissions) of two diesel commercial vehicles

This chapter presents and discusses the experimental results for the first study which is a pilot study investigating the potential role of the on-board safety device in positively influencing driving behavior and also fuel consumption and emissions. The experimental results of the on-road emissions measurement of on-board safety device will be discussed in three sections. Section 4.1 reports the effects of the on-board safety device on driving behavior. In section 4.2 the driving time distribution over the VSP mode is analysed. Section 4.3 reports the effects of driving behavior on fuel consumption and exhaust gas emissions results from two diesel goods vehicles.

4.1 Effects of safety device on driving performance

Driving performance was assessed by different driving parameters, including average vehicle speed, maximum vehicle speed, maximum acceleration and the number of warnings. To understand the effects of the safety device on driving performance, drivers' driving behaviors will be analysed by comparing the driving parameters with and without the device. An on-board safety device was installed to provide real-time feedback to the driver. It was originally used to alert the driver of a potentially dangerous situation and unindicated lane departure to improve driving behavior. Based on the experimental design of on-road emissions experiments described in Section 3.1.1, two drivers (driver A and driver B) were recruited to drive the LGV and MGV respectively. The LGV was driven by driver A and the MGV was driven by driver B in the on-road emissions experiments. In the first stage of the on-road experiments, the driver was requested to drive in their normal pattern and style without activation of the safety device. In the second stage of the experiments, an on-board safety device was activated to provide real-time warnings to the driver. In addition, the driving parameters and warning messages were recorded during the experiments. The emissions data were measured and recorded by an EMS 5003 emissions gas analyzer. This choice was made because the AVL PEMS system was not set-up and commissioned in time for the first study. Furthermore, the driving parameters including vehicle speed, acceleration and position were also recorded. Due to limitation of resources, the experiments were conducted on four days, including eight trips with 256 km being travelled which was evenly distributed over two stages of experiments both with and without activation of the on-board safety device. The details of monitored driving data in stage one and stage two of the on-road emission experiments are shown in Table 20. The impact of the ambient temperature on the recorded data was negligible because the variation of the ambient temperature was less than 2 degrees.

Table 20: Monitored driving data.

	Stage 1	Stage 2
Travelling time per trip (minutes)	46	49
Travelling distance per trip (km)	32	32
Number of Trips	4	4

Table 21 demonstrates the driving parameters of tested vehicles in two stages of experiments. As shown in Table 21, the average speed of the LGV was reduced by around 9% and the maximum speed of the vehicle was decreased from 97.7 km/h to 75.6 km/h from the first to the second stage. The total travelling time in the second stage of experiments was three minutes longer than that in the first stage. From a safety point of view, the number of tailgating warnings and aggressive braking events were both reduced by 54% and 86% respectively from the first to the second stage. The reduction of aggressive braking events can be explained with two reasons. Firstly, the coasting distance was increased so that it spent less time on idling at the traffic lights. Secondly, the number of heavy decelerations were also decreased. These two results indicate the reduction of braking number on achieving fuel savings when the driver closely followed the instruction from the on-board safety device and drove in a more environmentally friendly and safe manner. Compared with the LGV, results for the effects of the safety device on driving performance in the 16 tonnes MGV were very different. As shown in Table 21, the average speed of the MGV was reduced by 4% from the first to the second stage. However, the maximum acceleration was increased 7% from 1.5 m/s^2 to 1.6 m/s^2 after activation of the safety device. Furthermore, the numbers of tailgating warning and braking were reduced by 41% and 39% respectively for the MGV. To understand the results shown in Table 21, the distributions of the driving parameters of LGV and MGV over the VSP mode will be presented and analysed.

Table 21: Driving parameters of tested LGV and MGV between both monitoring stages. Data are presented in the format: average (minimum value - maximum value).

	LGV		MGV	
	Stage 1	Stage 2	Stage 1	Stage 2
Average vehicle speed (km/h)	43.8 (38.1 - 49.5)	40.1 (37.4 - 42.8)	36.8 (33.4 - 40.2)	35.2 (31.1 - 37.3)
Maximum vehicle speed (km/h)	97.7 (93.2 - 102.2)	75.6 (71.1 - 80.0)	70.6 (66.7.1 - 74.9)	71.9 (64.4 - 79.3)
Maximum acceleration (m/s^2)	3.3 (3.1 - 3.5)	2.9 (2.7 - 3.1)	1.5 (1.3 - 1.6)	1.6 (1.4 - 1.8)
Travelling time (minutes)	46 (44 - 48)	49 (47 - 51)	55 (52 - 58)	56 (52 - 59)
Tailgating warning (times)	54 (48 - 60)	25 (23 - 27)	49 (48 - 50)	29 (27 - 31)
Braking number (times)	44 (39 - 49)	6 (3 - 8)	28 (25 - 30)	17 (15 - 20)

4.2 Distribution of average travelling time over VSP mode

Travel time is quite often critical and affects vehicle emissions and fuel consumption. Shorter travel times are either 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. In the RDE experiments, the total traveling time of the diesel 5.5 tonnes LGV was 46 minutes in stage 1 and 49 minutes in stage 2. Figure 24 and Figure 25 show the average percentage of time spent on different VSP modes of the LGV and the MGV. As show in Figure 24, the percentage of time spent in modes 1 and 2 was reduced by 7% from stage 1 to 2. There is no difference in time spent in two stages of experiments for VSP mode 3. In the medium VSP modes 4 to 7, the percentage of time spent was increased from 37% to 47% from stage 1 to 2. The increase of average distribution from stage 1 to 2 in modes 4 to 7 can be related to a lower and steady speed of the vehicle as the driver controls the vehicle speed with assistance from the on-board system. It can be also explained as the driver controlled the speed of the vehicle more appropriately. In higher VSP modes 8 to 14, the percentage of time spent was decreased from 12% to 9% from stage 1 to 2. As mentioned previously, the maximum acceleration of the LGV was decreased from 3.3 m/s^2 to 2.9 m/s^2 from stage 1 to stage 2, indicating the reduced time spent on excess speeding and strong acceleration in stage 2 during the experiments. With the installation of the on-board safety device, it is possible to observe the average time spent is shifting from higher to lower VSP modes. As shown in Figure 25, the percentage of time spent of the MGV in modes 1 and 2 was reduced from 10% to 5% from stage 1 to 2. This can be explained as the braking number was reduced in stage 2 of the experiment. In VSP mode 3, the percentage of time spent was reduced by 12% from stage 1 to stage 2, due to the reduced time spent on idling in stage 2. In the medium VSP modes 4 to 7, the percentage of time spent is increased by 10% from stage 1 to 2 and by 8% in VSP modes 8 to 14. For the experimental results of MGV, the percentage of time spent on lower VSP modes is reduced with the activation of the safety device. However, the time spent on higher VSP modes is increased in the second stage of the experiment. It indicates that the driver tends to spend more time on excessive speeding, strong acceleration and deceleration, leading to the increase of fuel consumption after the activation of safety device on MGV which will be discussed in section 4.3.

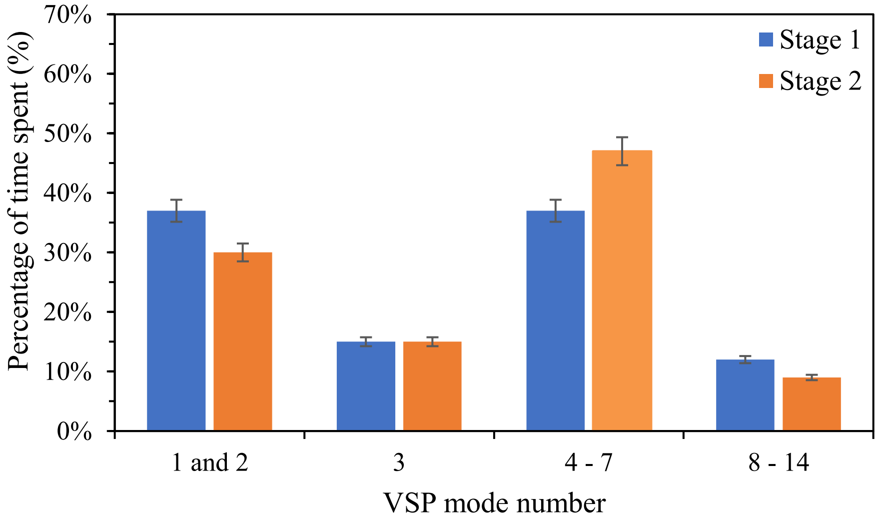


Figure 24: Comparison of average time distribution over VSP modes of LGV between stages without (stage 1) and with (stage 2) the on-board safety device. Error bars are represented by the standard deviation.

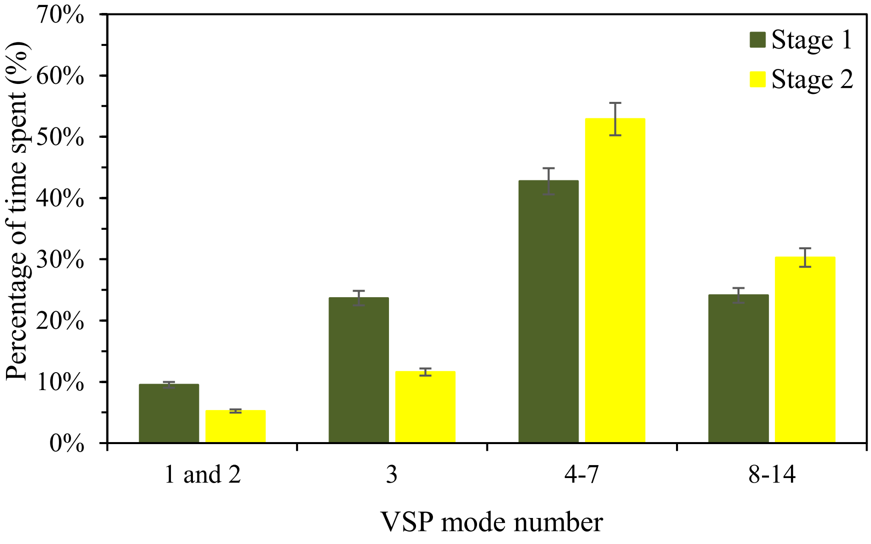


Figure 25: Comparison of average time distribution over VSP modes of MGV between stages without (stage 1) and with (stage 2) the on-board safety device. Error bars are represented by the standard deviation.

4.3 Effects of safety device on fuel consumption and exhaust gas emissions

To assess the effects of driving behavior on fuel consumption and gaseous emissions of the LGV and MGV under real-driving conditions, exhaust gas emissions and fuel economy in each of the VSP modes were calculated. Table 22 shows the overall fuel consumption and emission rates of two diesel goods vehicles with and without the activation of safety device. As shown in Table 22, the HC and CO_2 emission rates of the LGV were greatly reduced by 56% from 4×10^{-2} g/km to 2×10^{-2} g/km and 23% from 492.5 g/km to 381.4 g/km respectively from stage 1 to stage 2, demonstrating a strong impact of the safety device on HC and CO_2 emissions of the LGV. The results can be also supported by the driving parameters presented in section 4.1 and explained by the driver driving the LGV more carefully with a reduction in maximum acceleration and aggressive braking. In addition, with the reduction of time spent on excessive speeding, strong acceleration and deceleration, the NO emission rates of LGV were reduced by 10% in the second stage of experiment. However, the CO emission of the LGV was increased from 1.06 g/km to 1.39 g/km. This result is consistent with the previous study that the driving behavior did not show distinct differences in CO emissions [127]. In addition, this is expected as many studies have reported that for CO emissions other parameters than driving style were more important, e.g. engine air-fuel mixture, intake temperature and the cold start [76, 167]. The fuel consumption of the LGV is calculated by using a carbon balance methodology [168]. A reduction of 23% of fuel consumption was achieved when the on-board safety device was used. As shown in Table 22, the HC and CO_2 emission rates of the MGV were increased by 5% and 4% respectively from stage 1 to stage 2. This is mainly because the percentage of time spent on higher VSP mode is increased and the driver tends to spend more time on excessive speeding and strong acceleration. The HC emissions were increased from 66×10^{-4} g/km without the device to 69×10^{-4} g/km with device, and the CO_2 from 602.2 g/km to 626.1 g/km. The increased CO_2 emissions are mainly due to the fuel consumption which was increased from 22.9 L/100 km without the device to 23.8 L/100 km with the device. After activation of the on-board safety device, the maximum acceleration of the MGV was increased around 7%. With the higher acceleration of the test vehicle, the fuel consumption was increased by 4% from the first stage to the second stage of the experiment.

Table 22: Averaged exhaust gas emission rates and fuel consumption of diesel LGV and MGV.

	LGV			MGV		
	Stage 1	Stage 2	% of change	Stage 1	Stage 2	% of change
HC (g/km)	4×10^{-2}	2×10^{-2}	-56%	66×10^{-4}	69×10^{-4}	5%
CO (g/km)	1.06	1.39	31%	1.40	0.91	-35%
CO_2 (g/km)	492.5	381.4	-23%	602.2	626.1	4%
NO (g/km)	3.84	3.47	-10%	0.81	0.45	-44%
Fuel economy (L/100 km)	15.6	12.1	-23%	22.9	23.8	4%

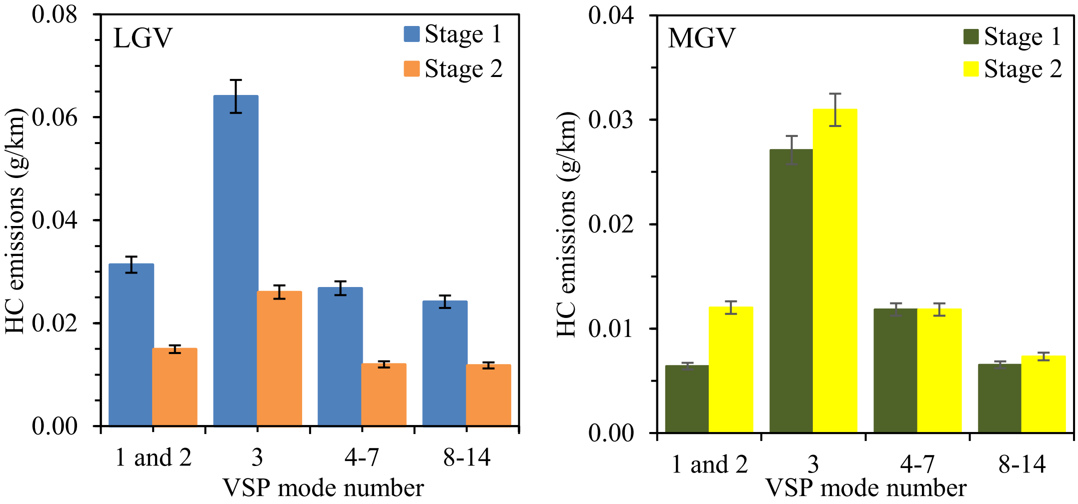
To understand the averaged results shown in Table 22, distributions of the emissions and fuel consumption over the VSP mode were analysed. Figure 26 and Figure 27 shows the distribution of emissions for the LGV and the MGV over the VSP modes. As shown in Figure 26a and 26c, using the on-board safety device for LGV, the emission rates of HC in VSP modes 1 and 2 were reduced by 52% and CO_2 were reduced by 17% in stage two of the on-road emissions experiment. On the other hand, CO emission rates were increased by 31%. It is reasonable to assume that CO emissions were not corresponding to the driving behavior when the test vehicle was decelerating in VSP modes 1 and 2. For the emission rates of the MGV in VSP modes 1 and 2, CO (Figure 26b) and NO (Figure 26d) emissions were reduced by 33% and 39% respectively from stage 1 to stage 2. This is mainly because the percentage of time spent in VSP modes 1 and 2 was reduced from 10% without the safety device to 5% with the safety device. As shown in Figure 27a, the fuel consumption of the LGV in VSP modes 1 and 2 was reduced by 17% in stage two when the on-board safety device was activated. This indicates a strong impact of the driving style such as reduction of aggressive braking and an increase of the coasting distance on fuel economy as shown in the experimental results.

For the emission rates of LGV in VSP mode 3 which is the idling condition, HC, CO_2, and NO emissions were reduced by 59%, 29% and 23% respectively from stage 1 to stage 2. The emission rates of HC were reduced from 6×10^{-2} g/km without activation of the on-board safety device to 3×10^{-2} g/km with activation of the on-board safety device. The CO_2 emissions were reduced from 756.2 g/km to 539.4 g/km and NO from 7.02 g/km to 5.43 g/km. A reduction of 29% of fuel consumption was observed in VSP mode 3 when the on-board safety device was used. For the emission rates of MGV in VSP mode 3, the HC and CO_2 emissions were increased by 14% and 25% respectively from stage 1 to stage 2. The increased emission rates of CO_2 are caused by the fuel consumption which was increased by 25% from 48.3 L/100 km without activation of the device to 60.3 L/100 km with activation of the device. The increased emission rates of HC and CO_2 can be also explained as the on-board safety device was originally designed for the passenger cars and LGV to enhance the driving behavior of drivers. Therefore, the effects of the device were not obvious on the MGV. The device needs to be optimized for different vehicle types so that the driving behavior can be enhanced. The optimized on-board safety device with new control functions aimed for eco-driving applications can be incorporated for use with an MGV, by including features such as a gear shift indicator and real-time auditory feedback system. A gear shift indicator can be integrated in the on-board safety device to provide real-time information to the driver, which allows the driver to engage the next higher or lower gear to maintain the proper engine speed to improve drivers' driving behavior and hence to reduce vehicle emissions and fuel consumption. In addition, a real-time auditory feedback system can minimise the distraction caused by on-board devices, since the driver is not required to look away from the road to take in the information. The information provided can be made as simple as possible to understand to minimise the cognitive effort required to process it.

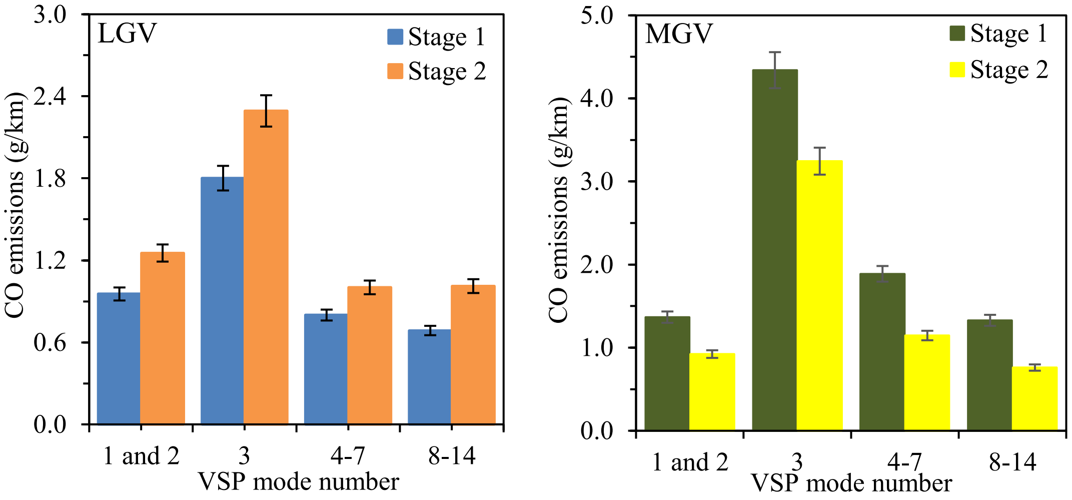
For the emission rates of LGV in the medium VSP modes 4 to 7 which represents normal driving conditions, the emission rates of HC, CO_2 and NO were reduced 55%, 24% and 6% respectively from stage 1 to stage 2. With the increase of the percentage of time spent in VSP modes 4 to 7 as presented in section 4.2, the HC emissions were reduced from 3×10^{-2} g/km without activation of the on-board safety device to 1×10^{-2} g/km with activation of the on-board safety device. The CO_2 emissions were reduced from 405.0 g/km to 308.5 g/km and the NO from 2.82 g/km to 2.65 g/km. This can be explained by the driver controlling the speed of the LGV more appropriately so that more time was spent on driving slowly and steadily. These results can be also supported by the differences found with the calculations of the driving parameters. The average vehicle speed of the vehicle was reduced around 10% from the first to the second stage of the on-road emissions experiment. Therefore, resulting in the reduction of CO_2, the fuel consumption of LGV was reduced by 24% from 12.8 L/100 km in stage 1 to 9.8 L/100 km in stage 2. For the emission rates of MGV, the CO emissions were greatly reduced by 39% from 1.9 g/km without activation of the device to 1.1 g/km with activation of the device. There are no differences exist for the HC, CO and NO emissions between both monitoring stages. The CO_2 emissions were increased by 6% from 643.6 g/km to 684.6 g/km. The increased emission rates of CO_2 were mainly due to the fuel consumption which was increased by 6% from 24.5 L/100 km without activation of the device to 26.0 L/100 km with activation of the device.

In higher VSP modes 8 to 14 with heavy acceleration, the emission rates for HC and CO_2, of the LGV were reduced by 51% and 15% respectively from stage 1 to stage 2. These results can be supported by the differences found with the calculations of the driving parameters. After the installation of the on-board safety device, the maximum acceleration of the LGV was decreased by 12% from 3.3 m/s^2 to 2.9 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 LGV as shown in the experimental results. In addition, the maximum speed of the vehicle was decreased from 97.7 km/h to 75.6 km/h from stage 1 to stage 2. With the lower and steady speeds of the test vehicle, fuel consumption was reduced by 15% from the first stage to the second stage of experiment. For the emission rates of the MGV, the emission rates CO and NO were reduced by 43% and 42% respectively from stage 1 to stage 2. However, the HC emissions were increased by 12%. In addition, the CO_2 emissions and fuel consumption were increased 0.3% after activation of the safety device. These results can be explained as the maximum speed and maximum acceleration of the vehicle was slightly increased from 70.6 km/h to 71.9 km/h and from 1.5 m/s^2 to 1.6 m/s^2, respectively.

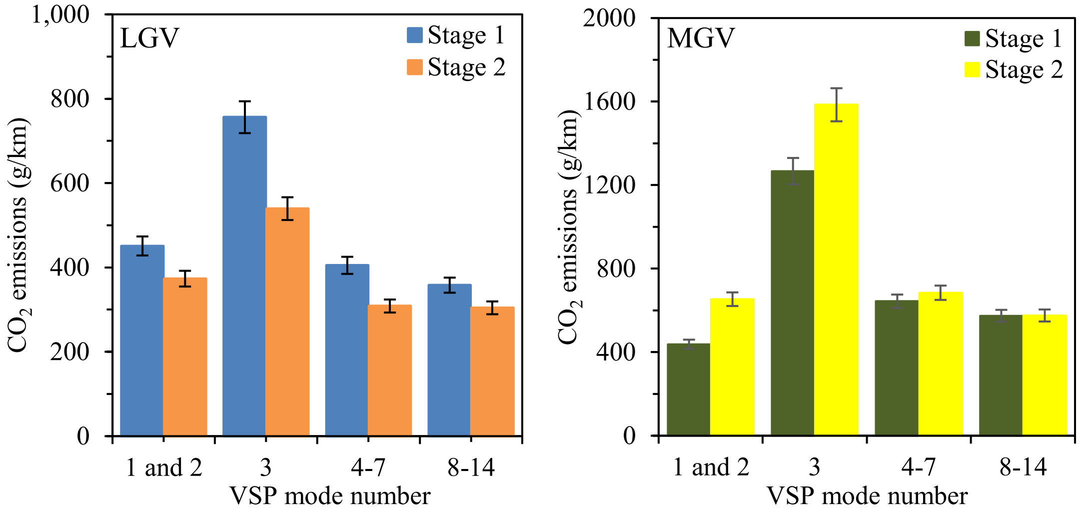
In the on-road emissions experiments, the tested LGV and MGV were manufactured in 2003 and 2013 respectively as shown in Table 4. The vehicle age and technological change may influence greenhouse and pollutant emissions of on-road vehicles. To understand the impact of the differences of vehicle age and emissions control, the variance of technologies and total travel mileage of the vehicles are important factors that need to be investigated. Zhang et al. [169] analysed the effects of engine and catalyst deterioration and technological variables on air pollutants for gasoline light-duty trucks. The results indicated that vehicle deterioration has a large influence on vehicle emission including HC, CO and NO_x. Pang et al. [170] investigated that vehicles start to show emission deterioration from age 3 – 5 years; most vehicles exhibit some degree of deterioration after 6 year and vehicle deterioration continued from age 9 – 11 years. However, Caserini et al. [171] found that the average mileage of 10–year old cars is only around 40% of the mileage driven on the first and only 10% for 20–year old cars. Based on the reduction of annual mileage, the NO_x and PM emissions drop by more than 20% when the corrected functions are used compared to using a constant mileage.



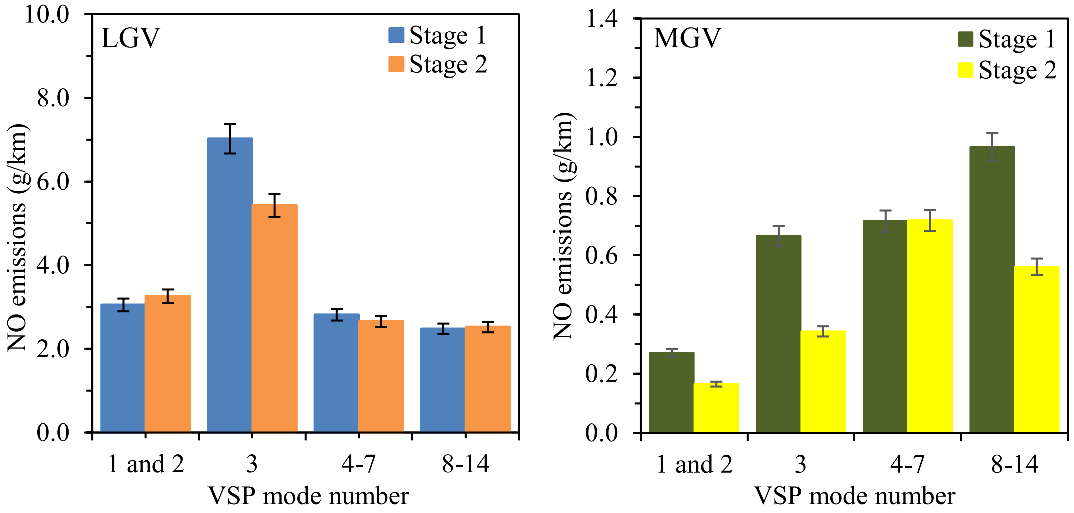
(a): HC emission factors.



(b): CO emission factors.



(c): CO_2 emission factors.



(d): NO emission factors.

Figure 26: The emissions of the LGV and MGV in each group of the VSP modes in both monitoring stages. Error bars are represented by the standard deviation.

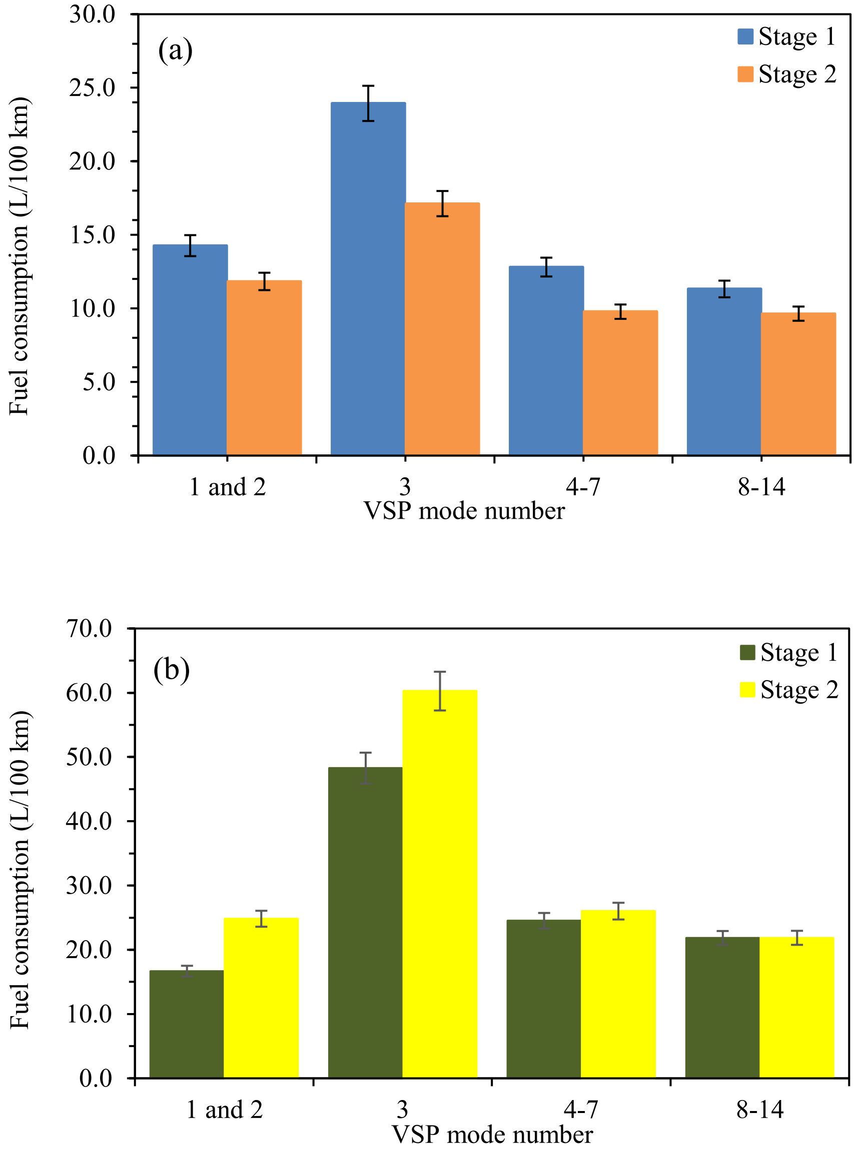


Figure 27: The fuel consumption of diesel 5.5 tonnes LGV (a) and diesel 16 tonnes MGV (b) in each group of the VSP modes in both monitoring stages. Error bars are represented by the standard deviation.

4.4 Summary

This chapter presented and discussed the experimental results from the first study. A pilot was conducted with on-road emissions measurement to investigate the effects of an on-board safety device on the emissions and fuel consumption of a diesel LGV and MGV. It was assessed in terms of pollutant emissions, greenhouse emission and fuel consumption and their correlation with the driving behavior. A PEMS device was installed on two diesel goods vehicles. A specific driving route was designated for the experiments. The VSP methodology was applied to process and analyse the experimental data. The major results of this chapter can be concluded as follows.

1) The numbers of tailgating warnings and aggressive braking events were greatly reduced by 41 - 54% and 39 - 86% respectively when the on-board safety device was activated.

2) With activation of the on-board safety device on the LGV, the percentage of time spent on lower VSP modes was increased. The driver drove more carefully at a smoother speed than that without the safety device. In addition, the time spent on excessive speeding, strong acceleration and deceleration was reduced. For the MGV, the driving behavior has the opposite trends as the LGV. The driver may ignore the instructions from the safety device and tends to spend more time on higher VSP modes in the second stage of the experiment.

3) Driving behavior had a positive effect on fuel consumption and gaseous emissions of the LGV. Compared with the results without the safety device, the average HC was reduced by 56%, CO_2 by 23%, NO by 10% and fuel

consumption by 23% with activation of the safety device. This was due to the driving behavior improved by increased coasting distance, reduced aggressive braking and the number of tailgating events.

4) On the other hand, the average CO and NO of MGV were reduced by 35% and 44%. HC, CO_2 and fuel consumption were increased by 5%, 4% and 4% respectively. The MGV results may be due to driver factors (e.g. aggressive driving) and the driver's response to the warnings provided by the safety device. This implies that the new control functions are necessary to recommend for the development of the safety device in future.

5) This pilot study was conducted to fill the research gap of the application of on-board safety devices on the fuel consumption and emissions performance under real-driving conditions. Driving behavior was improved in the second stage of experiment. The improved driving behavior was effective at reducing fuel consumption and emissions for the LGV, but the types of vehicles, number of trips and drivers were limited in this study. Only two dominant vehicle types in Hong Kong were selected, to conduct on-road emissions experiments on a designated typical and popular test route. This pilot study identified the need to undertake more comprehensive eco-driving experiments that explored the role of different driver's driving characteristics, route features and vehicle types to help extend these results.

Chapter Five

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

This chapter presents the experimental results of the second study which is a suite of RDE experiments evaluating the effects of driving behavior on improving fuel consumption and vehicle emissions from the application of a safety device. The experimental results of the second study will be discussed in three sections. Section 5.1 reports the effects of the on-board safety device on driving behavior and presents the statistical results of experienced and less-experienced drivers. In section 5.2 the driving time distribution for different VSP modes will be statistically analysed. The effects of driving behavior on fuel consumption and exhaust gas emissions and the statistical results will be reported in 5.3.

5.1 Effects of on-board safety device on driving performance

To understand the effects of on-board safety device on driving performance (or fuel consumption and emissions), driver behavior is analysed by comparing the driving parameters with and without activation of the safety device. A total of 30 drivers with different levels of driving experience were recruited to conduct the on-road emissions experiments. In the experiments, the 15 drivers recruited were full time drivers and they had at least 15 years of driving experience, and were grouped into the experienced driver category. For the other 15 drivers, their average ages were less than the experienced drivers and they had between three to five years of driving experience. Therefore, they were grouped into the less-experienced driver category. In the on-road emissions experiments, an on-board safety device was installed on a diesel 3.3 tonnes LGV. A diesel 3.3 tonnes LGV was selected to conduct the experiments in this study because it is a dominant vehicle type in Hong Kong. As mentioned in section 3.2.1, the number of registered diesel LGVs was more than 75,000 and accounted for 50% of the total registered diesel goods vehicles in Hong Kong. The on-road emissions experiments were conducted in two stages. In the first stage of experiments, drivers were requested to drive along the testing route normally that followed their own driving style. In the second stage of experiments, an on-board safety device was activated to provide drivers with information and guidance on how to improve their driving behavior. Table 24 shows the driving parameters of 30 experienced and less-experienced drivers on a 3.3 tonnes LGV. To understand the effects of safety device on driving performance of 30 experienced and less-experienced drivers, the percentages of individual driving parameter will be presented and analysed. In addition, a one-way repeated measures multivariate analysis of variance (MANOVA) (Table 23) and a paired t-test (Table 24) were conducted to discover the significant effects of the safety device on driving parameters in the RDE experiments. One-way repeated measures MANOVA is a statistical test used to determine whether there are any differences in multiple dependent variables over time or between treatments. In addition, this statistical analysis method is an asymptotically valid procedure allowing for unequal covariance matrices and possibly non-normal multivariate observations. The one-way repeated measures MANOVA has the advantage is that it is applicable for a wide range of designs in a unified way, by choosing appropriate hypothesis matrices. Furthermore, one-way repeated measures MANOVA doesn't only compare differences in mean scores between multiple groups but assumes a cause effect relationship whereby one or more independent, controlled variables (the factors) cause the significant difference of one or more characteristics. On the other hand, the limitation of this statistical analysis method is that it has poor performance for small to moderate samples and the results may become quite liberal [172-174]. The statistical results are undertaken with a p-value of < 0.05 threshold for statistical significance indicating that the effects of the safety device on driving parameters between both monitoring stages were significantly different [175-177].

As shown in Table 23a and 23b, one-way repeated measures MANOVA test results indicated that the driving parameters of experienced and less-experienced drivers in stage 2 were statistically different from stage 1 ($p < 1.0 \times 10^{-3}$). For the driving parameters of experienced drivers, the average vehicle speed of the experienced drivers was significantly reduced by 8% ($p < 1.0 \times 10^{-3}$) and 10% ($p < 1.0 \times 10^{-3}$) for less-experienced drivers in the second stage compared to the first. The maximum vehicle speed of the experienced drivers was significantly reduced by 22% ($p < 1.0 \times 10^{-3}$) and 9% ($p < 1.0 \times 10^{-3}$) for less-experienced drivers in the second stage compared to the first. The average and maximum engine speed of the experienced drivers were significantly reduced by 5% ($p < 1.0 \times 10^{-3}$) and 20% ($p < 1.0 \times 10^{-3}$) while that the less-experienced drivers were reduced by 8% and 11% in the second stage compared to the first, respectively in a statistically significant manner ($p < 1.0 \times 10^{-3}$). In addition, the average accelerator pedal position of the experienced and less-experienced drivers was significantly reduced by 5% ($p < 1.0 \times 10^{-3}$) and 8% ($p < 1.0 \times 10^{-3}$) from the first to the second stage, respectively. The maximum accelerator pedal position of the experienced drivers was reduced by 17% ($p < 1.0 \times 10^{-3}$) while that the less-experienced drivers was reduced by 28% from the first to the second stage, respectively in a statistically significant manner ($p < 1.0 \times 10^{-3}$). Furthermore, the overall statistics (Table 23c) showed that the driving parameters of drivers' experience and stages with and without the safety device were not significantly different ($p = 0.65$). As shown in Table 24, the overall statistics showed that the on-board safety device was effective in improving the eco-driving abilities for both experienced and less-experienced drivers. The safety device also improved drivers' ability to maintain speed stability and decide an appropriate speed choice for both driver groups. The average, maximum and variation of vehicle speed, engine speed and accelerator pedal position for experienced and less-experienced drivers were significantly reduced ($p < 1.0 \times 10^{-3}$) in the second stage of experiment. In addition, the variation of acceleration was significant for experienced and less-experienced drivers between both monitoring stages ($p < 1.0 \times 10^{-3}$). On the other hand, no statistically significant difference exists for the maximum acceleration of experienced and less-experienced drivers between both monitoring stages ($p = 0.18$ for the experienced drivers and $p = 0.30$ for less-experienced drivers). From the driving performance of 30 drivers tested on an LGV, the percentage reduction of average vehicle speed, engine speed and accelerator pedal position for the less-experienced drivers were higher than those of the experienced drivers after activation of the on-board safety device. In contrast, the percentage reduction of maximum vehicle speed and engine speed of the experienced drivers were higher than the less-experienced drivers from the first stage to the second stage of experiments.

Table 23a: One-way repeated measures MANOVA for driving parameters of experienced drivers between trips with and without the on-board safety device.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage	27.576	5	$< 1.0 \times 10^{-3}$

Table 23b: One-way repeated measures MANOVA for driving parameters of less-experienced drivers between trips with and without the on-board safety device.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage	77.273	5	$< 1.0 \times 10^{-3}$

Table 23c: One-way repeated measures MANOVA for driving parameters of drivers' experience and stages with and without the on-board safety device.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage and drivers' experience	3.304	5	0.65

* Significance level = 0.05.

Table 24a: Summary statistics and paired t-tests for driving parameters of experienced drivers for stages 1 and 2.

Parameter		**Stage 1 Mean**	**Stage 2 Mean**	**T-value**	**Df**	**P-value for paired t-test***
Vehicle speed (km/h)	Average	44.6 (39 - 54)	41.4 (35 - 46)	3.8	29	$< 1.0 \times 10^{-3}$
	Max	95.9	74.5	4.1	29	$< 1.0 \times 10^{-3}$
	Stdev	23.5	20.8	4.3	29	$< 1.0 \times 10^{-3}$
Engine speed (rpm)	Average	1,378	1,314	4.0	29	$< 1.0 \times 10^{-3}$
	Max	3,789	3,027	4.7	29	$< 1.0 \times 10^{-3}$
	Stdev	497	412	4.9	29	$< 1.0 \times 10^{-3}$
Acceleration (m/s^2)	Average	0.0	0.0	0.33	29	0.43
	Max	2.9	1.8	0.93	29	0.18
	Stdev	0.1	0.1	0.93	29	$< 1.0 \times 10^{-3}$
Accelerator pedal position (%)	Average	22.8	21.6	4.3	29	$< 1.0 \times 10^{-3}$
	Max	48.0	39.6	5.2	29	$< 1.0 \times 10^{-3}$
	Stdev	7.5	5.6	4.8	29	$< 1.0 \times 10^{-3}$
Travelling time (minutes)	Average	25	27	-3.8	29	$< 1.0 \times 10^{-3}$

Table 24b: Summary statistics and paired t-tests for driving parameters of less-experienced drivers for stages 1 and 2.

Parameter		**Stage 1 Mean**	**Stage 2 Mean**	**T-value**	**Df**	**P-value for paired t-test***
Vehicle speed (km/h)	Average	46.5 (40 - 53)	42.1 (25 - 48)	6.9	29	$< 1.0 \times 10^{-3}$
	Max	85.0	77.4	11.4	29	$< 1.0 \times 10^{-3}$
	Stdev	25.6	21.9	7.6	29	$< 1.0 \times 10^{-3}$
Engine speed (rpm)	Average	1,432	1,324	9.9	29	$< 1.0 \times 10^{-3}$
	Max	3,748	3,333	8.9	29	$< 1.0 \times 10^{-3}$
	Stdev	542	419	10.6	29	$< 1.0 \times 10^{-3}$
Acceleration (m/s^2)	Average	0.0	0.0	0.22	29	0.78
	Max	2.2	1.3	0.78	29	0.30
	Stdev	0.1	0.1	0.53	29	$< 1.0 \times 10^{-3}$
Accelerator pedal position (%)	Average	23.4	21.6	9.7	29	$< 1.0 \times 10^{-3}$
	Max	53.3	38.3	8.4	29	$< 1.0 \times 10^{-3}$
	Stdev	8.4	5.7	9.5	29	$< 1.0 \times 10^{-3}$
Travelling time (minutes)	Average	24	27	-7.2	29	$< 1.0 \times 10^{-3}$

* Significance level = 0.05.

According to the driving performance of 30 drivers, the maximum vehicle speed and engine speed of the experienced drivers were higher than that of the less-experienced drivers. This may be explained by the experienced drivers possessing better driving skills, experienced drivers chose a higher speed on highway in the first stage of the experiment. In addition, the percentage reduction of average vehicle speed, engine speed, acceleration and accelerator pedal position for less-experienced drivers were higher than those of the experienced drivers after activation of the on-board safety device. This was mainly due to the long-term formed habits of experienced drivers who were harder or less willing to be changed to accept the assistance of the on-board safety device, whereas less-experienced drivers are likely to be more receptive to change and improve their driving behaviors [22]. This is evidenced by the statistical analysis results showing that the effects of on-board safety devices on driving performance of experienced and less-experienced drivers are not only for safety assurance during driving but also achieving eco-driving outcomes. Furthermore, the total travelling time of the experienced and less-experienced driver in the second stage of experiments were two and three minutes longer ($p < 1.0 \times 10^{-3}$) than that in the first stage respectively.

To understand the effects of the on-board safety device on driving behavior with different levels of driving experience, drivers' behavior and performance will be analysed by comparing the warning parameters with and without activation of the safety device. The warning parameters of 30 experienced and less-experienced drivers on the RDE experiments were calculated and presented in Table 26. A one-way repeated measures MANOVA (Table 25) and a paired t-test (Table 26) were performed to assess whether the numbers of warning parameters differ significantly according to the driving behavior. As shown in Table 25a and 25b, one-way repeated measures MANOVA test results indicated that the warning parameters of experienced ($p = 1.0 \times 10^{-3}$) and less-experienced ($p < 1.0 \times 10^{-3}$) drivers in stage 2 were statistically different from stage 1. On the other hand, there is no statistically significant difference in warning parameters of drivers' experienced and the stages of experiments ($p = 0.20$). As shown in Table 26a and 26b, it was clear that all warning parameters of both experienced and less-experienced drivers were reduced after activation of the on-board safety device. The numbers of aggressive braking warnings for experienced and less-experienced drivers were reduced by 62% ($p = 0.02$) and 72% ($p < 1.0 \times 10^{-3}$) from the first to the second stage, respectively in a statistically significant manner. For the experienced and less-experienced drivers, the numbers of forward collision, lane departure and headway monitor warnings were significantly reduced more than 50% after activation of the on-board safety device ($p < 5.0 \times 10^{-2}$). For the numbers of aggressive accelerations, aggressive decelerations and aggressive turning warnings, they were greatly reduced by 48% ($p = 0.03$), 100% ($p = 0.16$) and 72% ($p = 0.02$) for the experienced drivers and 74% ($p = 6.2 \times 10^{-3}$), 78% ($p = 0.11$) and 60% ($p = 0.01$) for the less-experienced drivers from the first to the second stage. From the statistical analysis results, the safety device significantly reduced the average number of aggressive acceleration and turning warnings for experienced and less-experienced drivers ($p < 5.0 \times 10^{-2}$). However, no statistically significant difference exists between the number of aggressive deceleration warnings for experienced ($p = 0.16$) and less-experienced drivers ($p = 0.11$) of trips with and without the safety device. This indicated a strong impact of on-board safety device on improving the driving behaviors of both experienced and less-experienced drivers. The significant reduction of forward collision, lane departure and headway monitor warnings indicating that the safety device was effective in improving drivers' compliance with eco-driving principles. The reduction of aggressive accelerations, aggressive decelerations and aggressive turning warnings indicated that the safety device was effective to help both experienced and less-experienced drivers to avoid aggressive driving and enhance understanding of eco-driving.

The statistical analysis results indicated that the on-board safety device was effective in improving the safety and eco-driving abilities for both experienced and less-experienced drivers. The improvement level of driving performance for each warning parameter between experienced and less-experienced drivers were different. Therefore, the safety device effectively improved the driving performance for both experienced and less-experienced drivers, but the acceptance level of the safety device between experienced and less-experienced drivers was different. In the first stage of the experiment, the average number of all warning parameters of experienced drivers were lower than less-experienced drivers. The experimental results showed that the experienced drivers possessed better driving skills to maintain a safer driving ability than the less-experienced drivers in stage one of the experiment. On the other hand, the percentage reduction of the warning parameters for the less-experienced drivers were higher than those of the experienced drivers after activation of the safety device. The results indicated that there are more driver errors to correct with less-experienced drivers and less-experienced drivers are more compliant with that. In addition, the repeated measures MANOVA test results indicated that the total numbers of warnings for the experienced and less-experienced driver's group were reduced by 71% ($p = 1.0 \times 10^{-3}$) and 72% ($p < 1.0 \times 10^{-3}$) from the first stage to the second stage respectively in a statistically significant manner. It is evident that by following the instructions provided by the safety device, drivers drove more carefully at a smoother speed than that without the device and achieved a more appropriate vehicle speed when driving. Moreover, both experienced and less-experienced drivers' driving behavior were found to be improved by reducing the time spent on excessive speeding, strong accelerations and decelerations.

Table 25a: One-way repeated measures MANOVA for warning parameters of experienced drivers between both monitoring stages.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage	23.554	7	1.0×10^{-3}

Table 25b: One-way repeated measures MANOVA for warning parameters of less-experienced drivers between both monitoring stages.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage	84.592	7	$< 1.0 \times 10^{-3}$

Table 25c: One-way repeated measures MANOVA for warning parameters of drivers' experience and stages with and without the on-board safety device.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage and drivers' experience	9.877	7	0.20

* Significance level = 0.05.

Table 26a: Summary statistics and paired t-tests for warning parameters of experienced drivers for stages 1 and 2.

Parameter	**Stage 1 Mean**	**Stage 2 Mean**	**T-value**	**Df**	**P-value for paired t-test***
Braking number (times)	95	36	2.7	29	0.02
Forward collision warning (times)	10	2	2.1	29	0.03
Lane departure warning (times)	34	15	2.4	29	0.04
Headway monitor warning (times)	109	16	3.8	29	1.0×10^{-3}
Aggressive acceleration warning (times)	56	29	2.4	29	0.03
Aggressive deceleration warning (times)	2	0	1.4	29	0.16
Aggressive turning warning (times)	43	12	2.5	29	0.02
Total number of warning (times)	254	74	-	-	-

Table 26b: Summary statistics and paired t-tests for warning parameters of less-experienced drivers for stages 1 and 2.

Parameter	**Stage 1 Mean**	**Stage 2 Mean**	**T-value**	**Df**	**P-value for paired t-test***
Braking number (times)	177	29	5.4	29	$< 1.0 \times 10^{-3}$
Forward collision warning (times)	24	29	3.0	29	3.8×10^{-3}
Lane departure warning (times)	102	29	3.2	29	0.03
Headway monitor warning (times)	185	29	9.1	29	$< 1.0 \times 10^{-3}$
Aggressive acceleration warning (times)	57	29	3.3	29	6.2×10^{-3}
Aggressive deceleration warning (times)	18	29	1.9	29	0.11
Aggressive turning warning (times)	62	29	2.9	29	0.01
Total number of warning (times)	448	125	-	-	-

* Significance level = 0.05.

5.2 Distribution of travelling time over different VSP mode

As shown in Table 27, the RDE experiments were conducted in 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 safety device.

Table 27: Driving data between both monitoring 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 28 presents the average time spent on different VSP modes without and with activation of the on-board safety device for both experienced and less-experienced drivers. As shown in Figure 28, a shift in the VSP distribution for experienced and less-experienced drivers between both monitoring periods can be observed. These results can be also supported by the statistical differences found with the calculation of the driving parameters for 30 experienced and less-experienced drivers. In stage two of the RDE experiment, drivers increased the average time spent on lower VSP modes (VSP modes 4 to 7) as the drivers controlled the speed of the vehicle more appropriately. It is also related to a more adequate use of the engine as well as lower and steady speeds. In addition, the reduction of time spent in higher VSP modes (VSP modes 8 to 14) of experienced and less-experienced drivers were also found in stage two of the experiment, indicating the time spent on excess speeding and strong acceleration is reduced. It is possible to observe the average time spent is shifting from higher to lower VSP modes after activation of the on-board safety device. In addition, a one-way repeated measures MANOVA (Table 28) was conducted to assess whether the average time distribution over VSP modes differ significantly according to the driving behavior. As shown in Table 28a and 28b, statistically significant difference exists ($p < 1.0 \times 10^{-3}$) between average time distribution over VSP modes for both experienced and less-experienced drivers of trips with and without the on-board safety device. This indicated that the safety device was effective to help both experienced and less-experienced drivers to avoid excess speeding and strong acceleration in stage two of the experiment. Furthermore, the overall statistics (Table 28c) showed that the average time distribution over VSP modes of drivers' experience and stages with and without the safety device were not significantly different ($p = 0.42$).

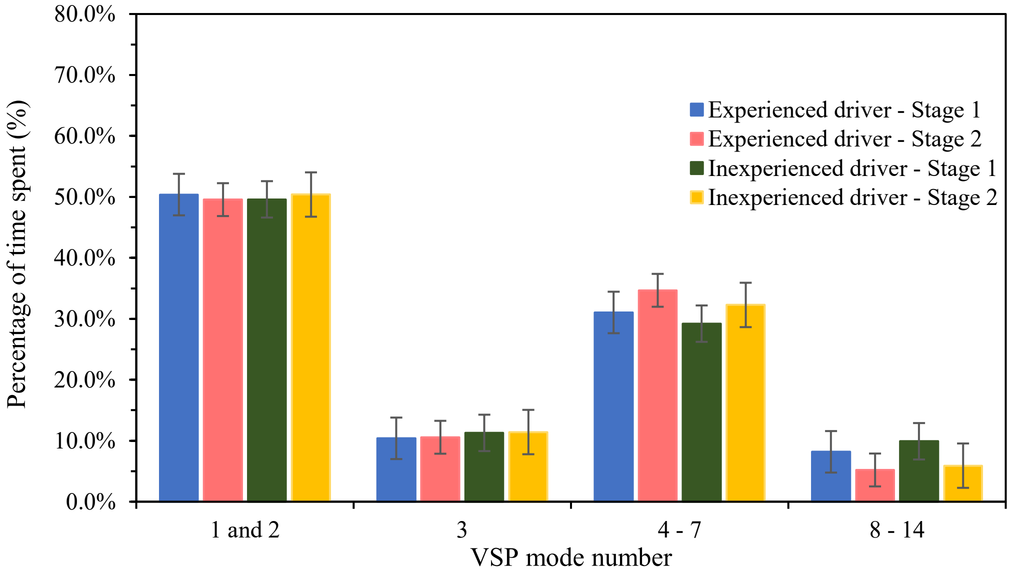


Figure 28: Comparison of average time distribution over VSP modes of experienced drivers and less-experienced drivers without (stage 1) and with (stage 2) the on-board safety device. Error bars are the standard deviation.

Table 28a: One-way repeated measures MANOVA for average time distribution over VSP modes of experienced drivers for both monitoring stages.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage	31.435	4	$< 1.0 \times 10^{-3}$

Table 28b: One-way repeated measures MANOVA for average time distribution over VSP modes of less-experienced drivers for both monitoring stages.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage	70.870	4	$< 1.0 \times 10^{-3}$

Table 28c: One-way repeated measures MANOVA for average time distribution over VSP modes of drivers' experience and stages with and without the on-board safety device.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage and drivers' experience	3.874	4	0.42

* Significance level = 0.05.

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 between experienced and less-experienced drivers. Table 29 and Table 30 show the comparison and summary statistics of average time spent on different VSP modes without and with activation of the on-board safety device. As shown in Table 29, the percentage of time spent in modes 1 and 2 of experienced group's drivers was reduced from 50.4% to 49.3% from stage 1 to 2. This can be explained via the number of braking events being reduced by the drivers. In contrast, the percentage of time spent in modes 1 and 2 for less-experienced group's drivers was slightly increased by 0.8% from stage 1 to 2. These results may be related to the better driving skills of experienced driver's group where experienced drivers chose a steadier speed than the less-experienced drivers did. Experienced drivers reduced the number of braking events and also increased of the coasting distance in the second stage of experiment. Furthermore, the on-board safety device improved experienced drivers' ability to maintain a more consistent driving behavior to reduce the number of aggressive decelerations. These results can be also supported by the statistical differences found with the calculations of the driving parameters and warning parameters for both experienced and less-experienced drivers. In stage two of the experiment, the average vehicle speed and braking number of experienced drivers were lower than that for less-experienced drivers. The overall statistics (Table 30a and 30b) showed that the on-board safety device generally have insignificant influences in the percentage of time spent for both VSP 1 - 2 (experienced drivers: $p = 0.17$ and less-experienced drivers: $p = 0.12$) and VSP mode 3 (experienced drivers: $p = 0.40$ and less-experienced drivers: $p = 0.42$).

In the medium VSP modes 4 to 7, the percentage of time spent by experienced and less-experienced group's drivers were increased by 3.7% ($p < 1.0 \times 10^{-3}$) and 3.1% ($p < 1.0 \times 10^{-3}$) from stage 1 to 2, respectively in a statistically significant manner. The increase of average distribution from stage 1 to 2 in modes 4 to 7 can be related to a lower and steady speed of the vehicle as controlled by the on-board safety device. It can also be explained that the driver controlled the speed of the vehicle more appropriately. These results can also be supported by the calculations of the driving parameters for both experienced and less-experienced drivers. After activation of on-board safety device, the average vehicle speed and engine speed of experienced drivers were lower than that of the less-experienced drivers.

In higher VSP modes 8 to 14, the percentage of time spent by experienced and less-experienced drivers were significantly reduced by 3.0% ($p < 1.0 \times 10^{-3}$) and 4.0% ($p < 1.0 \times 10^{-3}$) from stage 1 to stage 2, respectively. This was due to the reduced time spent on excess speeding and strong acceleration in the heavy acceleration driving modes in stage 2. The on-board safety device was effective to improve drivers' ability to perform eco-driving and reduce the time spent on excess speeding and heavy accelerations. These results can be also supported by the calculations of the driving parameters and warning parameters for both experienced and less-experienced drivers. In stage two of the experiment, the percentage reduction of average vehicle speed, acceleration and the number of aggressive acceleration warnings of less-experienced drivers were higher than experienced drivers. Moreover, the results of average time distribution over VSP modes provide an indication that the long-term formed habits of experienced drivers are less willing to be changed to accept the assistance of the on-board safety device, whereas less-experienced drivers were found to be more receptive to change and improve their driving behaviors.

As reviewed above, 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. The results showed that the percentage of time spent on lower VSP modes was increased and the time spent on higher VSP modes was significantly reduced after the safety device was activated. However, this study was carried out in a short period and each driver was responsible for four trips in one day. Furthermore, many studies indicate that when the experiments were carried out in very short periods (a few runs in one or two days) that their percentages of fuel savings were typically higher than 10% [178-180]. On the other hand, longer term studies (several weeks or months) showed much lower fuel savings (< 8%) [181-183]. This indicates that on-board safety devices have the same limitation as training programs, while long-term studies showed that the impact of on-board safety device faded and the drivers revert to their original behaviors over time. That is, the effectiveness attenuates over time.

Table 29: Comparison of average time distribution over VSP modes of experienced and less-experienced drivers between trips without (stage 1) and with (stage 2) the safety device.

		Experienced drivers		**Less-experienced drivers**	
Driving condition	**VSP Mode**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**
Deceleration	1	40.5%	39.6%	39.6%	40.1%
	2	9.9%	9.9%	10.0%	10.3%
Idling	3	10.4%	10.6%	11.3%	11.4%
Mild driving	4	9.1%	10.3%	8.7%	9.5%
	5	8.1%	9.9%	7.8%	8.6%
	6	7.6%	8.3%	6.8%	7.6%
	7	6.2%	6.1%	5.8%	6.5%
	8	4.6%	3.9%	5.1%	4.1%
Heavy acceleration	9	2.5%	1.2%	3.2%	1.6%
	10	0.8%	0.1%	1.4%	0.2%
	11	0.2%	0%	0.2%	0%
	12	0%	0%	0%	0%
	13	0%	0%	0%	0%
	14	0%	0%	0%	0%

Table 30a: Summary statistics and paired t-tests for average time distribution over VSP modes of experienced drivers for stages 1 and 2.

	Stage 1 Mean	Stage 2 Mean	T-value	Df	P-value for paired t-test*
VSP modes 1 and 2	50.4%	49.6%	1.0	29	0.17
VSP mode 3	10.4%	10.6%	-0.3	29	0.40
VSP modes 4 to 7	31.0%	34.7%	-4.1	29	$< 1.0 \times 10^{-3}$
VSP modes 8 to 14	8.2%	5.2%	5.5	29	$< 1.0 \times 10^{-3}$

Table 30b: Summary statistics and paired t-tests for average time distribution over VSP modes of less-experienced drivers for stages 1 and 2.

	Stage 1 Mean	Stage 2 Mean	T-value	Df	P-value for paired t-test*
VSP modes 1 and 2	49.6%	50.4%	-1.2	29	0.12
VSP mode 3	11.3%	11.4%	-0.2	29	0.42
VSP modes 4 to 7	29.2%	32.3%	-3.7	29	$< 1.0 \times 10^{-3}$
VSP modes 8 to 14	9.9%	5.9%	9.4	29	$< 1.0 \times 10^{-3}$

* Significance level = 0.05.

5.3 Effects of on-board safety device on fuel consumption and exhaust gas emissions

To assess the effects 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. A one-way repeated measures MANOVA (Table 31) and a paired t-test (Table 32) were conducted to discover the significant effects of the safety device on measured emissions and fuel consumption rates. As shown in Table 31, one-way repeated measures MANOVA test results indicated that the emissions and fuel consumption results of experienced drivers ($p < 1.0 \times 10^{-3}$) and less-experienced drivers ($p < 1.0 \times 10^{-3}$) are statistically different between both monitoring stages. However, there is no statistically significant difference in averaged exhaust gas emission rates and fuel consumption of drivers' experienced and the stages of experiments ($p = 0.50$). Table 32 shows the overall fuel consumption and emission rates of the tested diesel 3.3 tonnes LGV. In addition, summary statistics and paired t-test for both experienced and less-experienced drivers between trips with and without the activation of the safety device are presented. As shown in Table 32a, THC and CO_2 emission rates of the experienced drivers were reduced by 3% ($p = 0.99$) and 5% ($p = 6.0 \times 10^{-3}$) respectively from stage 1 to stage 2. The results can be explained via the experienced drivers driving the LGV more carefully with the reduction of average vehicle speed and engine speed under the instructions given by the safety device. In addition, with the reduction of the maximum acceleration and engine speed, the NO emission rates of the experienced drivers were significantly reduced by 56% ($p = 3.6 \times 10^{-3}$) from 0.36 g/km without the activation of device to 0.16 g/km with device, and the

NO_2 significantly reduced by 39% ($p = 1.0 \times 10^{-3}$) from 0.49 g/km to 0.30 g/km. This result demonstrates a strong impact of the on-board safety device on NO and NO_2 emissions for the experienced drivers. This result can be also supported by the statistical differences found with the calculations of the driving parameters for the experienced drivers. In stage two of the experiment, the maximum acceleration of experienced drivers was greatly reduced by 61%. However, the CO emission rates of the experienced drivers were increased from 9×10^{-3} g/km to 1.4×10^{-2} g/km. The CO emission rates are affected by large variability, thus a statistically significant difference does not exist ($p = 0.29$) between both monitoring stages. Generally, CO emission rates are relatively low for both driver groups, with the median and mean values very close to zero. Even their maximum values are well below the corresponding standard limits (i.e. 0.74 g/km for CO of Euro 5 1760 - 3500 kg diesel LGVs). During the on-road emissions experiments, the measured instantaneous CO concentrations were mostly below the detection limits of the PEMS gas analysers, which can be attributed to the lean combustion mode in diesel engines. As shown in Table 32, the CO emission rates of the experienced and less-experienced drivers were mostly around zero. Such low readings are more prone to be affected by measurement uncertainties. Furthermore, this result is consistent with the previous study that the driving behavior did not show distinct difference in the CO emissions in the previous study (Chapter 4.3; [76, 127, 167]). Thus, it is reasonable to assume that for CO emissions other parameters than driving style were more important, e.g. engine air-fuel mixture, ambient temperature or the cold start. As reported in [76], the ambient temperature has a more pronounced impact on CO emissions than the driving style. In the second stage of the on-road emissions experiment, the maximum acceleration and average vehicle speed of experienced drivers were reduced by 61% and 8% respectively. With the lower acceleration and average vehicle speed of the test vehicle, the soot mass emission rates and fuel consumption were reduced by 35% ($p = 0.12$) and 5% ($p = 6.0 \times 10^{-3}$) from the first stage to second stage of experiment.

For the tests with less-experienced drivers, the THC and CO_2 emission rates were reduced by 5% ($p = 0.73$) and 6% ($p = 0.02$) respectively from stage 1 to stage 2. These 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 speeds and accelerations. As shown in Table 32b, the THC emissions were reduced from 8.1×10^{-3} g/km without the activation of device to 7.7×10^{-3} g/km with device, and the CO_2 from 286.0 g/km to 268.9 g/km. These results can also be supported by the statistical differences found with the calculations of the driving parameters for the less-experienced drivers. In stage two of the experiment, the average vehicle speed and engine speed of less-experienced drivers were reduced by 10% and 8% respectively. Furthermore, the emission rates of NO and NO_2 were significantly reduced by 65% ($p < 1.0 \times 10^{-3}$) from 0.44 to 0.15 g/km and 50% ($p < 1.0 \times 10^{-3}$) from 0.55 to 0.27 g/km 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 less-experienced drivers. These results can be explained as the less-experienced drivers drove the LGV more carefully with the reduction of time spent on excessive speeding, strong acceleration and deceleration. In the second stage of the on-road emissions experiment, the maximum acceleration and averaged vehicle speed of less-experienced drivers were reduced by 69% and 10% respectively. 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% ($p = 0.19$) and 6% (p

= 0.02) respectively from the first stage to the second stage of experiment.

Table 31a: One-way repeated measures MANOVA for averaged exhaust gas emission rates and fuel consumption of experienced drivers between both monitoring stages.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage	35.123	7	$< 1.0 \times 10^{-3}$

Table 31b: One-way repeated measures MANOVA for averaged exhaust gas emission rates and fuel consumption of less-experienced drivers between both monitoring stages.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage	66.685	7	$< 1.0 \times 10^{-3}$

Table 31c: One-way repeated measures MANOVA for averaged exhaust gas emission rates and fuel consumption of drivers' experience and stages with and without the on-board safety device.

Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
Stage and drivers' experience	6.389	7	0.50

* Significance level = 0.05.

Table 32a: Summary statistics and paired t-tests for exhaust gas emission rates and fuel consumption of experienced drivers for stages 1 and 2.

	Stage 1 Mean	**Stage 2 Mean**	**T-value**	**Df**	**P-value for paired t-test***
THC (g/km)	8.2×10^{-3}	7.9×10^{-3}	0.01	29	0.99
CO (g/km)	9×10^{-3}	1.4×10^{-2}	-1.08	29	0.29
CO_2 (g/km)	280.7	266.7	2.99	29	6.0×10^{-3}
NO (g/km)	0.36	0.16	3.20	29	3.6×10^{-3}
NO_2 (g/km)	0.49	0.30	3.77	29	1.0×10^{-3}
Soot mass (μg/km)	1.9×10^{-2}	1.3×10^{-2}	1.59	29	0.12
Fuel economy (L/100 km)	10.6	10.1	2.99	29	6.0×10^{-3}

Table 32b: Summary statistics and paired t-tests for exhaust gas emission rates and fuel consumption of less-experienced drivers for stages 1 and 2.

	Stage 1 Mean	**Stage 2 Mean**	**T-value**	**Df**	**P-value for paired t-test***
THC (g/km)	8.1×10^{-3}	7.7×10^{-3}	0.35	29	0.73
CO (g/km)	1.6×10^{-2}	1.7×10^{-2}	-0.03	29	0.98
CO_2 (g/km)	286.0	268.9	2.40	29	0.02
NO (g/km)	0.44	0.15	5.53	29	$< 1.0 \times 10^{-3}$
NO_2 (g/km)	0.55	0.27	6.20	29	$< 1.0 \times 10^{-3}$
Soot mass (μg/km)	3.3×10^{-2}	2.7×10^{-2}	1.34	29	0.19
Fuel economy (L/100 km)	10.8	10.2	2.39	29	0.02

To understand the averaged results shown in Table 32, distributions of the gaseous emissions and fuel consumption over the VSP mode will be analysed. A one-way repeated measures MANOVA (Table 33) and a paired t-test (Table 34) were performed to assess whether the emissions and fuel consumption over the VSP mode differ significantly according to the driving behavior. As shown in Table 33a and 33b, one-way repeated measures MANOVA test results indicated that statistically significant differences exist for the fuel consumption ($p < 1 \times 10^{-3}$), CO_2 ($p < 1 \times 10^{-3}$), NO ($p < 1 \times 10^{-3}$) and NO_2 ($p < 1 \times 10^{-3}$) emission rates of experienced and less-experienced drivers of trips with and without the on-board safety device. On the other hand, no statistically significant differences exist for the emission rates of HC (experienced drivers: $p = 0.95$ and less-experienced drivers: $p = 0.84$), CO (experienced drivers: $p = 0.54$ and less-experienced drivers: $p = 0.96$) and soot emissions (experienced drivers: $p = 0.08$ and less-experienced drivers: $p = 0.19$) between both monitoring stages.

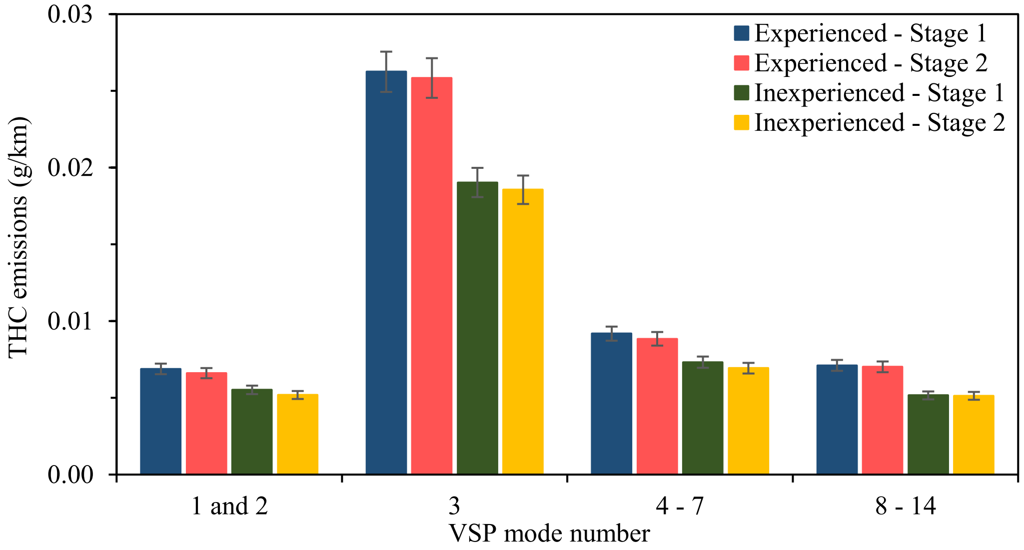
Figure 29 shows the distribution of emissions over the VSP modes in both monitoring stages. As shown in Figure 29, after activation of the on-board safety device for experienced drivers, the emission rates of THC in VSP modes 1 and 2 were reduced by 4% ($p = 0.27$). In addition, CO_2 emission rates were reduced by 7% ($p = 1.4 \times 10^{-3}$), NO by 54% ($p = 3.8 \times 10^{-3}$) and NO_2 by 39% ($p = 1.3 \times 10^{-3}$) in a statistically significant manner. The results can be explained as the experienced drivers reducing the number of aggressive braking events and increasing the coasting distance. The percentage of time spent on VSP modes 1 and 2 were reduced by 0.8% from stage 1 to 2. However, the CO emission rates were increased from 7×10^{-3} g/km to 1.1×10^{-2} g/km and no statistically significant difference exists ($p = 0.07$) between both monitoring stages.

Furthermore, the soot mass emission rates were greatly reduced by 20% ($p = 0.29$) from the first stage to second stage of experiment. For the emission rates of less-experienced drivers in VSP modes 1 and 2, THC and CO_2 emissions were reduced by 6% ($p = 0.30$) and 3% ($p = 0.07$) respectively from stage 1 to stage 2. NO emissions were reduced by 62% and NO_2 by 46% between trips with and without the safety device in a statistically significant manner ($p < 1.0 \times 10^{-3}$). In addition, the CO emission rates were weakly affected by the driving behavior and remains unchanged in both monitoring stages ($p = 0.48$). The soot mass emission rates were greatly reduced by 28% ($p = 0.17$) from the first stage to the second stage of the experiment. As shown in Figure 30, the fuel consumption of experienced and less-experienced drivers in VSP modes 1 and 2 were reduced by 7% ($p = 1.4 \times 10^{-3}$) and 3% ($p = 0.07$) respectively from stage 1 to stage 2. This indicates a strong impact of the driving style such as reduction of braking number and an increase of the coasting distance on fuel economy as shown in the experimental results. Comparing the experimental results of the on-board safety device for experienced and less-experienced drivers in VSP modes 1 and 2, the percentages of improvement for CO_2 emission rates and fuel economy for experienced drivers were slightly higher than those of less-experienced drivers after activation of the on-board safety device. The results can be explained by the experienced drivers driving the LGV more carefully with the reduction of braking number and the time spent in VSP modes 1 and 2.

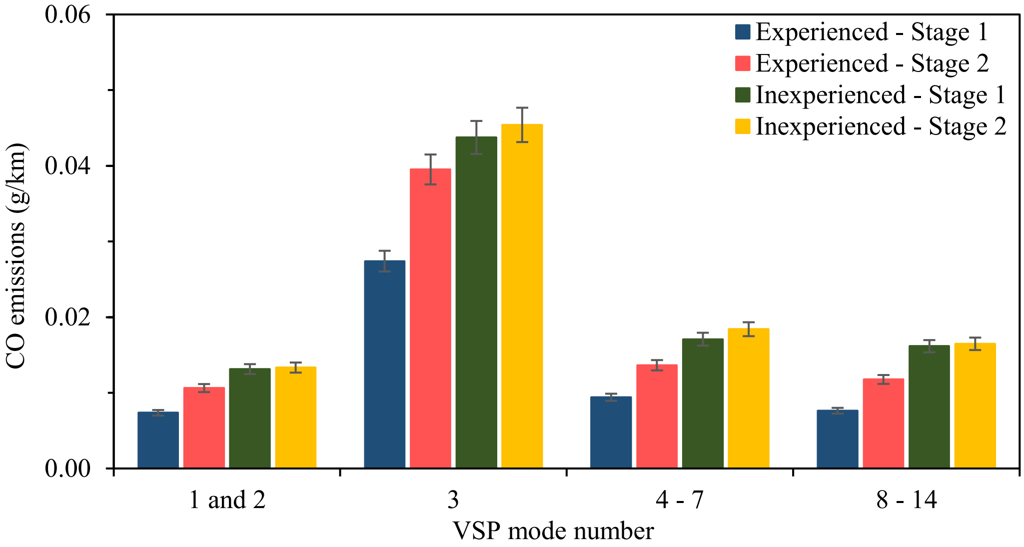
For the emission rates of experienced drivers in VSP mode 3 which is the idling condition, THC and CO_2 emission rates were reduced by 2% ($p = 0.46$) and 5% ($p = 0.19$) respectively from stage 1 to stage 2. In addition, NO emission rates were reduced by 39% ($p = 0.01$) and NO_2 by 19% ($p = 0.03$) in a statistically significant manner. However, the emission rates of CO were increased after activation of the on-board safety device ($p = 0.09$). For the emission rates of less-experienced drivers in VSP mode 3, THC, CO_2, NO and NO_2 emission rates were reduced by 2% ($p = 0.43$), 7% ($p = 0.20$), 58% ($p < 1.0 \times 10^{-3}$) and 33% ($p = 1.0 \times 10^{-3}$) respectively from stage 1 to stage 2. On the other hand, the emission rates of CO were increased by 4% ($p = 0.45$) after activation of the on-board safety device. The emission rates of the idling state should be the same for both experienced and less-experienced drivers. However, previous studies [184] have found that, during idling, although the vehicle speed was zero, the engine operating conditions were different between the beginning and the end of the idling. Thus, it may be the reason why there were few differences with experienced and less-experienced drivers when the vehicle speed was idling. Furthermore, the soot mass emission rates of experienced and less-experienced drivers were reduced by 14% ($p = 0.38$) and 16% ($p = 0.41$) respectively from the first stage to second stage of experiment. As shown in Figure 30, the fuel consumption of experienced drivers in VSP modes 3 was reduced by 5% ($p = 0.19$) and less-experienced drivers were reduced by 7% ($p = 0.20$) from stage 1 to stage 2.

For the emission rates of experienced drivers in the medium VSP modes 4 to 7 which represents normal driving conditions [127], the emission rates of THC were reduced 4% ($p = 0.23$) from stage 1 to stage 2. In addition, CO_2, NO and NO_2 emissions were significantly reduced by 5% ($p = 0.04$), 51% ($p = 2.3 \times 10^{-3}$) and 37% ($p = 1.0 \times 10^{-3}$) respectively. With the increase of the percentage of time spent in VSP modes 4 to 7, the THC emissions were reduced from 9.2×10^{-3} g/km without activation of the on-board safety device to 8.8×10^{-3} g/km with activation of the on-board 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. These results can be supported by the statistical differences found with the calculations of the driving parameters for the experienced drivers. In stage two of the experiment, the average vehicle speed and engine speed of the experienced drivers were significantly reduced by 8% and 5% respectively. The results also indicated that experienced drivers control 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 drivers was significantly reduced by 5% ($p = 0.04$) from 12.5 L/100 km in stage 1 to 11.9 L/100 km in stage 2. In addition, the soot mass emission rates of experienced drivers were greatly reduced by 57% ($p = 0.17$) 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 less-experienced drivers, the THC emissions were reduced by 5% ($p = 0.29$) from 7.3×10^{-3} g/km to 6.9×10^{-3} g/km. The CO_2 emissions were reduced by 12% from 346 g/km to 305 g/km, the NO emissions were 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 in a statistically significant manner ($p < 1.0 \times 10^{-3}$). The reduction of CO_2 was mainly due to the fuel consumption which was significantly reduced by 12% ($p < 1.0 \times 10^{-3}$) from 13.1 L/100 km without the activation of device to 11.6 L/100 km with the device. These results can be supported by the statistical differences found with the calculations of the driving parameters for the less-experienced drivers. In stage two of the experiment, the average vehicle speed and engine speed of the less-experienced drivers were significantly reduced by 10% and 8% respectively. These results also indicated that less-experienced drivers control 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 less-experienced drivers were greatly reduced by 35% ($p = 0.28$) from stage 1 to stage 2.

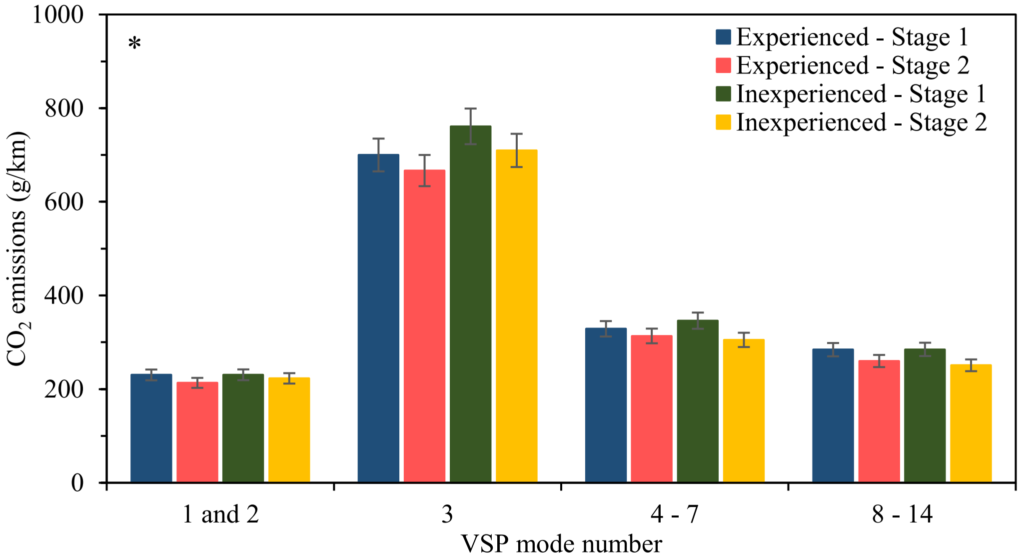
In higher VSP modes spanning from mode 8 to mode 14, with heavy acceleration, the THC emission rates of the experienced drivers were reduced by 1% ($p = 0.43$) from stage 1 to stage 2. In addition, CO_2, NO and NO_2 emissions were reduced by 9% ($p = 6.5 \times 10^{-3}$), 64% ($p = 6.9 \times 10^{-3}$) and 43% ($p = 2.6 \times 10^{-3}$) respectively in a statistically significant manner. In the second stage of the experiment, the maximum acceleration of the experienced drivers 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 a reduction of excess speeding and strong acceleration on emission rates of experienced drivers as shown in the experimental results. In addition, the maximum speed of the vehicle was decreased by 53% from stage 1 to stage 2. With the lower and steady speeds of the test vehicle, the fuel consumption of experienced drivers was significantly reduced by 9% ($p = 6.5 \times 10^{-3}$) from the first stage to the second stage of experiment. Furthermore, the soot mass emission rates of experienced drivers were reduced by 52% ($p = 0.05$) from stage 1 to stage 2. For the emission rates of the less-experienced drivers, the THC emissions were reduced by 1% ($p = 0.48$) from 5.2×10^{-3} g/km to 5.1×10^{-3} g/km. The CO_2 emissions were reduced by 12% ($p = 2.8 \times 10^{-3}$) from 285 g/km to 251 g/km, the NO emissions were reduced by 72% ($p < 1.0 \times 10^{-3}$) from 0.57 g/km to 0.16 g/km and NO_2 emissions by 58% ($p < 1.0 \times 10^{-3}$) from 0.65 g/km to 0.27 g/km in a statistically significant manner. These results can be supported by the statistical differences found with the calculations of the driving parameters. After the activation of the on-board safety device, the maximum acceleration and speed of the less-experienced drivers were 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 less-experienced drivers 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% ($p = 2.8 \times 10^{-3}$) from 10.8 L/100 km to 9.5 L/100 km and 6% ($p = 0.47$) from 7.2×10^{-3} µg/km to 6.7×10^{-3} µg/km respectively from stage 1 to stage 2.



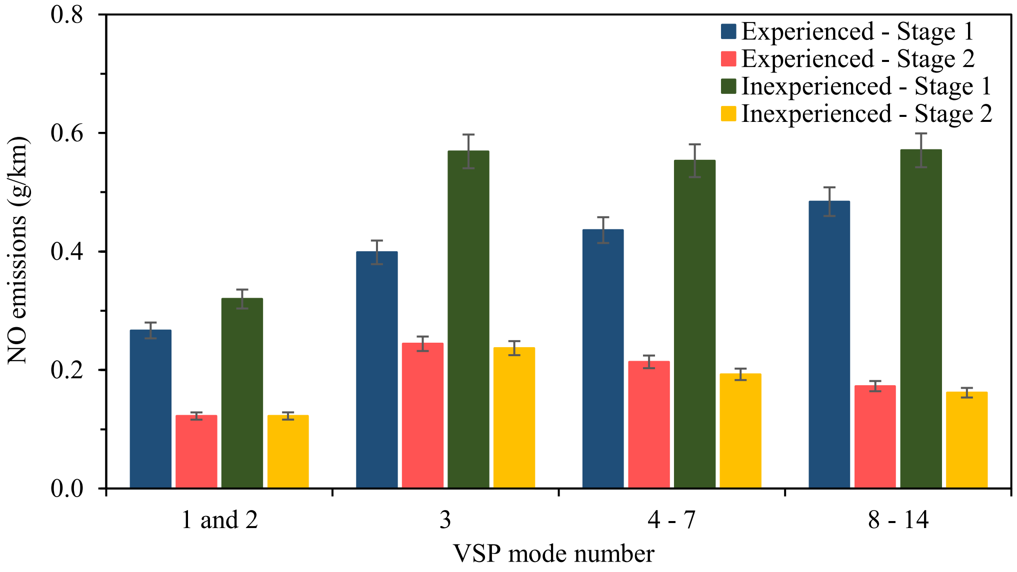
(a): THC emission factors of experienced and less-experienced drivers.



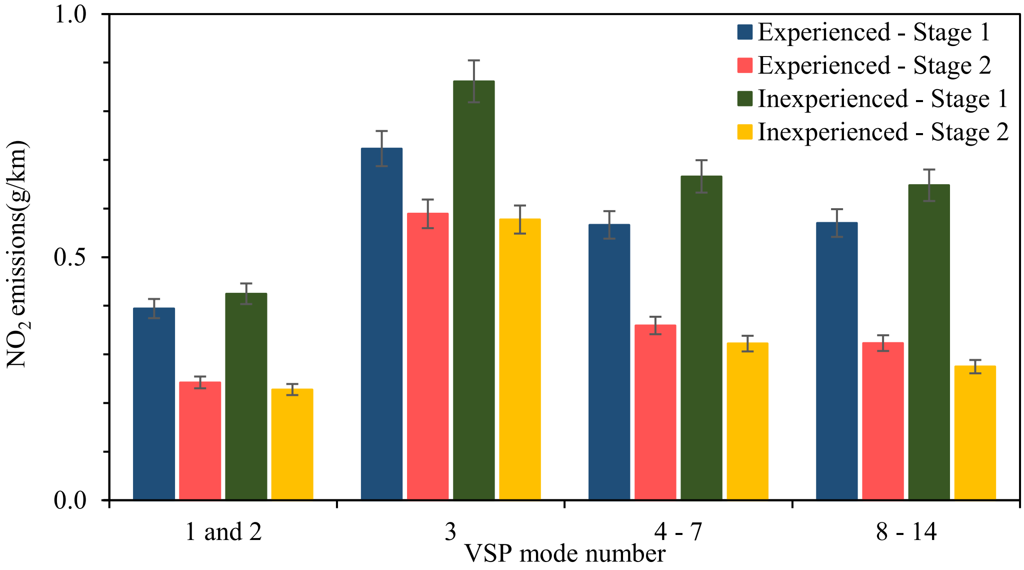
(b): CO emission factors of experienced and less-experienced drivers.



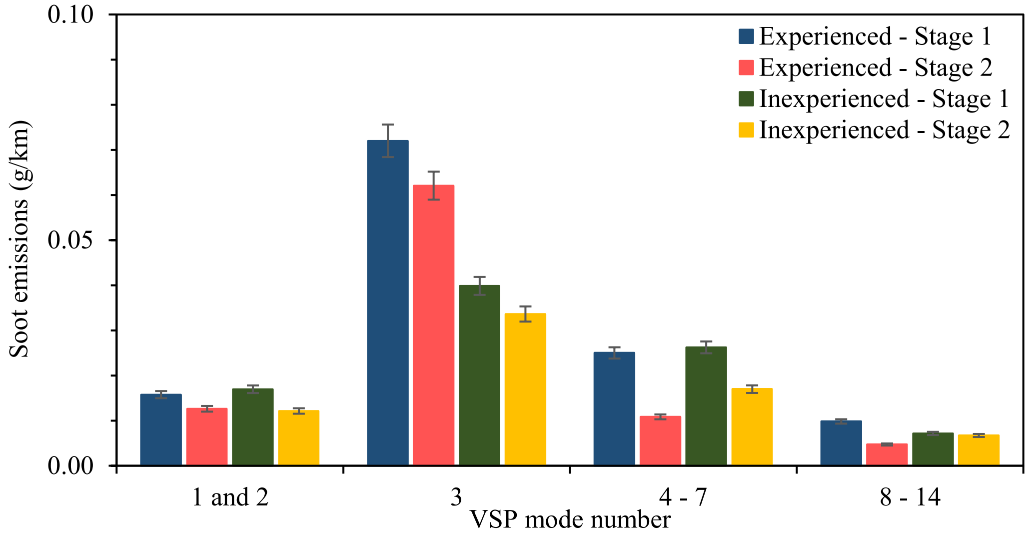
(c): CO_2 emission factors of experienced and less-experienced drivers.



(d): NO emission factors of experienced and less-experienced drivers.



(e): NO_2 emission factors of experienced and less-experienced drivers.



(f): Soot emission factors of experienced and less-experienced drivers.

Figure 29: The THC (a), CO (b), CO_2 (c), NO (d), NO_2 (e) and soot (f) emissions of the LGV for experienced and less-experienced drivers in each group of the VSP modes in both monitoring stages. Error bars are the standard deviation.

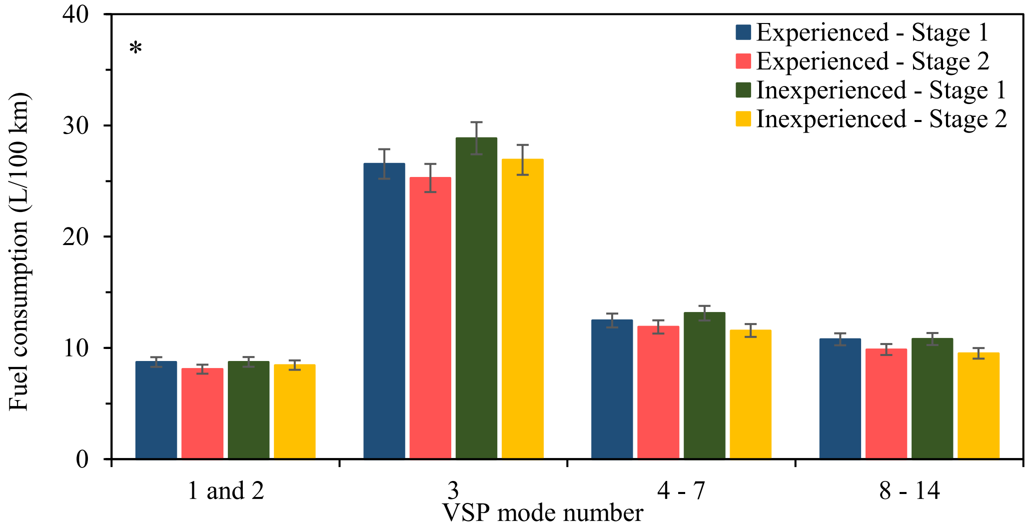


Figure 30: The fuel consumption of the LGV for experienced and less-experienced drivers in each group of the VSP modes in both monitoring stages. Error bars are the standard deviation.

Table 33a: One-way repeated measures MANOVA for fuel consumption and exhaust emissions of experienced drivers for both monitoring stages.

	Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
HC	Stage	0.692	4	0.95
CO	Stage	3.089	4	0.54
CO_2	Stage	25.758	4	$< 1.0 \times 10^{-3}$
NO	Stage	31.872	4	$< 1.0 \times 10^{-3}$
NO_2	Stage	45.410	4	$< 1.0 \times 10^{-3}$
Soot mass	Stage	8.335	4	0.08
Fuel consumption	Stage	25.736	4	$< 1.0 \times 10^{-3}$

Table 33b: One-way repeated measures MANOVA for fuel consumption and exhaust emissions of less-experienced drivers for both monitoring stages.

	Source of variation	**Test statistic**	**Degrees of freedom**	**P-value***
HC	Stage	1.418	4	0.84
CO	Stage	0.618	4	0.96
CO_2	Stage	59.258	4	$< 1.0 \times 10^{-3}$
NO	Stage	105.749	4	$< 1.0 \times 10^{-3}$
NO_2	Stage	86.513	4	$< 1.0 \times 10^{-3}$
Soot mass	Stage	6.144	4	0.19
Fuel consumption	Stage	59.113	4	$< 1.0 \times 10^{-3}$

* Significance level = 0.05.

Table 34a: Summary statistics and paired t-tests for fuel consumption and exhaust emissions of experienced drivers in each group of the VSP modes between both monitoring stages.

a) Experienced drivers		VSP modes 1 and 2	VSP mode 3	VSP modes 4 to 7	VSP modes 8 to 14
THC	Df	29	29	29	29
	T-value	0.61	0.11	0.76	0.18
	P-value*	0.27	0.46	0.23	0.43
CO	Df	29	29	29	29
	T-value	-1.53	-1.39	-1.28	-1.75
	P-value*	0.07	0.09	0.11	0.05
CO_2	Df	29	29	29	29
	T-value	3.63	0.92	1.92	2.85
	P-value*	1.4×10^{-3}	0.19	0.04	6.5×10^{-3}
NO	Df	29	29	29	29
	T-value	3.11	2.47	3.36	2.82
	P-value*	3.8×10^{-3}	0.01	2.3×10^{-3}	6.9×10^{-3}
NO_2	Df	29	29	29	29
	T-value	3.64	2.11	3.59	3.31
	P-value*	1.3×10^{-3}	0.03	1.0×10^{-3}	2.6×10^{-3}
Soot mass	Df	29	29	29	29
	T-value	0.57	0.30	0.98	1.74
	P-value*	0.29	0.38	0.17	0.05
Fuel consumption	Df	29	29	29	29
	T-value	3.63	0.92	1.92	2.84
	P-value*	1.4×10^{-3}	0.19	0.04	6.5×10^{-3}

Table 34b: Summary statistics and paired t-tests for fuel consumption and exhaust emissions of less-experienced drivers in each group of the VSP modes between both monitoring stages. * Significance level = 0.05.

b) Less-experienced drivers		VSP modes 1 and 2	VSP mode 3	VSP modes 4 to 7	VSP modes 8 to 14
THC	Df	29	29	29	29
	T-value	0.54	0.18	0.56	0.06
	P-value*	0.30	0.43	0.29	0.48
CO	Df	29	29	29	29
	T-value	-0.04	-0.12	-0.23	-0.05
	P-value*	0.48	0.45	0.41	0.48
CO_2	Df	29	29	29	29
	T-value	1.54	0.86	4.68	3.27
	P-value*	0.07	0.20	$<1.0 \times 10^{-3}$	2.8×10^{-3}
NO	Df	29	29	29	29
	T-value	5.46	5.07	7.34	6.98
	P-value*	$<1.0 \times 10^{-3}$	$<1.0 \times 10^{-3}$	$<1.0 \times 10^{-3}$	$<1.0 \times 10^{-3}$
NO_2	Df	29	29	29	29
	T-value	7.81	3.87	7.39	7.57
	P-value*	$<1.0 \times 10^{-3}$	1.0×10^{-3}	$<1.0 \times 10^{-3}$	$<1.0 \times 10^{-3}$
Soot mass	Df	29	29	29	29
	T-value	0.97	0.24	0.60	0.08
	P-value*	0.17	0.41	0.28	0.47
Fuel consumption	Df	29	29	29	29
	T-value	1.53	0.86	4.67	3.27
	P-value*	0.07	0.20	$<1.0 \times 10^{-3}$	2.8×10^{-3}

5.4 Summary

In the second study, a total of 120 RDE experiments (~2,244 km in total) were conducted to investigate the effects of driving behavior on fuel consumption and gaseous and particulate emissions from the application of a safety device. A state-of-the-art PEMS was used to measure the emissions data, driving parameters and environmental parameters from a diesel 3.3 tonnes 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 safety device for both experienced and less-experienced drivers and the effects of driving behavior on fuel consumption and emissions were examined. The VSP model and repeated measures MANOVA was applied to analyse the experimental data. The major results can be summarised as follows.

1) The on-board safety device improved driving behavior substantially for both experienced and less-experienced drivers. The total number of warnings for the experienced and less-experienced drivers were significantly reduced by 71% and 72% respectively.

2) The maximum vehicle speed and engine speed for the experienced drivers were reduced by 22% and 20% which were more than 9% and 11% for the less-experienced drivers after activation of the safety device. In contrast, the average vehicle and engine speeds for the less-experienced drivers were reduced by 10% and 8% which were more than 8% and 5% for the experienced drivers in the second stage of experiment. Significant changes on driving parameters occurred

with the activation of the safety device.

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

4) By following the instructions from the on-board safety device, both experienced and less-experienced drivers improved their driving behavior resulting in a positive effect on fuel consumption and gaseous emissions. For the experienced drivers, 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 safety device. For the less-experienced drivers, 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. The overall statistics showed that statistically significant difference exists for fuel consumption, CO_2, NO and NO_2 emissions for both experienced and inexperienced drivers between trips with and without the safety device.

5) The effects of the safety device are very strong when considering the stage 1 versus 2 results. The driver experience factor is quite often small in terms of differences in fuel consumption and emissions (e.g. CO_2) but sometimes the

driver experience is quite important (e.g. NO_x and PM). Furthermore, the RDE testing results indicated that the on-board 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.

Chapter Six

6 Conclusions and future work

6.1 Conclusions

To contribute to the reduction of vehicle emissions and fuel consumption, on-road emissions experiments have been conducted to investigate the effects of driving behavior on fuel consumption and gaseous emissions of diesel commercial vehicles. Drivers' driving behaviors were analysed by comparing the driving parameters with and without the safety device. VSP methodology was applied to process and analyse the experimental data.

In the first study, the on-road emissions experiments conducted by two diesel goods vehicles (a 5.5 tonnes LGV and a 16 tonnes MGV) were aimed to investigate the effects of driving behavior on fuel consumption and gaseous emissions. The effects of an on-board safety device were assessed in terms of pollutant emissions, greenhouse emission and fuel consumption and their correlation with the driving behavior [31]. PEMS was installed to measure the emissions data, driving parameters and environmental parameters. A specific driving route was designated for the experiments. The VSP model was applied to process and analyse the experimental data. The major conclusions of the first study can be summarised as follows.

1) Driving behavior was improved from the first stage to second stage of the on-road emissions experiment, which are demonstrated by the reduction of the number of tailgating warnings (41 - 54%) and aggressive braking warnings (39 - 86%). In addition, the VSP analysis results of the LGV indicated that the percentage of time spent on lower VSP modes was increased while that the percentage of time spent on higher VSP modes was reduced. On the other hand, the analysis results of the MGV have the opposite trends as the LGV. Thus, the safety device should be optimized by recommending new control functions for different vehicle types. The new control functions will be described in detail in Section 6.2.

2) The improved driving behavior had little influence on the fuel consumption and emissions of MGV, but effectively reduced the fuel consumption and emissions of LGV. As a result, the fuel consumption and emissions of the LGV was improved by 10% to 56% when the on-board safety device was activated. The average HC and CO emissions of the LGV were reduced. However, the positive benefits of the device were not obvious on the MGV and only had influence on the CO and NO emissions with the activation of the safety device.

3) Overall, the first study was conducted to fill the research gap of the application of the on-board safety device on the fuel consumption and emissions performance under real-driving conditions. The relationship between driving behavior and gaseous emissions and fuel consumption was investigated. Due to limitation of resources, the number of RDE trips, types of vehicles and driver's driving characteristics were limited in this study. In the second study, the number of

participants and on-road emissions experiments was enhanced to provide insight into the advantages and disadvantages of safety device to test the hypothesis.

To obtain significant comparison between both monitoring periods and statistically validate the experimental results, a total number of 120 on-road emissions experiments (~2,244 km in total) were performed in the second study. In addition, 30 drivers with different levels of driving experience were recruited to conduct the on-road emissions experiments. A gas and PM PEMS were used to measure the emissions data, driving parameters and environmental parameters of the diesel 3.3 tonnes LGV. The results from on-road emissions experiments were analysed for each vehicle in terms of fuel consumption, gaseous emissions and PM and their correlation with the driving behavior. The effectiveness of the on-board safety device for both experienced and less-experienced drivers and the effects of driving behavior on fuel consumption and gaseous emissions were examined. From the experimental results, it is clearly demonstrated that the safety device had a more significant effect on less-experienced drivers than experienced drivers based on fuel consumption and gaseous emissions performance. The major conclusions of the second study can be drawn as follows:

1) Less-experienced drivers are likely to be more receptive to change and improve their driving behaviors, which are demonstrated by their higher percentage reduction on warning parameters, average vehicle speed and engine speed after activation of on-board safety device. On the other hand, the average number of all warning parameters of experienced drivers were lower than less-experienced drivers in the first stage of the experiments. The results showed that experienced drivers possessed better driving skills to maintain a safer driving ability without

activation of the on-board safety device.

2) By following the instructions from the on-board safety device, driving behavior had a positive effect on fuel consumption and gaseous emissions of both experienced and less-experienced drivers. The average emissions and fuel consumption were reduced by 3% to 56% for experienced drivers and 5% to 65% for less-experienced drivers. As a result, less-experienced drivers have greater potential for reducing vehicle emissions and improve fuel economy by implementing an on-board safety device. In addition, less-experienced drivers reduce more time spend on driving modes of heavy acceleration and spend more time on cruising modes in the second stage of experiment. Based on eco-driving criteria, less-experienced drivers perform better than experienced drivers.

3) Overall, the experimental results validate the hypothesis that real-time feedback on driving safety can simultaneously facilitate the reduction on vehicle emissions and fuel consumption performance. The RDE results showed that the on-board safety device obviously improved the driving behavior and the time spent on excessive speeding, strong acceleration and deceleration was significantly reduced. Thus, the findings suggest that the on-board safety device not only positively influence driving behavior but also to successfully reduce vehicle emissions and fuel consumption under real-world driving conditions.

6.1.1 Limitations of this study

As reviewed above, this study investigated the effects of driving behavior on fuel consumption and gaseous emissions of diesel goods vehicles by using a PEMS under real-driving conditions. However, the types of vehicles, numbers of trips, driving routes and driver's driving characteristics were limited in this study. Due to limitation of resources, only three dominant diesel vehicle types were selected to conduct on-road emissions experiment on two designated test routes in Hong Kong. The experimental analysis of the effect of driving behavior was only focused on the short-term individual's fuel consumption, gaseous emissions, driving and warning parameters results. The long-term effectiveness and acceptance level of the on-board safety device were not evaluated. Therefore, it is necessary to further explore the long-term effectiveness and the design of the on-board system in future studies. In addition, the network-wide impacts of eco-driving were not considered. In future research, more comprehensive eco-driving experiments will be conducted to help extend these results and to provide insight into the advantages and disadvantages of the safety device in reducing fuel consumption and pollutant emissions under real-driving conditions. More details about future work will be discussed in section 6.3.

6.2 Recommendations on new control functions for the on-board safety device

On-road emissions experiments and statistical analysis have been conducted to investigate the effects of an on-board safety device on driving behavior and fuel consumption and emissions of three diesel goods vehicles. According to the experimental results, the on-board safety device effectively led to improvements in a drivers' driving behavior thereby reducing LGVs emissions and fuel consumption. However, the effects of the device were not obvious on the MGV. Therefore, the development of new control functions aimed for eco-driving applications can be recommended to incorporate into an improved safety device in the future. In addition, types of feedback and warning information are an important factor to minimise the distraction caused by on-board devices. Therefore, the newly developed control functions can be used to enable the driver to improve their driving behavior and to further enhance the eco-driving functions for reduction of emissions and fuel consumption. The new recommend type of feedback and control function as follows.

Safety is the most important concern in a driving task. Generally, eco-driving largely overlaps with safe driving. Eco-driving recommends avoiding excessive speed and aggressive driving which are highly linked with crash risk and severity. However, the feedback information of on-board devices will inevitably draw some attention away from the driving task. Therefore, types of feedback and warning information are an important factor to minimise the distraction caused by on-board devices. Different types of feedback information from the on-board devices would cause different distraction for drivers (e.g. visual, manual and cognitive). Investigations showed that continuous real-time visual feedback was the most effective for fuel efficiency and safety performance, but obviously reduced attention to the forward view and increased subjective workload. On the other hand, haptic feedback had little effect on workload, but was less effective than visual feedback [185]. Therefore, a voice or auditory feedback might be preferable from a driver distraction point of view because it does not require the driver to look away from the road to take in the information. An auditory only approach may also be more convenient for the user as it eliminates the need to install an aftermarket display and potentially connect the wires to it. In addition, the information provided should be made as simple as possible to understand to minimise the cognitive effort required to process it.

The current on-board safety device provides forward collision warnings, lane departure warnings, headway monitor warnings, speed limit warnings as well as aggressive acceleration, deceleration and turning warnings. However, an important driving parameter that is not currently considered in the device that may improve vehicle emissions and fuel economy significantly is engine speed. Fuel consumption rate firstly decreases with the increase of engine speed due to reduced heat losses, reaches the optimal point and then increases at high speeds due to increased friction losses [162]. As a result, the fuel consumption-driving speed curve shows a U-shape. This efficiency speed curve also applies for hybrid and electric vehicles. The optimal speeds for hybrid vehicles are in similar ranges as ICE vehicles, but much lower for electric vehicles [54]. Therefore, a gear shift indicator can be integrated to provide real-time information to the driver when it is appropriate to engage the next higher or lower gear to maintain the proper engine speed to improve drivers' driving behavior and hence to reduce vehicle emissions and fuel consumption. In addition, the new control functions can be implemented into the safety device to obtain a more significant effects on fuel savings and emissions reduction for different types of vehicles.

6.3 Suggestions for future work

Based on the current research study, a more detailed study may be needed in a few aspects.

Firstly, the on-board safety device has been proven effective in improving drivers' driving behavior and reducing vehicle emissions and fuel consumption for both experienced and less-experienced drivers. The average emissions and fuel consumption of experienced and less-experienced drivers were reduced by 3% to 65% with the on-board safety device. However, the drivers’ age is directly proportional to drivers’ driving experience in this study and the average age of all less-experienced drivers is less than the experienced drivers. Therefore, based on the current experimental results, it will be interesting to improve the RDE experiment by introducing a correlation between driver’s age and driving experience on fuel economy and emissions performance so that the effects of safety device on drivers with different levels of driving experience and different age groups can be clearly demonstrated.

Secondly, the experimental results indicated that the effects of the safety device on improving the drivers’ driving behavior were significant. The numbers of aggressive driving warnings were greatly reduced by 59% to 68% and consequently reduced the average emissions and fuel consumption by 3% to 65%. To better understand the effects of driving behavior on fuel economy and gaseous emissions, more RDE experimental works are needed to investigate the other important factors of eco-driving technology. For example, it will be interesting to investigate the gaseous emissions and fuel consumption in vehicle starting and braking with different acceleration and deceleration rates. In addition, the fuel economy and emissions performance can be evaluated in different scenarios, such as the vehicle speed continuously increasing from zero to the moment when the driver shifted to the second gear and the first braking point to the point when the vehicle speed is reduced to zero. Then, the ideal acceleration and deceleration rates on vehicle fuel economy and emissions performance can be evaluated to develop a more comprehensive eco-driving strategy and training program.

Finally, on-road emissions experiments showed that the effects of the safety device on fuel consumption and vehicle emissions were significant. However, this study was only focused on the effects of on-board safety device of the dominant diesel commercial vehicles. In future study, different types of vehicles will be included to help extend the results. In addition, this study only focused on two designated test routes but different traffic conditions, routes and network-level features were not considered. Therefore, more comprehensive and long-term on-road emissions experiments based on different driver's driving characteristics, route features and vehicle types are needed to address this concern. For example, the effects of the on-board safety device on diesel private cars, light buses and heavy-duty trucks on different test routes could be investigated in future research.

References

1. Norbert E. Ligterink, et al., *Supporting analysis on real-world light-duty vehicle CO_2 emissions.* European Commission, 2016. **TNO report R10419v3**.

2. Alshehry, A.S. and M. Belloumi, *Study of the environmental Kuznets curve for transport carbon dioxide emissions in Saudi Arabia.* Renewable and Sustainable Energy Reviews, 2017. **75**: p. 1339-1347.

3. European Environment Agency, *Carbon dioxide emissions from Europe's heavy-duty vehicles*. 2018.

4. European Commission, *Evaluation of Regulations 443/2009 and 510/2011 on CO_2 emissions from light-duty vehicles*. 2015.

5. Peter Mock, *2020–2030 CO_2 standards for new cars and light-commercial vehicles in the European Union*, in *ICCT BRIEFING*. 2016: The International Council on Clean Transportation. p. 1-8.

6. Sausen, R., *Transport impacts on atmosphere and climate.* Atmospheric Environment, 2010. **44**(37): p. 4646-4647.

7. Ren, W., et al., *Inter-city passenger transport in larger urban agglomeration area: emissions and health impacts.* Journal of Cleaner Production, 2016. **114**: p. 412-419.

8. WHO Regional Office for Europe, *Review of evidence on health aspects of air pollution - REVIHAAP Project*, in *World Health Organization Technical Report*. 2013. p. 1-309.

9. International Energy Agency. *Tracking Clean Energy Progress 2017: Transport*. 2017; Available from: https://www.iea.org/etp/tracking2017/transport/.

10. Fang, M., C.K. Chan, and X. Yao, *Managing air quality in a rapidly developing nation: China.* Atmospheric Environment, 2009. **43**(1): p. 79-86.

11. Huang, Y., et al., *Tackling nitric oxide emissions from dominant diesel vehicle models using on-road remote sensing technology.* Environmental Pollution, 2018. **243**: p. 1177-1185.

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

13. Huang, Y., et al., *Remote sensing of on-road vehicle emissions: Mechanism, applications and a case study from Hong Kong.* Atmospheric Environment, 2018. **182**: p. 58-74.

14. Hong Kong Environmental Protection Department Air Science Group, *Hong Kong air pollutant emission inventory report*. 2018: Hong Kong Environmental Protection Department's website. p. 1-36.

15. United Nations, *Paris Agreement.* 2015.

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

17. Huang, Y., et al., *Emission measurement of diesel vehicles in Hong Kong through on-road remote sensing: Performance review and identification of high-emitters.* Environmental Pollution, 2018. **237**: p. 133-142.

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

19. Xu, Y., et al., *Eco-driving for transit: An effective strategy to conserve fuel and emissions.* Applied Energy, 2017. **194**: p. 784-797.

20. United Nations. *Summary of the Paris Agreement, United Nations Framework Convention on Climate Change.* 2015; Available from: http://bigpicture.unfccc.int/#content-the-paris-agreemen.

21. Foley, A.M., et al., *A review of developments in technologies and research that have had a direct measurable impact on sustainability considering the Paris agreement on climate change.* 2017. **68**: p. 835-839.

22. Wu, Y., et al., *The effectiveness of eco-driving training for male professional and non-professional drivers.* Transportation Research Part D: Transport and Environment, 2018. **59**: p. 121-133.

23. Martinez, C.M., et al., *Driving style recognition for intelligent vehicle control*

and advanced driver assistance: A survey. IEEE Transactions on Intelligent Transportation Systems, 2018. **19**(3): p. 666-676.

24. Jeffreys, I., G. Graves, and M. Roth, *Evaluation of eco-driving training for vehicle fuel use and emission reduction: A case study in Australia.* Transportation Research Part D: Transport and Environment, 2018. **60**: p. 85-91.

25. Barkenbus, J.N., *Eco-driving: An overlooked climate change initiative.* Energy Policy, 2010. **38**(2): p. 762-769.

26. Garcia-Castro, A., et al., *Modeling different penetration rates of eco-driving in urban areas: Impacts on traffic flow and emissions.* International Journal of Sustainable Transportation, 2016. **11**: p. 00-00.

27. Andrieu, C. and G.S. Pierre, *Comparing effects of eco-driving training and simple advices on driving behavior.* Procedia - Social and Behavioral Sciences, 2012. **54**: p. 211-220.

28. Zeng, W., T. Miwa, and T. Morikawa, *Prediction of vehicle CO_2 emission and its application to eco-routing navigation.* Transportation Research Part C: Emerging Technologies, 2016. **68**: p. 194-214.

29. Alzaman, C., *Impact of optimisation on idle time's fuel consumption and CO_2 emissions in urban transportation.* International Journal of Business Performance and Supply Chain Modelling, 2016. **Vol. 8, No. 2,** : p. 157-179.

30. Gonder, J., M. Earleywine, and W. Sparks, *Analyzing vehicle fuel saving opportunities through intelligent driver feedback.* SAE International Journal of Passenger Cars - Electronic and Electrical Systems, 2012. **5**(2): p. 450-461.

31. Atiyeh Vaezipour, Andry Rakotonirainy, and Narelle Haworth, *Reviewing in-vehicle systems to improve fuel efficiency and road safety.* Procedia Manufacturing, 2015. **3**: p. 3192-3199.

32. 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**.

33. Lacal Arantegui, R. and A. Jäger-Waldau, *Photovoltaics and wind status in the European Union after the Paris Agreement.* Renewable and Sustainable Energy Reviews, 2018. **81**: p. 2460-2471.

34. Foley, A., et al., *A review of developments in technologies and research that have had a direct measurable impact on sustainability considering the Paris agreement on climate change.* Renewable and Sustainable Energy Reviews, 2017. **68**: p. 835-839.

35. United Nations. *Paris Agreement - Status of Ratification, United Nations Framework Convention on Climate Change*. 2016; Available from: http://unfccc.int/paris_agreement/items/9444.php.

36. U.S. Department of State. *Leaders Summit on Climate*. 2021; Available from: https://www.state.gov/leaders-summit-on-climate/.

37. Shahbaz, M., N. Khraief, and M.M.B. Jemaa, *On the causal nexus of road transport CO_2 emissions and macroeconomic variables in Tunisia: Evidence from combined cointegration tests.* Renewable and Sustainable Energy Reviews, 2015. **51**: p. 89-100.

38. Hong Kong Environmental Protection Department. *Air pollution control strategies*. 2020; Available from: https://www.epd.gov.hk/epd/english/environmentinhk/air/prob_solutions/strategies_apc.html.

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

40. Alam, M.S. and A. McNabola, *A critical review and assessment of Eco-Driving policy & technology: Benefits & limitations.* Transport Policy, 2014. **35**: p. 42-49.

41. Greene, D.L., *Driver energy conservation awareness training: Review and recommendations.* Department of Energy (United States), 1986.

42. World Health Organization - Social Determinants of Health, *Global status report on road safety 2018*. 2018. p. 403, Accessed at https://www.who.int/publications/i/item/9789241565684.

43. Young, M.S., S.A. Birrell, and N.A. Stanton, *Safe driving in a green world: A review of driver performance benchmarks and technologies to support 'smart' driving.* Applied Ergonomics, 2011. **42**(4): p. 533-539.

44. McKenna, F.P., *The human factor in driving accidents An overview of approaches and problems.* Ergonomics, 1982. **25**(10): p. 867-877.

45. Department for Transport of UK, *Statistical data set - Reported road accidents, vehicles and casualties tables for Great Britain,.* 2021: RAS30006: Casualties by speed limit, road class and severity.

46. Taylor, M.C., A. Baruya, and J.V. Kennedy. *THE RELATIONSHIP BETWEEN SPEED AND ACCIDENTS OF RURAL SINGLE-CARRIAGEWAY ROADS.* 2002.

47. af Wåhlberg, A., *Speed choice versus celeration behavior as traffic accident predictor.* Journal of safety research, 2006. **37**: p. 43-51.

48. Brackstone, M. and M. McDonald, *Driver headway: How close is too close on a motorway?* Ergonomics, 2007. **50**: p. 1183-95.

49. Jackson, P., et al., *Fatigue and road safety: a critical analysis of recent evidence.* 2011.

50. Zhao, X., X. Zhang, and J. Rong, *Study of the Effects of Alcohol on Drivers and Driving Performance on Straight Road.* Mathematical Problems in Engineering, 2014. **2014**: p. 1-9.

51. American Automobile Association Foundation for Traffic Safety, *Aggressive Driving: Research Update.* 2009: Washington, DC 20005.

52. Narelle Haworth and Mark Symmons, *The relationship between fuel economy and safety outcomes*. 2001, Victoria (Australia): Monash University Accident Research Centre.

53. Staubach, M., et al., *Evaluation of an eco-driving support system.* Transportation Research Part F: Traffic Psychology and Behaviour, 2014. **27**: p. 11-21.

54. Sanguinetti, A., K. Kurani, and J. Davies, *The many reasons your mileage may vary: Toward a unifying typology of eco-driving behaviors.* Transportation

Research Part D: Transport and Environment, 2017. **52**: p. 73-84.

55. Chang, D.J. and E.K. Morlok, *Vehicle speed profiles to minimize work and fuel consumption.* Journal of Transportation Engineering, 2005. **131**(3): p. 173-182.

56. Lee, T. and J. Son, *Relationships between driving style and fuel consumption in highway driving.* SAE Technical Paper, 2011. **28-0051**.

57. US Department of Energy. *Driving more efficiently*. 2017; Available from: http://www.fueleconomy.gov/feg/driveHabits.jsp.

58. Government of Canada. *Fuel-efficient driving techniques* 2020; Available from: https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-transportation/personal-vehicles/fuel-efficient-driving-techniques/21038.

59. Ahn, K., *Modeling light duty vehicle emissions based on instantaneous speed and acceleration levels.* Doctoral Dissertations, 2002.

60. Pulkrabek, W.W., *Engineering fundamentals of the internal combustion engine (2nd Edition)*. 2003, Englewood Cliffs, New Jersey: Prentice-Hall.

61. El-Shawarby, I., K. Ahn, and H. Rakha, *Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions.* Transportation Research Part D: Transport and Environment, 2005. **10**(1): p. 13-30.

62. Wang, J. and H.A. Rakha, *Fuel consumption model for conventional diesel buses.* Applied Energy, 2016. **170**: p. 394-402.

63. Wang, H., et al., *Modelling of the fuel consumption for passenger cars regarding driving characteristics.* Transportation Research Part D: Transport and Environment, 2008. **13**(7): p. 479-482.

64. European Environment Agency, *Do lower speed limits on motorways reduce fuel consumption and pollutant emissions?* 2019.

65. Barnard, A.R., Z. Wang, and Y.M. Chung, *Drag-reduction devices to improve the aerodynamic efficiency of close-coupled large goods vehicles.* The international vehicle aerodynamics conference, 2015: p. 239-248.

66. Mensing, F., et al., *Trajectory optimization for eco-driving taking into account traffic constraints.* Transportation Research Part D: Transport and Environment,

2013. **18**: p. 55-61.

67. Birrell, S., et al., *Analysis of three independent real-world driving studies: A data driven and expert analysis approach to determining parameters affecting fuel economy.* Transportation Research Part D: Transport and Environment, 2014. **33**: p. 74-86.

68. Wang, M., et al., *Potential impacts of ecological adaptive cruise control systems on traffic and environment.* IET Intelligent Transport Systems, 2014. **8**(2): p. 77-86.

69. D'Amato, A., et al., *Development of a cruise controller based on current road load information with integrated control of variable velocity set-point and gear shifting.* SAE Technical Paper, 2017. **01-0089**.

70. Li, S.E., et al., *Fuel-saving servo-loop control for an adaptive cruise control system of road vehicles with step-gear transmission.* IEEE Transactions on Vehicular Technology, 2017. **66**(3): p. 2033-2043.

71. Larsson, H. and E. Ericsson, *The effects of an acceleration advisory tool in vehicles for reduced fuel consumption and emissions.* Transportation Research Part D: Transport and Environment, 2009. **14**(2): p. 141-146.

72. Ahn, K., et al., *Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels.* Journal of Transportation Engineering-asce, 2002. **128**.

73. Department of the Environment Australian Government. *10 Top tips for fuel efficient driving*. 2008; Available from: https://www.environment.gov.au/settlements/transport/fuelguide/tips.html.

74. Yang, H., H. Rakha, and M.V. Ala, *Eco-cooperative adaptive cruise control at signalized intersections considering queue effects.* IEEE Transactions on Intelligent Transportation Systems, 2017. **18**(6): p. 1575-1585.

75. Pelkmans, L., et al., *Influence of vehicle test cycle characteristics on fuel consumption and emissions of city buses.* SAE Technical Paper, 2001. **01-2002**.

76. Gallus, J., et al., *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**: p. 215-226.

77. Chen, C., et al., *On-road emission characteristics of heavy-duty diesel vehicles in Shanghai.* Atmospheric Environment, 2007. **41**(26): p. 5334-5344.

78. Choi, E. and E. Kim, *Critical aggressive acceleration values and models for fuel consumption when starting and driving a passenger car running on LPG.* International Journal of Sustainable Transportation, 2017. **11**(6): p. 395-405.

79. Intelligent Energy in Europe. *ECODRIVEN campaign catalogue for European ecodriving & traffic safety campaigns* 2009; Available from: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/ecodriven_catalogue_campaign_en.pdf.

80. Argonne National Laboratory. *Idling reduction savings calculator*. 2018; Available from: https://www.anl.gov/sites/www/files/2018-02/idling_worksheet.pdf.

81. US Department of Energy. *Idling reduction for personal vehicles*. 2015; Available from: https://afdc.energy.gov/files/u/publication/idling_personal_vehicles.pdf.

82. Carrico, A.R., et al., *Costly myths: An analysis of idling beliefs and behavior in personal motor vehicles.* Energy Policy, 2009. **37**(8): p. 2881-2888.

83. Rahman, S.M.A., et al., *Impact of idling on fuel consumption and exhaust emissions and available idle-reduction technologies for diesel vehicles – A review.* Energy Conversion and Management, 2013. **74**: p. 171-182.

84. Li, M., et al., *Traffic energy and emission reductions at signalized intersections: A study of the benefits of advanced driver information.* International Journal of Intelligent Transportation Systems Research, 2009. **7**(No. 1).

85. Yao, E. and Y. Song, *Study on Eco-Route Planning Algorithm and Environmental Impact Assessment.* Journal of Intelligent Transportation Systems, 2013. **17**(1): p. 42-53.

86. Nie, Y. and Q. Li, *An eco-routing model considering microscopic vehicle operating conditions.* Transportation Research Part B: Methodological, 2013. **55**: p. 154-170.

87. Lee, S., et al., *Modeling and validation of 12V lead-acid battery for stop-start technology.* SAE Technical Paper, 2017. **01-1211**.

88. Abas, M.A., et al., *Evaluation between engine stop/start and cylinder deactivation technologies under southeast Asia urban driving condition*, in *SAE Technical Paper*. 2017, SAE International.

89. Fonseca, N., J. Casanova, and M. Valdés, *Influence of the stop/start system on CO_2 emissions of a diesel vehicle in urban traffic.* Transportation Research Part D: Transport and Environment, 2011. **16**(2): p. 194-200.

90. Ericsson, E., *Independent driving pattern factors and their influence on fuel-use and exhaust emission factors.* Transportation Research Part D: Transport and Environment, 2001. **6**(5): p. 325-345.

91. Ericsson, E., H. Larsson, and K. Brundell-Freij, *Optimizing route choice for lowest fuel consumption – Potential effects of a new driver support tool.* Transportation Research Part C: Emerging Technologies, 2006. **14**(6): p. 369-383.

92. Ahn, K. and H. Rakha, *The effects of route choice decisions on vehicle energy consumption and emissions.* Transportation Research Part D: Transport and Environment, 2008. **13**(3): p. 151-167.

93. Kuo, Y., *Using simulated annealing to minimize fuel consumption for the time-dependent vehicle routing problem.* Computers & Industrial Engineering, 2010. **59**(1): p. 157-165.

94. Natural Resources Canada, *Canadian vehicle survey 2007 summary report, Office of Energy Efficiency.* Energy Publications, Ottawa, Canada., 2009.

95. Boriboonsomsin, K. and M. Barth, *Impacts of road grade on fuel consumption and carbon dioxide emissions evidenced by use of advanced navigation systems.* Transportation Research Record, 2009. **2139**(1): p. 21-30.

96. Jin, Q., et al., *Power-based optimal longitudinal control for a connected eco-driving system.* IEEE Transactions on Intelligent Transportation Systems, 2016. **17**(10): p. 2900-2910.

97. Boriboonsomsin, K., et al., *Eco-routing navigation system based on multisource historical and real-time traffic information.* IEEE Transactions on Intelligent

Transportation Systems, 2012. **13**(4): p. 1694-1704.

98. Ahn, K. and H.A. Rakha, *Network-wide impacts of eco-routing strategies: A large-scale case study.* Transportation Research Part D: Transport and Environment, 2013. **25**: p. 119-130.

99. Rakha, H.A., K. Ahn, and K. Moran, *INTEGRATION framework for modeling eco-routing strategies: Logic and preliminary results.* International Journal of Transportation Science and Technology, 2012. **1**(3): p. 259-274.

100. Jiang, H., et al., *Eco approaching at an isolated signalized intersection under partially connected and automated vehicles environment.* Transportation Research Part C: Emerging Technologies, 2017. **79**: p. 290-307.

101. Surcel, M.-D. and J. Michaelsen, *Evaluation of tractor-trailer rolling resistance reducing measures.* SAE Technical Paper, 2010. **01-1917**.

102. Jacobson, S.H. and L.A. McLay, *The economic impact of obesity on automobile fuel consumption.* The Engineering Economist, 2006. **51**(4): p. 307-323.

103. Transportation Research Board, *Tires and passenger vehicle fuel economy: Informing consumers, improving performance*, in *Transportation Research Board of the National Academies*. 2006, The National Academy of Sciences: Committee for the National Tire Efficiency Study. p. 174.

104. US Environmental Protection Agency. *Gas mileage tips-keeping your car in shape*. 2011; Available from: https://www.fueleconomy.gov/feg/maintain.jsp.

105. Liu, B.-S. and Y.-H. Lee, *In-vehicle workload assessment: Effects of traffic situations and cellular telephone use.* Journal of Safety Research, 2006. **37**(1): p. 99-105.

106. Rouzikhah, H., M. King, and A. Rakotonirainy, *Examining the effects of an eco-driving message on driver distraction.* Accident Analysis & Prevention, 2013. **50**: p. 975-983.

107. Cristea, M., F. Paran, and P. Delhomme, *The role of motivations for eco-driving and social norms on behavioural intentions regarding speed limits and time headway*. 2012.

108. af Wåhlberg, A.E., *Long-term effects of training in economical driving: Fuel*

consumption, accidents, driver acceleration behavior and technical feedback. International Journal of Industrial Ergonomics, 2007. **37**(4): p. 333-343.

109. M. Wang, et al., *Investigating potential impacts of an optimization based Eco-ACC system on traffic and environment.*, in *Transportation Research Board (TRB) 2012 Annual Meeting Technical Papers*, s.n., Editor. 2012, Transportation Research Board (TRB): Washington DC. p. 1-21.

110. Alam, M.S. and A. McNabola, *Network-wide traffic and environmental impacts of acceleration and deceleration among Eco-Driving Vehicles in different road configurations.* Transportation Planning and Technology, 2018. **41**(3): p. 244-264.

111. US Environmental Protection Agency. *Vehicle and fuel emissions testing - Engine testing regulations*. Available from: https://www.epa.gov/vehicle-and-fuel-emissions-testing/engine-testing-regulations#engine-test-procedures.

112. Franco, V., et al., *Road vehicle emission factors development: A review.* Atmospheric Environment, 2013. **70**: p. 84-97.

113. Martin Williams and R. Minjares, *A technical summary of Euro 6/VI vehicle emission standards*, in *ICCT BRIEFING*. 2016: The International Council on Clean Transportation. p. 1-12.

114. United Nations Economic Commission for Europe, *Regulation No 101 of the Economic Commission for Europe of the United Nations (UN/ECE)) - Uniform provisions concerning the approval of passenger cars powered by an internal combustion engine only, or powered by a hybrid electric power train.* Official Journal of the European Union. **158 (2007) 34-105.**

115. Giorgos, M., et al., *Parameterisation of fuel consumption and CO_2 emissions of passenger cars and light commercial vehicles for modelling purposes*, in *JRC Scientific and Technical Reports*. 2011. p. 1-108.

116. Zhao, X., et al., *Development of a driving simulator based eco-driving support system.* Transportation Research Part C: Emerging Technologies, 2015. **58**: p. 631-641.

117. Meuleners, L. and M. Fraser, *A validation study of driving errors using a driving simulator.* Transportation Research Part F: Traffic Psychology and

Behaviour, 2015. **29**: p. 14-21.

118. Helland, A., et al., *Driving simulator sickness: Impact on driving performance, influence of blood alcohol concentration, and effect of repeated simulator exposures.* Accident Analysis & Prevention, 2016. **94**: p. 180-187.

119. European Commission, *Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6)* Official Journal of the European Union., 2016. **109 (2016) 1-22.**

120. US Environmental Protection Agency. *Vehicle emissions on-board diagnostics (OBD)*. 2009; Available from: https://www.epa.gov/state-and-local-transportation/vehicle-emissions-board-diagnostics-obd.

121. A.E. af Wa˚ hlberg, *Long-term effects of training in economical driving: Fuel consumption, accidents, driver acceleration behavior and technical feedback.* International Journal of Industrial Ergonomics, 2007. **37**(4): p. 333-343.

122. Symmons, M.A. and G. Rose, *Ecodrive training delivers substantial fuel savings for heavy vehicle drivers.* Proceedings of Driving Assessment 2009 Conference, 2017: p. 46 - 53.

123. Helena K. Strömberg and I.C.M. Karlsson, *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**: p. 28-33.

124. Martina Högberg, *Eco-driving? A discrete choice experiment on valuation of car attributes.* Department of Economics, Lund University, 2007.

125. Elliot Martin, Nelson D. Chan, and Susan A. Shaheen, *Understanding How Ecodriving Public Education Can Result in Reduced Fuel Use and Greenhouse Gas Emissions.* 2012 Transportation Research Board Annual Meeting, 2012.

126. Smit, R., L. Ntziachristos, and P. Boulter, *Validation of road vehicle and traffic emission models – A review and meta-analysis.* Atmospheric Environment, 2010. **44**(25): p. 2943-2953.

127. Rolim, C.C., et al., *Impacts of on-board devices and training on light duty vehicle driving behavior.* Procedia - Social and Behavioral Sciences, 2014. **111**: p. 711-720.

128. Samaras, Z., et al., *Development of a Methodology and Tool to Evaluate the Impact of ICT Measures on Road Transport Emissions.* Procedia - Social and Behavioral Sciences, 2012. **48**: p. 3418-3427.

129. Linton, C., S. Grant-Muller, and W.F. Gale, *Approaches and Techniques for Modelling CO2 Emissions from Road Transport.* Transport Reviews, 2015. **35**(4): p. 533-553.

130. Nocera, S., M. Basso, and F. Cavallaro, *Micro and Macro modelling approaches for the evaluation of the carbon impacts of transportation.* Transportation Research Procedia, 2017. **24**: p. 146-154.

131. Barth, M. and K. Boriboonsomsin, *Energy and emissions impacts of a freeway-based dynamic eco-driving system.* Transportation Research Part D: Transport and Environment, 2009. **14**(6): p. 400-410.

132. Naujoks, F. and A. Neukum, *Timing of in-vehicle advisory warnings based on cooperative perception.* Human Factors and Ergonomics Society Europe Chapter Annual Meeting, 2013.

133. Seeliger, F., et al., *Advisory warnings based on cooperative perception.* IEEE Intelligent Vehicles Symposium Proceedings, 2014: p. 246-252.

134. Wang, M., et al., *How drivers respond to visual vs. auditory information in advisory traffic information systems.* Behaviour & Information Technology, 2020. **39**(12): p. 1308-1319.

135. Lindgren, A., et al., *Driver behaviour when using an integrated advisory warning display for advanced driver assistance systems.* IET Intelligent Transport Systems, 2009. **3**(4): p. 390-399.

136. Gaffary, Y. and A. Lécuyer, *The use of haptic and tactile information in the car to improve driving safety: A review of current technologies.* 2018. **5**(5).

137. Winkler, S., J. Kazazi, and M. Vollrath, *Driving with a multi stage warning system in the head-up display – How do drivers react upon it?* Proceedings of the Human Factors and Ergonomics Society Europe,Prague, Czech Republic, 2015.

138. Zhang, Y., et al., *Effect of warning system on interactive driving behavior at unsignalized intersection under fog conditions: A study based on multiuser*

driving simulation. Journal of Advanced Transportation, 2020. **2020**: p. 8871875.

139. Bergasa, L.M., et al. *DriveSafe: An app for alerting inattentive drivers and scoring driving behaviors*. in *2014 IEEE Intelligent Vehicles Symposium Proceedings*. 2014.

140. Castignani, G., et al., *Driver behavior profiling using smartphones: A low-cost platform for driver monitoring.* IEEE Intelligent Transportation Systems Magazine, 2015. **7**(1): p. 91-102.

141. Öz, B., T. Özkan, and T. Lajunen, *Professional and non-professional drivers' stress reactions and risky driving.* Transportation Research Part F: Traffic Psychology and Behaviour, 2010. **13**(1): p. 32-40.

142. Zhang, J., et al., *Research on the Differences of Risk Perception Ability Between Novice and Experienced Drivers*. 2019. p. 433-447.

143. Transport Department of Hong Kong. *Table 4.4: Registration and Licensing of Vehicles by Fuel Type (May 2020)*. 2020; Available from: https://www.td.gov.hk/filemanager/en/content_4974/table44.pdf.

144. Transport Department of Hong Kong. *Table 4.4: Registration and Licensing of Vehicles by Fuel Type (2015)*. 2015; Available from: https://www.td.gov.hk/filemanager/en/content_4708/table44.pdf.

145. Strömberg, H., I.C.M. Karlsson, and O. Rexfelt, *Eco-driving: Drivers' understanding of the concept and implications for future interventions.* Transport Policy, 2015. **39**: p. 48-54.

146. Jamson, A.H., D.L. Hibberd, and N. Merat, *Interface design considerations for an in-vehicle eco-driving assistance system.* Transportation Research Part C: Emerging Technologies, 2015. **58**: p. 642-656.

147. Harvey, J., N. Thorpe, and R. Fairchild, *Attitudes towards and perceptions of eco-driving and the role of feedback systems.* Ergonomics, 2013. **56**.

148. Fors, C., K. Kircher, and C. Ahlstrom, *Interface design of eco-driving support systems – Truck drivers' preferences and behavioural compliance.* Transportation Research Part C: Emerging Technologies, 2015. **58**.

149. Brouwer, R.F.T., et al., *Personalised feedback and eco-driving: An explorative study.* Transportation Research Part C: Emerging Technologies, 2015. **58**.

150. Stillwater, T. and K. Kurani, *Drivers discuss ecodriving feedback: Goal setting, framing, and anchoring motivate new behaviors.* Transportation Research Part F: Traffic Psychology and Behaviour, 2013. **19**: p. 85–96.

151. Michal Vojtisek-Lom and James T. Cobb Jr., *Vehicle mass emissions measurement using a portable 5 gas exhaust analyzer and engine computer data.* Emission paper 1997.

152. Frey, H.C., et al., *On-road measurement of vehicle tailpipe emissions using a portable instrument.* Journal of the Air & Waste Management Association, 2003. **53**(8): p. 992-1002.

153. Huang, Y., et al., *Fuel consumption and emissions performance under real driving: Comparison between hybrid and conventional vehicles.* Science of The Total Environment, 2019. **659**: p. 275-282.

154. Zhang, S., et al., *Real-world fuel consumption and CO_2 (carbon dioxide) emissions by driving conditions for light-duty passenger vehicles in China.* Energy, 2014. **69**: p. 247-257.

155. Jiménez-Palacios, J.L., *Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing.* Thesis (Ph.D.) - Massachusetts Institute of Technology, , 1999: p. p. 345-361.

156. Yu, Q., T. Li, and H. Li, *Improving urban bus emission and fuel consumption modeling by incorporating passenger load factor for real world driving.* Applied Energy, 2016. **161**: p. 101-111.

157. Boroujeni, B.Y. and H.C. Frey, *Road grade quantification based on global positioning system data obtained from real-world vehicle fuel use and emissions measurements.* Atmospheric Environment, 2014. **85**: p. 179-186.

158. Song, G. and L. Yu, *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**: p. 90-98.

159. USEPA, *Methodology for developing modal emission rates for EPA's multi-*

scale motor vehicle and equipment emission system. 2002.

160. Zhai, H., H.C. Frey, and N.M. Rouphail, *A vehicle-specific power approach to speed- and facility-specific emissions estimates for diesel transit buses.* Environmental Science & Technology, 2008. **42**(21): p. 7985-7991.

161. Hong Kong Transport Bureau, *Speed Limit in Hong Kong.* Legislative Council Panel on Transport, 2000.

162. Pulkrabek, W.W., *Engineering fundamentals of the internal combustion engine (2nd Edition).* Journal of Engineering for Gas Turbines and Power, 2004. **126**(1): p. 198-198.

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

164. United States Environmental Protection Agency. *Ambient air monitoring reference and equivalent methods: Designation of three new reference methods*. Sep 25, 2017; Available from: https://www.epa.gov/castnet/forms/procedure-requesting-archived-filters-and-extracts.

165. Birrell, S.A. and M. Fowkes, *Glance behaviours when using an in-vehicle smart driving aid: A real-world, on-road driving study.* Transportation Research Part F: Traffic Psychology and Behaviour, 2014. **22**: p. 113-125.

166. Frey, H.C., N.M. Rouphail, and H. Zhai, *Speed- and Facility-Specific Emission Estimates for On-Road Light-Duty Vehicles on the Basis of Real-World Speed Profiles.* Transportation Research Record, 2006. **1987**(1): p. 128-137.

167. Amir Khajepour, M. Saber Fallah, and A. Goodarzi, *Electric and hybrid vehicles - Technologies, modeling and control: A mechatronic approach*. 2014: John Wiley & Sons, Ltd.

168. Burke, R.D., C.J. Brace, and J.G. Hawley, *Critical evaluation of on-engine fuel consumption measurement.* Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2011. **225**(6): p. 829-844.

169. Zhang, Q., et al., *The effects of deterioration and technological levels on pollutant emission factors for gasoline light-duty trucks.* J Air Waste Manag Assoc, 2017. **67**(7): p. 814-823.

170. Pang, Y., M. Fuentes, and P. Rieger, *Trends in the emissions of Volatile Organic Compounds (VOCs) from light-duty gasoline vehicles tested on chassis dynamometers in Southern California.* Atmospheric Environment, 2014. **83**: p. 127-135.

171. Caserini, S., et al., *Impact of the dropping activity with vehicle age on air pollutant emissions.* Atmospheric Pollution Research, 2013. **4**(3): p. 282-289.

172. Friedrich, S., F. Konietschke, and M. Pauly, *Analysis of Multivariate Data and Repeated Measures Designs with the R Package MANOVA.RM.* The R Journal, 2018. **11**.

173. Gupta, A.K., S.W. Harrar, and Y. Fujikoshi, *MANOVA for large hypothesis degrees of freedom under non-normality.* TEST, 2008. **17**(1): p. 120-137.

174. Konietschke, F., et al., *Parametric and nonparametric bootstrap methods for general MANOVA.* Journal of Multivariate Analysis, 2015. **140**: p. 291-301.

175. S. Dai, et al., *Chemical and stable carbon isotopic composition of PM2.5 from on-road vehicle emissions in the PRD region and implications for vehicle emission control policy.* Atmos. Chem. Phys., 2015. **15**(6): p. 3097-3108.

176. Yanowitz, J. and R.L. McCormick, *Effect of E85 on tailpipe emissions from light-duty vehicles.* J Air Waste Manag Assoc, 2009. **59**(2): p. 172-182.

177. Montgomery, D.C., *3.2 The Analysis of Variance*, in *Design and Analysis of Experiments (8th Edition)*. John Wiley & Sons. p. 68.

178. Kim, S.Y., et al., *Development of Eco-Driving Guide System*. 2011, The Automotive Research Association of India.

179. Orfila, O., G. Saint Pierre, and M. Messias, *An android based ecodriving assistance system to improve safety and efficiency of internal combustion engine passenger cars.* Transportation Research Part C: Emerging Technologies, 2015. **58**: p. 772-782.

180. Magaña, V.C. and M. Muñoz-Organero, *Artemisa: A Personal Driving Assistant for Fuel Saving.* IEEE Transactions on Mobile Computing, 2016. **15**(10): p. 2437-2451.

181. Vagg, C., et al., *Development and Field Trial of a Driver Assistance System to*

Encourage Eco-Driving in Light Commercial Vehicle Fleets. IEEE Transactions on Intelligent Transportation Systems, 2013. **14**(2): p. 796-805.

182. Vagg, C., et al., *A Driver Advisory Tool to Reduce Fuel Consumption*. 2013, SAE International.

183. Caulfield, B., et al., *Measuring the success of reducing emissions using an on-board eco-driving feedback tool.* 2014. **32**: p. 253-262.

184. Yu, Q. and T. Li, *Evaluation of bus emissions generated near bus stops.* Atmospheric Environment, 2014. **85**: p. 195-203.

185. Jamson, S.L., D.L. Hibberd, and A.H. Jamson, *Drivers' ability to learn eco-driving skills; effects on fuel efficient and safe driving behaviour.* Transportation Research Part C: Emerging Technologies, 2015. **58**: p. 657-668.