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Eco-driving: Trends and Potential Impacts for Irish Heavy-duty Vehicles

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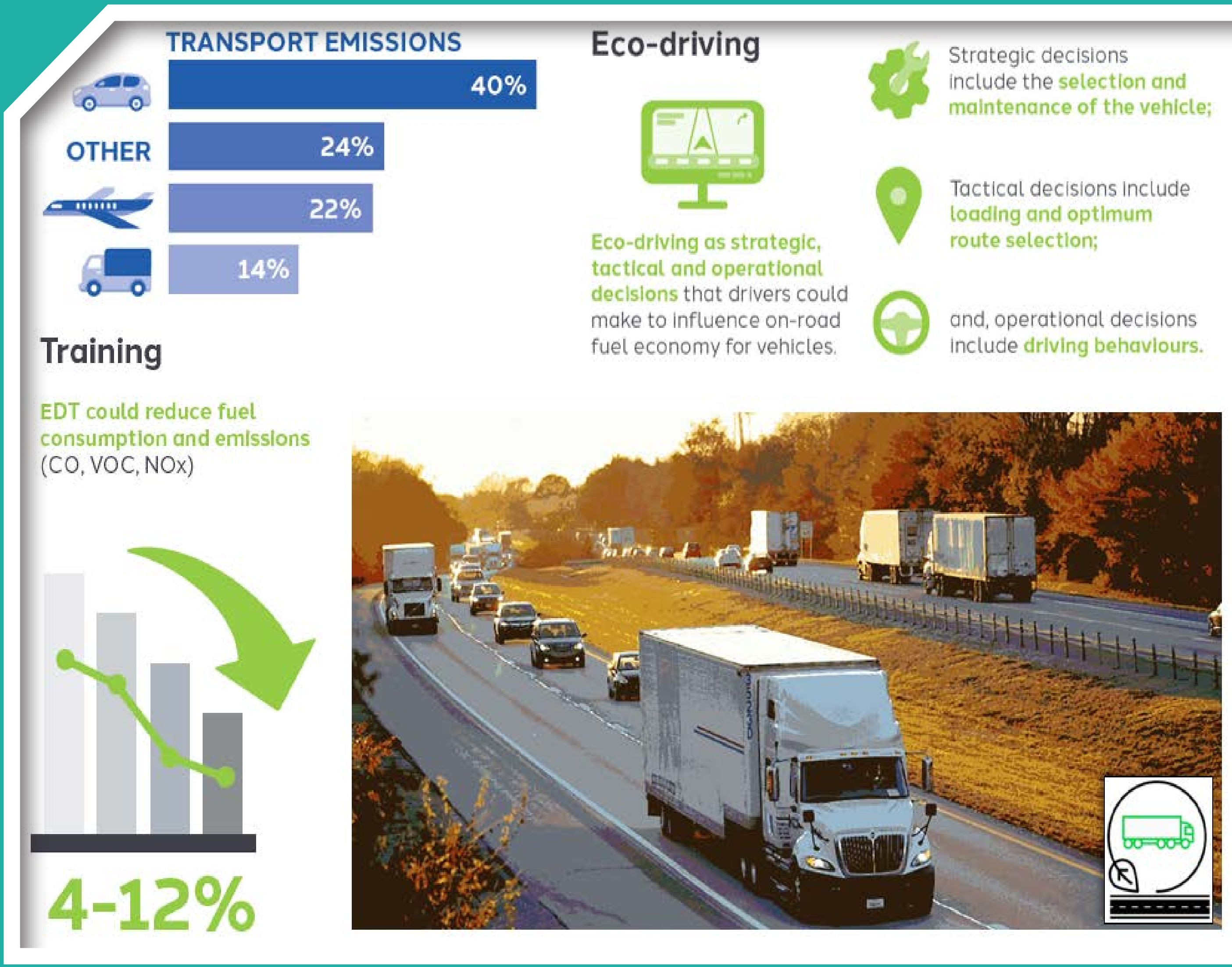

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Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

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- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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EPA RESEARCH PROGRAMME 2021–2030

Eco-driving: Trends and Potential Impacts for Irish Heavy-duty Vehicles

(2018-CCRP-DS.15)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Trinity College Dublin Ireland

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DISCLAIMER

This report is based on research carried out/data from July 2019 to June 2020. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Contents

List of Figures

List of Tables

Executive Summary

In Ireland, in 2018, the transport sector accounted for the largest share of energy-related carbon dioxide emissions (40%), followed by heat (33%) and electricity generation (27%). The top three contributors to total transport emissions are private cars (40%), aviation (22%) and heavy-duty vehicles (HDVs) (14%). With the expected increase in transport activities, this project, “ECO-HDV”, aims to evaluate the impacts of adaptation of eco-driving programmes in the Irish HDV fleet, including the freight sector. Eco-driving and related practices have been shown to improve fuel efficiency and reduce vehicular emissions in HDV fleets internationally. Several methods, such as a detailed literature review, in-person interviews with haulage company owners, an online survey, the collection of real-world driving behaviour data and the development of traffic simulation models, were used to achieve the objectives of this project. Based on the literature review, the effect of eco-driving programmes was observed to be fuel saving of between 2% and 15%, depending on programmes and individuals (Huang *et al*., 2018). Some of the key findings of the “ECO-HDV” project are as follows.

1. A large number of Irish haulage companies are eager to introduce eco-driver training programmes. Based on the collection and analysis of real-world driver behaviour data, professional drivers should be trained or periodically instructed in how to reduce the number of incidents of harsh and general braking and idling during their journey, and how to improve their skills driving with smooth acceleration and deceleration.
2. Eco-driving tips given to drivers may help in reducing overall fuel consumption and emissions (e.g. of carbon monoxide, volatile organic compounds, nitrogen oxides) under low traffic conditions. From simulations, it can be inferred that the impact of eco-driving on fuel consumption is uncertain in congested conditions and at signalised intersections. A policy recommendation from this study is that HDV priority signals and/or lanes should be provided within the vicinity of the Dublin Port area along with barrier-free lanes at tolls.
3. Survey responses from both stakeholders and company owners showed that the top three expected government policies should be incentives for gas trucks, electric trucks and driver training programmes. In addition, the Irish government is encouraging gas/liquid natural gas technologies by implementing necessary infrastructure through the Causeway Project and the Green Connect Project. The new HDV purchase grant scheme will provide grants of up to 30% of the cost differential between a traditional fossil-fuelled HDV and an equivalent alternatively fuelled vehicle.

1 Introduction

1.1 Background and Project Objectives

According to the Intergovernmental Panel on Climate Change (IPCC), the Earth's climate warmed by 0.85°C from 1880 to 2012 and emission of greenhouse gases (GHGs) produced from anthropogenic sources critically affected the atmosphere. The harmful effects of GHGs, which comprise mainly carbon dioxide (CO_2), methane and nitrous oxide, include global warming and climate change. The transport sector is one of the industries that contributes significantly to GHGs. According to the European Environment Agency (EEA), road vehicles account for 82% of GHG emissions from transport and one-fifth of total GHG emissions from the European Union (EU) (EEA, 2018). Further breakdown of these figures shows that heavy-duty vehicles (HDVs) are responsible for 27% of road transport CO_2 emissions and almost 5% of the EU's GHG emissions.

In 2018, the transport sector in Ireland accounted for the largest share of energy-related CO_2 emissions (40%), followed by heat (33%) and electricity generation (27%). Regarding transport, private cars were responsible for 40% of transport emissions, aviation for 22% and HDVs for 14% (SEAI, 2020). The transport sector is dependent on fossil fuels, and CO_2 emissions from the transport sector are expected to increase in the absence of a fuel mix. According to the *Transport Trends 2019* report by the Department of Transport, Tourism and Sport (DTTAS, 2019a), expected improvement in the economy would increase activities related to land freight (see Figure 1.1 for freight activities). However, owing to the COVID-19 pandemic and Brexit, the expected improvement in the economy and resultant freight activities may not materialise. Since 2015, road freight activities have increased, as shown in Figure 1.1a; this follows the significant decrease in road activity observed after the economic recession in 2008. In 2018, ~150 million tonnes of goods were transported by road, covering a distance of 1595 million kilometres (CSO, 2018). Overall, in 2018, the total tonnage of goods transported was 1.9% higher than in 2017 (Figure 1.1b). It was estimated that in 2018, 118,032 Irish-registered goods vehicles (trucks >2 tonnes) operated in Ireland and abroad, which was 8.8% higher than in 2017. Based on the types of work, in 2018, more than 50 million tonnes of goods were transported for road work and building sites, followed by retail outlets deliveries (~17 million tonnes), as presented in Figure 1.2. Therefore, with an expected increase in road freight activities and their associated contribution to air pollution, policies need to be implemented to curb future emissions from HDVs. At the European level, the European Commission has developed policies and undertaken strategies, such as the Strategy for Reducing Heavy-duty Vehicles' Fuel Consumption and CO_2 Emissions ("HDV Strategy"), adopted in 2014 [COM(2014) 285; EC, 2014], and

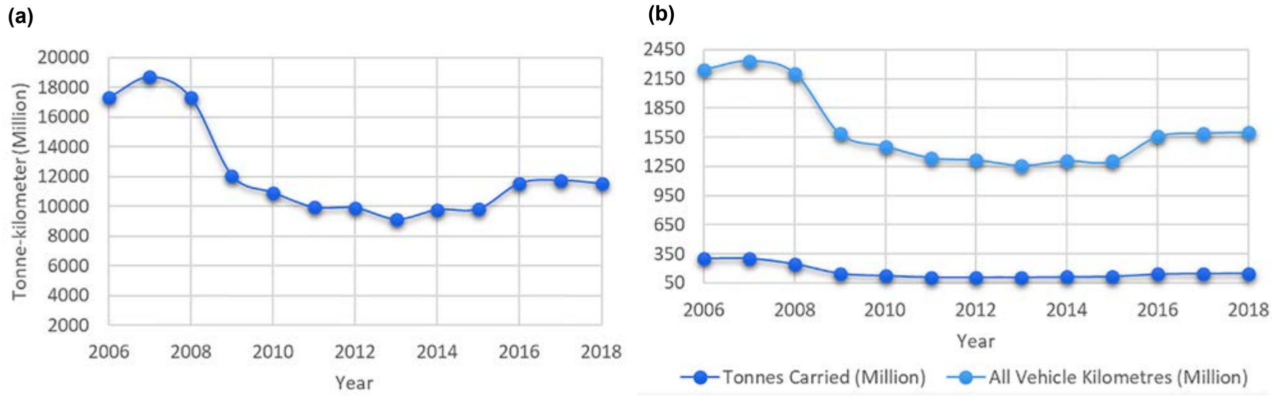

Figure 1.1. (a) Total road freight activity and (b) road freight activity in terms of tonnes carried and vehicle kilometres, between 2006 and 2018. Source: CSO (2018).

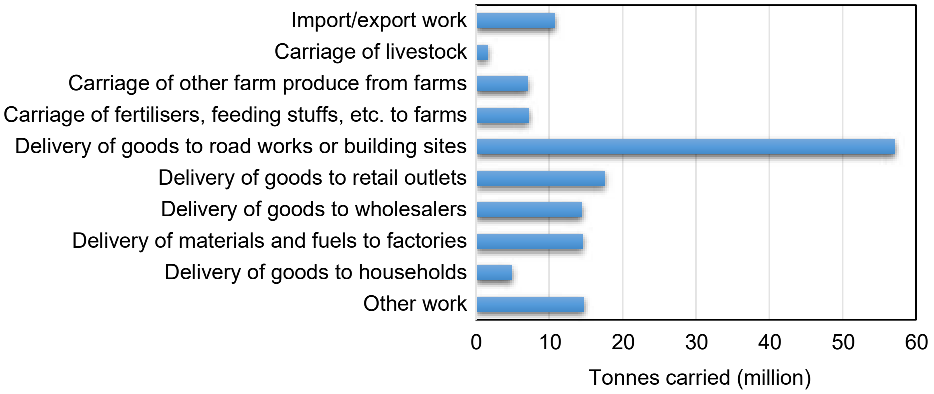

Figure 1.2. Quantity of goods hauled by types of work. Source: CSO (2018).

"A European Strategy for Low-emission Mobility", adopted in 2016 [COM(2016)0501; EC, 2016a], to reduce externalities such as air pollution from the HDV sector. The European Commission has listed three main strategies to reduce emissions from the transport sector (MEMO-16-2497; EC, 2016b):

1. increase efficiency by using digital technologies;
2. use alternative fuels;
3. encourage low-/zero-emission vehicles.

At the national level, the National Policy Framework (NPF) on Alternative Fuels Infrastructure Deployment (2014/94/EU) in Ireland, 2017 to 2030 – developed by DTTAS (2019) – indicates that eco-driving techniques could improve traffic movement and reduce GHG emissions. The National Mitigation Plan (NMP) published by the Department of Communications, Climate Action and Environment reiterates that the growth in the economy may increase pollution and GHG emissions from the HDV fleet in Ireland (DCCAE, 2017). In addition to eco-driving techniques, both the NPF and NMP indicate exploring other options, including alternative fuels.

Ireland's National Energy Efficiency Action Plan (NEEAP) has set a target of 20% energy efficiency to be achieved by all sectors including transport and provides a set of policy measures, such as electrification of the fleet and eco-driving, to improve energy efficiency in the transport sector (DECC, 2020). The recast Energy Efficiency Directive (2018/2002/EU) establishes binding measures to meet a collective energy efficiency target of 32.5% by 2030 (EU, 2018). Member States (including Ireland) are required to draw up integrated 10-year national energy and climate plans (NECPs) outlining how they intend to meet the energy efficiency target and other targets by 2030.

Consequently, fleet management and demand management strategies should be investigated to reduce emissions from HDVs. Fleet management strategies would help companies to reduce emissions by improving the aerodynamics of HDVs, reducing vehicles' tare mass and weight, making appropriate vehicle purchase decisions, assigning the appropriate HDV to the right job and driving in a fuel-efficient manner (McKinnon *et al*., 2015). Demand management strategies are addressed by government policies, such as by declaring low-emission zones, restricting HDV movements during particular times of the day and implementing vehicle weight restrictions. Furthermore, in the Climate Action Plan (Government of Ireland, 2019), the DTTAS committed to examining a range of travel demand management measures for Irish cities by commissioning a demand management study. This study aims to understand what measures are available to help address the impacts of growing transport levels in major cities in Ireland (Dublin, Cork, Limerick, Galway and Waterford). It will examine a range of factors (including congestion levels and air quality issues) and ultimately should recommend options on how travel demand in urban areas might be better managed; these may include congestion pricing, low-emission zones and parking policies. Huang *et al*. (2018) summarised several means to reduce emissions from the transport sector; these include improving mobility and reducing recurrent traffic congestion, fleet renewal (e.g. using vehicles with engines that meet the EURO VI emission standards), improving engine and vehicle technology (e.g. hybrid electric vehicles), better fuel quality and the use of renewable fuels (e.g. biofuels and higher octane rating petrol), and educating drivers within the fleet.

1.2 Scope of the Project

Decarbonisation of the Irish HDV fleet is of significant importance from the climate change perspective. One of the critical medium-term, soft measures of pollution mitigation in this sector has been identified as eco-driving. Eco-driving is an environmentally friendly, responsible driving style that improves safety and fuel economy and is often complemented with advanced vehicular and communication technologies. Eco-driving has been more widely adopted in passenger cars than in HDVs. Therefore, this project investigated eco-driving measures to reduce vehicular emissions and improve energy efficiency in the Irish HDV fleet. The project aims and objectives are linked with and are relevant to the Irish Environmental Protection Agency (EPA), the Sustainable Energy Authority of Ireland (SEAI) and the Irish energy and transport sectors.

The project examines European and Irish best practices regarding the adoption of eco-driving training (EDT) as a pollution mitigation and energy efficiency improvement measure in the freight sector. In-person interviews and an online survey were used to investigate current practices and the acceptance of eco-driving as a valid pollution mitigation measure in the freight sector, and also to establish the barriers, if any, to its implementation. Moreover, critical driver behaviour factors contributing to fuel consumption and pollution were identified based on the real-world telematics data, and a methodology to identify fuel-efficient drivers based on the real-world microscopic driving data is proposed. The project develops a transport model to estimate the impacts of eco-driving with the help of real-world microscopic driving data on fuel consumption and emissions. Overall, the project provides solutions and identifies the barriers to implementing eco-driving in the Irish HDV fleet. The project generates guidelines for the adaptation and evaluation of eco-driving programmes to reduce vehicular emissions from the Irish HDV fleet.

1.3 Structure of the Report

Chapter 2 summarises the state of the art in eco-driving programmes for the HDV fleet that have been adopted in Europe and globally to reduce vehicular emissions, including CO_2 and other harmful pollutants. Chapter 3 analyses the current eco-driving practices in the Irish HDV fleet and the attitude towards eco-driving adaptation in the logistics sector using in-person interviews and an online survey. It also presents a sample fuel-efficiency benchmarking database identifying the best fuel economy practices utilising eco-driving followed in Ireland. Chapter 4 proposes a methodology to identify important factors in the driver training programme. Chapter 5 presents a methodology for collecting real-world acceleration and deceleration profiles of drivers after providing them with eco-driving tips and for identifying fuel-efficient drivers. Chapter 6 focuses on the potential impacts of eco-driving on fuel economy and pollution rates using a microscopic traffic simulation model. Finally, Chapter 7 presents conclusions on the project.

2 Review of Eco-driving Approaches

This chapter aims to review past research studies and projects related to the state-of-the-art application of eco-driving in HDVs and eco-driving programmes for passenger cars, HDVs and buses. It provides an overview of factors contributing to fuel economy, the short- and long-term impact of training, different ways to enhance eco-driving, and global and national policies and legislation. Finally, based on the literature review, potential guidelines to reduce emissions in the Irish context are highlighted. Books, articles, project reports, research reports and national and global policies were reviewed. Furthermore, the most relevant national and international case studies were examined to identify strategies that could be useful in the Irish context.

2.1 Definition of Eco-driving

Eco-driving is a specific way of driving any vehicle. Typical characteristics of eco-driving are accelerating moderately, anticipating real-time traffic and signals, avoiding sudden stops and starts, eliminating excessive idling, and maintaining a constant driving speed using cruise control on motorways (Barkenbus, 2010). The definition of eco-driving is often limited, and numerous definitions can be found in the literature (e.g. Barkenbus, 2010; Sivak and Schoettle, 2012; Sanguinetti *et al*., 2017). In the Irish context, we recommend that eco-driving be defined as strategic, tactical and operational decisions that drivers could make to increase on-road fuel economy. Strategic decisions include the selection and maintenance of the vehicle, tactical decisions include loading and optimum route selection, and operational decisions include driving behaviours.

2.2 Methodology

To conduct the literature review, research databases (Inspec, Ei Compendex, ScienceDirect and Transport Research International Documentation – TRID) were searched using keywords such as eco-driving cars, trucks, buses, heavy goods vehicles (HGVs) and HDVs to identify research articles and projects related to eco-driving. The preliminary findings suggested that there were more studies about eco-driving cars and light-duty vehicles (LDVs) than about trucks, HDVs, HGVs and buses. This review covers different aspects of eco-driving, the short- and long-term effects of training programmes, and strategies to reduce fuel consumption in the eco-driving context. It also focuses on identifying factors contributing to fuel economy, based on the type of vehicles (cars, buses, trucks) and measures, such as driver training programmes, eco-driving assistance/feedback systems and eco-routing measures, to reduce fuel consumption. The literature review is categorised by books, academic research, project reports and policies. Most of the academic research studies and books (af Wåhlberg, 2007; Kobayashi *et al*., 2007; Zarkadoula *et al*., 2007; Qian and Chung, 2011; Liimatainen *et al*., 2012; Daun *et al*., 2013; Strömberg and Karlsson, 2013; Caulfield *et al*., 2014; McIlroy and Stanton, 2014; Rolim *et al*., 2014; Ferreira *et al*., 2015; Heyes *et al*., 2015; McKinnon, 2015; Walnum and Simonsen, 2015; Zhou and Yao, 2015; Schall *et al*., 2016; Wang and Rakha, 2016; Williams *et al*., 2016; Greene *et al*., 2017; McIroy and Stanton, 2017; Alam and McNabola, 2018; Zang *et al*., 2019; Yao *et al*., 2020) can be subdivided into studies related to identifying the factors influencing fuel consumption, the effect of EDT programmes and eco-routing. These are discussed in this chapter.

2.3 Factors Influencing Eco-driving

Several review articles (Ang-Olson and Schroeer, 2002; Alam and McNabola, 2014; Demir *et al*., 2014; McKinnon, 2015; Zuraida and Widjaja, 2017; Huang *et al*., 2018) have focused on technologies, factors contributing to eco-driving, and policies and implementation strategies of eco-driving. Driving speed, acceleration/deceleration, idling, route choice, tyre pressure, aerodynamic drag, air conditioning, vehicle maintenance and excessive load are some of the critical factors that influence eco-driving. Typically, engine dynamometers, chassis dynamometers, driving simulators, data loggers, odometer readings, surveys, modelling and portable emissions measurement systems (PEMSs) are used to study eco-driving. Moreover, Alam and McNabola (2014) reviewed technologies and policies related to eco-driving. The article reported several positive and negative impacts of eco-driving on fuel consumption and CO_2 emissions. One of the significant highlights was the implementation of eco-driving in congested traffic conditions, which may lead to higher emissions of CO_2 and safety concerns. Zhou *et al*. (2016) reviewed fuel consumption models based on the transparency of the models to evaluate the eco-driving and eco-routing strategies. It was observed that traffic, driver and roadway characteristics are significant contributing factors to fuel consumption. Based on the previous literature, Demir *et al*. (2014) considered that five factors contribute to fuel use in freight transport:

1. vehicle-related elements, comprising vehicle kerb weight, vehicle shape, engine size and type, engine temperature, fuel type, oil viscosity and other characteristics (maintenance, age accessories, etc.);
2. environmental factors comprising ambient temperature, altitude, wind conditions and other characteristics (humidity, surface conditions, etc.);
3. traffic-related factors, including speed, acceleration, deceleration and congestion;
4. driver-related factors, including driver aggressiveness, gear selection and idling time;
5. operations-related factors, including fleet size, payload, empty kilometres and the number of stops.

McKinnon *et al*. (2015) suggested several ways, such as improving aerodynamic profiling, reducing vehicles' tare mass and weight, vehicle purchase decisions and fuel-efficient driving style, to improve fuel efficiency in the road freight sector. Of these, driving style is the most critical factor in improving fuel efficiency. Ang-Olson and Schroeer (2002) studied the impact of several strategies on fuel saving for an average truck in the USA. The saving ranged from 0.6% by using an automatic tyre inflation system to maximum savings achieved by reducing vehicle idling times and speed. Driver training and monitoring were observed to be critical strategies to improve fuel savings. However, McKinnon (2015) noted that some of the strategies counteract each other; for example, reducing speed will reduce the effectiveness of the vehicle's aerodynamics. Therefore, aggregated fuel saving by considering all the real-world strategies would be unlikely.

Focus group and survey methods have been used to study the perception of eco-driving. McIlroy and Stanton (2014) presented a decision ladder analysis of the eco-driving behaviour of passenger cars by conducting a focus group meeting with four researchers, and, subsequently, five eco-driving experts were each interviewed once. Eco-driving was defined by activities such as deceleration at a lower speed and on curved roads, full stop by the early release of the acceleration pedal and headway maintenance.

Overall, vehicle, driver, roadway and traffic characteristics influence fuel consumption. Within each of these categories, several parameters contribute to fuel consumption. In addition, some characteristics counteract each other. However, driver behaviour/ driver skills contribute significantly to fuel consumption and, ultimately, to emissions.

2.4 Eco-driving Analysis Using Real-world Data and Eco-driving Training Programmes

Telematics data help to capture intricate details of driver and vehicle performance. The following sections focus on investigating eco-driving using real-world car data and quantify the impact of EDT programmes on fuel economy. Driving skills required for HDVs are significantly different from passenger cars because of the variation in vehicle length, weight, aerodynamics, turning radii and engine characteristics. However, some of the knowledge, skills and attitudes are readily transferable, and are discussed here for completeness. Furthermore, the impact of EDT programmes varies by the length of time after the EDT (short- and long-term effects), the experience of the drivers and the type of road (within the city and on motorways). As the operational characteristics of passenger cars and HDVs vary, the studies related to real-world data and the impact of EDT programmes are summarised separately.

2.4.1 Cars and light-duty vehicles

The following subsections focus on investigating eco-driving of cars and LDVs.

Real-world data

Studies have focused on identifying the contributing factors (El-Shawarby *et al*., 2005; Yao *et al*., 2020) and techniques (Zang *et al*., 2019) to quantify eco-driving. El-Shawarby *et al*. (2005) evaluated the impact of cruise speed and acceleration on fuel consumption and emission rates using real-world driving behaviour of a passenger car and concluded that optimal fuel consumption could be achieved while driving within the range of 60 to 90 km/h. A research study by Zang *et al*. (2019) stated that the baseline vehicle-specific power (VSP) distributions and individual driver-specific VSP distributions could be used to evaluate eco-driving behaviours of passenger cars. An eco-driving index (EDI) was proposed to define eco-driving behaviour based on the speed ranges. Greene *et al*. (2017) found that the fuel economy of conventional petrol and hybrid cars was improved during the first few thousand miles compared with average values, and although fuel consumption of petrol vehicles was relatively stable over time, in hybrid cars it decreased. However, in cold temperatures hybrid cars were found to be more fuel-efficient than petrol cars. Yao *et al*. (2020) collected driving behaviour data under varying traffic, roadway and weather conditions from 120 taxi drivers for 4 months. Based on the information from on-board diagnostic (ODB) units, and other relevant information, driving under heavy traffic conditions, light snow and dusty and rainy conditions could increase fuel consumption.

Overall, real-world car data suggested that driving at optimal speed could reduce fuel consumption; however, heavy traffic conditions and extreme weather conditions influence fuel consumption for passenger cars.

EDT for cars and light vehicles

Qian and Chung (2013) investigated the effect of eco-driving on private cars and traffic platoons in Japan. Fifteen test vehicles were tested on a 1-km section that included three intersections. A total of 10 scenarios were tested by keeping the eco-driving vehicles at several positions within the traffic platoon and comparing the fuel consumption and queue discharge of different scenarios. Fuel consumption was reduced for individual eco-driving vehicles, but the change in average fuel consumption of the whole traffic platoon in different situations was uncertain. Andrieu and Saint Pierre (2012) investigated the effect of eco-driving recommendations and full EDT on driver performance of cars in Pontchartrain (Yvelines), France. The study concluded that, regardless of the learning model, parameters such as average speed, average fuel consumption and average acceleration have a positive impact on eco-driving practices. The average fuel consumption decreased by 12.5% between regular drivers and those driving following eco-driving advice, and it decreased by 11.3% between normal and fully trained eco-driving drivers. Likewise, to investigate the effect of EDT, Rutty *et al*. (2013) conducted a research study in the city of Calgary, Canada, with the help of telematics data in cars. The research was conducted in three phases: pre-eco-driving to get baseline conditions, during EDT and post EDT. Behaviour parameters, such as hard acceleration, idling time, vehicle CO_2 emissions from idling, fuel consumed and the fuel cost from idling were compared. After the EDT programme, the average daily idling time for petrol and hybrid drivers decreased by 4% and 10% per vehicle per day, respectively.

In the study by Wu *et al*. (2017), two different EDT programmes – (1) an education programme and (2) a coaching plus education programme – were evaluated using a driver simulator. A total of 22 drivers were selected and each of the drivers drove the driving simulator three times: before driver training after education and after coaching. Education training helped to reduce both the incidence of and time spent idling and to avoid rapid accelerating when setting off. However, coaching after the education programme helped to improve fuel efficiency by improving smooth deceleration and steady speed on motorways and reducing idling time. Similarly, Lois *et al*. (2019) investigated the short-term impacts of eco-driving. In their study, they evaluated real-world data from 1156 car trips by 24 drivers (14 male and 10 female) in the cities of Madrid and Cáceres in Spain. The data from cars were collected using the on-board diagnostic (OBD) device and mobile phones. They concluded that eco-driving is influenced by driver behaviours, such as driving at higher speed, excessive revolutions per minute (RPM) and deceleration rate, which are not part of eco-driving, and that external factors such as traffic congestion and hilly roads contribute to fuel consumption. Beusen *et al*. (2009) evaluated the long-term impact of an EDT course by monitoring driving behaviour. The driving behaviour was monitored from the OBD logging device in cars, which captures global positioning system (GPS) tracking and speed. Engine data were obtained through a controller area network (CAN). Data on parameters such as mileage, RPM, position of the accelerator pedal and fuel consumption were collected from 10 different drivers for 10 months. Their study concluded that, after 4 months of training, average fuel consumption fell by 5.8%. Overall, in terms of immediate fuel consumption, a positive effect was shown by most of the drivers; however, some drivers were observed to revert to their original driving practice.

Jeffreys *et al*. (2018) evaluated the EDT of private drivers in Queensland, Australia. The training curriculum focused on several aspects of eco-driving: fuel monitoring; watching ahead and driving smoothly; braking and accelerating gently; not parking and idling; cruising at a steady speed on motorways; minimising air conditioner use; shifting gears as quickly as possible; removing excess weight from the vehicle; and servicing the car as per the manufacturer's schedule. Five interventions – (1) online learning, (2) classroom-based learning, (3) in-car driving lessons, (4) classroom learning and driving lessons and (5) a half-day workshop – were introduced in their research study. A total of 853 private drivers were educated using this EDT technique, and 203 private drivers without EDT were used as a control group; members of both groups were monitored for 7 months. Their study observed fuel reductions of 4.6% or 0.51 l/100 km fuel in the trained group compared with the control group. Barla *et al*. (2017) assessed the impact of eco-driving programmes for car drivers in terms of fuel consumption in Quebec, Canada, over a 10-month period. The programme involves a continuous 6 hours of theoretical and practical training, focusing on smooth acceleration and deceleration, optimal gear shifts, maintaining moderate and steady speeds, anticipating traffic, avoiding idling and ensuring proper maintenance of vehicles. On completion of the programme, a reduction in average fuel consumption of 4.6% and 2.9% was initially observed at the city level and on motorways, respectively; however, after the first 10 months the reduction in fuel consumption declined from 4.6% to 2.5% at city level.

EDT programmes help to reduce fuel consumption for passenger cars and LDVs by 5–15%. However, the short- and long-term effects could vary depending on the methodology, study location and techniques to quantify the impact of eco-driving.

2.4.2 Heavy-duty vehicles and buses

The following sections focus on investigating eco-driving using real-world data and quantifying the impact of EDT programmes on the fuel economy of HDVs and buses.

Real-world data

Studies have focused on identifying the factors contributing to eco-driving (Ferreira *et al*., 2015; Walnum and Simonsen, 2015) and the haulier's perspective of (Liimatainen *et al*., 2012) eco-driving. Walnum and Simonsen (2015) studied telematics data and driver, vehicle and infrastructure characteristics of a Norwegian HDV transport company and identified that the three most influencing factors contributing to fuel emissions were use of more than 90% torque power, horsepower and use of the highest gear while driving. Using a survey focused on assessing current and future energy efficiency and CO_2 emission reduction targets, Liimatainen *et al*. (2012) collected and analysed data from 295 road transport firms/hauliers in Finland. They concluded that small companies are familiar with energy efficiency actions but lack knowledge regarding implementation strategies. Large hauliers (those with more than five trucks) are more informed and active concerning fuel efficiency than smaller companies. Ferreira *et al*. (2015) investigated the effect of driving style on fuel consumption based on 3 years of vehicle data collected from the CAN of public buses. Their study concluded that simple driving practices, such as the optimal use of the clutch and reducing engine rotation and the time that the engine spends in the idle condition, could reduce fuel consumption by 3–5 l/100 km. Furthermore, Wang and Rakha (2016) found that the optimal fuel-economical cruising speed for diesel buses was 40–50 km/h, which was lower than for petrol-powered LDVs (60–80 km/h). The model was calibrated using second-by-second real-world bus data.

Like cars, driving at optimal cruising speed was a significant contributing factor for fuel consumption for HDVs and buses. However, the range for optimal speed for HDVs and buses is different from passenger cars and LDVs. Several other vehicle factors such as engine rotation, horsepower, top gear and idling contribute to fuel consumption for HDVs and buses.

EDT for HDVs and buses

In the research study by Ayyildiz *et al*. (2017), data were collected for 4 months from 15 HDVs and 10 light commercial vehicles in the province of Jiangsu, China. For their study, an advanced telematics platform was developed and tested on HDVs and light commercial vehicles. After EDT, fuel consumption was reduced by 5.5% in HDVs; however, no significant reduction in fuel consumption was observed in light commercial vehicles after the training.

Díaz-Ramirez *et al*. (2017) identified factors that contribute to fuel consumption of the HDV fleet in Columbia. Factors such as driver's profile and behaviour, errors in driving and operational characteristics were considered in their research study. Telematics data were collected before and after EDT. After EDT, fuel consumption was reduced by 7%. Regression analysis indicated that driving errors (speeding, excessive acceleration and deceleration), driver's experience, weight-to-capacity ratio and average speed contributed to the fuel consumption of the HDV fleet. The results of the study were company specific. Likewise, Zavalko (2018) evaluated the short- and long-term effects of EDT of truck drivers on fuel consumption. Higher qualified drivers had a better understanding of eco-driving skills. In the short term, it was observed that drivers who had EDT used 13.6% less fuel; after 3 months, this was reduced to a 4% fuel reduction. Af Wåhlberg (2007) investigated the effects of fuel-efficiency training on bus drivers. Information on driver behaviour, in terms of acceleration data, fuel consumption and crash data, were collected. Drivers were trained in the first phase and, in the second phase, 28 buses were equipped with a feedback system to indicate fuel consumption. The number of passengers on board and temperature were kept constant. The research study concluded that there were no clear short- or long-term effects of training on any of the variables considered. Driver training programmes can improve fuel efficiency by 8–10% (McKinnon, 2015). McKinnon (2015) suggested that increased awareness of the issue of fuel consumption by drivers, hauliers and all relevant parties, and incentives for drivers would help to achieve the long-term effect of eco-driving. However, an incentive programme could be a complex exercise because drivers would switch trucks and delivery runs (McKinnon *et al*., 1993). To overcome this challenge, electronic equipment (telematics data) should be installed in trucks to capture the driver's performance regarding harsh acceleration, harsh braking, speeding and timely gear changes. A driver's performance should be discussed with the driver and providing advice or additional training could result in improvements in fuel economy. McKinnon (2015) stated that fuel economy could be improved by 5–15% by enforcing telematics data for good driving practice. In addition to driving, engine idling significantly contributes to fuel consumption. A typical HDV in the UK consumes around 2 l of fuel and emits 5 kg of CO_2 per hour when idling. McKinnon (2015) also mentioned a study in which 550 drivers were trained using an English truck simulator and around 1000 drivers were trained and assessed using two truck simulators in Scotland. The study reported that, on average, a Scottish simulator driver improved the fuel efficiency by 13%. Schall *et al*. (2016) conducted a 12-month field experiment on the effect of training and incentives, in terms of fuel-efficient driving of light commercial vehicles, in a logistics company in Germany. They reported that purely theoretical training had no short- or long-term effects on fuel efficiency.

Zarkadoula *et al*. (2007) studied three bus drivers to evaluate the effect of eco-driving in terms of fuel consumption in Athens, Greece. After EDT, fuel consumption of buses driven by two of the participants reduced by between 13% and 18% for one driver and increased by 1.78% for the other driver. In a research study by Sullman *et al*. (2015), a total of 29 bus drivers underwent a 1-day eco-driving course while a control group of 18 bus drivers attended first aid courses. Using a driving simulator, the performance of the 29 drivers was evaluated before and after the EDT course. The study concluded that fuel economy of the treatment group improved by 11.6% just after the EDT, and the improvement was even higher after 6 months (16.9%).

Overall, based on the literature related to HDVs and buses, eco-driving could reduce fuel consumption by 4–14%, depending on the trip and driver characteristics.

2.5 Eco-driving Using Simulation Scenarios

This section summarises studies related to eco-driving under different simulation scenarios.

Kobayashi *et al*. (2007) studied the influence of eco-driving in a traffic network using field experiments and simulations. The study consists of three parts: (1) field experiment, (2) proposed eco-driving control algorithm and (3) simulation experiment. It concluded that the proposed eco-driving algorithm could significantly reduce emissions in congested traffic conditions and that the effect of eco-driving depends on traffic volume and traffic composition.

Qian and Chung (2011) evaluated the effect of eco-driving in terms of fuel consumption, CO_2 emissions and travel with different traffic conditions, acceleration and penetration rate. The model for northbound traffic on a particular signalised intersection on Peachtree Street, Atlanta, GA, was calibrated in Aimsun software and tested for several scenarios, including different traffic volumes, penetration rates and different acceleration rates. In their study, two styles of eco-driving were tested: reducing the maximum acceleration by 10% and 20%. In congested traffic conditions, eco-driving showed some negative impacts. With the increase in penetration rate (>50%) at 600 vehicles per hour traffic volume, the average individual fuel consumption was lower, except in a scenario with 25% penetration.

Likewise, in a later study Qian and Chung (2013) found that “gentle acceleration”, one of the eco-driving styles, could affect the queue discharge rate at the signalised intersection. In that study, Next Generation Simulation (NGSIM) community programme data were simulated for an intersection located on Peachtree Street in Atlanta, GA. In their research, a vehicle that attained a speed of 20 km/h in the first 5 seconds was considered to be gently accelerating (Association for Promotion of Eco-drive, 2012). Eco-driving vehicles were simulated and introduced in the range of 0–100%, and the results were compared with the base condition. The authors concluded that overall fuel consumption and CO_2 emissions decreased with increasing numbers of eco-drivers, whereas a slight increase in travel time was observed with an increase in eco-driver numbers.

Other research studies used simulation to investigate eco-driving (Orfila, 2011; Zhou and Yao, 2015; Williams *et al*., 2016; Garcia-Castro *et al*., 2017; Alam and McNabola, 2018). Williams *et al*. (2016) focused on two issues: (1) the effect of eco-driving on a road network that is calibrated for emission and energy estimation, and (2) investigating acceleration and deceleration behaviour that maximises energy saving. It was concluded that deceleration should be limited, in comparison with acceleration, to achieve maximum energy saving. Furthermore, the maximum energy saving was observed with a 10% reduction in acceleration rate and a 50% reduction in deceleration rate. Alam and McNabola (2018) found a significant increase in traffic congestion and CO_2 emissions (18%) in heavy traffic conditions and with an increase in eco-driving vehicles. Acceleration and deceleration of eco-driving vehicles at different penetration rates, traffic composition and volume were investigated in their research. Their study involved small and sizeable real-world road networks in Dublin, Ireland. Three desired speed distribution profiles were modified in VISSIM software to replicate eco-driving behaviour. Speed distribution profiles were applied at the fleet level.

Zhou and Yao (2015) conducted a field trial based on the golden rules (i.e. anticipating the traffic, driving with a steady speed and accelerating smoothly). Using these data, a four-legged intersection in Spain was modelled in VISSIM microsimulation software. Their study concluded that the effect of eco-driving is significant during congested traffic conditions. In addition, negative impacts, in terms of travel time, were observed at the penetration rate of 20–40% of eco-drivers. However, positive effects, in terms of travel time, were found when penetration rates of 40% of eco-drivers were exceeded. Similarly, Orfila (2011) investigated the effect of eco-driving on fuel consumption and congestion with an increase in the percentage of eco-drivers using Aimsun simulation software. Under free-flow traffic conditions on urban and inter-urban roads, eco-driving was found to be effective in reducing emissions. However, in intermediate traffic conditions on inter-urban roads, the emissions increased after the optimum penetration rate (i.e. 20%) of eco-driving vehicles.

Garcia-Castro *et al*. (2017) developed four traffic microsimulation models for different types of urban roads. In total, 72 scenarios were simulated by varying traffic demand, type of road and the percentage of eco-drivers. The presence of eco-drivers in low or medium traffic demand had a positive impact on reducing emissions. However, with increased traffic demand and proportion of eco-drivers, emissions were observed to increase because of higher headways, smooth acceleration and deceleration under congestion.

Overall, simulation tools can be useful to investigate eco-driving. Studies have replicated eco-driving behaviour at the fleet level (by considering all vehicles, irrespective of vehicle category) or only passenger cars. Vehicle operations for cars and LDVs are different from HDVs. Therefore, in simulation studies, it is necessary to quantify the effect of eco-driving behaviour of HDVs and passenger cars separately.

2.6 Eco-driving Assistance/Feedback System

Heyes *et al*. (2015) evaluated the effect of an eco-driving assistance system (EDAS) on the fuel efficiency of commercial vehicles near Munich, Germany, using GPS, fuel consumption, video, road and vehicle data. They developed the EDAS based on digital maps and consisting of modules such as situation detection, driving error detection, message filtering and prioritisation. The driving test results indicated improvement in fuel efficiency in commercial vehicles.

Daun *et al*. (2013) evaluated the performance of an EDAS on fuel consumption using driving simulator experiments. A linear mixed model was developed and the results suggested that instructions for economical driving could result in a 6.0% fuel saving, and with the addition of EDAS fuel consumption could reduce by a further 6.6%, compared with normal driving. In the Netherlands, Caulfield *et al*. (2014) evaluated the effectiveness of on-board eco-driving feedback tools on fuel consumption per kilometre. Their results showed that drivers who had some coaching were able to reduce emissions compared with control group drivers. Based on the theory of planned behaviour, Stillwater and Kurani (2012) investigated the changes in driver behaviour of 46 drivers using an on-board eco-driving feedback tool installed in plug-in hybrid electric vehicles. Their analysis indicates that the on-board eco-driving feedback tool encourages eco-driving behaviour and that the context of feedback information provided by the tool is vital for eco-driving behaviour. Furthermore, Martin *et al*. (2013) evaluated the effect of eco-driving feedback devices on fuel consumption. Their study concluded that different drivers reacted differently to feedback information and, after excluding the outlier, fuel savings of up to 1.4% were observed.

In Sweden, Strömberg and Karlsson (2013) employed field trials to examine the effect of urban bus drivers using an in-vehicle feedback tool. Drivers were divided into three groups: (1) a group using an in-vehicle feedback system, (2) a group using a feedback system and training session, and (3) the control group. A 6.8% fuel saving was observed as a result of eco-driving strategies. However, no difference was observed between either of the eco-driving approaches.

Rolim *et al*. (2014) evaluated the impact of EDT and real-time feedback devices on bus drivers' behaviour for the data collected between 2010 and 2013. The study comprised two monitoring periods, one with feedback in audio form and one without sound feedback. By comparing the monitoring periods, their study concluded that, without audio feedback, inexperienced and senior drivers spent more time in extreme brakes, acceleration and hard stops.

Overall and considering all vehicle types, Huang *et al*. (2018) summarised the studies using real-time feedback and delayed feedback devices. Real-time feedback was visual, audio, haptic or a combination of these. All three methods have advantages and limitations regarding driver behaviour. Furthermore, real-time feedback information is more effective than delayed feedback. Finally, Huang *et al.* (2018) concluded that short-term impact is greater than long-term effects in terms of fuel saving. Therefore, in-vehicle devices have similar limitations to training programmes.

2.7 Eco-routing

Eco-routing can also be known as route choice. Route choice is influenced by factors such as travel time, distance, road, speed limit and traffic conditions (Haung *et al*., 2018). In terms of fuel consumption and emissions, the shortest or fastest route is not the best choice (Boriboonsomsin *et al*., 2012; Masikos *et al*., 2015).

Ericsson *et al*. (2006) developed a navigation system that focuses on lowering total fuel consumption. Real-world driving patterns on the city streets of Lund, Sweden, were analysed in their research study. The data comprise 15,437 cases, and fuel consumption factors for 22 street classes were estimated for peak and off-peak periods using two mechanistic emission models. The results concluded that in 46% of cases the driver's natural route choice was not the most fuel-efficient route. Opting for fuel-efficient routes for all journeys in Lund could reduce fuel consumption by 4%. Zeng *et al*. (2016) developed a CO_2 emissions per kilometre model and tested the application for eco-routing navigation. In their study, CO_2 emissions were reduced, on average, by 11% using eco-routes for origin–destination distances of between 6 km and 9 km. Kuo (2010) proposed a time-dependent vehicle routing method by considering travel times and speed based on the time of travel. An algorithm was proposed to find a route with the lowest fuel consumption. Experimental evaluation of the proposed method has shown a 24.61% improvement in fuel consumption when compared with minimising travel time.

Sun and Liu (2015) developed an eco-routing algorithm that incorporated a microscopic emissions model for vehicles within a signalised traffic network. Two examples were presented based on field data from Pasadena, CA, and carbon monoxide (CO) emissions were observed to have reduced by 20%. Yao and Song (2013) developed mesoscopic vehicle emissions and fuel consumption models using vehicle operation and emissions data. With the help of the models developed, the eco-route algorithm was proposed; it replicates existing road network characteristics in Chinese cities. The proposed algorithm was evaluated using data from Beijing, China, and significant reductions in fuel consumption were found (Yao and Song, 2013).

Nie and Li (2013) addressed an eco-routing problem to find the optimal route that minimises operating costs in terms of both travel time and fuel. Fuel consumption and emission estimation models that considered the physical and operational properties of vehicles were developed. The developed model could also depict emissions related to delays. Numerical experiments performed in this study demonstrated the influence of weight and engine displacement on eco-routing. Furthermore, turning movements and acceleration were observed to be essential parameters and ignoring them might lead to the suboptimal route.

Bandeira *et al*. (2014) investigated the change in the eco-friendliness of routes based on vehicle characteristics that could affect the overall efficiency. Origin–destination data were used in this empirically based research study. More than 13,330 km of GPS data for nine different routes were used for analysis. Two different approaches for estimating CO_2, hydrocarbon (HC), CO and NO_X were tested: (1) a VSP instantaneous model and (2) European Monitoring and Evaluation Programme (EMEP)/EEA methodology. Their study concluded that for specific origin–destination pairs the eco-friendly route could differ based on the emission estimation method.

Barth and Boriboonsomsin (2009) studied the effect of dynamic eco-driving on fuel saving. In dynamic eco-driving, drivers are informed about the changes in traffic conditions in real time. In their study, simulation and real-work experiments were performed for several traffic congestion levels. Their simulation study concluded that fuel consumption could be reduced by 10–20% without affecting the travel time.

Similarly, Ahn and Rakha (2013) investigated the effect of a dynamic eco-routing system by considering different levels of congestion and market penetration of LDVs and light-duty trucks in downtown/city centres of Cleveland, OH, and Columbus, OH. Their study compared two routing options, one to minimise fuel consumption and the other to minimise travel time. They observed that the network-level average fuel saving of eco-routing vehicles was in the range of 3.3–9.3% compared with traditional travel time routing. Eco-routing systems may or may not reduce travel time but reduce the travel distance.

Likewise, Scora *et al*. (2015) developed an eco-routing system for heavy vehicles based on the emission model, which considered parameters such as real-time traffic, the gradient of roads and vehicle weight. The proposed eco-routing and navigation system undertook truck energy and emissions modelling, and the system they developed could predict fuel consumption within 7.5%. Further, sensitivity analysis provided the break-even condition between optimised fuel consumption and optimised travel time route (Scora *et al*., 2015).

Overall, eco-routing could be used as an effective navigation system to encourage eco-driving on a long-term basis. However, the impacts of an increase in eco-routing drivers on network performance are still unknown.

2.8 Research Projects

This section summarises funded and implemented research projects related to EDT programmes. Many EU Member States and other non-European countries have implemented education-based strategies to reduce GHG emissions from HDVs. In contrast to HDVs, eco-driving is one of the widely adopted methods for passenger cars to reduce emissions. In Finland, eco-driving was first introduced as part of novice driver training in 1995, and it became part of the driving test in 1998 (CIECA, 2007). Finland was followed by the Netherlands, Germany and many other European countries and eventually it was adopted for HDVs in Europe.

EcoEffect focused on developing an EDT scheme in Czechia, Poland and Romania. This project concluded that a 1-day training programme and correct monitoring would reduce fuel consumption by 5–9%. In this project, around 100 trainers were trained in giving eco-driving courses and 2600 professional drivers were given training in eco-driving, comprising five elements: educating novice drivers, re-educating licensed drivers, fuel-saving devices in cars, tyre pressures and purchasing behaviour.

Likewise, projects such as ECOWILL,[1] ECODRIVE,[2] TREATISE and FLEAT,[3] ACTUATE (Backhaus, 2014), RECODRIVE[4] and START focused on reducing emissions using eco-driving. The TREATISE project focused on the development of training and reference manuals on eco-driving, cleaner fuels and mobility. During this project, a total of 1722 trainers were trained across eight countries and three reference manuals were developed in eight languages. It is estimated that this project has achieved a saving of 95 kt in CO_2 emissions. TREATISE was a consortium of seven European national energy agencies that created suitable energy training programmes. In the TREATISE project, eco-driving was defined as “smart, smooth, and safe driving at lower engine speeds (1,200–2,500 revolutions per minute), which saves 5–10% fuel on average[, w]ithout an increase in travel time”.

The ECODRIVE project was an eco-driving campaign aimed at drivers of passenger cars, lorries, vans and buses in nine EU countries. It focused on the golden rules of eco-driving, namely accelerating between 2000 and 2500 RPM when setting off, maintaining a steady speed when using the highest gear and driving with lower RPM, anticipating the traffic scenario ahead, decelerating the vehicle smoothly by releasing the accelerator and keeping the car in gear, and checking the tyre pressures regularly. The ECOWILL (Ecodriving – Widespread Implementation for Learners and Licensed Drivers) project is a follow-up of European projects such as Eco-DRIVING Europe and ECODRIVE. The ECOWILL project aims to integrate EDT in driving schools and driving test curricula. It was found that the ECOWILL short-duration training course was challenging to sell to users of fleet and private cars unless it was free. The ECOWILL project was carried out between May 2010 and April 2013 in 13 European countries and provided seminars for both learner (level 1) and licensed (level 2) drivers on eco-driving.

The ACTUATE (Advanced Training and Education for Safe Eco-driving of Clean Vehicles) project worked with drivers of trams, trolleybuses and hybrid buses to improve their driving habits (Backhaus, 2014). A total of 500 trams, 310 trolleybuses and 19 hybrid buses were involved from five operators in four different European countries. In this project, a total of 1744 drivers (800 tram and 944 bus drivers) were trained, and the overall energy consumption reduced by 4.5%.

Several operational field studies have been carried out in the EU. Jonkers *et al*. (2018) developed an approach to scale up the localised field test results to the, at the time, 28 Member States of the EU (EU-28) level. The article by Jonkers *et al*. (2018) is related to the ecoDriver project (Olstam *et al*., 2016), which focused on developing and testing a driver support system for passenger cars and commercial vehicles. To apply a localised result for the entire EU, the study proposed several steps, such as projecting future technologies, scaling up based on the geographical area, and

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[1] https://www.cieca.eu/project/33 (accessed 22 September 2021).

[2] https://h2020-ecodrive.eu/project/ (accessed 22 September 2021).

[3] https://europamediatrainings.com/eu-projects/27/fleat (accessed 19 July 2021).

[4] https://trimis.ec.europa.eu/sites/default/files/project/documents/20140307_130303_86735_FR_RECODRIVE_publishable_report.pdf (accessed 19 July 2021).

predicting future economic, environmental and social impacts. Olstam *et al.* (2016) focused on reducing CO_2 emissions and fuel consumption by using green driving behaviour. Scenarios were built, and a microsimulation approach was proposed to scale up to the EU-28 level for the next 20 years. A cost–benefit analysis, from societal and stakeholders' perspectives, was performed in their research study. There are also eco-driving initiatives in Asia, including ReCoo[5] and the Japan Eco-driving initiative (IEA, 2017).

Under the UK government's Safe and Fuel Efficient Driving (SAFED) programme, an average improvement in fuel efficiency of just over 10% was observed (DfT, 2009a). In addition, as engine idling contributes significantly to fuel consumption and CO_2 emissions, four trials were undertaken that focused on an "anti-idling campaign", which highlighted switching off the engine when parked. In these trials, fuel consumption was reduced by 1–5% (DfT, 2010). Furthermore, anti-idling devices should be installed in trucks, which can switch off after several minutes of idling. In addition, for improved fuel efficiency, drivers should also be instructed to check tyre pressure at the start of their journey (DfT, 2009b). In Ireland, an education initiative (Measure T-22) related to encouraging eco-driving for HDVs (including freight) through incentives has been proposed in the NMP (DCCAE, 2017) for consideration.

Several research projects have conducted and implemented eco-driving programmes across the globe to encourage eco-driving. These programmes had a significant impact on fuel reduction. However, driver and trainer training programmes need to be formulated by involving experts from industry, drivers and policymakers.

2.9 Research Reports

This section focuses on research studies on strategies to reduce emissions with the help of eco-driving techniques. One of the measures to reduce fuel consumption could be to lower speed limits on motorways. The benefits of lowering the speed limit on motorways could depend on decreasing speed, fleet composition, driving patterns, frequency of speeding, congestion and diversion of traffic due to the speed limit. The simulation-based research study by the EEA reported that reducing the speed limit from 120 km/h to 110 km/h could reduce fuel consumption of passenger cars by 12–18% (EEA, 2020). In addition, this strategy could reduce NO_X and particulate matter (PM) emissions from diesel vehicles. Boriboonsomsin and Barth (2016) defined eco-driving as the "fuel-efficient operation of a vehicle to achieve better fuel economy and lower tailpipe emissions while not compromising the safety of oneself and other road users". The project focused on understanding the effect of recommendations and feedback to drivers on reducing fuel consumption. Based on the driver scenarios, it was expected that eco-driving technologies would reduce fuel consumption and GHG emissions by 5–20%.

Marcilio *et al.* (2018) studied and compared the variables of environment and performance in a green manufacturing and lean manufacturing context in road freight transport systems. In their study, a satisfaction survey was conducted among customers, workers and managers. It was observed that managers manage strategies related to the type of commercial vehicle, age of the vehicle and eco-driving among drivers. Using a simulation model, the study concluded that different scenarios would provide varying differences in the performance aspect when these factors were considered. In addition, the behaviour of a greener consumer would carry higher weight on the manager's decision in the supply chain mechanism.

In Germany, Rothengatter and Doll (2002) pointed out that higher user charges on the whole network of federal roads for HDVs, along with improving the service of the railways, could be a solution to reduce emissions. Furthermore, for diesel HDVs additional measures to reduce emissions were proposed in three cities in China (Shanghai, Nanjing and Wuxi), namely to increase the population share of natural gas and battery electric buses, phase out all pre-EURO III trucks registered before 2007 and retrofit EURO III diesel trucks by adding selective catalytic reduction (SCR) systems (Zhang *et al.*, 2017).

Boriboonsomsin *et al.* (2010) studied the effect of an eco-driving feedback system on car drivers. A total of 23 drivers in Southern California were selected for a questionnaire survey to understand the background and likelihood of eco-driving. Fuel economy was

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[5] http://www.recoo.jp/ (accessed 1 October 2019).

observed to improve by 6% in the city and 1% on motorways. Drivers were willing to adopt eco-driving practices; indeed, this survey indicated that 40% of drivers had practised eco-driving before, and up to 95% of drivers would adopt eco-driving practices if the petrol price increased to US$4.40 per gallon. Likewise, Tang *et al*. (2016) developed an eco-driving model in a high-fidelity driver simulator and eco-driving in traffic simulation software for automated vehicles. The following six situations were analysed: (1) the use of cruise control, (2) accelerate and pass, (3) decelerate and pass, (4) decelerate because of a queue and follow the leading car, (5) decelerate and stop at the stop line, and (6) decelerate and stop at the queue. Their study concluded that emissions are higher with an increase in volume to capacity (V/C) ratio, as automated vehicles were more likely to join a queue (Tang *et al*., 2016). Xiao *et al*. (2018) developed a two-level dynamic optimisation model to reduce the severe impacts of truck share on the road network performance. The isolated and coordinated corridors were simulated to understand the influence of truck share on the road network. The developed model replicated the eco-driving scenario by optimising travel time and minimising emissions, which can be incorporated into traffic controllers. At fixed traffic volume and with an increase in the share of trucks, the average delay was observed to increase. Wu *et al*. (2019) evaluated the effect of a deep learning-based trajectory-planning algorithm (DLTPA), an algorithm for eco-approach and departure (EAD). The proposed DLTPA was incorporated in VISSIM software, and the results were compared between two scenarios, namely with and without DLTPA on the simulated 3-mile corridor with 11 signalised intersections on University Avenue in Riverside, CA. Their study concluded that the proposed DLTPA could improve absolute energy consumption compared with the baseline by 13.76%. Funded and non-funded research projects have come up with strategies such as speed limit reductions on motorways, coordinated traffic signal systems, eco-routing algorithms and eco-driving feedback systems to encourage eco-driving and quantify its effect on fuel reduction.

2.10 Global and National Policies and Legislation

This section investigates the impact on eco-driving of global policies and new European policies that encourage eco-driving. Many national governments have adopted eco-driving policies to reduce emissions from the transport sector. The US Department of Energy developed the first eco-driving evidence using a training background study in 1976 (Gonder *et al*., 2010). Wisconsin Clean Cities conducted training in 1994 and provided an EDT programme in Sweden in 1998 (Quille *et al*., 2012). In Europe, the “Eco-driving Europe” programme was introduced in 2001 to provide guidance to drivers. In Switzerland, eco-driving has been promoted since 2007 as a policy to encourage fuel saving of between 10% and 15%, as mentioned by Alam and McNabola (2014). In the Netherlands, an eco-driving programme was initiated within the AID-EE (Active Implementation of the Directive on End-use Energy Efficiency and Energy) project. This policy package was undertaken to encourage efficient driving behaviour and an energy-efficient vehicle purchase. Between 1999 and 2004 the policy resulted in a 0.3–0.8% reduction in fuel consumption. By 2004, 31% of the general population was aware of an eco-driving programme (Harmsen *et al*., 2007). In Finland, an eco-driving programme was introduced in 1995 and was estimated to reduce average fuel consumption by 1.3 l/100 km. The training course was planned to train around 1000 bus and truck drivers and 15,000 car drivers during 2005 and 2006. Although Harmsen *et al*. (2007) stated that the post-evaluation performance of the Finnish programme was missing and that this made it challenging to compare the Dutch and Finnish eco-driving programmes, their study indicated that the Dutch eco-driving programme is more effective than Finland’s. In Japan, in 2006, an action plan was declared for promoting the eco-driving programme (IEA, 2017). The committee formulated 10 eco-driving recommendations, which included using gentle acceleration, maintaining a constant speed, decelerating gently, limiting use of the air conditioner, not idling the engine, not warming up the engine before starting the journey, following parking regulations, checking tyre pressures regularly, reducing vehicle load and knowing the itinerary (Hiraoka *et al*., 2009).

The Canadian eco-driving programme provides five recommendations: accelerate gently, maintain a steady speed, anticipate traffic, avoid high revs and coast to decelerate. Their free online eco-driving course claims that a 25-minute course would help drivers to save 25% in fuel costs. Ireland's national target is to reduce GHG emissions by 20% from 2005 levels by 2020 following the EU National Emission Ceilings (NEC) Directive (2001/81/EC). Furthermore, the new National Emission reduction Commitments Directive (2016/2284/EU) (EU, 2016), requires Ireland to reduce NO_X and PM levels by 49% and 18%, respectively, from 2005 levels over the period 2020–2030. At the EU level, the European Commission has developed policies and undertaken strategies, such as the HDV Strategy, COM(2014) 285 (EC, 2014), and the "low-emission mobility strategy", COM(2016) 501 (EC, 2016a), to reduce externalities such as air pollution from the HDV sector. At the national level, the *National Policy Framework on Alternative Fuels Infrastructure for Transport in Ireland – 2017 to 2030* (DTTAS, 2019b) indicates the eco-driving technique to be a possible measure to reduce GHG emissions. The NMP (DCCAE, 2017) reiterates that the growth in the economy may increase pollution and GHG emissions from the HDV fleet in Ireland. In addition to alternative fuels, both the NPF and NMP suggest exploring other options, including eco-driving techniques. The US EPA introduced the "Cleaner Truck Initiative" (CTI) on 13 November 2018, to update emission standards for NO_X from HDVs and their engines. However, the details regarding the emission standards are still not available and are expected to be published soon.

Following the legislative proposal on 17 May 2018 by the European Commission, a new regulation, (EU) 2019/1242, was enforced from 14 August 2019, and this sets new standards for CO_2 emissions for new HDVs. This legislation focuses on reducing CO_2 emissions from new trucks by 15% in 2025 compared with 2019. The new regulation aims to provide incentives to encourage zero- and low-emission vehicles. The new regulation also helps to reduce fuel consumption costs for small and medium-sized enterprises (SMEs) and consumers and to uphold the leadership of EU suppliers and manufacturers in technology.

In terms of implementation of eco-driving as a policy, Barkenbus (2010) stated that eco-driving could be encouraged through measures such as public awareness, reducing and enforcing speed limits on motorways, cost-sharing between government and industry on EDT, and feedback systems.

2.11 Discussion and Conclusions

The literature review suggests that, although driver behaviour, including sudden acceleration and deceleration, driving at higher speed, traffic congestion on roads, gradient and the curvature of roads, contribute to increased fuel consumption, eco-driving can be used as an effective measure to reduce fuel consumption and, ultimately, reduce emissions from vehicles. However, the impact of eco-driving on professional versus personal drivers may differ, and the short-term impacts of eco-driving are greater than the long-term effects. This could be addressed by providing an EDAS to the drivers. Under the different traffic volumes, simulated studies have produced mixed results; studies have shown that eco-driving in congested traffic conditions could increase fuel consumption and emissions and may have safety issues. Furthermore, faulty traffic signal plans could also increase the number of stops and delays for vehicles, which could increase fuel consumption and emissions. Therefore, it is essential to analyse and compare the speed, acceleration and deceleration profiles of regular and eco-driving-trained HDV drivers to understand the applicability of eco-driving in HDVs. Typically, eco-driving can be achieved through several strategies.

- EDT programme. Drivers can be trained through online courses, classroom training and in-vehicle training, by providing advice on a regular basis, or a combination of these. In addition, for HDVs, an EDT programme could be introduced in the driving test (written and practical driving test).
- Eco-driving assistance/feedback system. Electronic feedback device installed in a vehicle could improve fuel saving. Visual, auditory, haptic or a combination of these could be practical to inform drivers about their performance. This system can also be introduced within EDT programmes.
- Eco-routing navigation. Implementing this could be helpful in reducing overall fuel consumption. For effective implementation, this system can be developed as a package tool with telematics data, which most of the large companies use for tracking their vehicles and fuel consumption.
- Others. Other than vehicle-specific measures, reducing the maximum speed on motorways from 120 km/h to 110 km/h could also be a solution to improve fuel consumption, as mentioned in the

UK study. A research study should be carried out before applying it in Ireland. Furthermore, HDVs tend to have a higher fuel consumption rate than passenger cars; therefore, introducing anti-idling devices, which shut off the engine after a certain period, could be an effective way to reduce fuel consumption.

In general, eco-driving has shown a 2–15% improvement in fuel economy. Eco-driving for HDVs can be achieved by applying existing knowledge about vehicles (operation and maintenance), new technologies (feedback system, eco-routing, telematics data) and driver training (online, in-class, coaching).

3 Perception and Practices of Eco-driving in Ireland

This chapter discusses the perception of hauliers and stakeholders of adopting different eco-driving techniques and the current eco-driving practices in the Irish HDV fleet. The chapter also presents a sample fuel economy benchmarking dataset for the Irish HDV fleet.

3.1 Introduction

The perceptions of hauliers and stakeholders aids the understanding of the current and expected challenges in the road freight sector. It also helps in understanding the level of awareness and acceptability of, and barriers to, adopting eco-driving programmes in the Irish logistics industry. Discussions with fleet managers and stakeholders also provide attitudes, opinions and critical information from within haulage companies, which may help in drafting policies to improve efficiency and to reduce emissions from the road freight sector.

3.2 Methodology

A set of interviews and a questionnaire-based survey were performed. Figure 3.1 illustrates the complete methodology employed to find the best possible way to implement eco-driving practices in the Irish context. First, in-person interviews were conducted with haulage company owners and fleet managers. The pilot survey focused on understanding the background of haulage companies, in terms of the types of goods they transport, engine types in their fleets, trip characteristics, common routes travelled in Ireland, average fuel consumption at the fleet level and eco-driving practices adopted. Discussions were also targeted to understand their perceptions of emission mitigation measures, such as the use of alternative fuels, engine techniques, re-routing, diesel rebate policy and Physical Internet system. Finally, they were asked about which emission mitigation measures they expect the government to implement, their preparedness for them and perceived barriers to them.

Based on the results from the pilot survey, a detailed survey was designed to understand the perceptions of haulage company owners and stakeholders (government, consultancy and academia), which contribute to drafting the policies. This detailed survey was disseminated online and a total of 42 respondents

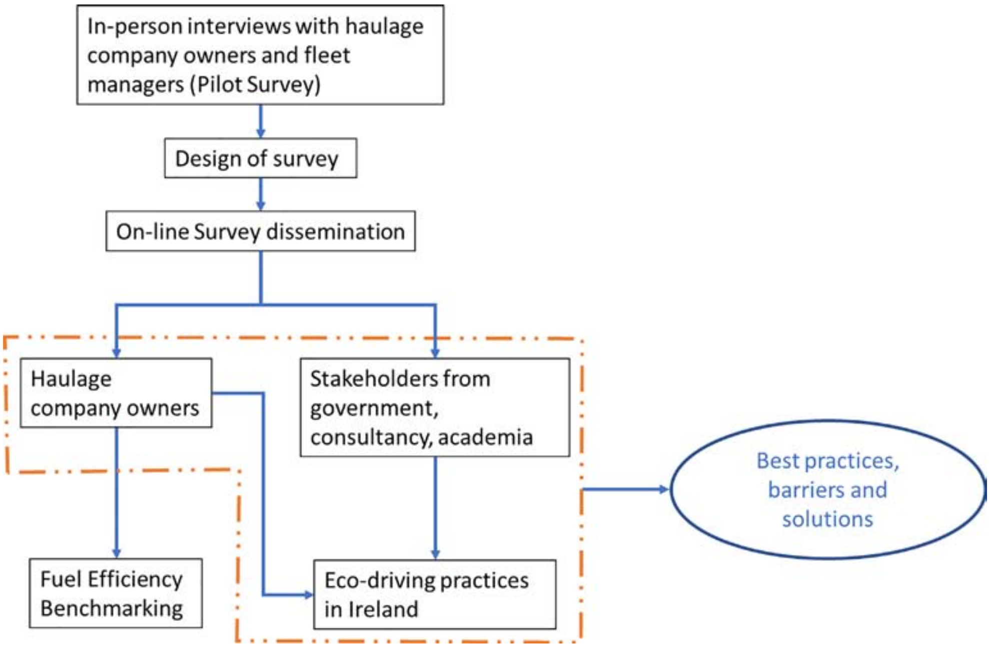


Figure 3.1. Flow chart of the methodology adopted to understand perceptions of eco-driving.

participated. Haulage company owners were asked about the fleet size, composition by engine types, driver information, average fuel economy, decisions based on vehicular emissions, incentive programmes for drivers and willingness to participate and implement different types of eco-driving measures. They were also queried about different driver behaviour factors contributing to fuel consumption and the importance of different emission mitigation measures. Furthermore, hauliers were asked about their readiness to include a driver training programme within the commercial drivers' licence test and their perception about the expected policies in Ireland. Moreover, stakeholders were asked about the importance of different emission mitigation measures, the suitability of different types of eco-driving measures, support for the driver training programme in commercial drivers' licence tests and the likeliness of several policies being implemented by the Irish government. The results from hauliers were used to develop a sample fuel efficiency benchmark. The opinions from both haulage company owners and stakeholders facilitated an understanding of the acceptability and methods of implementing eco-driving measures, and the barriers, challenges and possible solutions to improving fuel efficiency and ultimately to reducing emissions from the road haulage industry.

3.3 Perceptions of Hauliers by In-person Interviews

Six companies participated via in-person interviews, comprising two companies located in Waterford, three in Sligo and one in Kilkenny. Tables 3.1 and 3.2 present the key findings from the in-person interviews.

Table 3.1. Key points of the in-person interviews

	Company number and location					
Questions	**1 – Waterford**	**2 – Kilkenny**	**3 – Waterford**	**4 – Sligo**	**5 – Sligo**	**6 – Sligo**
What type of goods are typically transported by your company?	Refrigerated goods and food products	Beer, steel and animal feedstuffs	Raw materials for distilleries and producers	Timber	Food and medicines	Container transport
What are the most common HDVs your company owns in terms of the EURO engine?	EURO VI = 5	EURO VI = 4, EURO V = 7, EURO IV = 3	EURO VI = 1, EURO V = 3, EURO IV = 1	EURO VI = 17, EURO V = 5	EURO VI[a]	EURO VI = 25, EURO III = 2
Do you still use EURO III-engine trucks? If yes, how many of them are in operation?	No	No	No	Yes, only one	No	Yes, two for servicing and short trips
How many of your HDVs run in Ireland every week?	–	12	5	–	37	17
Which are the most common routes you use in Ireland?	Motorways	Motorways	All routes in south-east plus within Dublin city	Rural and motorways	All Ireland	–
What is the average fuel consumption in a week? Estimated/based on company data	25.02 l/100 km	31.67 l/100 km	EURO V: 27.67–26.13 mpg; EURO IV: < 29.4 mpg; Euro VI: 28.68 mpg	48 l/100 km	33 l/100 km	DAF EURO VI: 30 l/100 km; Volvo EURO VI: 32.5 l/100 km
Do your drivers have any type of formal eco-driving training?	Yes; weekly driver performance report to drivers	No	No	Yes; personalised training by owner	Yes; personalised training	No
What are the current measures you have undertaken to reduce emissions?	Upgrading vehicles, driver training, route management	Updated fleet and regular servicing	Drivers leave trucks in premises from where they work	Incentives programme started 4 years ago	Use of top-quality tyres and personalised driver training	From 2014, we changed all vehicles over a 5-year period

–, data unavailable; mpg, miles per gallon.

[a] number of vehicles not available.

Table 3.2. Perceptions of companies about emission mitigation measures from the in-person interviews

The company's perception on	Company number and location					
	1 – Waterford	2 – Kilkenny	3 – Waterford	4 – Sligo	5 – Sligo	6 – Sligo
Use of alternative fuels: electric/CNG/biodiesel	Lack of infrastructure	Not an option yet	Lack of fuel sizes. Electric is expensive and does not have range	EURO VI; difficult for electric and other fuels because of lack of infrastructure	EURO VI; no alternative fuels	Not enough infrastructure
Use of engine techniques such as particle filters/catalytic converter/waste heat recovery	Yes. Want to reduce emissions	Yes	Yes	Yes	Yes, personalised training	Yes
Re-routing: empty running/shorter routes/ less congested routes	–	We cannot afford to have an empty run	Stay on motorways as much as possible	Routing option is required	Use of telematics data	–
Diesel rebate policy	Helps, but it could be better	Not enough to support the industry	Helps to keep fuel costs steady and advantage to licensed hauliers	Could be improved by incentivising based on EURO-type engines	It helps, as diesel is the only viable option	Could be better; very low at present
Physical Internet system	–	Worth looking at	Not applicable	–	–	Not applicable
Have you already implemented/ introduced any of the measures mentioned earlier in your HDVs?	Yes	Updating the fleet and telematics	–	Upgrading the fleet	–	Yes, updated all EURO VI models
Are you prepared to introduce some additional measures to reduce emissions?	Yes	Yes	Yes	Yes	Yes	Yes
If yes, which one do you want to introduce and why?	Driver training, incentives to drivers	Eco-driving	New vehicles, lighter load, hydrogenated vegetable oil to reduce emissions	–	Fuel bonus and any new technology	Already upgraded the majority of the fleet to EURO VI
If not, what are the main barriers to the introduction of additional measures?	Cost	Cost of fleet replacement and risk of policy fluctuations in government	Cost and uncertainty over government policy in the future	Cost	Cost	Cost
Do you expect any support from the government for the implementation of additional measures?	The government should help to improve diesel rebate policy	Yes, to keep the national fleet viable, we need a better fuel rebate policy	A truck burns in a week what a house burns in a year. Supporting a transition of the national fleet to EURO VI achieves a lot	Better fuel rebate scheme	Better fuel rebate scheme	No, as we have had to implement ourselves and at additional costs to our company

–, data not available; CNG, compressed natural gas.

Haulage companies transport different types of materials, such as refrigerated goods, food products, steel, raw materials, timber and containers. The fuel economy of HDVs changes with the type of goods and type of engines. As fuel (diesel) cost is the primary factor in deciding income and profit margins, company owners tend to purchase upgraded engine trucks that are fuel efficient. Drivers are encouraged to use motorways rather than rural or urban routes. In terms of EDT and implementation, many of the companies provide personalised driver training and incentives to fuel-efficient drivers. For example, drivers are informed about their weekly performance in terms of percentage of hard acceleration, the number of harsh brakes, the percentage of speeding and overall fuel economy. This information is collected from telematics data. Based on the fuel economy and other driver behaviour characteristics, drivers are incentivised for adopting fuel-efficient driving. One large company reported that the use of top-quality tyres helped them to improve fuel economy.

Moreover, discussions were held on the acceptability of alternative energy sources [electricity, compressed natural gas (CNG) and biodiesel], use of engine techniques (particle filters, catalytic converters, waste heat recovery), re-routing, diesel rebate policy and Physical Internet system. Some of the companies have tried alternative fuels, but the lack of available infrastructure (e.g. CNG fuel stations), the mileage of alternatively fuelled trucks and the time required to fill CNG tanks were some of the restraining factors in adopting alternatively fuelled trucks. Most of the companies are moving towards the use of EURO VI engine trucks, which use advanced engine techniques and are fuel-efficient compared with EURO III and IV engine trucks. Further, companies stated that they cannot afford empty running of vehicles and encourage their drivers to use motorways to avoid congestion and to improve fuel economy. In terms of Ireland's diesel rebate policy, companies acknowledge that the current fuel rebate policy is useful and are hoping to get a better rebate scheme. One of the ways of incentivising could be based on advanced engine types and alternatively fuelled trucks. Companies with a higher number of low-emission trucks (EURO VI) would be more incentivised than companies with high-emission trucks (EURO III and EURO IV).

A Physical Internet system helps to avoid the empty running of trucks. In this system, registered trucks show their availability and destinations in real time. Companies can take orders from other companies to haul products from one point to another. Company owners have mixed responses in terms of its adaptability because of agreements between haulage companies and clients. Most of the companies are eager to introduce measures to reduce emissions, such as upgrading their fleet, eco-driver training, driver incentive programmes and the use of hydrogenated vegetable oil as a fuel. The main barriers to companies implementing additional measures to reduce emissions are the cost of vehicles and uncertainty around/fluctuations in policies from the government side.

3.4 Perception of Hauliers and Stakeholders on Eco-driving by Online Survey

Based on the discussions mentioned above, haulage company owners and stakeholders were asked a series of questions by online survey and responses were collected between February 2020 and April 2020. In total, 42 respondents participated in the survey; the ongoing COVID-19 pandemic has had an impact on response numbers. Out of the 42 respondents, 15 participants were haulage company owners and the remaining participants were stakeholders from the government sector, consultant agencies and academia, as shown in Figure 3.2.

3.4.1 Haulage company owners

Out of the total 15 participating companies, one company has fewer than five trucks, four of the companies have 5–10 trucks, four companies have 11–30 trucks, two companies have 31–50 trucks and one company has more than 50 trucks. Three respondents skipped the question or did not respond. The average number of drivers within these companies is 27, ranging from 5 to 160 drivers, and average fuel consumption at the fleet level is 32 l/100 km. Furthermore, 83.33% of the companies consider

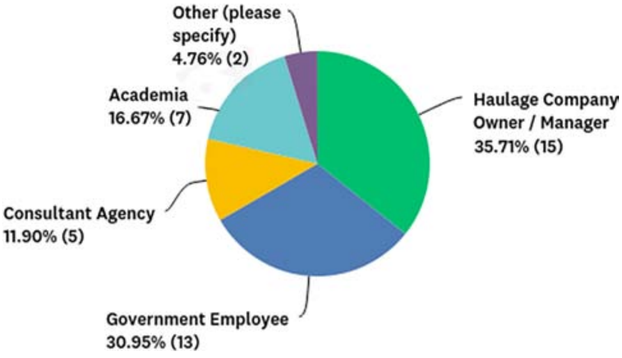


Figure 3.2. Survey sample distribution.

vehicular emissions while operating their business, and all the companies are willing to participate in the driver training programme to educate their drivers. Of the 12 companies, seven (58.33%) have an incentive programme for fuel-efficient drivers; the other five companies that have not implemented incentive programmes provided reasons for not introducing incentive programmes, such as time, do not think it works, tried it before and do not want to put drivers under pressure.

Typically, eco-driving can be achieved through driver training, eco-driving assistance or feedback technology, and by the use of eco-routing navigation systems. Out of these three, companies were more willing to adopt driver training programme (58% of respondents) than eco-driving assistance technology (33% of respondents) and eco-routing navigation systems (9% of respondents). Respondents were also asked to rate the importance of driver behaviour factors, such as hard acceleration, hard braking, speeding, idling, tyre pressure and excess gear changes, on fuel consumption using the scale "definitely contribute" to "definitely do not contribute". All the factors were considered to contribute to fuel consumption, with the top three being hard acceleration, hard braking and speeding (Figure 3.3).

When asked about the importance of several measures and scenarios to reduce fuel consumption, company owners stated that use of cruise control (100% of respondents), barrier-free toll lane (90% of respondents), maintenance of vehicles (90% of respondents), loading under the permitted limit (88% of respondents) and driver training (82% of respondents) were extremely important or very important measures that could reduce fuel consumption by HDVs (Figure 3.4). In contrast, 22% of the respondents stated that vehicle route based on the condition of the terrain was not an important measure to reduce fuel consumption, and 10% of the respondents stated that driving during off-peak hours, using barrier-free toll lanes and empty-running trucks were not essential measures to reduce fuel consumption.

Haulage company owners were asked about the policies they expected to come from the Irish government, as shown in Figure 3.5. Respondents considered that policies such as incentives for barrier-free toll lanes (45% of respondents), electric trucks (40% of respondents), CNG trucks (40% of

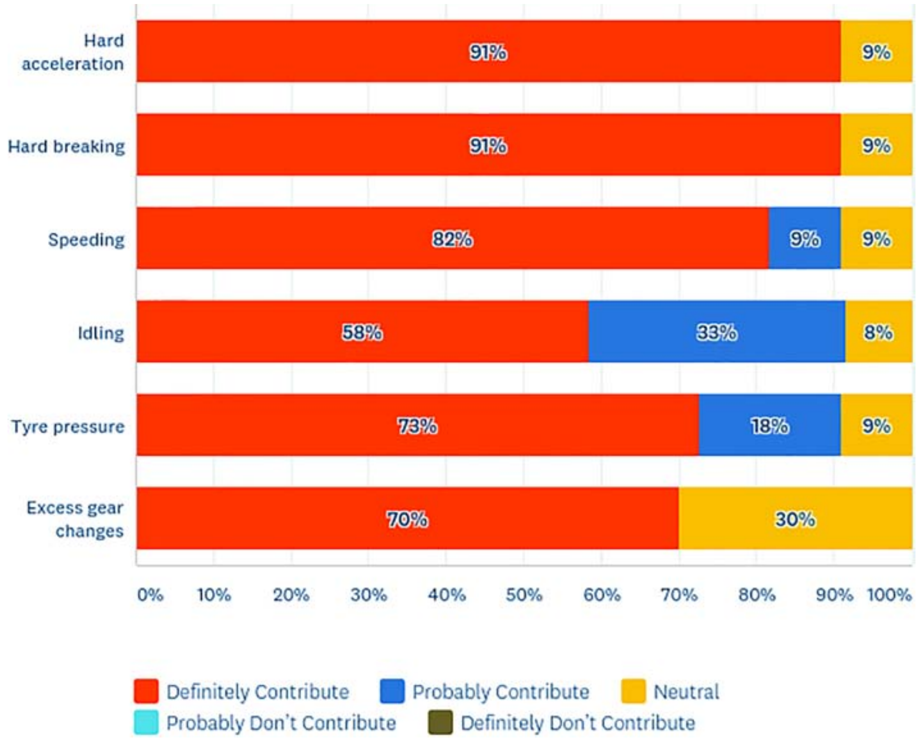


Figure 3.3. Responses from haulage company owners on driver behaviour factors contributing to fuel consumption.

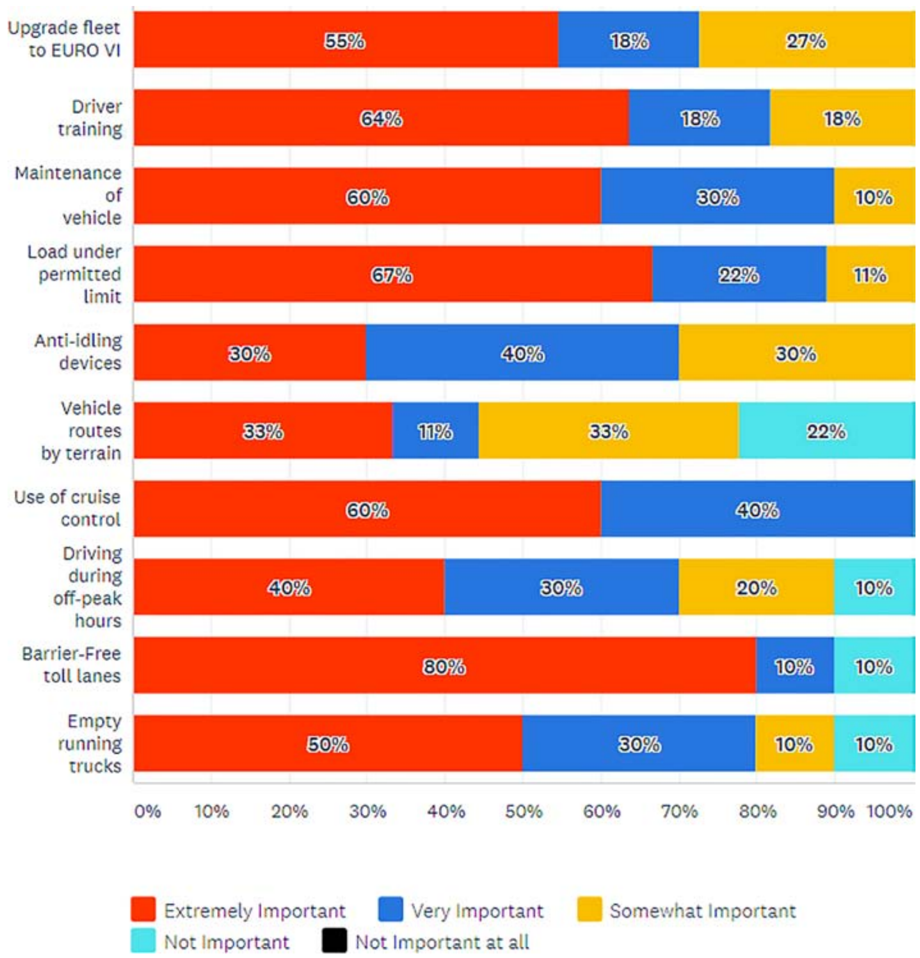


Figure 3.4. Perceptions of haulage company owners on measures to reduce fuel consumption.

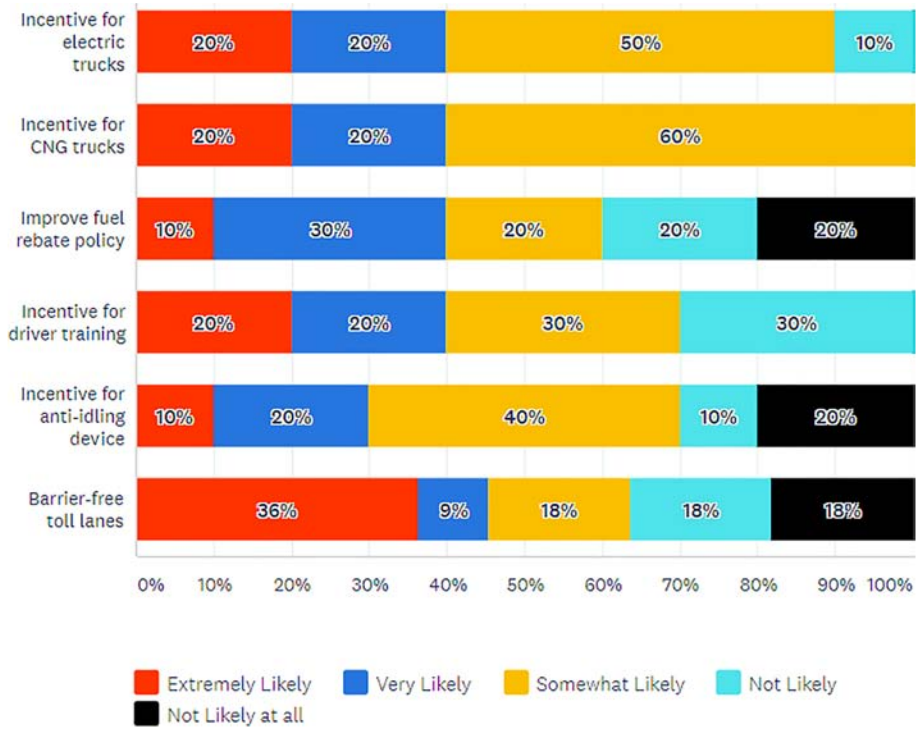


Figure 3.5. Responses from haulage company owners on expected policies in Ireland.

respondents) and driver training programmes (40% of respondents) are extremely likely or very likely to be adopted by the Irish government. Respondents stated that trucks powered using biodiesel (91% of respondents), hydrogen (80% of respondents), CNG (78% of respondents), liquefied petroleum gas (LPG) (75% of respondents) and electricity (55% of respondents) are extremely likely or very likely to be seen in the near future; however, 57% of respondents considered that autonomous trucks are very unlikely to be seen in the near future (Figure 3.6).

3.4.2. *Perception of stakeholders*

Participants from stakeholders were from government, consultant agencies, academia and energy sectors. The question of importance of several measures and scenarios to reduce fuel consumption was put to the stakeholders, as shown in Figure 3.7. Stakeholders stated that upgrading the fleet to EURO VI (88% of respondents), driver training (79% of respondents), use of alternative fuels (79% of respondents), loading under the permitted limit (69% of respondents), installation of anti-idling devices (69% of respondents) and restricting truck movements in urban centres during the daytime (68% of respondents) are extremely relevant or very relevant measures to reduce fuel consumption by HDVs. However, 26% of respondents stated that improvement to the fuel rebate scheme is not a relevant measure for fuel consumption.

Out of the three eco-driving measures, stakeholders stated that driver training (68% of respondents) and eco-driving assistance technology (53% of respondents) are extremely likely or very likely to be adopted by the Irish government, as shown in Figure 3.8. However, 16% of respondents stated that the eco-routing system is not likely to be adopted by the Irish government. Furthermore, 39% and 33% of stakeholders stated that a driver training programme is extremely likely or very likely, respectively, to be included in the commercial driving licence test.

Moreover, stakeholders were asked about the expected policies by the Irish government, as shown in Figure 3.9. Respondents stated that policies such as incentives for the driver training programme (63% of respondents), CNG trucks (53% of respondents) and electric trucks (48% of respondents) are extremely likely or very likely to be adopted by the Irish government. However, 32% of respondents stated that an improvement in fuel rebate policy is not likely to be adopted, and 21% of respondents stated that incentives for anti-idling devices and the use of

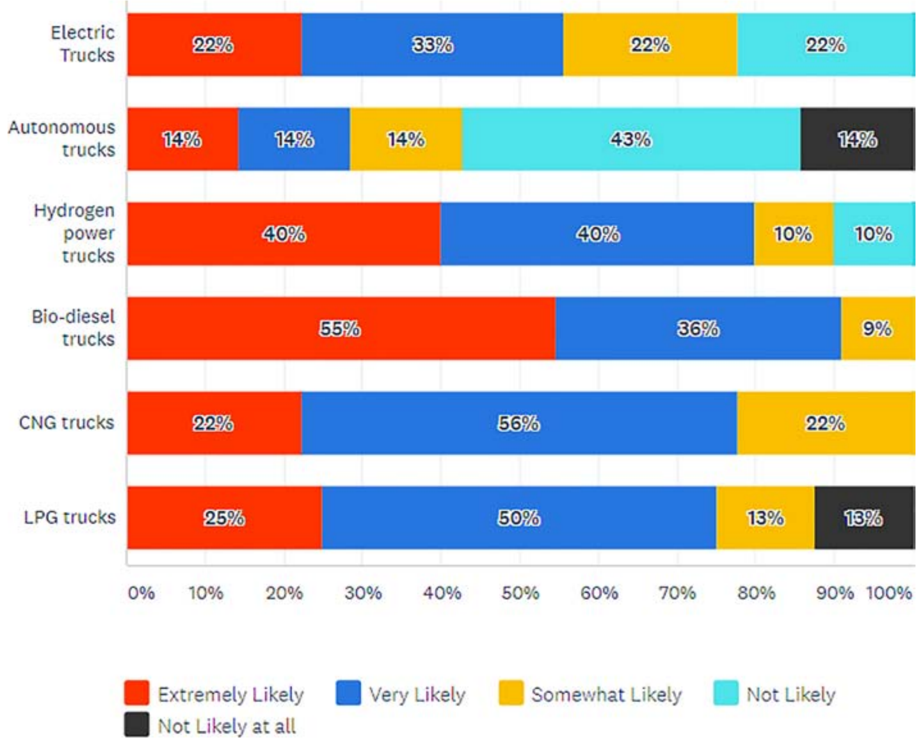


Figure 3.6. Responses from haulage company owners on expected alternatively fuelled vehicles in Ireland.

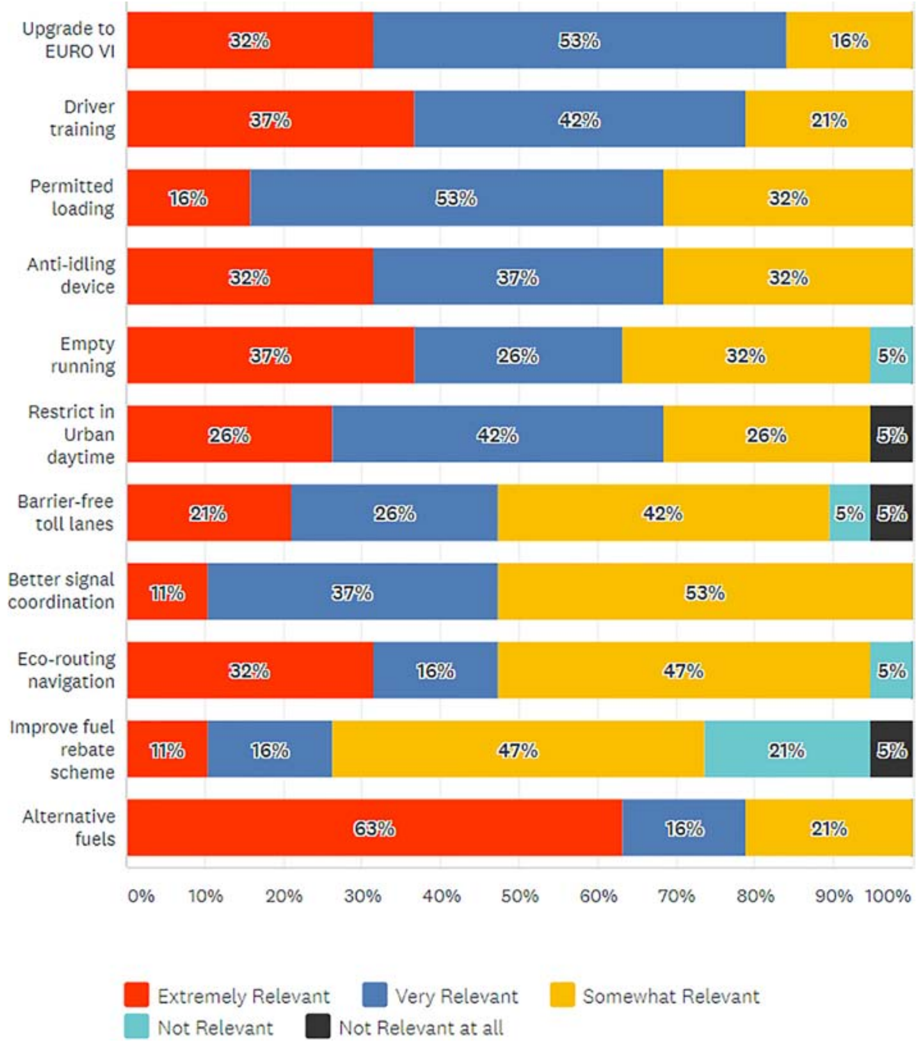


Figure 3.7. Perception of stakeholders on several measures to reduce fuel consumption.

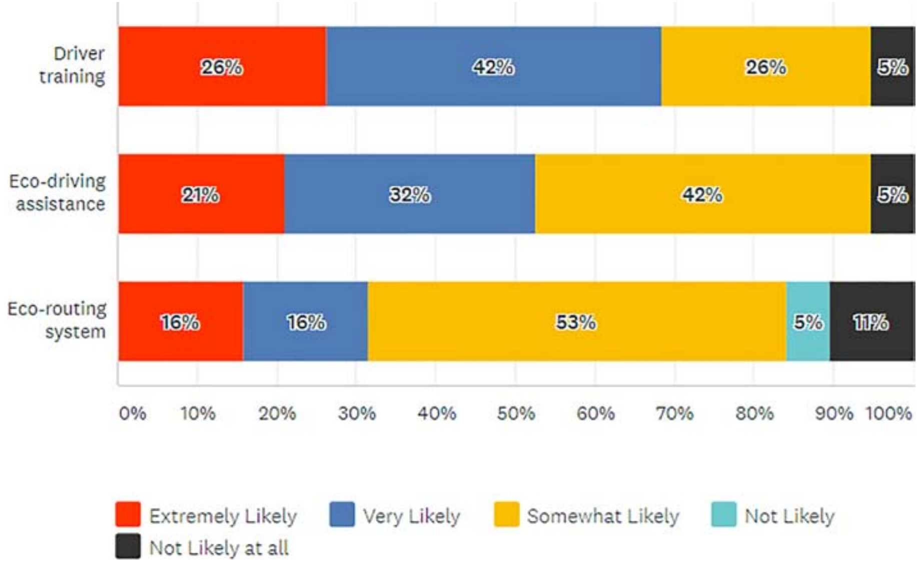


Figure 3.8. Responses from stakeholders on eco-driving measures.

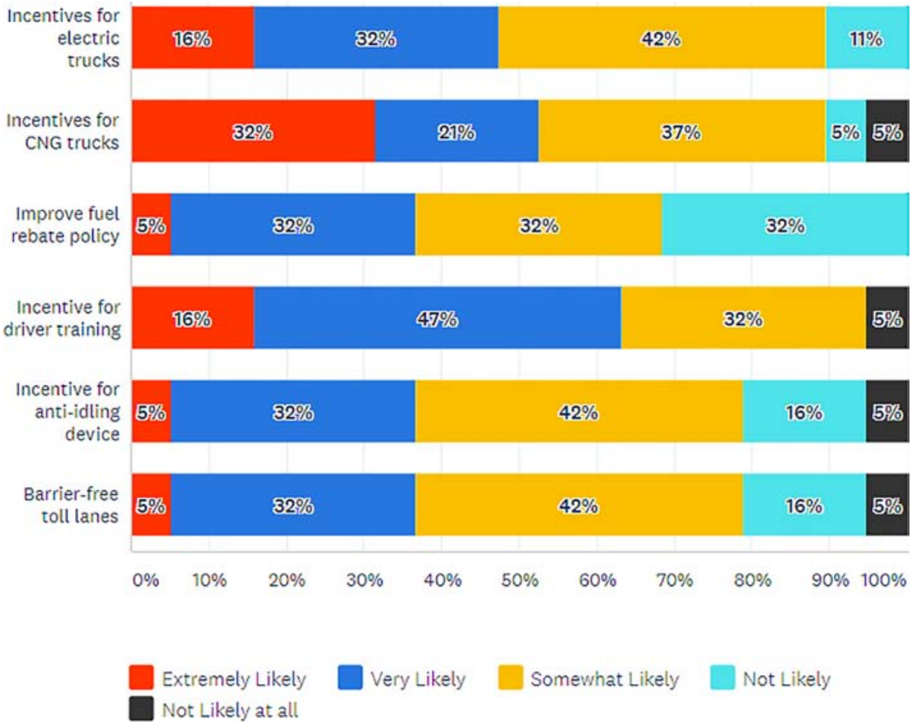


Figure 3.9. Responses from stakeholders on expected policies in Ireland.

barrier-free toll lanes are not likely or not likely at all to be adopted by the Irish government. Overall, both stakeholders and company owners agreed that the top three expected policies from the Irish government would be incentives for CNG trucks and electric trucks, and driver training programmes. Furthermore, improvement in fuel rebate policy had mixed responses from both companies and stakeholders, and this is least likely to be expected from the government.

3.5 Fuel Economy of Haulage Companies

Based on the pilot and online surveys, fuel economy data from different companies were collected and are presented in Table 3.3, which represents descriptive statistics of fuel economy at the fleet level. In an online survey, company owners were asked about the average fuel consumption at the fleet level. However, daily, weekly, monthly and quarterly fuel economy data were collected from the companies based on the availability of data. Therefore, the number of samples collected was different for different companies. The fuel economy data were collected in 2019 and 2020 and showed that average fuel consumption ranges from 24.8 to 48.8 l/100 km. The refrigerated transport company, which only has trucks with EURO VI engines, has the lowest average fuel consumption at the fleet level (23.11 l/100 km). The timber haulage company has the highest average fuel consumption, followed by a company that transports cars using HDVs.

Table 3.3. Sample fuel benchmarking of the Irish fleet

		Fuel consumption (l/100 km)			
Companies and survey	**Number of samples**	**Minimum**	**Maximum**	**Mean**	**Standard deviation**
Online survey of 12 companies	12	24	46	32.92	5.47
Companies					
General haulage	152	31.7	34.3	32.81	0.61
Timber haulage	171	24.19	98.82	48.86	9.87
Refrigerated transport (all EURO VI)	15	23.11	25.96	24.82	0.88
Car transport	893	29.41	76.92	35.57	3.22

The Global Logistics Emissions Council (GLEC) Framework document (https://www.smartfreightcentre.org/en/how-to-implement-items/what-is-glec-framework/58/) provides a global method for the calculation and reporting of the GHG footprint across the multi-modal supply chain. It considers air, inland waterways, rail, road, sea transport and logistics sites and estimates emissions by considering full life cycle emissions from well to tank (WTT) and from tank to wheel (TTW). The GLEC Framework gives CO_2-equivalent (CO_2e) emissions factors for both WTT and TTW phases of most fuels. A fuel emission factor is the ratio of the mass of CO_2e (kg) released from fuel and the mass of fuel (kg) used. In the European context, recommended emission factors for diesel are 0.57, 2.67 and 3.24 kgCO_2e/l fuel for WTT, TTW and well-to-wheel (WTW) phases, respectively. For a biodiesel blend of 5% biodiesel and 95% diesel, recommended emission factors are 0.63, 2.54 and 3.17 kgCO_2e/l fuel for WTT, TTW and WTW, respectively. For emissions from the road sector, the GLEC Framework suggested two methodologies: the European Standard EN16258 and the US EPA's SmartWay Truck Carrier Tool (https://app4.erg.com/smartwayonramp/onramp/index.cfm; accessed July 2021). To improve accuracy in estimating emission, the GLEC suggests the collection of several parameters related to vehicles and activities, which include weight class, engine class, volume, year, fuel type, topography, road type (urban versus rural), distance (long distance vs short haul), traffic conditions and regular deviation from a planned distance. Furthermore, information related to cargo type, condition (ambient or temperature-controlled), journey type (point-to-point or multiple collection and delivery) and contract type (shared or dedicated transport) needs to be collected to improve the accuracy of estimated emissions.

3.6 Current Eco-driving Programmes in Ireland

There are several EDT modules/courses/programmes in Ireland. The Road Safety Authority (RSA) provides Driver Certificate of Professional Competence (CPC) training, which has a module on eco-driving techniques. This is the only known mandatory eco-driver training module in Ireland. Several haulage associations and the Irish Road Haulage Association (IRHA) and Freight Transport Association of Ireland (FTA Ireland) conduct their own EDT programmes. The IRHA, along with the Mayo, Sligo and Leitrim Education and Training Board (MSLETB) and the Waterford and Wexford Education and Training Board (WWETB), has introduced a SMART Driving training programme, which focuses on a safe and fuel-efficient training programme (https://smartdriving.ie/). FTA Ireland conducts an eco-driving programme called "ECOdrive Training" (http://ftai.ie/ecodrive-training). DAF, a truck manufacturing company, has its own "Eco-Drive" driver training programme (https://www.daf.co.uk/en-gb/daf-services/driver-services/daf-driver-academy; accessed July 2021). proDRIVERS (https://www.prodrivers.ie/) and the Irish School of Motoring Training (www.ism.ie) also provide eco-driver training programmes. ECOFLEET is a training programme that trains trainers and drivers (https://ecofleet.ie/).

Even with the presence of several independent eco-driver training programmes, there is a need to have a government-sponsored, mandatory and standardised eco-driver training programme in Ireland. This could be achieved by introducing an eco-driver training programme with in-class and practical coaching during the licence training programme or through CPC training programmes for professional HDV drivers.

3.7 Discussion on Alternative Fuels Infrastructure and Incentives for HDVs in Ireland

The *National Policy Framework on Alternative Fuels Infrastructure for Transport in Ireland (2017–2030)* (DTTAS, 2019b) stated that natural gas, along with electrification of the fleet, would be an interim solution for larger buses and freight. In terms of hydrogen-fuelled vehicles, a pilot scheme of three hydrogen buses by Translink is under way in Northern Ireland and a similar small-scale hydrogen-fuelled bus study is expected in Dublin in the near future.

In terms of current infrastructure for alternatively fuelled vehicles, three large EU and government co-funded projects have been undertaken: the Causeway Project, the Green Connect Project and the GRAZE Gas Project by Gas Networks Ireland (GNI). As part of the Causeway Project, 14 high-capacity, fast-fill CNG/gas stations should be developed along the Trans-European Transport Network (TEN-T) core network, in tandem with the establishment of a biogas injection point. To date, a total of five CNG stations are operational in Ireland, of which two are public and the other three are privately operated and located in Dublin, Cork and Shannon, County Clare. The Green Connect Project aims to establish CNG stations along the core road network in Ireland and it is due to cover an additional 21 CNG stations, four CNG trailers, four renewable gas injection facilities and 400 CNG vehicles through a vehicle grant scheme.

In terms of forthcoming incentive schemes to promote the use of CNG as a fuel in Ireland, a CNG Vehicle Fund was established and is administered by GNI, initially under the Causeway Project and subsequently under the Green Connect Project. The Vehicle Fund is supported by the Commission for Energy Regulation (CER) and is co-financed by the EU's TEN-T Programme under the Connecting Europe Facility (CEF). Under the Causeway Project, funds of up to €20,000 are provided to businesses towards the purchase of new CNG-powered commercial vehicles, including trucks, buses and vans. Furthermore, on account of the ongoing COVID-19 crisis, GNI's launch of the Green Connect vehicle purchase scheme, which was scheduled to take place in April 2020, has been delayed and will be rescheduled when circumstances allow.

By the end of 2020, the Irish government introduced a new purchase grant scheme for alternatively fuelled HDVs (electric, CNG, liquid natural gas and hydrogen-fuelled vehicles) to support increased uptake of low-emission vehicles. Under this scheme, grants of up to 30% of the cost differential between a traditional fossil-fuelled HDV and an equivalent alternatively fuelled vehicle will be available.

Overall, based on the survey, from the stakeholders' perspective, the top five measures to reduce fuel consumption and emissions are (1) alternative fuels, (2) upgrading the fleet to EURO VI, (3) driver training programmes, (4) use of anti-idling devices and (5) loading within the permitted limit. From the companies' perspectives, the top five measures to reduce fuel consumption and emissions are (1) the use of cruise control, (2) the maintenance of vehicles, (3) loading within the permitted limit, (4) driver training programmes and (5) upgrading the fleet to EURO VI. Comprehensive conclusions based on this chapter are listed and discussed in Chapter 7.

4 Driving Behaviour Analysis for Eco-driving

This chapter provides a quantitative tool to identify driver behaviour parameters influencing eco-driving efficiency by analysing real-driving telematics data and proposes a framework for an incentive scheme to promote eco-driving among professional HDV drivers.

4.1 Introduction

Hauliers transport different goods, including refrigerated food, raw materials, machinery, chemicals, wood, textiles, coal and natural gas; therefore, hauliers require specific sets of axle configuration trucks, including rigid, two to five axles and articulated trucks, which affects the overall fuel economy at the fleet level. Driving skills and associated driving behaviour of professional drivers change with the type of vehicles (rigid and articulated) being driven, the types of goods transported and the laden weight (<7.5 t, 7.5–12 t, 12–14 t, 50–60 t). Identifying the crucial driving behaviour factors using real-world data would help to develop eco-driver training programmes. The proposed methodology is explained in section 4.2 and the results and discussions are explained in sections 4.3 and 4.4. Finally, conclusions are presented in section 4.5.

4.2 Methodology

Statistical tools such as Pearson correlation coefficient and generalised estimation equations (GEE) were used for the analysis. The complete methodology is shown in Figure 4.1. First, real-world telematics data were collected from the haulage company. In the telematics system, a device is connected to on-board diagnostics (OBD-II) or a CAN-BUS port with a SIM card. The device collects information related to location, speed, idling time, the number of braking events, fuel consumption and any vehicle faults, and transfers the information to vehicle owners in real time. Second, Pearson correlation analysis was conducted to understand the linear relationship between different driver behaviour parameters and fuel consumption. Finally, GEE, a type of regression analysis, was used to identify and quantify the importance of key driver behaviour parameters contributing to fuel consumption.

4.2.1 Case study data collection

The timber haulage company considered here is one of the leading timber hauliers in Ireland. The company collects wood from forests located in

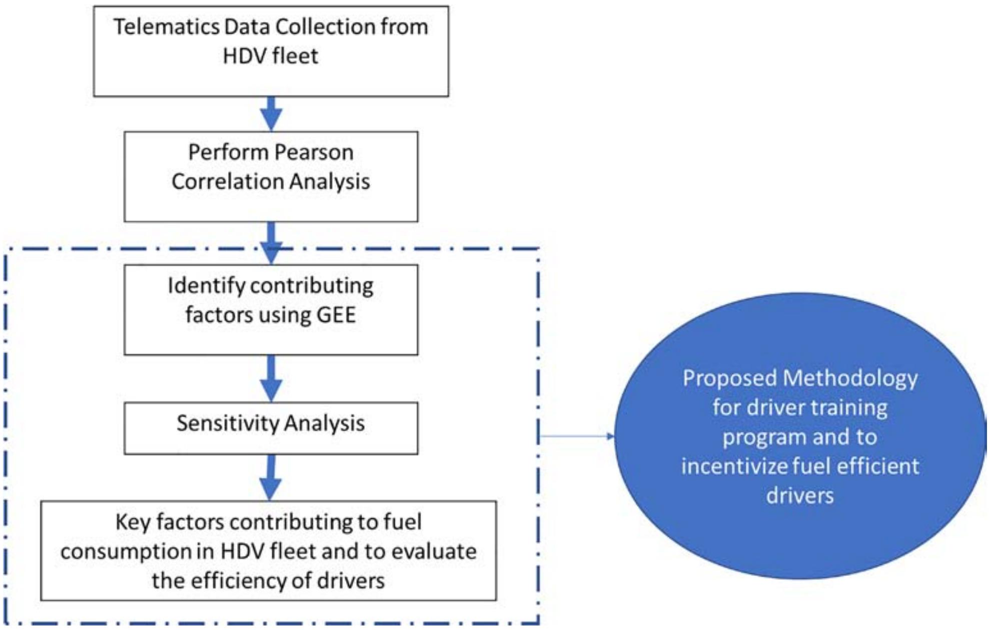


Figure 4.1. Flow chart to identify factors for driver training.

north-western parts of Ireland and distributes it to sawmill companies located in the western parts of Ireland; it transports around 3000 t of timber (e.g. firewood, softwood, hardwood and kindling) every week. It has a total of 22 trucks, of which 80% are EURO VI diesel engine trucks, and 30 trailers. All of the trucks in this company are equipped with a telematics system; nowadays, companies are adopting telematics systems to track their vehicles and fuel consumption. In this system, a telematics control unit (TCU) collects vehicle information via a CAN-BUS port and GPS and transfers the collected information to a cloud server using LTE, cellular or GPRS. The data stored in the cloud server are processed and driver behaviour parameters such as fuel consumption, distance, average speed, idling, hard acceleration, hard deceleration, over-revving, coasting, the number of stops and brakes are provided to the end-user in the form of a web/mobile application. A dataset containing 10 months of observations from January to October 2019 was analysed for this study. The dataset contained information from 30 male drivers of various ages.

4.2.2 *Background of the generalised estimation equation*

GEE was used to identify the driver behaviour factors contributing to fuel consumption. The GEE method is an extension of the generalised linear model and helps to generate unbiased regression coefficients with a non-normal response and/or dependent variable. Ballinger (2004) provides detailed information about the applicability of the GEE method. To check the goodness-of-fit for GEE models, Pan (2001) introduced an extension of Akaike information criterion (AIC) statistics as quasi-likelihood under independence model criterion (QIC) and corrected quasi-likelihood under independence model criterion (QICC) parameters. This model is a more complex and advanced tool to study telematics data than previously available in the literature.

4.2.3 *Selection of driver behaviour parameters and model development*

Pearson correlation analysis was performed to check the collinearity between the predictor variables. This helps to select predictor variables for the GEE model and to reduce multicollinearity between predictor variables in the developed model. The Pearson correlation coefficient describes the linear relationship between two variables and the confidence interval at which the computed coefficient is significant. The Pearson correlation coefficient ranges from –1 to +1. The closer the values are to –1 or +1, the stronger the relationship between the two variables. In this study, thresholds for the Pearson correlation coefficient were set at –0.3 and +0.3 at a 95% confidence interval. In other words, if the coefficient between two predictor variables is observed to be ≤ -0.3 or ≥ 0.3 at a 95% confidence interval, then out of the two predictor variables, only one predictor variable is selected at a time for model development. This model helps to forecast the dependent variable accurately and to quantify the influence of significant predictor variables on the dependent variable while minimising the effect of multicollinearity (Gujarati and Porter, 2012, p. 365).

Furthermore, a separate backward elimination GEE model was developed by considering all the predictor variables listed in Table 4.3 and the insignificant predictor variables were removed one at a time. The best-fitting model, out of the two GEE models, was selected based on the QIC and QICC. Smaller QIC and QICC values indicate better performance of the models (Ribeiro *et al*., 2016; Mane and Pulugurtha, 2020); a smaller difference between QIC and QICC is preferred for a good model. Models were developed and validated using 80% and 20% of the data, respectively. Both of the developed models were validated using root mean square error (RMSE), mean absolute percentage error (MAPE) and mean percentage error (MPE).

4.3 Analysis and Results

Descriptive statistics of the driver parameters considered are presented in Table 4.1. A total of 173 samples were considered for the analysis and a linear relationship between the parameters was investigated by Pearson correlation (Table 4.2). The results indicate that fuel consumption is significantly positively correlated with hard acceleration and the number of brakes per 100 km and significantly negatively correlated with average speed, distance, over-revving, coasting and the number of stops. Furthermore, over-revving is endemic in timber haulage because of the nature of the work (off-road); it should be zero or near zero in other types of work.

Table 4.1. Summary of telematics data collected from the timber company

Parameters	Minimum	Maximum	Mean	Standard deviation
Fuel consumption (l/100 km)	33	98.8	49.6	8.9
Driver's age (years)	25	55	42.8	9.9
Distance (km)	33.4	12,820.2	7621.3	3772.4
Average speed (km/h)	7.0	64.0	45.9	13.2
Over-revving (%)	0.1	51.4	18.5	16.4
Harsh brake (number)	0.0	45.0	7.2	9.5
Idling (%)	0.5	26.9	6.4	4.1
Top gear (%)	0.0	58.9	15.0	19.8
Hard acceleration (%)	39.3	79.0	62.8	6.7
Hard deceleration (%)	6.2	29.6	19.2	4.2
Coasting (%)	0.0	75.7	9.3	10.0
Brake (number/100 km)	80.0	501.9	157.0	65.7

GEE models were developed using SPSS software. The log link with gamma distribution model was observed to be the best-fitting model for the data used in this research. Both of the GEE models are presented in Table 4.3. The coefficient of predictor variables, which were found to be significant at a 95% confidence interval (i.e. $p \leq 0.05$), are presented in equations 4.1 and 4.2. Both models indicate that increased average speed and coasting negatively contribute to fuel consumption. Parameters such as the number of harsh brakes, idling and the number of brakes per 100 km contribute positively to fuel consumption.

Mathematical expressions of the GEE models are expressed below.

$$\text{Ln(fuel consumption)} = 4.267 - 0.008 \times \text{average speed} - 0.006 \times \text{coasting} + 3.77\text{E–}04 \times \text{number of brakes per 100 km} \tag{4.1}$$

$$\text{Ln(fuel consumption)} = 4.314 - 0.010 \times \text{average speed} + 0.002 \times \text{number of harsh brakes} + 0.004 \times \text{idling} \tag{4.2}$$

Based on QIC and QICC, both GEE models are acceptable (see Table 4.3). Based on the validation results (lower MAPE, MAE and RMSE values), the "key factor model" was observed to be a better fit than the backward elimination model. The validity of the models can also be represented using scatterplots and Figure 4.2 illustrates the scatterplot between predicted and actual fuel consumption for all validation samples. Linear trendlines with intercept zero were fitted to represent the prediction capability of developed models.

4.4 Discussion

The study quantitatively identified that, for the particular timber haulage company studied in this chapter, the number of harsh brakes, idling, the number of brakes per 100 km and hard acceleration positively contributed to fuel consumption. These findings are consistent with previous research studies (Ferreira *et al*., 2015; Walnum and Simonsen, 2015). However, the factors that are determinants of fuel efficiency or eco-driving may vary from haulier to haulier depending on company practices in relation to strategic, operational and tactical factors, such as laden weights, terrain, routes and driver behaviour. The GEE analysis can be carried out on driver statistics to identify specific factors for individual companies and personalised incentive schemes can be developed to improve performance by monitoring changes in key factors, rather than focusing on just the final outcome of fuel economy, which may not be comparable for all routes, journeys and vehicles.

Based on the validation and performance of models, the key factor model was found to be the best-fitting model for the data used in this research. In this particular company, drivers could be advised to drive at a speed of around 60 km/h to achieve fuel economy (as shown in Figure 4.3, which is created from real-world telematics data used in this research).

Table 4.2. Pearson correlation analysis

Parameters	Driver's age	Average speed	Distance	Over-revving (%)	Harsh brake (number)	Idling (%)	Top gear (%)	Hard acceleration (%)	Hard deceleration (%)	Coasting (%)	Brake (number/100 km)	Number of stops
Fuel consumption	–0.061	–0.780[a]	–0.538[a]	–0.245[a]	–0.116	0.125	–0.197[b]	0.336[a]	0.123	–0.361[a]	0.780[a]	–0.320[a]
Driver's age	1	0.028	0.016	0.104	0.078	0.028	–0.088	–0.090	–0.120	0.151	0.059	0.019
Average speed		1	0.762[a]	0.416[a]	0.254[a]	–0.036	0.160	–0.284[a]	0.123	–0.011	–0.724[a]	0.417[a]
Distance			1	0.298[a]	0.342[a]	–0.294[a]	0.244[a]	–0.300[a]	0.084	–0.154	–0.617[a]	0.817[a]
Over-revving (%)				1	0.240[a]	0.081	–0.186[b]	–0.121	–0.036	–0.143	–0.244[a]	0.162
Harsh brake (number)					1	–0.178[b]	–0.236[a]	0.227[a]	0.340[a]	–0.112	–0.097	0.321[a]
Idling (%)						1	–0.236[a]	0.120	0.159	–0.169[b]	0.181[b]	–0.351[a]
Top gear (%)							1	–0.531[a]	–0.388[a]	0.189[b]	–0.207[b]	0.254[a]
Hard acceleration (%)								1	0.773[a]	–0.164[b]	0.414[a]	–0.297[a]
Hard deceleration (%)									1	–0.472[a]	0.199[b]	–0.006
Coasting (%)										1	–0.281[a]	–0.179[b]
Brake (number/100 km)											1	–0.460[a]

[a] The correlation is significant at the *p* < 0.01 level.

[b] The correlation is significant at the *p* < 0.05 level.

Table 4.3. GEE models using telematics data

	Backward elimination model			Key factor model		
Parameters	Coefficient	Standard error	*p*-value	Coefficient	Standard error	*p*-value
Intercept	4.267	0.043	< 0.01	4.314	0.076	< 0.01
Average speed	–0.008	0.001	< 0.01	–0.010	0.001	< 0.01
Over-revving (%)	–	–	–	–	–	–
Harsh brake (number)	–	–	–	0.002	0.001	0.035
Idling (%)	–	–	–	0.004	0.002	0.016
Coasting (%)	–0.006	< 0.001	< 0.01	–	–	–
Brake (number/100 km)	3.77E–04	< 0.001	< 0.01	–	–	–
Number of stops	–	–	–	–	–	–
QIC	12.999			25.004		
QICC	8.693			9.235		
MAPE	17%			15%		
MAE	–11%			–9%		
RMSE	10.54			8.70		

MAE, mean absolute error.

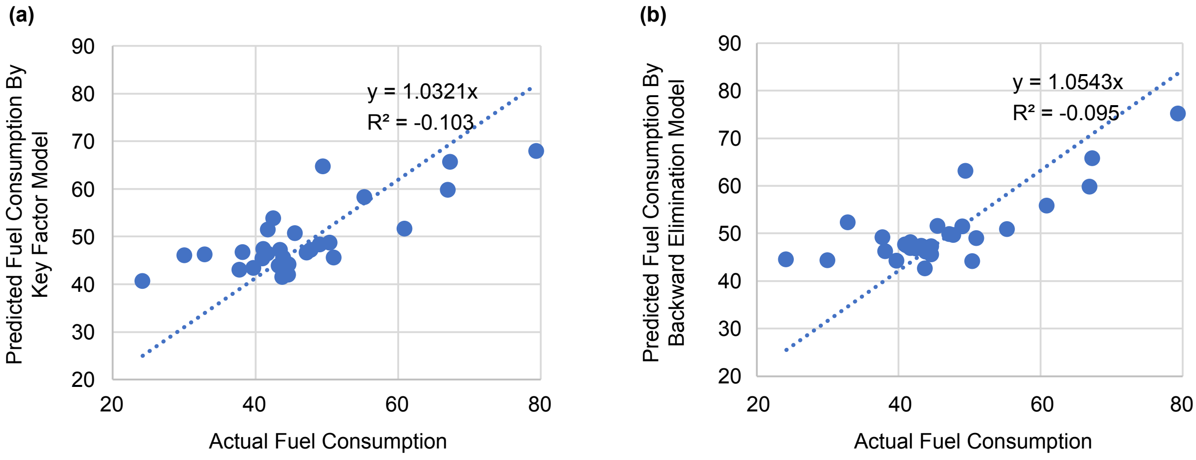


Figure 4.2. Scatterplots of actual and predicted fuel consumption using (a) the key factor model and (b) the backward elimination model.

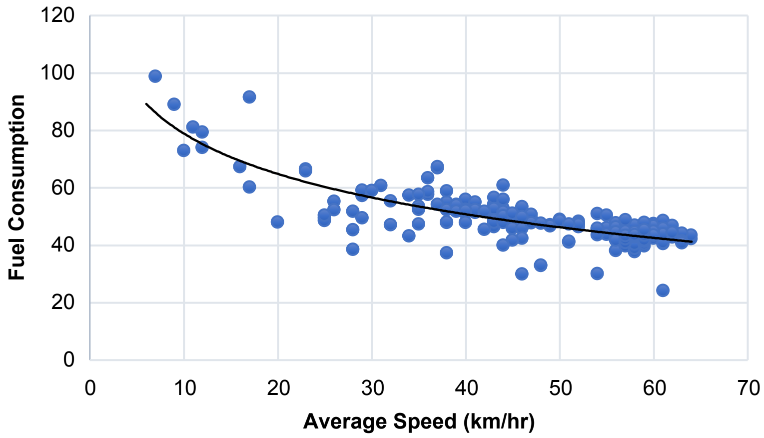


Figure 4.3. Scatterplot of fuel consumption and average speed.

4.5 Conclusion

In the road haulage sector, the use of telematics data helps to track vehicles and their fuel consumption and to capture the driver's performance in terms of harsh acceleration, harsh braking, overspeeding and timely gear change. This chapter focused on developing an analytical tool for individual hauliers to identify specific driver behaviour parameters contributing to fuel consumption of HDVs for the specific activities of the company. The tool identified the key factors that should be discussed with individual drivers, and suggests that providing advice or coaching could improve fuel economy. Such driver training and incentive programmes focusing on a small number of factors can improve the fuel economy of and reduce emissions from any haulage company. Based on GEE and Pearson correlation analysis (equations 4.1 and 4.2), improved performance of professional drivers with a targeted fuel consumption level can be rewarded within an incentive scheme.

5 Effects of Eco-driving Tips on Driver Behaviour

This chapter focuses on developing a tool for evaluating the performance efficiency of drivers when provided with eco-driving tips by analysing their driving behaviour, specifically focusing on acceleration and deceleration profiles.

5.1 Introduction

The effect of providing eco-driving tips to drivers is investigated using real-world acceleration–deceleration profiles. Furthermore, a methodology has been proposed to identify fuel-efficient drivers from the collected data. The proposed methodology to identify eco-drivers is discussed in section 5.2. The step-by-step analysis and results associated with the proposed methodology are presented in section 5.3, and the conclusions are given in section 5.4.

5.2 Methodology

In an EDT programme, drivers are often informed and trained through online courses, classroom training and in-vehicle training, and by receiving advice regularly. In this method, three drivers were selected from a haulier that transports cars from Dublin port to different parts of Ireland. Drivers were provided with eco-driving tips, which were adopted from the SAFED programme. A type of HDV used by these professional drivers is shown in Figure 5.1. The VBOX Mini instrument was used in this analysis, and Figure 5.2 shows the position of the VBOX within a truck's cabin. The VBOX Mini collects accurate GPS data at 10 Hz. The data logger calculates parameters such as time, position, speed, distance, heading, cornering force, acceleration/braking force, vertical velocity and yaw rate from the GPS 10 times per second (i.e. at 0.1-second intervals). In this methodology, we have extensively used time, position, speed, distance and acceleration parameters.

The Dublin port area has the highest levels of HDV traffic in Ireland. After providing the eco-driving recommendations (post training), drivers were tested between 14 January and 26 March 2020. Out of all the journeys, around 20 trips were in the vicinity of Dublin port. These trips were segregated by drivers and by trips within the Dublin port area. Figure 5.3 shows typical trips made by drivers in the Dublin port area.

Collected data from the VBOX instrument were processed, and acceleration–deceleration values for every 5 km/h and 10 km/h were calculated. Trendlines were fitted for acceleration and deceleration profiles

Figure 5.1. Type of HDV considered for the study.

Figure 5.2. Position of VBOX Mini within the HDV cabin.

separately. Literature and the prior investigations using the GEE model above suggested that smooth acceleration–deceleration, avoiding excessive acceleration–deceleration and maintaining driving pace would improve fuel consumption in HDVs (Barkenbus, 2010; Rutty *et al.*, 2013; Zhou and Yao, 2015; Barla *et al.*, 2017; Díaz-Ramirez *et al.*, 2017; Garcia-Castro *et al.*, 2017). The developed trendlines were compared and they represent driving behaviour in the Dublin port area. The area under these trendlines was computed to identify fuel-efficient drivers. Smoother curves and smaller areas under the curve would represent fuel-efficient drivers. The area under any curve can be calculated using the trapezoidal formula presented in equation 5.1:

$$\text{Area under curve} = \frac{h}{2}(y_0 + 2y_1 + 2y_2 + 2y_3 + \ldots + y_n) \quad (5.1)$$

where h = width of sub-interval, here 10 km/h. y_0, y_1, y_2, y_3, …, and y_n are the magnitude of acceleration or deceleration. Here, y_0 is the magnitude of acceleration or deceleration profiles at 0 km/h, y_1 at 10 km/h, y_2 at 20 km/h, y_3 at 30 km/h, and so on.

The detailed step-by-step analysis and results of the proposed methodology are provided in section 5.3.

5.3 Analysis and Results

The collected sample data at every 0.1-second interval are shown in Figure 5.4a. They do not indicate any specific trendlines of acceleration and deceleration profiles and show a range of values between 0.9 m/s^2 and –0.9 m/s^2; therefore, to get a better representation of acceleration and deceleration profiles, data were aggregated at 1-second intervals. Figure 5.4b shows pre-processed data for all of the drivers. In general,

Figure 5.3. Typical trips made by drivers in the Dublin port area. Source: Google Maps, ©2019.

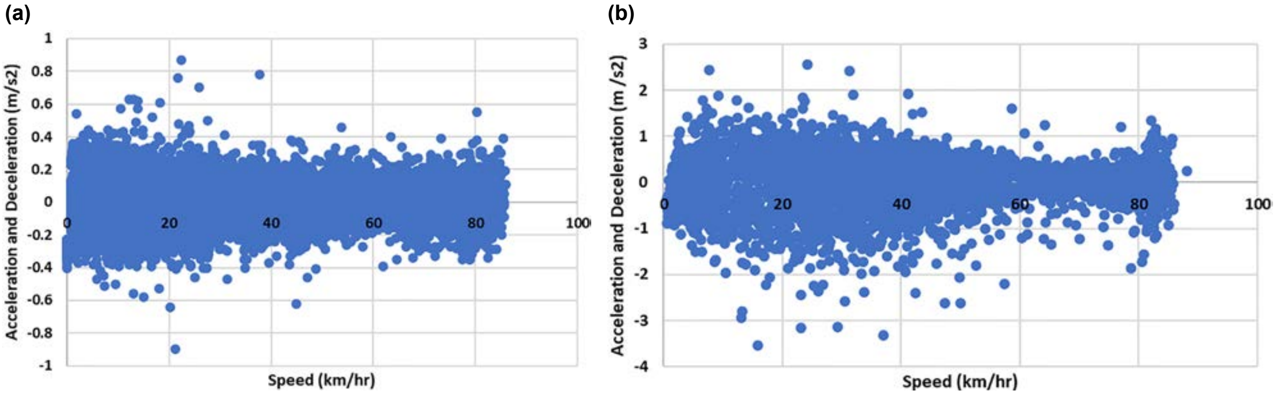


Figure 5.4. Scatterplots of acceleration and deceleration values for (a) the sample data at 0.1-second intervals and (b) all of the drivers at 1-second intervals.

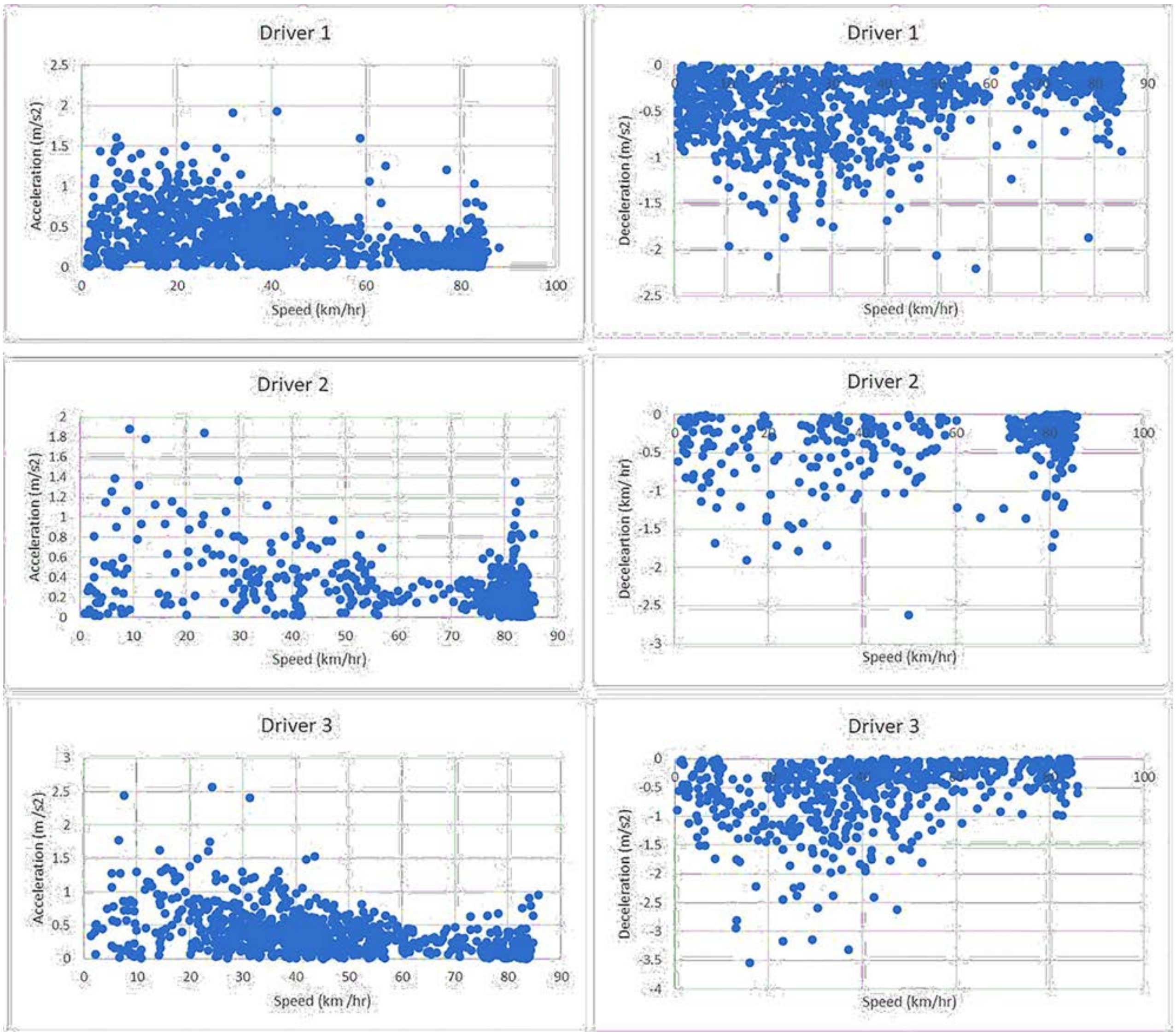


Figure 5.5. Acceleration (left-hand side) and deceleration (right-hand side) profiles of each driver.

the acceleration rate increases up to 20 km/h, and the acceleration rate tends to be constant when a vehicle reaches 60 km/h. The deceleration rate decreases up to 20 km/h, and it becomes constant after 60 km/h. Typically, each driver has a specific driving habit and therefore data for each of the drivers were processed separately. Figure 5.5 shows the values for acceleration and deceleration adopted by each driver by aggregating at 1-second intervals.

Moreover, acceleration and deceleration values, which were aggregated at 1-second intervals, were further aggregated every 5 km/h and 10 km/h. Finally, acceleration–deceleration profiles were defined using the trendline-fitting function in Excel.

Figures 5.6 and 5.7 show the acceleration and deceleration profiles by aggregating every 5 km/h (plots on the left side) and 10 km/h (plots on the right side), respectively.

Typically, smooth acceleration–deceleration, avoiding excessive acceleration–deceleration and maintaining driving pace improve fuel economy in HDVs. Comparing Figures 5.6 and 5.7, driver 1 was observed to accelerate and decelerate smoothly and avoid sudden excessive acceleration and deceleration compared with drivers 2 and 3. In addition, as per the trendlines, the maximum acceleration for driver 1 is around 0.5 m/s^2, which is lower than drivers 2 and 3 (0.7 m/s^2), at 20 km/h. Likewise, as per

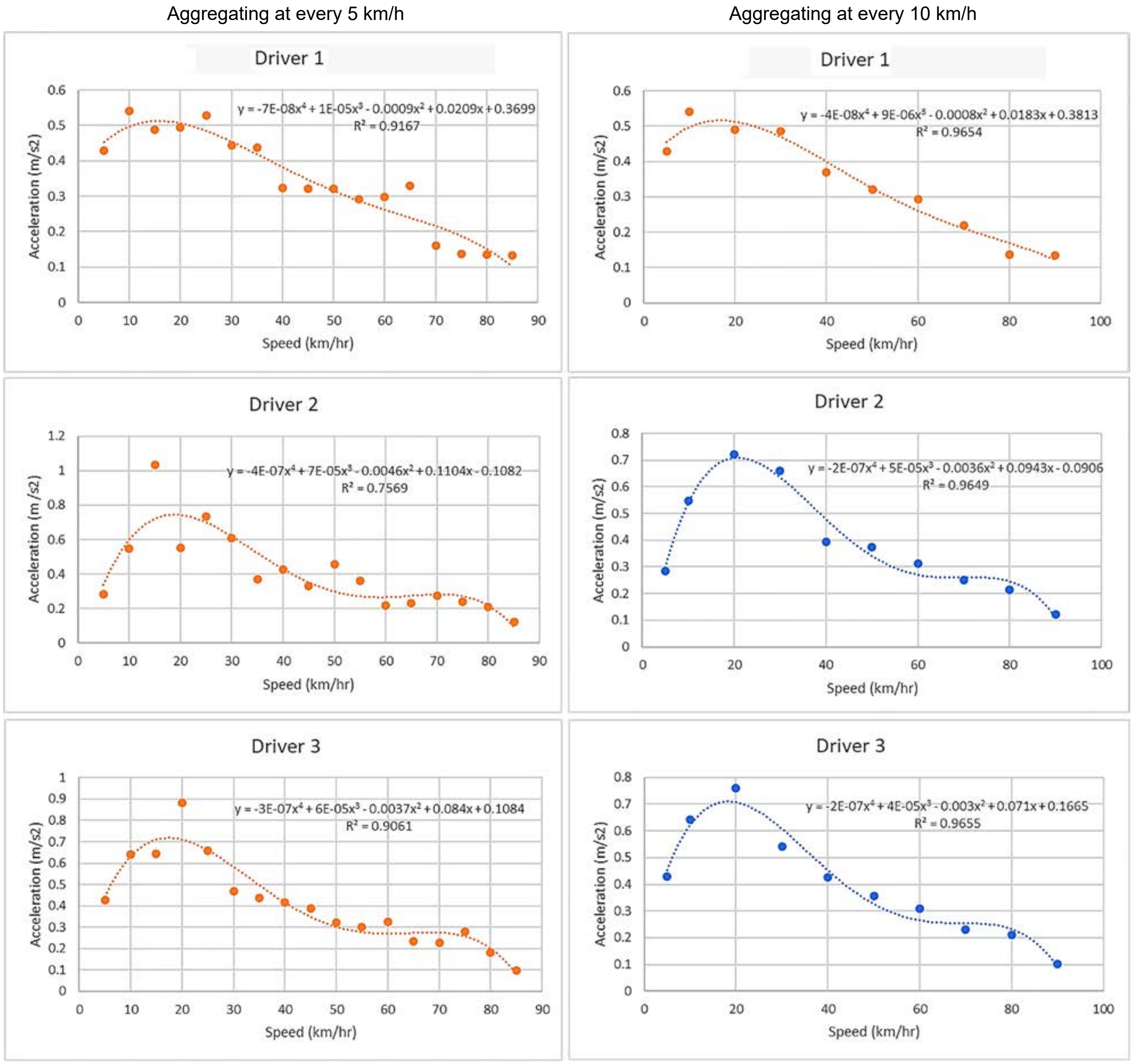


Figure 5.6. Acceleration profiles of individual drivers at every 5 km/h and 10 km/h.

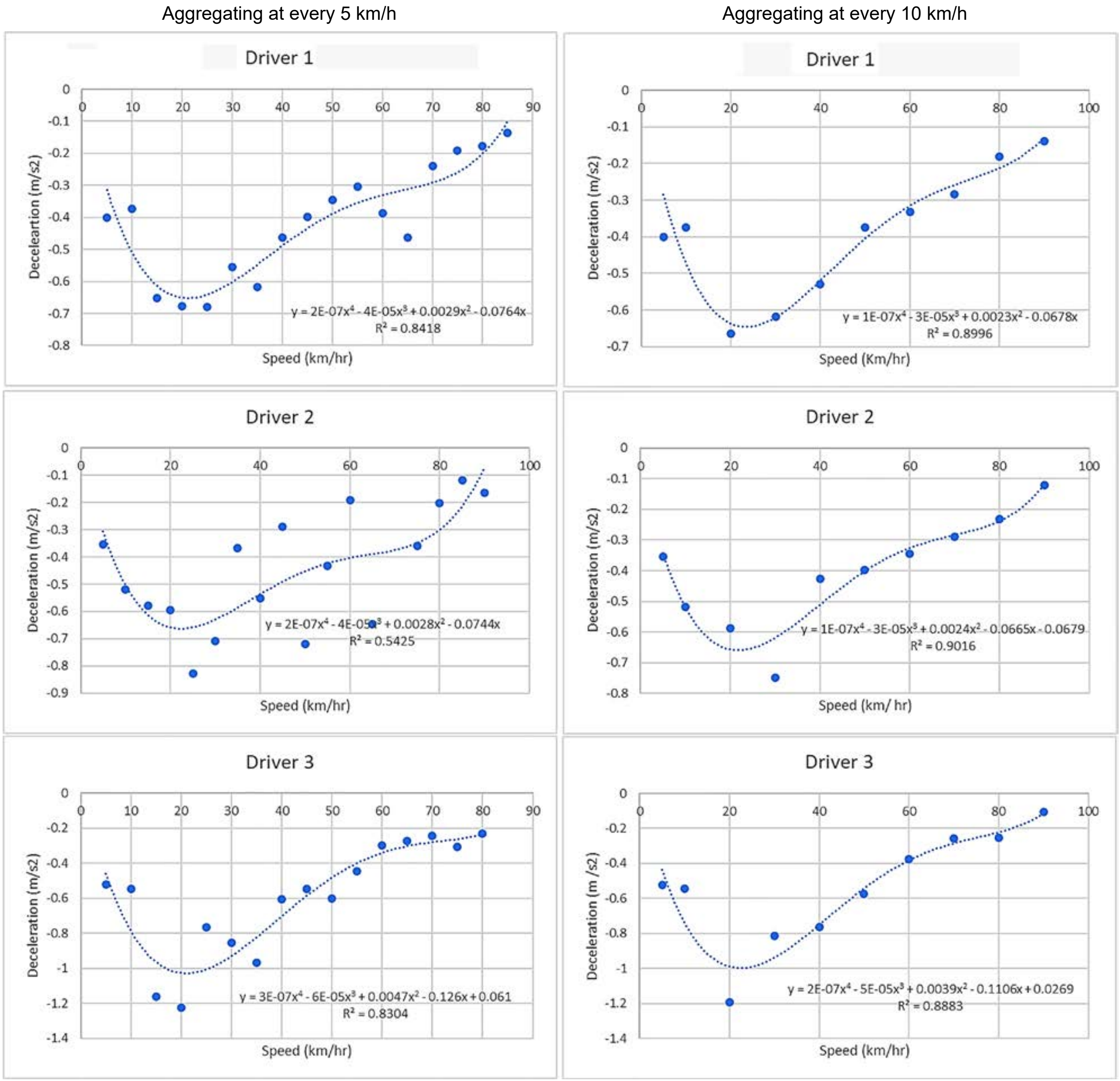


Figure 5.7. Deceleration profiles of individual drivers at every 5 km/h and 10 km/h.

the trendlines, the maximum deceleration for driver 1 was around 0.62 m/s^2, which is also lower than driver 2 (0.65 m/s^2) and driver 3 (1 m/s^2) at 20 km/h. These profiles have a similar trend to the passenger car's profile defined by Kobayashi *et al*. (2007), where best-fitting trendlines of acceleration and deceleration were represented using fourth-degree polynomial equations. Trendlines for acceleration and deceleration profiles that are aggregated every 10 km/h were found to be the best fit for the data used in this research. Furthermore, Yang *et al*. (2016) observed that average acceleration rates for HDVs (all three drivers) from zero to 50 km/h (31 mph) was observed to be around 1.96 ft/s^2 (0.6 m/s^2), which is similar to the values observed in Figure 5.6 (figures on the right side).

Table 5.1. Computed areas under acceleration and deceleration profiles

Driver	The area under acceleration profile	The area under deceleration profile
Driver 1	31.41	–34.24
Driver 2	36.79	–36.07
Driver 3	37.42	–48.23

Based on the fuel consumption report, driver 2 was observed to be the most fuel efficient (32.69 l/100 km). However, driver 2 drove approximately 200 km, which is a shorter distance than the other two drivers. Likewise, in terms of acceleration–deceleration trendlines, a smoother curve and smaller area under the curve represent fuel-efficient drivers. Based on Table 5.1 and Figures 5.6 and 5.7, driver 1 drives in a more fuel-efficient manner than drivers 2 and 3. Therefore, the proposed methodology helps to identify and compare the performance of drivers.

5.4 Conclusions

This chapter proposed a methodology to identify fuel-efficient drivers using microscopic real-world telematics data. We proposed a method to evaluate and compare driver behaviour using observed acceleration and deceleration profiles, as a smoother curve and lower area under the curve represent fuel-efficient drivers. The study was affected by the COVID-19 pandemic and could be conducted for only three drivers. A future project utilising this technique can be used to study behaviour before and after EDT, as well as comparing different driver behaviours within the same organisation. The developed trendlines of acceleration and deceleration profiles by providing eco-driving tips to drivers will help to quantify the potential impacts of eco-driving at the road network level. This concept and the associated results are explained in Chapter 6.

6 Potential Impacts of Eco-driving

This chapter focuses on developing a tool to compare on-road driver performances through simulation and evaluate the effect of eco-driving penetration on fuel consumption, emissions and average speed at the road network level.

6.1 Introduction

A microscopic traffic simulation study helps to replicate real-world scenarios in the simulation environment. Simulation studies help to develop and investigate the effectiveness of futuristic scenarios. Eco-driving tips were provided to professional HDV drivers, and their driving behaviour was collected and incorporated in the simulation environment. The proposed methodology helps to identify the effectiveness and limitations of eco-driving at different locations and at the road network level. Results obtained would help to draft policies and mitigation measures to reduce emissions from HDVs. Detailed methodology is explained in section 5.2 and the subsequently developed traffic models, and associated results, are explained in the following sections.

6.2 Methodology

The proposed methodology comprises several steps to evaluate the effect of eco-driving on fuel consumption and emissions using traffic software VISSIM version 11.0 and is presented in Figure 6.1. First, the baseline model was developed by considering road geometry, traffic volume, signals and default acceleration and deceleration profiles. For this study, the Dublin port tunnel area was selected, and Figure 6.2 illustrates the road network selected for this study. The Dublin port area has the highest number of HDV activities in Ireland. The study area consists of two tollbooths, and one major and two minor signalised intersections for entering and exiting the port area. The road network also consists of a tunnel that has a speed limit of 80 km/h; the speed limit of other urban roads is 50 km/h.

Geometric characteristics such as the number of lanes, turning lanes, speed limit and merging and diverging sections were captured using Google Earth. The road network model was developed in traffic microsimulation software (VISSIM). Traffic volume,

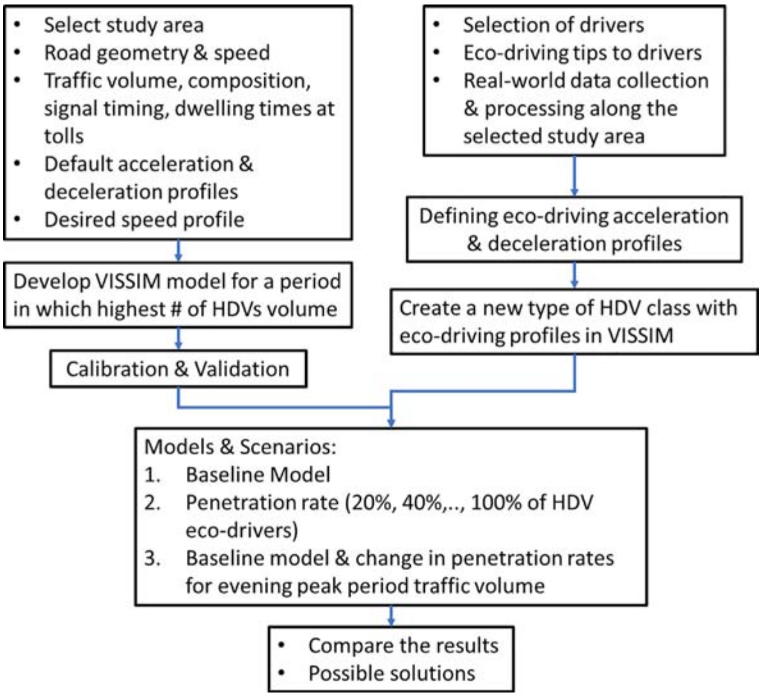


Figure 6.1. Methodology adopted to quantify the impacts of eco-driving.

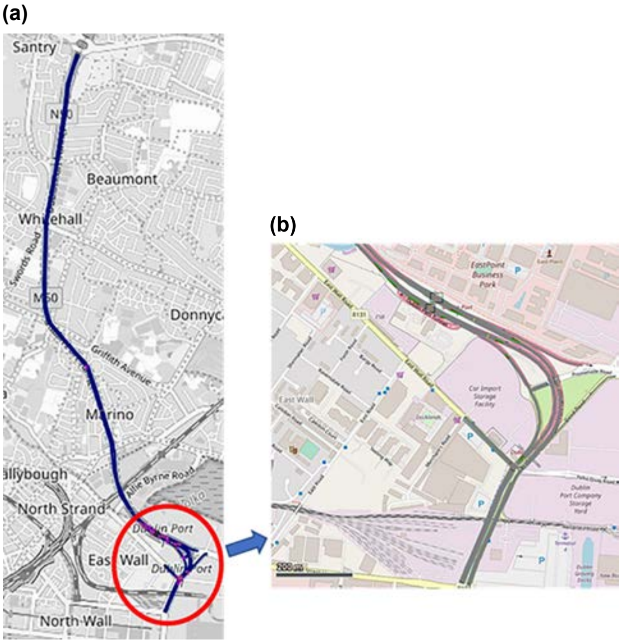


Figure 6.2. The road network considered as the study area. (a) The overall road network from Dublin port to the M50 and (b) the various intersections and tollbooths in the study area. Source: VISSIM model; created by the authors.

composition and signal information were collected from the Department of Transport in Dublin City Council (DCC). Traffic data on 10 October 2019 were simulated, as it was a typical weekday without any special event. Traffic volume from 10:45 to 12:00 was selected as the period during which the number of HDVs was the highest. Information related to traffic signals was selected based on the time-of-day and day-of-the-week signal plan from DCC. A traffic signal plan consists of timings for each turning movement, along with yellow clearance time and all-red clearance time. The developed baseline model was calibrated and validated to replicate real-world traffic conditions in the simulation environment, as explained in section 5.3.

Real-world eco-driving behaviour of HDVs was defined in VISSIM software by creating a vehicle type “eco-hdv” (eco-driving HDVs). Real-world data collection and processing of eco-drivers are explained in sections 4.2 and 4.3. The desired acceleration and deceleration profiles of eco-driving HDVs are represented in Figure 6.3. These desired acceleration and deceleration profiles reflect the eco-driving behaviour of three professional HDV drivers after they were given eco-driving recommendations. Finally, the impact of eco-driving of HDVs was investigated by increasing the penetration of eco-driving vehicles within the composition of HDVs, as shown in Table 6.1.

Two different hours were selected and analysed: the evening peak hour and the hour with the highest number of HDVs. A total of 12 simulation models were developed and each model was run for 10 simulations with random seed numbers. For developing baseline scenarios for two different hours, traffic volume, composition and signal timings were considered separately. The peak hour for HDVs was observed to be between 11:00 and 12:00 and the evening peak hour was observed to be between 16:00 and 17:00. An additional 15-minute period (10:45–11:00 and 15:45–16:00) was also considered for training the baseline models in simulation. Each of the baseline models was calibrated and validated based on real-world data (see section 6.3). Finally, the eco-driving of HDVs was introduced stepwise by increasing the penetration of eco-driving vehicles within the composition of HDVs.

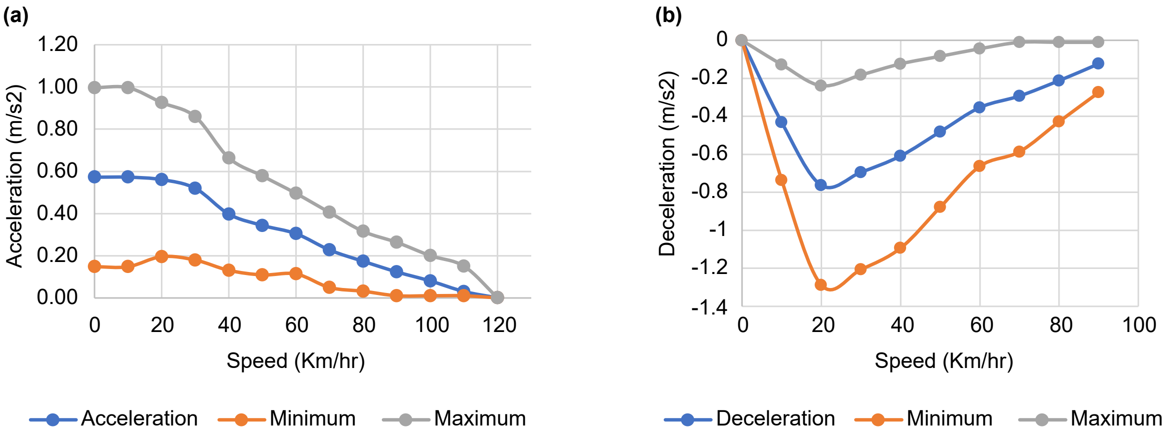


Figure 6.3. Eco-driving (a) acceleration and (b) deceleration profiles for HDVs in VISSIM software.

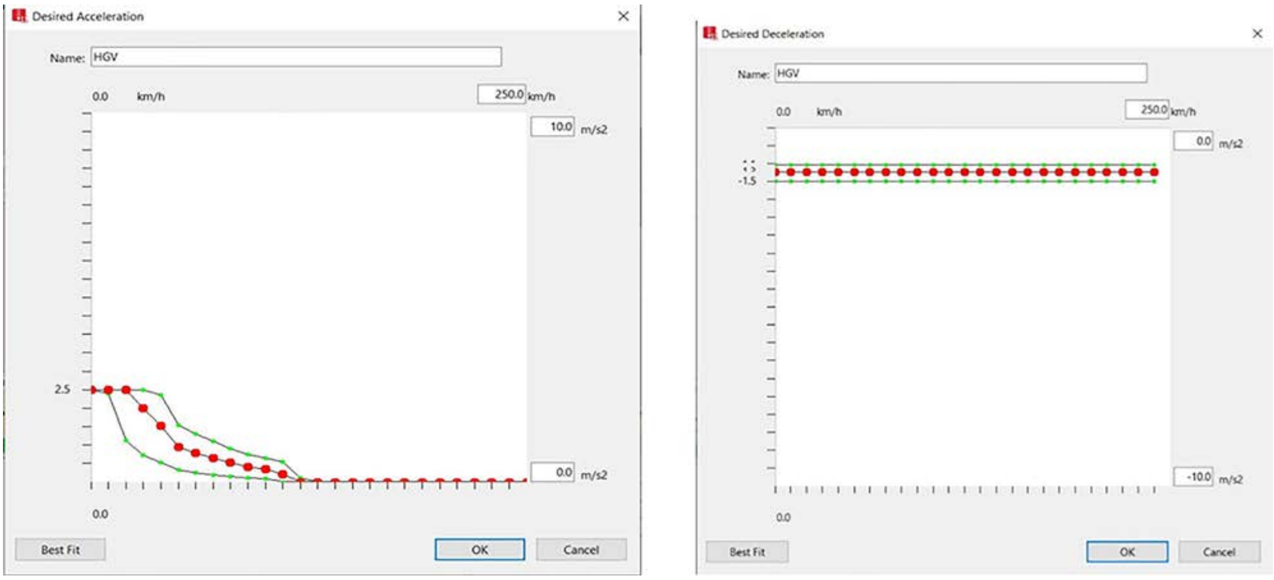
Table 6.1. Scenarios developed for peak hour for HDVs and evening peak hour

	Peak hour for HDVs		Evening peak hour	
Scenarios	**% HDV**	**% Eco-HDV**	**% HDV**	**% Eco-HDV**
Baseline	15	0	8	0
20% Eco-HDV	12	3	6.4	1.6
40% Eco-HDV	9	6	4.8	3.2
60% Eco-HDV	6	9	3.2	4.8
80% Eco-HDV	3	12	1.6	6.4
100% Eco-HDV	0	15	0	8

Parameters such as fuel consumption, emissions level, queue length and average speed at the network level were compared with baseline and penetration rate models to investigate the effect of eco-driving of HDVs.

6.3 Calibration and Validation

Several traffic parameters, such as desired speed, vehicle routes and driver behaviour, were introduced in the baseline model. As road links were considered as urban (motorised) roads, Wiedemann 74 was considered as the car-following model. Driver behaviour parameters such as car-following parameters, lane change and lateral distance were selected from the research study related to tolls by Bains *et al*. (2017). Default values for the look-ahead distance, the look-back distance, the average still distance, the additive part of safety distance, the multiplicative part of safety distance, the minimum lateral distance at 0 km/h and the minimum distance driving at 50 km/h were selected to calibrate the baseline model. Dwelling/idling time for vehicles at the tollbooth was observed to be around 5 seconds. The first 15-minute traffic volume (10:45–11:00) was used to train the baseline model, and the time period from 11:00 to 12:00 was considered for model evaluation. The desired speed distribution was selected as an S-curve in the baseline model. Furthermore, the default desired acceleration and deceleration profiles of HDVs in the VISSIM software were considered in the baseline model, as shown in Figure 6.4. Ten simulations were performed using random seed numbers and the average of these 10 simulations was compared with actual traffic volume, as presented in Figure 6.5. The results show that the simulated traffic scenario in the baseline model replicated actual traffic volumes.



Name: HGV
0.0 km/h
250.0 km/h
10.0 m/s2
0.0 m/s2

Name: HGV
0.0 km/h
250.0 km/h
0.0 m/s2
-10.0 m/s2

Figure 6.4. Desired acceleration (left) and deceleration (right) profiles for HDVs in VISSIM software.

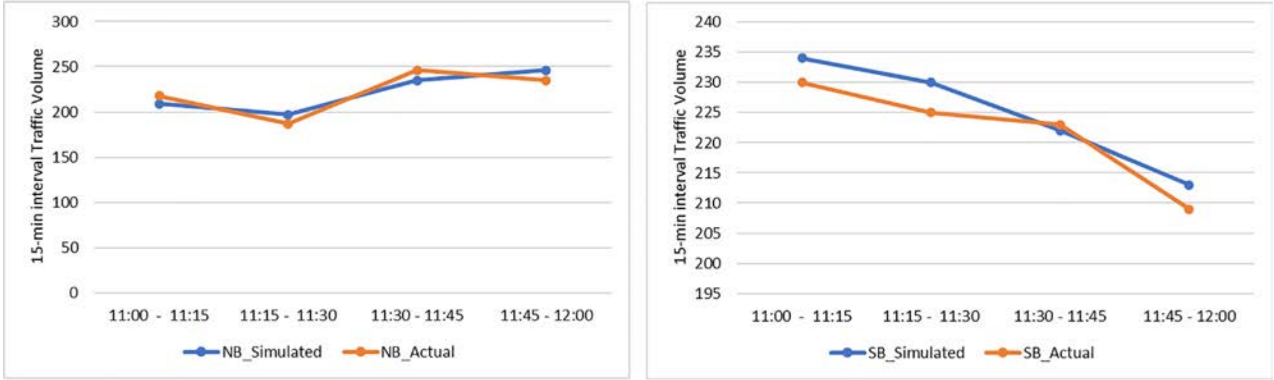


Figure 6.5. Comparison between simulated and actual traffic volume for HDVs. Left, northbound (NB) traffic; right, southbound (SB) traffic.

Moreover, a typical weekday travel time was collected using the VBOX Mini instrument. The average travel time for the northbound (NB) direction from the East Wall Road intersection to the start of the tunnel was observed to be 110 seconds and the average travel time for the southbound (SB) toll road was found to be 103 seconds. Simulated average travel times for NB and SB directions were observed to be 96 seconds and 94 seconds, respectively. Therefore, the developed and calibrated baseline model has a 90% accuracy of replicating the real-world scenario in the simulation environment.

Moreover, emissions and fuel consumption were estimated using the node feature in VISSIM. It uses equation 6.1 to estimate fuel consumption. These are the same as the default formulae for fuel consumption used by TRANSYT 7-F (traffic simulation and signal timing designing software) (Wallace *et al*., 1984).

$$\text{FC} = \text{total travel} \times \text{k1} + \text{total delay} \times \text{k2} + \text{stops} \times \text{k3} \qquad (6.1)$$

where k1 = 0.075283 – 0.0015892 × speed + 0.000015066 × speed ^ 2, k2 = 0.7329, k3 = 0.0000061411 × speed ^ 2, FC = fuel consumed in gallons, speed = cruise speed in mph, total travel = vehicle miles travelled, total delay = total signal delay in hours and stops = total stops in vehicles per hour.

Node evaluation may be useful for comparing the before and after scenarios. As per equation 6.1, acceleration and deceleration do not directly influence the estimation of fuel consumption. However, acceleration and/or deceleration has an impact on speed, which is one of the essential factors in equation 6.1. Further, emissions calculations are based only on fuel consumption. The somewhat simplified calculation multiplies fuel consumption by the following factors to determine emission rates, as presented in equations 6.2–6.4:

$$\text{CO} = F \times 69.9\,\text{g/gal} = \text{carbon monoxide emissions (g)} \qquad (6.2)$$

$$\text{NO}_X = F \times 13.6\,\text{g/gal} = \text{nitrogen oxides emissions (g)} \qquad (6.3)$$

$$\text{VOC} = F \times 16.2\,\text{g/gal} = \text{volatile organic compounds emissions (g)} \qquad (6.4)$$

where F = fuel consumption (gal).

6.4 Results

The impacts of eco-driving of HDVs during a peak hour and an evening peak hour on the road network are discussed in the following sections.

6.4.1 Peak hour by HDV traffic

As discussed in sections 6.2 and 6.3, a baseline model and scenarios with different penetration rates of eco-driving HDVs (20%, 40%, 60%, 80% and 100% of eco-HDVs) were developed and the node analysis feature in VISSIM was used to estimate and compare fuel consumption and emissions at both NB and SB tolls (see Figure 6.6) and at a major signalised intersection in the Dublin port area. For each of the scenarios 10 simulation runs were performed with random seed numbers. Finally, the average values of fuel consumption, emissions, average speed and

Figure 6.6. Created node features in the VISSIM model: (1) indicates the NB toll and (2) shows the SB toll.

average queue length from these 10 simulations were compared with the baseline model and scenarios with different penetration rates of eco-HDVs.

Figure 6.7 shows the averaged values of fuel consumption and emissions from baseline models and subsequent eco-HDV scenarios. Each bar in Figure 6.7 represents the average of 10 simulation runs of each scenario. In Figures 6.7 to 6.11, the *x*-axis indicates three different locations (NB toll, SB toll and intersection) and for each location there are four sets; each set represents a 15-minute interval. Furthermore, in each set there are six bars; each bar represents results from a particular scenario. For example, the first set of six bars represents fuel consumption at the NB toll during the first 15-minute time interval (11:00–11:15) and the second set of six bars represents fuel consumption at the NB toll during the next 15-minute interval (11:15–11:30), and so on.

For NB and SB tolls, an increase in eco-driving HDVs decreases fuel consumption; however, for a traffic signal, an increase in the percentage of eco-driving HDVs increases fuel consumption. Total fuel consumption was observed to be reduced between 3% and 16% when compared with baseline for eco-driving

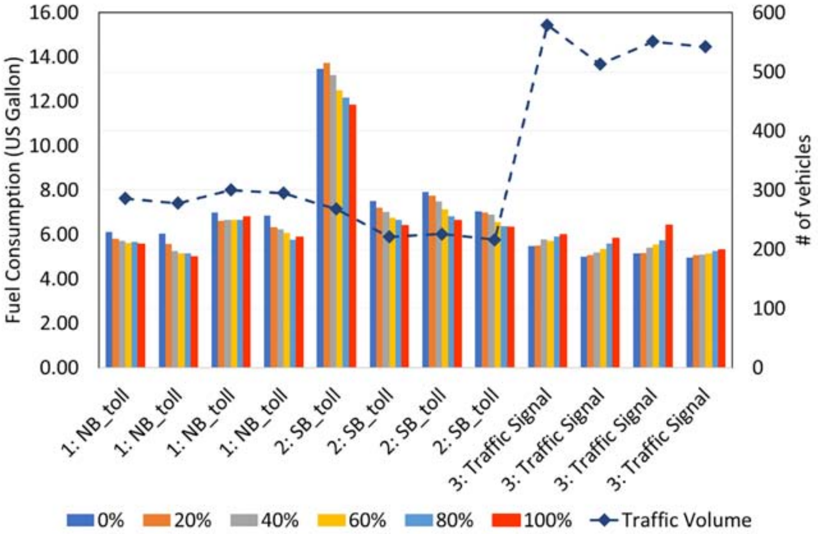


Figure 6.7. Fuel consumption at 15-minute intervals during peak hour by HDVs.

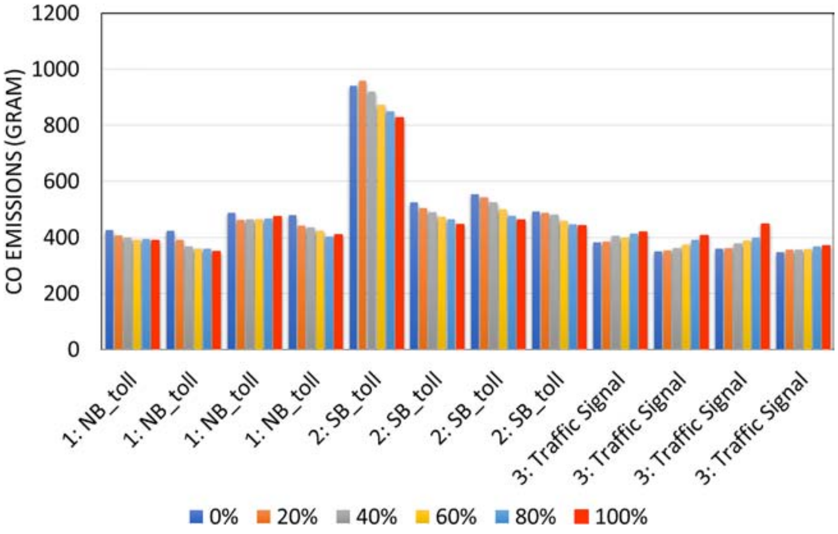


Figure 6.8. CO emissions at 15-minute intervals during peak hour by HDVs.

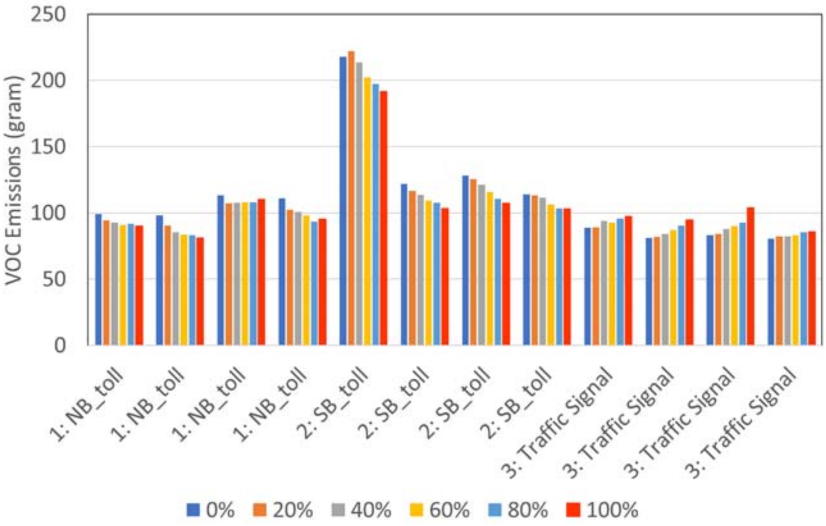


Figure 6.9. VOC emissions at 15-minute intervals during peak hour by HDVs.

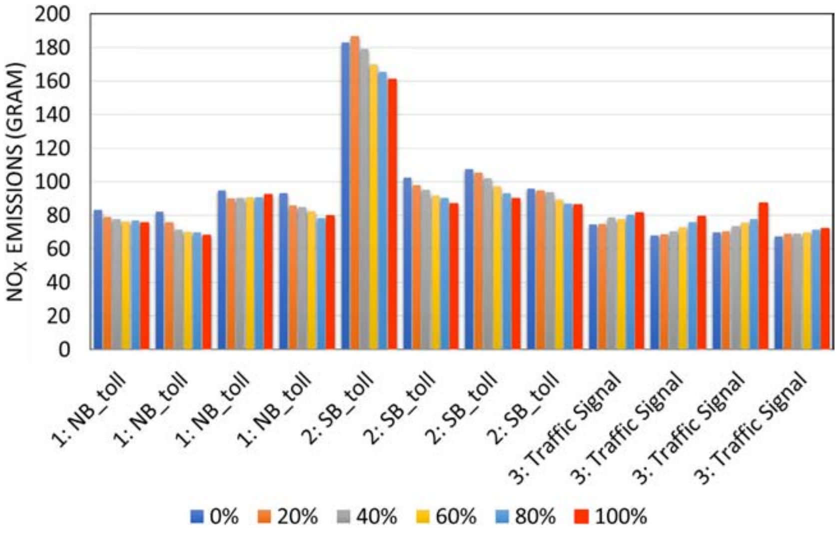


Figure 6.10. NO_x emissions at 15-minute intervals during peak hour by HDVs.

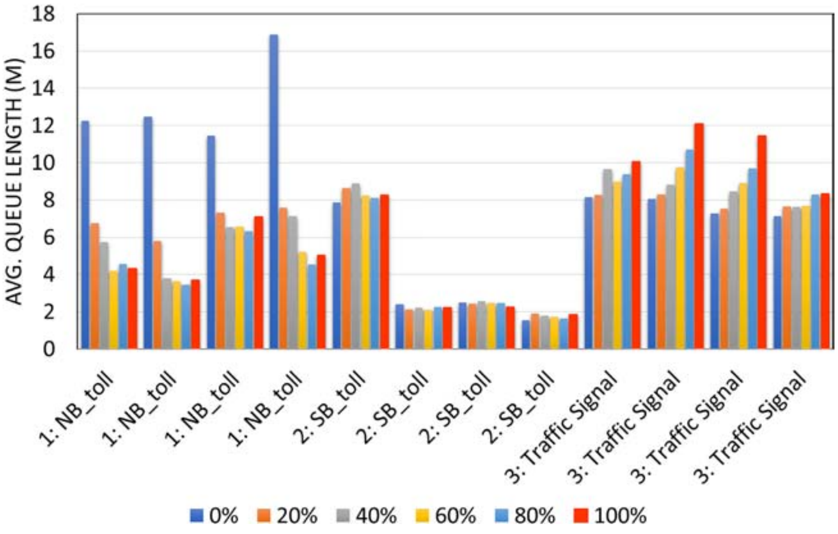


Figure 6.11. Average queue length at 15-minute intervals during peak hour by HDVs.

penetration rate of up to 100% in HDVs. Likewise, for NB and SB tolls, with an increase in penetration rate, emissions such as CO, volatile organic compounds (VOC) and NO_X were observed to decrease, as shown in Figures 6.8–6.10. However, for a traffic signal, emissions were observed to increase with the increase in the percentage of eco-driving HDVs. An increase in fuel consumption and emissions at traffic intersections could be the result of a higher traffic volume as well as an increase in stop-and-go activities. Moreover, with the increase in the penetration rate of eco-driving HDVs, the average queue length decreased at the NB toll, as shown in Figure 6.11. At the SB toll, the average queue length was observed to be consistent with the increase in the percentage of eco-driving HDVs. Although for the signalised intersection the average queue length increased with increasing penetration rate, at the road network level an increased percentage of eco-driving HDVs could reduce the average speed by 4–5 km/h, as illustrated in Figure 6.12.

6.4.2 Evening peak hour

For evening peak hour, the traffic volume between 15:45 and 17:00 was considered in the baseline model, in which 8% of vehicles are HDVs. Table 6.1 represents six simulation scenarios for baseline and an increase in the penetration rate of eco-driving HDVs. Fuel consumption for all six simulation scenarios for every 15-minute interval at the NB toll, SB toll and the traffic signal is shown in Figure 6.13. Each bar represents the aggregation of 10 simulation runs for a 15-minute interval. The *x*-axes in Figures 6.13–6.17 indicate three different locations (NB toll, SB toll and intersection) and for each location there are four sets of bars and each set represents a 15-minute interval.

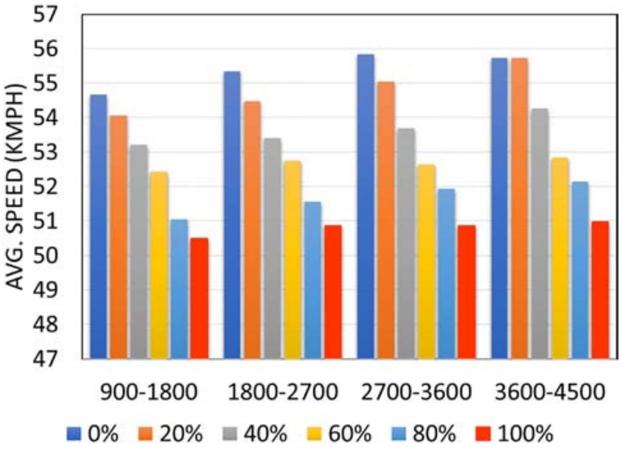


Figure 6.12. Average speed at the road network level during peak hour by HDVs.

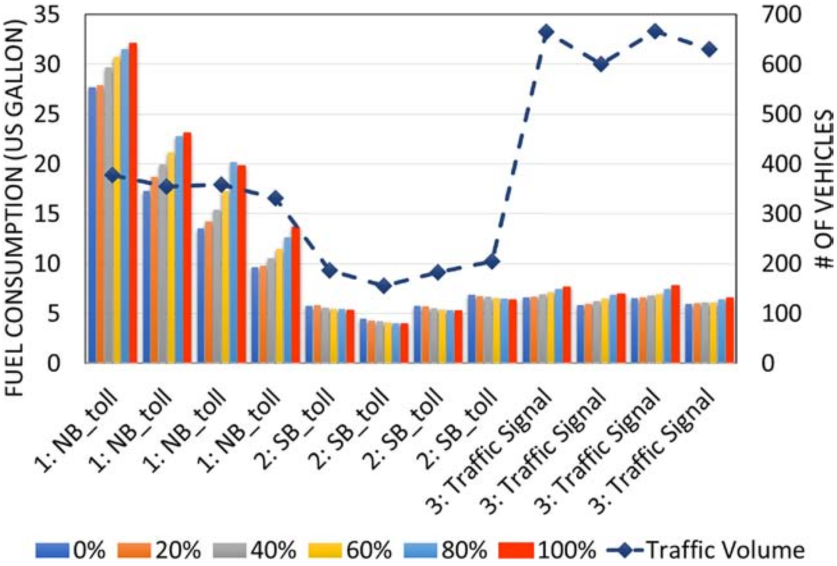


Figure 6.13. Fuel consumption at 15-minute intervals during evening peak hour.

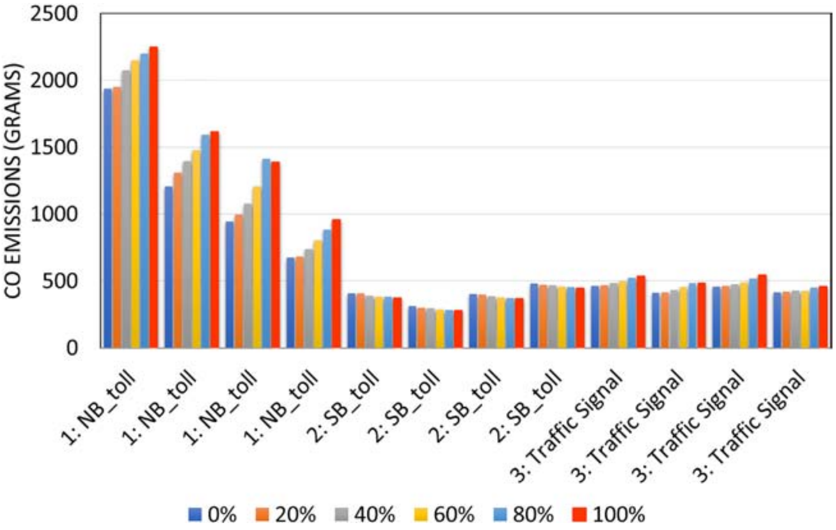


Figure 6.14. CO emissions at 15-minute intervals during evening peak hour.

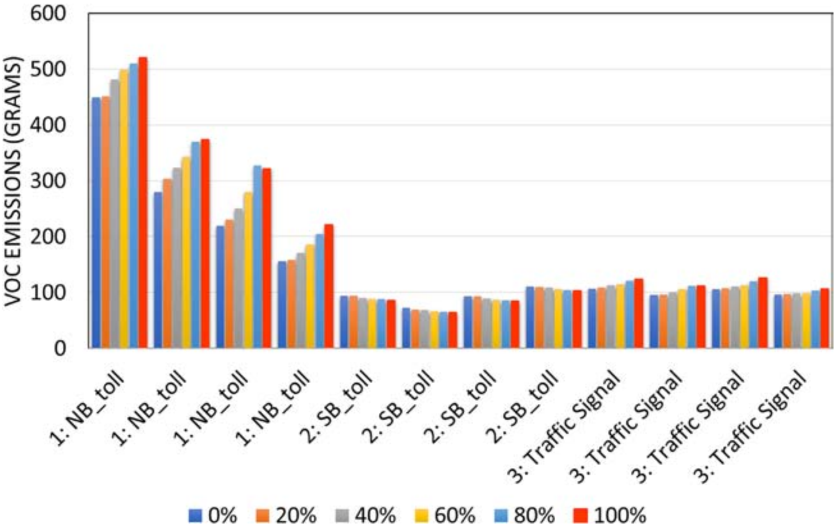


Figure 6.15. VOC emissions at 15-minute intervals during evening peak hour.

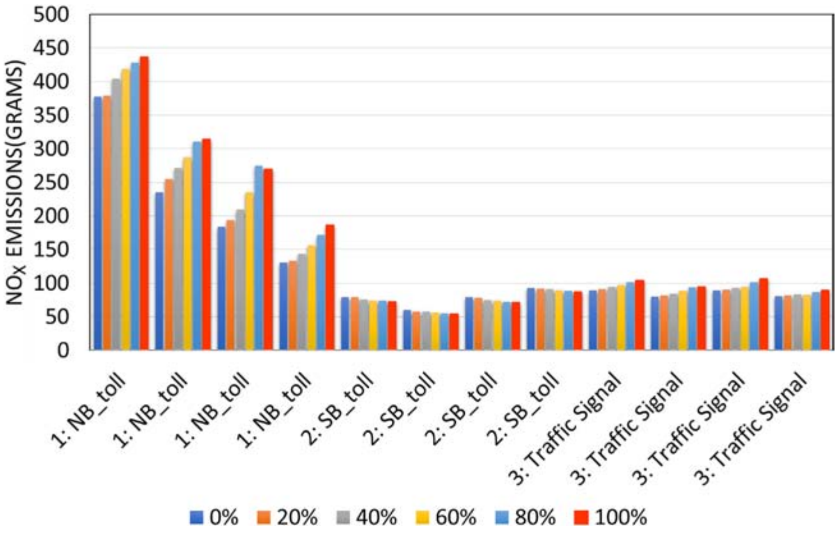


Figure 6.16. NO_x emissions at 15-minute intervals during evening peak hour.

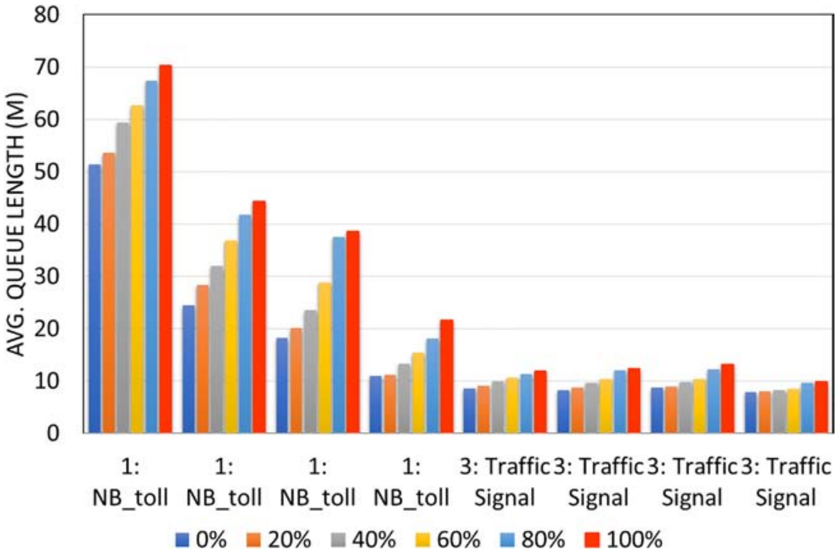


Figure 6.17. Average queue length at 15-minute intervals during evening peak hour.

Furthermore, in each set there are six bars; each bar represents results from a particular scenario. So, as in section 6.4.1, a set of six bars represents the results of every 15-minute time interval during 16:00–17:00 (16:00–16:15, 16:15–16:30, 16:30–16:45 and 16:45–17:00), at each location.

For the NB toll and signalised intersection, fuel consumption increased with an increase in eco-driving HDVs for all four 15-minute intervals. However, at the SB toll, an increase in the percentage of eco-driving HDVs decreased fuel consumption. Similar trends were observed for emissions (CO, VOC, NO_x), as shown in Figures 6.14–6.16. Both Figures 6.7 and 6.13 indicate that, if traffic volume is more than 300 vehicles per 15-minute interval, even with an increase in eco-driving HDVs, fuel consumption increases. In low-traffic conditions (fewer than 300 vehicles per 15 minutes), fuel consumption decreases by 4–12%.

Moreover, an increased penetration of eco-driving HDVs results in an increase in the average queue length at all selected locations (Figure 6.17) and reduces the average speed by 5–6 km/h at the road network level (Figure 6.18).

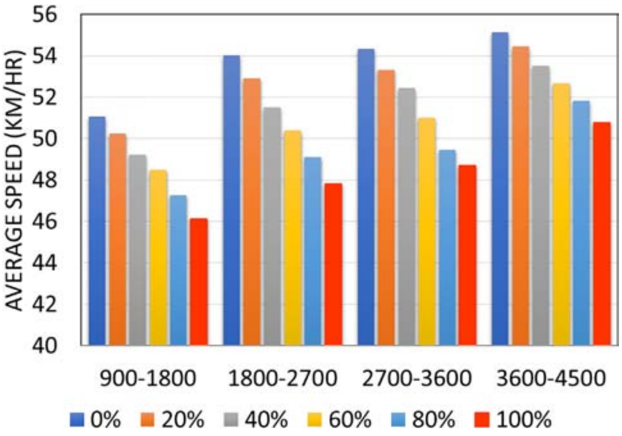


Figure 6.18. Average speed at the road network level during evening peak hour.

6.5 Conclusions

Providing eco-driving tips to drivers could reduce fuel consumption and emissions (of CO, VOC, NO_x) under low-traffic conditions (< 300 vehicles per 15 minutes) by 4–12%. However, the impact of eco-driving in high traffic volume and at signalised intersections on fuel consumption is questionable because of the increase in stop-and-go activities. Likewise, the average queue length was observed to decrease with an increased percentage of eco-driving HDVs under low-traffic conditions. However, under high-traffic conditions, the average queue length increased with increased penetration of eco-driving HDVs. At the overall road network level, the average speed tends to decrease by 4–6 km/h with an increased penetration of eco-driving HDVs. Therefore, to improve the mobility under high-traffic conditions, priority signals or lanes for HDVs at signalised intersections in the Dublin port area and barrier-free lanes at tolls could reduce overall emissions and delays at these locations, and could improve the fuel economy of HDVs. Indeed, the Sydney Coordinated Adaptive Traffic System (SCATS), which is already present in the Dublin network, can respond to transponders fitted to HDVs and help to prioritise these vehicles.

7 Conclusions and Recommendation

The transport sector in Ireland relies heavily on fossil fuel, and the sector accounted for 40% of total CO_2 emissions in 2018. HDVs account for 14% of transport emissions. With the improvement in economic activities, the movement of HDVs in Ireland is expected to increase, which could increase emissions from the transport sector unless efforts to decarbonise transport are implemented. However, owing to the COVID-19 pandemic, the expected improvement in the economy and resultant freight activities might not materialise and might even be reversed.

Eco-driving is one soft measure that could be implemented in the freight sector to mitigate pollution in the medium term. This report evaluated the effectiveness of eco-driving as a potential emissions mitigation measure, particularly for HDVs. The opinions of hauliers and stakeholders were collected to understand the current and expected challenges, their state of awareness, and the acceptability of and barriers to adopting eco-driving programmes in the Irish logistics industry (Chapter 3). Furthermore, driver behaviour factors contributing to fuel economy were identified, based on real-world telematics data from an individual haulier as an example (Chapter 4). The study was based on a limited number of responses, and care should be taken when generalising the outputs. A simulation tool was developed to compare the eco-driving performances of individual drivers and to evaluate the effectiveness of eco-driving penetration in a transport network (Chapters 5 and 6).

The key findings and policy implications from this project are as follows.

1. There are numerous private EDT programmes in Ireland. Two major freight organisations, the IRHA and FTA Ireland, conduct their own EDT programmes. The Driver CPC training by the RSA has a module on eco-driving techniques, which is a part of mandatory training. Furthermore, stakeholders and company owners agree that driver training programmes could be an effective solution in encouraging eco-driving measures in HDVs (sections 3.3 and 3.4). Therefore, as a policy, the RSA or DTTAS needs to introduce a mandatory driver training programme or provide guidelines or certification, which need to be acquired by these private programmes to standardise the EDT programmes in the Irish context. Furthermore, a systematic way to collect, store and analyse driver performance data from these private programmes would help to generalise the effect of EDT in the Irish context.
2. EDT should include driver behaviour, attitudes and knowledge of the strategic, tactical and operational aspects of eco-driving.
3. The impact of eco-driving in high traffic volume and at signalised intersections on fuel consumption is questionable as a result of the increase in stop-and-go conditions (section 6.4). Therefore, HDV priority signals and/or lanes at intersections and barrier-free lanes at tolls would complement the EDT programme to reduce emissions within the Dublin port area.
4. Stakeholders and company owners think that CNG trucks, electric trucks and driver training programmes are the three policies that should be incentivised by the Irish government (section 3.4). Furthermore, the Irish government is also making efforts to encourage these technologies by implementing necessary infrastructure through the Green Connect Project and the Causeway Project. It also plans to provide grants of up to 30% of the cost differential between a traditional fossil-fuelled HDV and an equivalent alternatively fuelled vehicle (section 3.7). The Causeway Project plans to develop a total of 14 high-capacity, fast-fill CNG stations along the TEN-T, in tandem with the establishment of a biogas injection point. At present, a total of five CNG stations are operational in Ireland, of which two are public, and the other three are privately operated and located in Dublin, Cork and Shannon. Likewise, the Green Connect Project is the continued CNG infrastructure development project along the core road network in Ireland. In this project, there are 21 CNG stations, four CNG trailers and four renewable gas injection facilities; 400 CNG vehicles will be delivered through a vehicle grant scheme.

References

af Wåhlberg, A.E., 2007. Long-term effects of training in economical driving: fuel consumption, accidents, driver acceleration behavior and technical feedback. *International Journal of Industrial Ergonomics* 37(4): 333–343.

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

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

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

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

Ang-Olson, J. and Schroeer, W., 2002. Energy efficiency strategies for freight trucking: potential impact on fuel use and greenhouse gas emissions. *Transportation Research Record* 1815: 11–18.

Association for Promotion of Eco-drive, 2012. Available online: http://www.ecodrive.jp/eco_10.html (accessed 11 September 2019).

Ayyildiz, K., Cavallaro, F., Nocera, S. and Willenbrock, R., 2017. Reducing fuel consumption and carbon emissions through eco-drive training. *Transportation Research Part F: Traffic Psychology and Behaviour* 46: 96–110.

Backhaus, W., 2014. Eco-driving for clean vehicles: optimise energy use for trams and e-buses. *Proceedings of the Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to Deployment.* 14–17 April, Paris. European Commission Conference of European Directors of Roads (CEDR), European Road Transport Research Advisory Council (ERTRAC), WATERBORNE TP, European Rail Research Advisory Council (ERRAC), Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR), Ministère de l'Écologie, du Développement Durable et de l'Énergie.

Bains, M.S., Arkatkar, S.S., Anbumani, K.S. and Subramaniam, S., 2017. Optimizing and modeling tollway operations using microsimulation: case study Sanand Toll Plaza, Ahmedabad, Gujarat, India. *Transportation Research Record* 2615: 43–54.

Ballinger, G.A., 2004. Using generalized estimating equations for longitudinal data analysis. *Organizational Research Methods* 7(2): 127–150.

Bandeira, J.M., Fontes, T., Pereira, S.R., Fernandes, P., Khattak, A. and Coelho, M.C., 2014. Assessing the importance of vehicle type for the implementation of eco-routing systems. *Transportation Research Procedia* 3: 800–809.

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

Barla, P., Gilbert-Gonthier, M., Castro, M.A.L. and Miranda-Moreno, L., 2017. Eco-driving training and fuel consumption: impact, heterogeneity and sustainability. *Energy Economics* 62: 187–194.

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

Beusen, B., Broekx, S., Denys, T., Beckx, C., Degraeuwe, B., Gijsbers, M., Kristof, S., Govaerts, L., Torfs, R. and Panis, L.I., 2009. Using on-board logging devices to study the longer-term impact of an eco-driving course. *Transportation Research Part D: Transport and Environment* 14(7): 514–520.

Boriboonsomsin, K., Vu, A. and Barth, M., 2010. Eco-driving: pilot evaluation of driving behavior changes among U.S. drivers. University of California Transportation Center. Available online: https://escholarship.org/uc/item/9z18z7xq (accessed 19 May 2021).

Boriboonsomsin, K., Barth, M.J., Zhu, W. and Vu, A., 2012. Eco-routing navigation system based on multisource historical and real-time traffic information. *IEEE Transactions on Intelligent Transportation Systems* 13(4): 1694–1704.

Boriboonsomsin, K., Vu, A. and Barth, M., 2016. *Environmentally Friendly Driving Feedback Systems Research and Development for Heavy Duty Trucks. A Research Report from the National Center for Sustainable Transportation.* National Center for Sustainable Transportation, University of California, Oakland, CA.

Canadian Eco-driving Program, no date. Eco driving. Available online: https://www.caa.ca/sustainability/eco-driving/ (accessed September 2019).

Caulfield, B., Brazil, W., Fitzgerald, K.N. and Morton, C., 2014. Measuring the success of reducing emissions using an on-board eco-driving feedback tool. *Transportation Research Part D: Transport and Environment* 32: 253–262.

CIECA (International Commission for Driver Testing, 2007. CIECA Internal Project on 'Eco-Driving' in Category B Driver Training and the Driving Test. CIECA. Available online: https://trimis.ec.europa.eu/sites/default/files/project/documents/20091210_155535_71033_ECODRIVEN%20Final%20Report.pdf (accessed 16 July 2021).

CSO (Central Statistics Office), 2018. Road transport survey. Quarter 4 and year 2018. Available online: https://www.cso.ie/en/releasesandpublications/er/rfts/roadfreighttransportsurveyquarter4andyear2018/ (accessed 19 May 2021).

Daun, T.J., Braun, D.G., Frank, C., Haug, S. and Lienkamp, M., 2013. Evaluation of driving behaviour and the efficacy of a predictive eco-driving assistance system for heavy commercial vehicles in a driving simulator experiment. In *16th International IEEE Conference on Intelligent Transportation Systems* (ITSC 2013), pp. 2379–2386.

DCCAE (Department of Communications, Climate Action and Environment), 2017. *National Mitigation Plan. July 2017*. DCCAE, Dublin. Available online: https://static.rasset.ie/documents/news/national-mitigation-plan2017.pdf (accessed 19 May 2021).

DECC (Department of the Environment, Climate and Communications), 2020. National Energy Efficiency Action Plan. DECC, Dublin. Available online: https://www.gov.ie/en/publication/93ee2-national-energy-efficiency-action-plan-neeap/ (accessed 16 July 2021).

Demir, E., Bektaş, T. and Laporte, G., 2014. A review of recent research on green road freight transportation. *European Journal of Operational Research* 237(3): 775–793.

DfT (Department for Transport), 2009a. *SAFED for HGVs: A Guide to Safe and Fuel-efficient Driving for HGVs. Freight Best Practice: Guide*. The Stationery Office, London.

DfT (Department for Transport), 2009b. *The Fuel-efficient Truck Drivers' Handbook*. Freight Best Practice Programme, London.

DfT (Department for Transport), 2010. *Engine Idling – Costs Money and Gets You Nowhere*. Freight Best Practice Programme, London.

Díaz-Ramirez, J., Giraldo-Peralta, N., Flórez-Ceron, D., Rangel, V., Mejía-Argueta, C., Huertas, J.I. and Bernal, M., 2017. Eco-driving key factors that influence fuel consumption in heavy-truck fleets: a Colombian case. *Transportation Research Part D: Transport and Environment* 56: 258–270.

DTTAS (Department of Transport, Tourism and Sport), 2019a. *Transport Trends 2019. An Overview of Ireland's Transport Sector*. DTTAS, Dublin. Available online: https://www.gov.ie/en/publication/8cd518-transport-trends-2019/ (accessed 16 July 2021).

DTTAS (Department of Transport, Tourism and Sport), 2019b. *National Policy Framework on Alternative Fuels Infrastructure for Transport in Ireland, 2017 to 2030*. DTTAS, Dublin. Available online: https://assets.gov.ie/27463/6ce8a48a99c44e1dbf40a59a073cb06d.pdf (accessed 24 May 2021).

EC (European Commission), 2014. Communication from the Commission to the Council and the European Parliament "Strategy for reducing Heavy-Duty Vehicles' fuel consumption and CO2 emissions". COM(2014) 285 final, 21.5.2014, Brussels. Available online: https://ec.europa.eu/transparency/regdoc/rep/1/2014/EN/1-2014-285-EN-F1-1.Pdf (accessed 19 May 2021).

EC (European Commission), 2016a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions "A European strategy for low-emission mobility". COM(2016) 501, 20.7.2016, Brussels.

EC (European Commission), 2016b. A European Strategy for low-emission mobility. MEMO/16/2497. Available online: https://ec.europa.eu/commission/presscorner/detail/en/MEMO_16_2497 (accessed 19 May 2021).

ECODRIVE. https://ec.europa.eu/energy/intelligent/projects/en/projects/ecodriven and ecodrive.org

EcoEffect. https://ec.europa.eu/energy/intelligent/projects/en/projects/ecoeffect

ECOWILL. https://ec.europa.eu/energy/intelligent/projects/en/projects/ecowill

EEA (European Environment Agency), 2018. Progress of EU transport sector towards its environment and climate objectives. Available online: https://www.eea.europa.eu/themes/transport/term/term-briefing-2018 (accessed 19 May 2021).

EEA (European Environment Agency), 2020. Do lower speed limits on motorways reduce fuel consumption and pollutant emissions? Available online: https://www.eea.europa.eu/themes/transport/speed-limits-fuel-consumption-and/speed-limits (accessed 19 May 2020).

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

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

EU (European Union), 2016. Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC. OJ L 344, 17.12.2016, p. 1–31.

EU (European Union), 2018. Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency. OJ L 328, 21.12.2018, pp. 210–230.

Ferreira, J.C., de Almeida, J. and da Silva, A.R., 2015. The impact of driving styles on fuel consumption: a data-warehouse-and-data-mining-based discovery process. *IEEE Transactions on Intelligent Transportation Systems* 16(5): 2653–2662.

FLEAT, undated. Available online: https://europamediatrainings.com/eu-projects/27/fleat (accessed 19 July 2021).

Garcia-Castro, A., Monzon, A., Valdes, C. and Romana, M., 2017. Modeling different penetration rates of eco-driving in urban areas: impacts on traffic flow and emissions. *International Journal of Sustainable Transportation* 11(4): 282–294.

Gonder, J., Earleywine, M., Sparks, W. and Fauria, K., 2010. *Interim Report on the Fuel Saving Effectiveness of Various Driver Feedback Approaches*. Technical Report Deliverable to the U.S. Department of Energy Vehicle Technologies Program.

Government of Ireland, 2019. *Climate Action Plan 2019. Ireland's Plan To Tackle Climate Breakdown*. Dublin. Available online: https://www.gov.ie/en/publication/ccb2e0-the-climate-action-plan-2019/ (accessed 16 July 2021).

Greene, D.L., Liu, J., Khattak, A.J., Wali, B., Hopson, J.L. and Goeltz, R., 2017. How does on-road fuel economy vary with vehicle cumulative mileage and daily use? *Transportation Research Part D: Transport and Environment* 55: 142–161.

Gujarati, D.N. and Porter, D.C., 2012. Basic Econometrics. Fifth edition. McGraw-Hill/Irwin, New York, NY.

Harmsen, R., van den Hoed, R. and Harmelink, M., 2007. Improving the energy efficiency of road transport: the case of eco-driving in the Netherlands. In *Proceedings of the European Council for an Energy Efficient Economy Conference*, La Colle-sur-Loup, France.

Heyes, D., Daun, T.J., Zimmermann, A. and Lienkamp, M., 2015. The Virtual Driving Coach – design and preliminary testing of a predictive eco-driving assistance system for heavy-duty vehicles. *European Transport Research Review* 7(3): 25.

Hiraoka, T., Terakado, Y., Matsumoto, S. and Yamabe, S., 2009. Quantitative evaluation of eco-driving on fuel consumption based on driving simulator experiments. In *Proceedings of the 16th World Congress on Intelligent Transport Systems*, pp. 21–25.

Huang, Y., Ng, E.C., Zhou, J.L., Surawski, N.C., Chan, E.F. and Hong, G., 2018. Eco-driving technology for sustainable road transport: a review. *Renewable and Sustainable Energy Reviews* 93: 596–609.

IEA (International Energy Agency), 2017. National promotion of eco-driving in Japan. Available online: https://www.iea.org/policies/1539-national-promotion-of-eco-driving (accessed 19 May 2021).

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

Jonkers, E., Nellthorp, J., Wilmink, I. and Olstam, J., 2018. Evaluation of eco-driving systems: a European analysis with scenarios and microsimulation. *Case Studies on Transport Policy* 6(4): 629–637.

Kobayashi, I., Tsubota, Y. and Kawashima, H., 2007. Eco-driving simulation: evaluation of eco-driving within a network using traffic simulation. *WIT Transactions on the Built Environment* 96: 741–750.

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

Liimatainen, H., Stenholm, P., Tapio, P. and McKinnon, A., 2012. Energy efficiency practices among road freight hauliers. *Energy Policy* 50: 833–842.

Lois, D., Wang, Y., Boggio-Marzet, A. and Monzon, A., 2019. Multivariate analysis of fuel consumption related to eco-driving: interaction of driving patterns and external factors. *Transportation Research Part D: Transport and Environment* 72: 232–242.

Mane, A.S. and Pulugurtha, S.S., 2020. Influence of proximal land use and network characteristics on link travel time. *Journal of Urban Planning and Development* 146(3): 04020028.

Marcilio, G.P., de Assis Rangel, J.J., de Souza, C.L.M., Shimoda, E., da Silva, F.F. and Peixoto, T.A., 2018. Analysis of greenhouse gas emissions in the road freight transportation using simulation. *Journal of Cleaner Production* 170: 298–309.

Martin, E., Boriboonsomsin, K., Chan, N., Williams, N., Shaheen, S. and Barth, M., 2013. Dynamic eco-driving in Northern California: a study of survey and vehicle operations data from an eco-driving feedback device. In *92nd Annual Meeting of the Transportation Research Board*, Washington, DC.

Masikos, M., Demestichas, K., Adamopoulou, E. and Theologou, M., 2015. Energy-efficient routing based on vehicular consumption predictions of a mesoscopic learning model. *Applied Soft Computing* 28: 114–124.

McIlroy, R.C. and Stanton, N.A., 2015. A decision ladder analysis of eco-driving: the first step towards fuel-efficient driving behaviour. *Ergonomics* 58(6): 866–882.

McIlroy, R.C. and Stanton, N.A., 2017. *Eco-Driving: From Strategies to Interfaces*. CRC Press, Boca Raton, FL.

McKinnon, A., 2015. Increasing fuel efficiency in the road freight section. In McKinnon, A., Browne, M. and Whiteing, A. (eds), *Green Logistics: Improving the Environmental Sustainability of Logistics.* Kogan Page Publishers, London, pp. 237–249.

McKinnon, A.C., Stirling, I. and Kirkhope, J., 1993. Improving the fuel efficiency of road freight operations. *International Journal of Physical Distribution & Logistics Management* 23(9): 3–11.

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

Olstam, J., Bernhardsson, V., van Noort, M., Wilmink, I., Klunder, G., Choudhury, C., Tate, J., Carsten, O. and Tapani, A., 2016. Traffic system impacts of green driving support systems. Available online: https://www.transportportal.se/energieffektivitet/etapp2/D531-Traffic-system-impacts-of-green-driving-support-systemsresubmitted-May-2016.pdf (accessed 20 September 2021).

Orfila, O., 2011. Impact of the penetration rate of eco-driving on fuel consumption and traffic congestion. Available online: https://pdfs.semanticscholar.org/15b3/ee454d56f47034ac35fb7bc6f9f749799b5f.pdf (accessed 20 September 2021).

Pan, W., 2001. Akaike's information criterion in generalized estimating equations. *Biometrics* 57: 120–125.

PTV VISSIM, 2016. *Version 11. User Manual*. Planning Transport Verkehr AG, Karlsruhe, Germany.

Qian, G. and Chung, E., 2011. Evaluating effects of eco-driving at traffic intersections based on traffic micro-simulation. In Tisato, P., Oxlad, L. and Taylor, M. (eds), *Evaluating Effects of Eco-driving at Traffic Intersections Based on Traffic Micro-simulation*, PATREC, Adelaide Hilton Hotel, Adelaide, Australia, pp. 1–11.

Qian, G. and Chung E., 2013. Microscopic simulation study of eco-driving performance at urban intersections. *13th World Conference of Transportation Research*, 15–18 July, Rio de Janeiro, Brazil.

Quille, J., Sabina, B. and Superstine, S., 2012. Eco-Drive Chicago: saving millions, reducing emissions. Penn Public Policy Challenge. National Invitational Competition, Harris School of Public Policy, Chicago, IL.

RECODRIVE, undated. *Publishable Result-oriented Report Containing Lessons Learned and Recommendations*. Available online: https://trimis.ec.europa.eu/sites/default/files/project/documents/20140307_130303_86735_FR_RECODRIVE_publishable_report.pdf (accessed 19 July 2021).

Ribeiro, M.J.M., Rosa, M.H.F., Bruhn, F.R.P., Garcia, A.D.M., Rocha, C.M.B.M.D. and Guimarães, A.M., 2016. Seroepidemiology of *Sarcocystis neurona*, *Toxoplasma gondii* and *Neospora* spp. among horses in the south of the state of Minas Gerais, Brazil. *Revista Brasileira de Parasitologia Veterinária* 25(2): 142–150.

Rolim, C., Baptista, P., Duarte, G., Farias, T. and Shiftan, Y., 2014. Quantification of the impacts of eco-driving training and real-time feedback on urban buses driver's behaviour. *Transportation Research Procedia* 3: 70–79.

Rothengatter, W. and Doll, C., 2002. Design of a user charge for heavy-duty vehicles on German motorways considering the objectives of efficiency, fairness and environmental protection. *IATSS Research*, 26.

Rutty, M., Matthews, L., Andrey, J. and Del Matto, T., 2013. Eco-driver training within the City of Calgary's municipal fleet: monitoring the impact. *Transportation Research Part D: Transport and Environment* 24: 44–51.

Sanguinetti, A., Kurani, K. and Davies, J., 2017. The many reasons your mileage may vary: toward a unifying typology of eco-driving behaviors. *Transportation Research Part D: Transport and Environment 52*: 73–84.

Schall, D.L., Wolf, M. and Mohnen, A., 2016. Do effects of theoretical training and rewards for energy-efficient behavior persist over time and interact? A natural field experiment on eco-driving in a company fleet. *Energy Policy* 97: 291–300.

Scora, G., Boriboonsomsin, K. and Barth, M., 2015. Value of eco-friendly route choice for heavy-duty trucks. *Research in Transportation Economics* 52: 3–14.

SEAI (Sustainable Energy Authority Ireland), 2020. *Energy-related CO_2 Emissions in Ireland 2005–2018. CO_2 Emissions from Fossil Fuel Combustion*. SEAI, Dublin.

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

Stillwater, T. and Kurani, K., 2012. In-vehicle eco-driving interface: theory, design and driver responses. In*: 91st Annual Meeting of the Transportation Research Board*, January, Washington, DC.

Strömberg, H.K. and Karlsson, I.M., 2013. Comparative effects of eco-driving initiatives aimed at urban bus drivers – results from a field trial. *Transportation Research Part D: Transport and Environment* 22: 28–33.

Sullman, M.J., Dorn, L. and Niemi, P., 2015. Eco-driving training of professional bus drivers – does it work? *Transportation Research Part C: Emerging Technologies* 58: 749–759.

Sun, J. and Liu, H.X., 2015. Stochastic eco-routing in a signalised traffic network. *Transportation Research Part C: Emerging Technologies* 59: 32–47.

Tang, P., Azimi, M., Qiao, F. and Yu, L., 2016. *Advancing eco-driving strategies for drivers and automated vehicles traveling within intersection vicinities (No. TranLIVE/TSU/16/02).* TranLIVE, University of Idaho, ID.

US EPA (United States Environmental Protection Agency). Cleaner Trucks Initiative. Available online: https://www.epa.gov/regulations-emissions-vehicles-and-engines/cleaner-trucks-initiative (accessed 19 July 2021).

Wallace, C., Courage, K., Reaves, D., Schoene, G. and Euler, G., 1984. TRANSYT-7F user's manual. US Department of Transportation, Washington, DC.

Walnum, H.J. and Simonsen, M., 2015. Does driving behavior matter? An analysis of fuel consumption data from heavy-duty trucks. *Transportation Research Part D: Transport and Environment* 36: 107–120.

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

Williams, N., Boriboonsomsin, K., Wu, G. and Barth, M., 2016. Environmental and mobility impacts of large-scale adoption of eco-driving: an urban arterial case. In 95th Transportation Research Board Annual Meeting Compendium of Papers, No. 16–6474.

Wu, G., Ye, F., Hao, P., Esaid, D., Boriboonsomsin, K. and Barth, M.J., 2019. *Deep Learning–based Eco-driving System for Battery Electric Vehicles*. National Center for Sustainable Transportation, University of California Davis, CA.

Wu, Y., Zhao, X., Rong, J. and Zhang, Y., 2017. How eco-driving training course influences driver behavior and comprehensibility: a driving simulator study. *Cognition, Technology & Work* 19(4): 731–742.

Xiao X, Zhang, Y. and Wang, B., 2018. *Eco-Driving Study on Trucks Along a Signalized Arterial with Significant Freight Traffic. Project Id: Y1r2–17*. Freight Mobility Research Institute, College of Engineering & Computer Science, Florida Atlantic University, FL.

Yang, G., Xu, H., Wang, Z. and Tian, Z., 2016. Truck acceleration behavior study and acceleration lane length recommendations for metered on-ramps. *International Journal of Transportation Science and Technology 5*(2): 93–102.

Yao, E. and Song, Y., 2013. Study on eco-route planning algorithm and environmental impact assessment. *Journal of Intelligent Transportation Systems* 17(1): 42–53.

Yao, Y., Zhao, X., Zhang, Y., Chen, C. and Rong, J., 2020. Modelling of individual vehicle safety and fuel consumption under comprehensive external conditions. *Transportation Research Part D: Transport and Environment* 79: 102224.

Zang, J., Song, G., Wu, Y. and Yu, L., 2019. Method for evaluating eco-driving behaviors based on vehicle specific power distributions. *Transportation Research Record: Journal of the Transportation Research Board* 2673(11): 409–419. Available online: https://doi.org/10.1177/0361198119853561

Zarkadoula, M., Zoidis, G. and Tritopoulou, E., 2007. Training urban bus drivers to promote smart driving: a note on a Greek eco-driving pilot program. *Transportation Research Part D: Transport and Environment* 12(6): 449–451.

Zavalko, A., 2018. Applying energy approach in the evaluation of eco-driving skill and eco-driving training of truck drivers. *Transportation Research Part D: Transport and Environment* 62: 672–684.

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

Zhang, S., Wu, Y., Zhao, B., Wu, X., Shu, J. and Hao, J., 2017. City-specific vehicle emission control strategies to achieve stringent emission reduction targets in China's Yangtze River Delta region. *Journal of Environmental Sciences* 57: 75–87.

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

Zhou, Y. and Yao, E., 2015. Effects evaluation of eco-driving behaviors on urban intersection based on microscopic simulation model. *Energy* 70(54.247): 23–24.

Zuraida, R. and Widjaja, D., 2017. Eco-driving behavior tendency among Indonesian people: a preliminary study. In *IOP Conference Series: Earth and Environmental Science,* Yogyakarta, Indonesia, 14–15 November, Vol. 109(1): 012022.

Abbreviations

CAN	Controller area network
CNG	Compressed natural gas
CO_2e	CO_2 equivalent
CPC	Certificate of Professional Competence
DCC	Dublin City Council
DLTPA	Deep learning-based trajectory-planning algorithm
DTTAS	Department of Transport, Tourism and Sport
EDAS	Eco-driving assistance system
EDT	Eco-driving training
EEA	European Environment Agency
EU	European Union
FTA	Freight Transport Association
GEE	Generalised estimation equation
GHG	Greenhouse gas
GLEC	Global Logistics Emissions Council
GNI	Gas Networks Ireland
GPS	Global positioning system
HDV	Heavy-duty vehicle
HGV	Heavy goods vehicle
IRHA	Irish Road Haulage Association
LDV	Light-duty vehicle
MAE	Mean absolute error
MAPE	Mean absolute percentage error
NB	Northbound
NMP	National Mitigation Plan
NOx	Nitrogen oxide
NPF	National Policy Framework
OBD	On-board diagnostic
PM	Particulate matter
QIC	Quasi-likelihood under independence model criterion
QICC	Corrected quasi-likelihood under independence model criterion
RMSE	Root mean square error
RPM	Revolutions per minute
RSA	Road Safety Authority
SAFED	Safe and Fuel Efficient Driving
SB	Southbound
TEN-T	Trans-European Transport Network
TTW	Tank-to-wheel
VOC	Volatile organic compound
VSP	Vehicle-specific power
WTT	Well to tank
WTW	Well to wheel

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 398

Eco-driving: Trends and Potential Impacts for Irish Heavy-duty Vehicles

Authors: Ajinkya S. Mane and Bidisha Ghosh

The “Eco-HDV” research project evaluated the impacts of adaptation of eco-driving programmes in the Irish heavy-duty vehicle fleet, focusing especially on the freight sector. Eco-driving and related practices have been shown to improve fuel efficiency and reduce vehicular emissions in heavy-duty vehicle fleets internationally. The research identified perceptions and awareness of eco-driving training in the freight sector, reviewed the best eco-driving practices that exist at present in Ireland, analysed the possibilities of adaptation of eco-driving programmes and developed simulation models to estimate future policy implications. The project generated guidelines for the implementation of eco-driving programmes and other measures to reduce vehicular emissions from the Irish heavy-duty vehicle fleet.

Identifying Pressures

In Ireland, in 2018, the transport sector accounted for the largest share (40%) of energy-related CO2 emissions, and heavy-duty vehicles were one of the top three contributors, accounting for 14% of total transport emissions. The transport sector is dependent on fossil fuels, and CO2 emissions from the transport sector are expected to increase in the absence of a fuel mix. It is expected that activities related to land freight will increase as the economy improves. Furthermore, a new European Union (EU) regulation (2019/1242) has set new standards for CO2 emissions for new heavy-duty vehicles, providing incentives to encourage zero- and low-emission vehicles.

Informing Policy

In the light of new EU policies and legislation related to heavy-duty vehicles and the freight sector, it is necessary to develop national policies in Ireland. These policies should introduce a mandatory driver training programme, guidelines and certification for the continuing professional development of heavy-duty vehicle drivers. Eco-driving training should include driver behaviour, attitudes and knowledge of the strategic, tactical and operational aspects of eco-driving. There are multiple private eco-driving training programmes in Ireland and a module on eco-driving techniques is included in the Driver Certificate of Professional Competence training by the Road Safety Authority. The programmes should be standardised for quantifiable benefits. Furthermore, a systematic way to collect, archive and analyse driver performance data from all eco-driving training programmes is essential. The top three government policies expected are incentives for gas-fuelled trucks, electric trucks and driver training programmes.

Developing Solutions

In addition to the implementation of, and policies related to, eco-driving training, a set of solutions related to reductions in vehicular emissions from the Irish heavy-duty vehicle fleet were developed. The research identified that many Irish haulage companies are eager to introduce eco-driving training programmes into their organisations. Based on the collection and analysis of real-world driver behaviour data, professional drivers should be trained or periodically instructed to reduce the number of harsh and general brakes, reduce the amount of vehicle idling during their journeys and improve their skills to drive with smooth acceleration and deceleration. Eco-driving tips given to drivers may help in reducing overall fuel consumption and emissions (carbon monoxide, volatile organic compounds and oxides of nitrogen) in low traffic conditions. The impact that eco-driving has on fuel consumption is uncertain in congested traffic conditions and at signalised intersections. Heavy-duty vehicle priority signals or exclusive lanes at intersections and barrier-free tolls should complement the eco-driving training programme to reduce emissions. In addition, the Irish government is encouraging the use of gas/liquid natural gas technologies by implementing the necessary infrastructure through the Green Connect Project and the Causeway Project. The new heavy-duty vehicle purchase grant scheme will provide grants for up to 30% of the cost differential between a traditional fossil-fuelled heavy-duty vehicle and an equivalent alternatively fuelled vehicle.

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