

Eco-driving technology for sustainable road transport: A review

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ABSTRACT

Road transport consumes significant quantities of fossil fuel and accounts for a significant proportion of CO₂ and pollutant emissions worldwide. The driver is a major and often overlooked factor that determines vehicle performance. Eco-driving is a relatively low-cost and immediate measure to reduce fuel consumption and emissions significantly. This paper reviews the major factors, research methods and implementation of eco-driving technology. The major factors of eco-driving are acceleration/deceleration, driving speed, route choice and idling. Eco-driving training programs and in-vehicle feedback devices are commonly used to implement eco-driving skills. After training or using in-vehicle devices, immediate and significant reductions in fuel consumption and CO₂ emissions have been observed with slightly increased travel time. However, the impacts of both methods attenuate over time due to the ingrained driving habits developed over the years. These findings imply the necessity of developing quantitative eco-driving patterns that could be integrated into vehicle hardware so as to generate more constant and uniform improvements, as well as developing more effective and lasting training programs and in-vehicle devices. Current eco-driving studies mainly focus on the fuel savings and CO₂ reduction of individual vehicles, but ignore the pollutant emissions and the impacts at network levels. Finally, the challenges and future research directions of eco-driving technology are elaborated.

1. Introduction

Worldwide concerns regarding global warming and fossil fuel depletion have driven many countries to take more serious actions in energy saving and CO₂ emissions reduction initiatives. On 12 December 2015, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) reached a landmark agreement – the Paris Agreement – to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future. The central aim of the Paris Agreement is to keep global temperature rises well below 2 °C relative to pre-industrial levels and to pursue further efforts to limit the temperature increase to 1.5 °C [1–3]. The Paris Agreement entered into force on 4 November 2016 and 175 Parties had ratified it as of April 2018 [4]. To meet the targets of the Paris Agreement, greenhouse gas emissions have to be reduced significantly. Fig. 1 shows the Intended Nationally Determined Contributions (INDCs) as percentages in CO₂ reduction by 2030 below 2005 levels for the major CO₂ emitting countries [5], together with their shares of global CO₂ emissions in 2015 [6]. These major countries accounted for 80% of global CO₂ emissions in 2015. As shown in Fig. 1, on

average, most countries are planning to reduce their CO₂ emissions by 33% in 2030 compared to 2005 levels. The transport sector consumes about 20% of global energy and is responsible for nearly 25% of global energy related CO₂ emissions, 75% of which are emitted by road transport [7]. Moreover, it is estimated that the energy consumption and CO₂ emissions of world transport in 2030 will increase by more than 50% due to population and economic growth [7,8]. To achieve this abatement target, the road transport sector must make a significant contribution.

A variety of efforts have been undertaken to improve fuel economy and reduce emissions of on-road vehicles, including more stringent automotive emission standards (e.g. Euro 6/VI standards [9]), new engine and vehicle technologies (e.g. engine downsizing and hybrid/electric vehicles [10,11]), better fuel quality and renewable fuels (e.g. higher octane rating petrol and bio-fuels [12]). However, an important factor which is often overlooked and may improve vehicle fuel economy significantly is eco-driving technology. The investment for new vehicle technologies and fuels is usually significant and long-term, and an improvement of a few percentages may be considered significant. It was estimated that the potential efficiency improvements of

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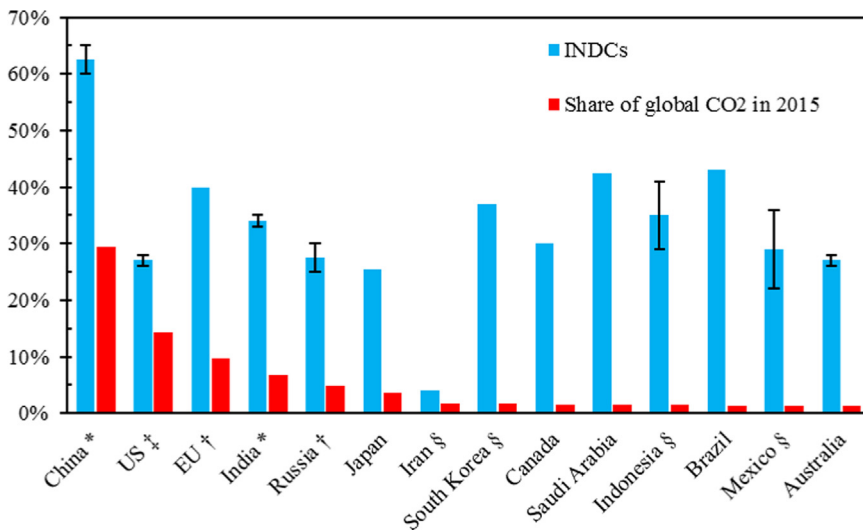


Fig. 1. INDCs as percentages in CO₂ reduction by 2030 below 2005 levels for the major CO₂ emitting countries, as well as their shares of global CO₂ emissions in 2015. Data sources are [5] for INDCs and [6] for shares of CO₂. Error bars indicate the ranges of INDCs. Symbols for INDCs: * per unit of GDP, ‡ target for 2025, † base level in 1990, § base level if business as usual.

advanced engine and vehicle technologies were only about 4–10% and 2–8% respectively [13]. However, the implementation of eco-driving is relatively low-cost and immediate, and the improvement in fuel efficiency can be up to 45% [14]. Eco-driving is also more cost-effective than fleet retrofit programs (e.g. replacing existing diesel buses with new compressed natural gas ones) [15]. Eco-driving is an initiative which has seen worldwide adoption and investigation in the past decade [16] although great efforts are needed to convert the claimed benefits of eco-driving into real-driving practice with lasting and uniform effects.

The aim of this study is to review and analyse the published studies on eco-driving technology. Specifically this review will cover the major influencing factors, research methods, implementation, and challenges and future research directions of eco-driving.

2. Major factors of eco-driving

Eco-driving involves a number of factors and has different definitions or scope in the literature. Sivak and Schoettle [14] defined eco-driving as decisions that a driver could make to influence the fuel economy of light-duty vehicles, ranging from vehicle purchase to post-purchase decisions. These decisions could be categorised into three groups, namely strategic decisions (vehicle selection and maintenance), tactical decisions (route planning and weight) and operational decisions (driving style). Among these decisions, vehicle selection was the single most important factor and post-purchase decisions could not fully compensate for buying a low-efficiency vehicle. Therefore it was suggested that the focus of policy should emphasize vehicle selection [14]. However, fuel economy was not the only factor that determined people's vehicle selection and the post-purchase factors could still contribute a lot, in total up to 45% reduction of fuel consumption per driver. Based on the concept of behavioural functions, Sanguinetti et al. [17] identified six classes of eco-driving behaviour including driving, cabin comfort, trip planning, load management, fuelling and maintenance. The driving behaviour was further divided into accelerating, cruising, decelerating, waiting, driving mode selection and parking. Zhou et al. [13] identified six groups of factors affecting fuel consumption, namely travel-, weather-, vehicle-, roadway-, traffic- and driver-related factors. A broader scope of eco-driving also involved public education, driving feedback devices, regulation, fiscal incentives and social norm reinforcement [18].

In this study, eco-driving is narrowed to the driving behaviours or the control a driver has over the vehicle during a journey that can influence fuel consumption and emissions. These factors include driving speed, acceleration, deceleration, route choice, idling and vehicle

accessories (other factors). This is because these factors are the most common and useful eco-driving skills that every driver can implement in practice every day, rather than purchasing a new fuel-efficient car. In addition, changes in these driving behaviours could lead to significantly higher reductions in fuel consumption and emissions than other behaviours such as better maintenance practices [16].

2.1. Driving speed

Constant speed is the optimal speed profile for fuel consumption under various road conditions [19,20]. Therefore using cruise control when possible is commonly recommended for eco-driving [14,21,22]. Fuel economy also varies with the cruising speed. This is because each internal combustion engine (ICE) has a speed for optimal fuel economy. Fuel consumption rate firstly decreases with the increase of engine speed due to reduced heat losses, reaches the optimal point and then increases at high speed due to increased friction losses [23]. As a result, the fuel consumption-driving speed curve shows a U-shape. This curve also applies for hybrid and electric vehicles. The optimal speeds for hybrid vehicles are in similar ranges as ICE vehicles, but much lower for electric vehicles [17]. El-Shawarby et al. [24] investigated the effect of constant cruise speed on fuel consumption and emissions based on a sequence of 10 1-km trips. The results showed that the optimal fuel consumption and emission rates per unit distance were in the range of 60–90 km/h, with considerable increases outside this range. Wang et al. [25] reported that fuel consumption per unit time was positively correlated with cruise speed and fuel consumption per unit distance was optimal between 50 and 70 km/h. Wang and Rakha [26] found that the optimal cruising speed of diesel buses (40–50 km/h) was lower than that of light-duty gasoline vehicles (60–80 km/h). The optimal speed for motor efficiency of electric vehicles was in the range of 50–60 km/h [27]. The Australian Department of Environment suggested that fuel consumption increased significantly over 90 km/h, so that a car would use up to 25% more fuel at 110 km/h than cruising at 90 km/h [21]. The US Department of Energy suggested that fuel economy usually decreased rapidly at speed above 80 km/h although each vehicle reached its optimal fuel economy at a different speed (or range of speed) [22]. It can be seen that the above suggested optimal cruising speeds are usually below the speed limits on motorways (e.g. 110 km/h in NSW Australia). Therefore, reducing motorway speed limits may help reduce fuel consumption and emissions. The European Environment Agency estimated that reducing motorway speed limit from 120 to 110 km/h could reduce fuel consumption significantly by 12% for diesel cars and 18% for gasoline cars, assuming smooth driving and 100% compliance with speed limit [28]. In addition, reducing speed

limit would also achieve reductions of other pollutants, in particular NO_x and PM emissions for diesel cars, and safety gains as well. However, fuel savings would be only 2–3% when relaxing the ideal assumptions to a more realistic situation (speed limit of 110 km/h was not fully respected and some speeding occurred). Therefore, to achieve the claimed benefits, it is essential to have tighter enforcement and improve people's understanding on the benefits (fuel savings, emissions reduction and safety gains) and costs (slightly longer travel time) of lower speed limits. In some cases, time saving would have higher priority than reducing fuel consumption and emissions, such as emergency service operations (e.g. ambulances, police cars and fire trucks) and travellers with a tight time schedule. However, in most daily driving tasks, the benefits of eco-driving should outweigh its costs. There is no uniform optimisation strategy for all drivers and the drivers should have the right to choose the driving strategy according to their needs.

When it comes to real-world conditions, driving speed cannot be maintained ideally constant and must consider the speed limit, travel time, road grade, traffic signals and traffic flow [29]. Therefore, eco-driving speed is usually recommended at or safely below the speed limit [17,18,30]. Many studies have been carried out to estimate the optimal driving speed profile under various real-world conditions, such as congestion levels [31], road grades [32,33], car-following scenarios [34], signalized roads [35–38], and hybrid electric vehicles [39].

2.2. Acceleration and deceleration

A general rule of eco-driving is to change the aggressive driving style, which mainly refers to hard acceleration and deceleration, to a smoother one. The function of acceleration/deceleration is to increase/reduce the driving speed or to start/stop the vehicle. However, there are always more or less efficient ways to do that, and the strategies vary and have no consensus [17,40]. Most eco-driving programs recommend smooth driving and minimising acceleration and braking [21,22]. The US Department of Energy [22] suggested that aggressive driving could lower fuel economy by 15–30% at highway speed and 10–40% in stop-and-go traffic. Drivers could avoid unnecessary acceleration/deceleration by keeping a good distance to the car in front so that drivers can anticipate the road and traffic flow as far ahead as possible [41]. However, a few studies [42,43] reported that more aggressive acceleration/deceleration to the target speed would save fuel in certain situations. A Swedish eco-driving training program suggested bus drivers accelerate more strongly and start acceleration earlier, which worsened the passengers' comfort [44].

Generally, a smooth driving style saves fuel and increases safety compared to aggressive driving. Eco-driving usually encourages drivers to minimise the use of accelerator and brake pedals by looking ahead at the traffic flow, signals and road grade. This kind of anticipation can help shift the gear more efficiently and avoid unnecessary accelerating, braking, excessive speed and idling. A number of studies have been carried out to investigate the effect of acceleration/deceleration on fuel consumption and emissions. Ericsson [45] analysed the effect of 16 independent driving pattern factors on fuel consumption and emissions. It was found that nine factors played an important role, four of which were associated with acceleration and power demand, three were related to gear changing and two were related to driving speed. Pelkmans et al. [46] reported that acceleration was the dominant factor for a bus in real-city traffic, which shared 35% of the driving time but was responsible for 70% of fuel consumption and 60–80% of CO, HC and NO_x emissions of the entire cycle. El-Shawarby et al. [24] found that aggressive driving at the maximum acceleration capacity had 50% more fuel consumption, 3% more CO_2 , 20 times more CO, six times more HC, but 65% less NO_x emissions compared with mild driving (40% of the maximum acceleration capacity). Chen et al. [47] reported that low-speed conditions with frequent acceleration and deceleration, particularly in congested conditions, were the main factors resulting in high CO and HC emissions. Gallus et al. [48] used several acceleration based

parameters to characterise the aggressiveness of driving style, including mean positive acceleration (MPA), relative positive acceleration (RPA) and 95th percentile of velocity multiplied by positive acceleration ($v \times a_{\text{pos}95\%}$). The results showed that CO_2 and NO_x emissions of aggressive driving (larger MPA, RPA and $v \times a_{\text{pos}95\%}$ values) were 20–40% and 50–255% higher than those of normal driving, respectively. However, CO and HC emissions did not show distinct difference between driving styles. Wang et al. [49] reported that frequent acceleration, especially sharp acceleration, would increase emissions and fuel consumption for buses. Berry [50] found that reducing speed on highways would save roughly the same amount of fuel as reducing acceleration during all driving. However, when it came to individuals, it was suggested that aggressive drivers should focus on reducing acceleration, while less aggressive drivers should focus on reducing speed on highways. The greatest fuel saving could be attained if the most aggressive drivers drove with lower acceleration.

As reviewed above, acceleration and deceleration are the key factors that influence fuel economy and emissions. Therefore, efforts have been devoted to find the optimum acceleration/deceleration values or strategies. Choi and Kim [51] investigated the critical aggressive acceleration values that caused an abrupt increase in fuel consumption for a LPG passenger car. The results showed that the critical values were 2.598 m/s^2 for vehicle starting and 1.4705 m/s^2 during driving. The most efficient use of gears and acceleration strategy was low engine speed and moderate throttle position (50%) for both petrol and diesel cars [41]. Birrell et al. [30] recommended using smooth and positive acceleration to reach high gears and the desired cruising speed sooner, and using a uniform throttle set at no more than 50%. Regarding deceleration, they recommended applying engine brake (without changing down through gears) for smooth deceleration and minimising the use of foot brake where appropriate. Sun et al. [52] proposed a speed smoothing scheme for eco-driving to avoid temporarily stopping and unnecessary acceleration/deceleration at road intersections. Hellström et al. [53] proposed a look-ahead control system which decelerated prior to travelling downhill and accelerated before going uphill so that vehicle speed was maintained in a defined range and the time lost at one point was gained at another point. Birrell et al. [54] investigated the effect of a vibrotactile accelerator pedal on driving performance, which was triggered when throttle pedal was pressed by more than 50%. The results showed a significant decrease in the mean acceleration values, as well as maximum and excess throttle use.

2.3. Idling

Idling should be minimised because every vehicle achieves zero fuel efficiency (0 km/L) when idling [17]. An idling vehicle consumes 0.6–5.7 L/h fuel depending on the vehicle type, engine size, fuel type and load [55]. It was estimated that idling wasted about 22.7 billion litres fuel in the US annually, half of which was contributed by personal vehicles [56]. Eliminating unnecessary idling of personal vehicles would be the same as taking 5 million vehicles off the road in terms of saving fuel and reducing emissions [56]. Idling also produces high pollutant emissions of CO, HC, NO_x and PM [57].

Idling time can be reduced in many ways. Firstly, it is needed to update people's understanding and knowledge on idling. Modern cars do not need to idle to warm up the engine or catalytic converter [56]. Reaching the ideal operating temperature is achieved more quickly by driving than idling. Even on the coldest days, most manufacturers recommend avoiding idling and driving off gently for about 30 s to warm up the engine. Similarly, modern cars do not suffer damage by being turned on and off, and 10 s idling has more fuel consumption and emissions than stop-and-restart does [21,56]. It was suggested that the engine should be turned off when waiting time was expected to be longer than 1 min and the fuel economy could be improved by 19% if turning the engine off for 10 2-min idling periods on a 10-mile course [14]. However, a survey showed that the average total idling time of

American drivers was 16.1 min per day [58]. At least 80% of the respondents thought that idling a vehicle for more than 30 s was better than stop-and-restart. The average respondent believed that a vehicle should be idled for at least 2 min before driving in mild weather and even longer in cool or cold weather. Consequently, a large amount of fuel was wasted in idling due to inaccurate or outdated knowledge. A recent online survey also demonstrated that although the majority of people were aware of eco-driving and had a positive attitude towards it, their knowledge of specific fuel saving behaviour was generally low [59]. Therefore, like the concept of eco-driving, changing people's idling behaviour is a more efficient, faster and cheaper way to save fuel than idling reduction technologies.

The above knowledge mainly targets idling off road, such as avoiding long idling before driving or stopping, and turning the engine off while waiting for passengers. However, drivers usually have less control over idling in traffic and it may be inconvenient or even unsafe to turn off the engine. This kind of idling can be reduced or avoided by more efficient speed, accelerating, decelerating and routing behaviours. By looking ahead at the changes in traffic flow or signals, idling time in congested traffic or intersections could be reduced by decelerating earlier and more smoothly (releasing throttle and using engine brake rather than foot brake) and avoiding unnecessary accelerating and hard braking again, which save fuel during both driving and idling. Mahler and Vahidi [60] proposed an optimal velocity-planning algorithm to minimise the idling time behind red lights and maximise the chance of going through green lights based on probabilistic traffic-signal timing models. The model showed a 61% increase in fuel economy in a motivating case study (ideal and best condition), but 16% for fixed-time signals and 6% for actuated signals compared with the un-informed drivers. Mandava et al. [61] developed an algorithm to provide drivers dynamic speed advice based on real-time signal information, so that drivers could maximise the probability of passing through green lights without idling and adjust their speed smoothly to minimise emissions from sharp acceleration and deceleration. The algorithm showed a 12–14% reduction in energy and emissions. Li et al. [62] proposed an advisory system to alert drivers to release the throttle earlier and brake gently in response to a change of traffic signal. The results showed 8% of fuel savings in medium congested traffic. Idling time at intersections, congestions and accidents could be reduced or avoided by eco-routing devices [63,64]. New engine technologies can also help reduce idling in traffic. For example, many new vehicles are now equipped with stop-start technology which turns off the engine whenever idling and restarts comfortably when drivers touch the accelerator pedal [65,66]. Fonseca et al. [67] reported that a vehicle with a stop-start system had more than 20% CO₂ reduction than a similar vehicle without stop-start technology, partly due to zero idling emissions. Hybrid vehicles turn off the engine when idling and even at low driving speed.

2.4. Route choice

Route choice is another major factor that determines the total fuel consumption and emissions for a given origin-destination trip. Once the route is chosen, the aforementioned eco-driving factors will be largely limited by the route characteristics. Route choosing involves a number of factors including travel time, distance, speed limit, and road and traffic conditions. There are usually several routes for a given origin-destination trip. Mostly, a driver would choose a route with either the shortest travel distance or the fastest travel time. However, the shortest or fastest route is not always the best choice in terms of fuel consumption and emissions [68–70]. A Swedish study found that 46% trips of the drivers' spontaneous choices were not the most fuel-efficient routes and 8.2% of fuel could be saved by using a fuel-optimised navigation system [71]. This is because the fastest route may be longer and include highways that do not allow the vehicles to run at the eco-driving speed (50–90 km/h, as discussed in Section 2.1), thus resulting in higher fuel consumption. While the shortest route may contain

congested traffic, leading to higher fuel consumption and longer travel time. Trade-off is needed between travel time, distance and fuel consumption. Zeng et al. [72] developed an eco-routing approach to determine the path with minimum CO₂ emissions while satisfying time constraints. They found that the average reduction of CO₂ could reach 11% when the travel time buffer was 10%. Kuo [73] proposed a model to calculate the fuel consumption for a time-dependent routing problem. The results showed that the proposed method could have 25% reduction in fuel consumption over the fastest-route method and 23% over the shortest-route method. Ahn and Rakha [74] found that eco-routing system typically reduced travel distance but not necessarily travel time.

Road type and grade could influence fuel economy and emissions significantly. Road type determines the speed, acceleration and deceleration profiles, and consequently fuel economy. For example, the average fuel economy of highways with an 80 km/h speed limit or higher is about 9% better than other roads [14]. Choosing a flat and constant speed limit road is not only safer, but also saves fuel. Gallus et al. [48] reported that, with accelerations within $\pm 0.1 \text{ m/s}^2$, CO₂ and NO_x emissions showed a linear correlation with road grade for all urban, rural and motorway conditions. The step from 0% to 5% road grade led to a 65–81% increase in CO₂ and 85–115% increase in NO_x. Jin et al. [75] reported that, for a 250-metre freeway segment with the same initial speed, final speed and trip time, the fuel consumption of a 6% grade route was 86% and 171% higher than those of 0 and –6% grade routes, respectively. Higher road grade required the vehicle to run at high engine load condition more frequently, causing higher fuel consumption and emissions. A small proportion of the entire trip with high engine load condition was responsible for a significant amount of trip emissions and fuel consumption [70]. Therefore, routes with large road grade should be avoided. It was reported that fuel economy of flat routes would be 15–20% better than that of hilly roads [76].

Traffic conditions should also be considered when choosing the route. A fuel efficient route should avoid congested roads and minimise idling time at intersections or traffic lights. Several studies had been performed regarding this aspect. Boriboonsomsin et al. [69] presented an eco-routing navigation system based on the historical and real-time traffic information. The results showed that, compared with the fastest route, an eco-route would provide 12–14% average fuel savings but incur 16–22% longer travel time depending on the trip distance. Sun and Liu [52] developed an eco-routing algorithm by considering vehicle arrival and signal status information in a signalized traffic network. On average, a 20% reduction of CO emissions was observed compared with a traditional shortest path algorithm. Yao and Song [63] proposed an eco-routing algorithm based on locally collected vehicle operation and emissions data and a dynamic traffic information database. Compared with the fastest route, the eco-route could reduce fuel consumption by 2.2–7.4% depending on the vehicle type, travel distance and traffic flow. The maximum fuel savings could be achieved under heavy congestion and 10–15 km conditions. Nie and Li [64] presented an eco-routing model to find the path with the minimum total travel time and fuel costs, which considered the major acceleration events associated with link changes and intersection idling. The results showed that vehicle characteristics (especially weight and engine displacement), turning movements and acceleration had significant influence on the choice of the eco-route. Some of the above studies have mentioned that the amount of fuel savings on the chosen eco-route was dependent on vehicle type [63,64], which should also be considered in eco-routing algorithms. Ahn and Rakha [70] found that each vehicle type would have a different optimal route for HC and CO, but the same route for NO_x, CO₂ and fuel consumption. Bandeira et al. [77] reported that eco-route differed according to the vehicle model and emissions estimation method.

A commonly ignored factor in eco-routing studies was how individual vehicle's route choice would affect others at network levels. The above studies mostly investigated the effectiveness of eco-routing

system for individual vehicles. Rakha and Ahn used an INTEGRATION eco-routing framework to evaluate the network-wide impacts [74,78]. The results showed that the system-wide benefits of eco-routing generally increased with the increase of system market penetration rate [74]. However, Garcia-Castro et al. [79] reported that a high percentage of eco-drivers would have negative effects on global emissions under high traffic demand conditions because higher headways and smooth acceleration/deceleration increased congestion. Moreover, it is possible that if too many drivers are directed into the same route, then the initially calculated eco-route may become congested and thus not be fuel efficient [69]. This will need not only real-time traffic information, but also communication between vehicles. Jiang et al. [80] reported that the benefits of eco-driving increased with the market penetration rate of connected and automated vehicles until levelling off at a 40% penetration rate.

2.5. Other factors

Air conditioning system uses extra fuel and eco-driving principles suggest using it conservatively. It is the single largest auxiliary load on a vehicle [81]. An air conditioner compressor could use up to 5–6 kW power from the engine, equivalent to driving a vehicle steadily at 56 km/h. It was estimated that 13.5 billion litres fuel (or 3% fuel consumption) could be saved in the US by reducing the use of air conditioners by 50% [82]. Experimental results showed that a small passenger car consumed more fuel with maximum cooling than with windows-down when cruising speed was between 64 and 113 km/h [83]. However, fuel consumption with windows-down overtook air conditioner at 129 km/h due to the increased aerodynamic drag. Therefore, rolling windows down for ventilation and cooling is more efficient at low speed (e.g. on city streets) but air conditioner becomes more efficient at high speed (e.g. on motorways) if it is not operated at the maximum cooling load. Parking the car in the shade in hot weather and in a warm place in cool weather could save fuel from the engine warm-up and usage of air conditioner. Using other vehicle accessories, such as cabin and seat heating, headlights, entertainment systems and cigarette lighters, also increases fuel consumption. Conservative use of these features is recommended [17]. However, generally their effect is insignificant and the drivers' safety and comfort should not be compromised for eco-driving.

Other factors influencing fuel consumption include vehicle weight, tyre pressure, maintenance and aerodynamic drag [14,17,21,22,41]. Vehicle weight should be minimised by removing unnecessary items. 45 kg of extra weight can increase fuel consumption by 1–2% and the impact is more significant for small vehicles [16,22]. It was estimated that each additional pound of average passenger weight would increase US petrol consumption by more than 148 million litres per year [84]. Proper maintenance can reduce fuel consumption. Fuel consumption could increase 1–2% by driving with under-inflated tires, by 4% with a poorly tuned engine, and by as much as 40% with a faulty oxygen sensor [14]. Aerodynamic drag should be minimised. Additional parts on the exterior of a vehicle or having the windows open could increase air resistance and fuel consumption by over 20% at high driving speed [21]. A large blunt roof cargo box can reduce fuel economy by 2–25% and a rear cargo box or tray can reduce fuel economy by 1–5% depending on the driving speed [22]. Therefore, it is recommended to store necessary cargo in the vehicle rather than on external racks, to use rear racks rather than roof racks, and to use aerodynamic racks and to pack cargo tight and low if roof cargo cannot be avoided [17]. However, drivers usually do not have much control over these factors during a trip and the chance of implementing these skills is relatively low.

2.6. Comparison of eco-driving factors

Fig. 2 compares the ranges of percentages of fuel savings or CO₂ reduction contributed by each eco-driving factor. Savings in fuel

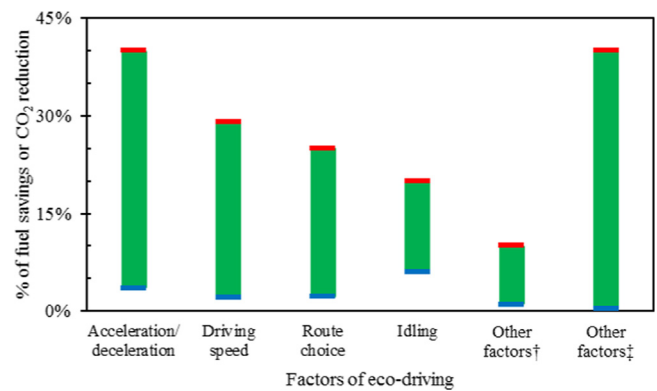


Fig. 2. Ranges of percentages of fuel savings or CO₂ reduction contributed by each eco-driving factor. Data is derived from [22,24,48,53] for acceleration/deceleration, [21,22,28,32–38] for driving speed, [14,60–62,67] for idling, [14,63,69–74,76,78] for route choice, [16,22,82] for other factors[†] that drivers have control over and [14,17,21,22] for other factors[‡] that drivers have no control over.

consumption are taken from experimental or numerical studies for a given origin-destination trip. Some data indicating the potential benefits of a single factor in ideal or extreme conditions is not comparable and thus excluded. For example, although fuel consumption of a 6% grade road is 86% and 171% higher than those of 0% and – 6% grade roads [75], there are no three such routes containing only uphill, flat or downhill roads for a given origin-destination trip. It should also be noted that eco-driving factors are not independent and mostly overlap with each other, as shown in Table 1. As shown in Fig. 2, the primary eco-driving factor is acceleration/deceleration, contributing to 3.5–40% fuel savings or CO₂ reduction. This justifies the effectiveness of avoiding aggressive driving style that is commonly recommended in eco-driving programs. Driving speed and route choice could contribute to 2–29% and 2.2–25% fuel savings, respectively. They are followed by idling reduction (6–20%). Other factors (indicated by [†]) that the drivers have control over during a trip (e.g. air conditioner) have insignificant effect on fuel consumption (< 10%). Although a faulty oxygen sensor can cause up to 40% more fuel consumption, such factors (indicated by [‡]) are not frequent and drivers have no control over them during a trip. Therefore, the majority of eco-driving studies focused on the driving behaviours of acceleration, deceleration, driving speed, route choice and idling.

3. Research methods for eco-driving

This section reviews the methods used to investigate eco-driving technology, including laboratory testing, on-road experiments and numerical modelling. Their mechanisms, advantages/disadvantages and applications are discussed and compared.

3.1. Laboratory experiments

Fuel consumption and emissions for different driving styles can be measured in laboratory using a chassis dynamometer, engine dynamometer or driving simulator. Laboratory experiments are performed under controlled conditions and their accuracy and repeatability are relatively high.

3.1.1. Engine dynamometer

Engine dynamometers are commonly used to investigate the engine power and emission characteristics. In an engine dynamometer test cell, the engine driveshaft is directly coupled to the dynamometer shaft. An absorption unit is used to absorb any specific load and measure the engine power, torque and speed. In engine dynamometer testing, the engine and exhaust after-treatment system are required to be removed

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

Eco-driving factors	Parameters considered	Refs.
Driving speed	Cruise control, vehicle speed, speed limit, compliance of speed limit, travel time, traffic flow, traffic signal, fuel type, road grade, gear shifting.	[21,22,28,32–38]
Acceleration/ deceleration	Aggressiveness, anticipation, headways, traffic flow, traffic signal, road grade, throttle position, engine/foot brake.	[22,24,48,53]
Idling	Knowledge on idling, anticipation, traffic flow, traffic signal, vehicle speed, acceleration/deceleration, route choice, stop-start and hybrid technologies.	[14,60–62,67]
Route choice	Travel time, travel distance, when to travel, road grade, road type, speed limit, congestion, idling at intersections, network-wide impacts, market penetration rate, vehicle type.	[14,63,69–74,76,78]
Other factors [†]	Air conditioner, excess weight (45 kg), aerodynamic drag (windows).	[16,22,82]
Other factors [‡]	Under-inflated tires (1–5 psi), out of tune engine, faulty oxygen sensor, aerodynamic drag (external cargos).	[14,17,21,22]

Other factors[†]: factors that drivers have control over during driving and can be frequently applied.

Other factors[‡]: factors that drivers have no control over during driving or are not frequent.

from the vehicle and the tests follow the procedures specified in regulations [85]. Various engine operating parameters can be monitored in real-time, including exhaust emissions, fuel consumption, torque, speed, in-cylinder pressure, etc. The major advantage of an engine dynamometer is that the test cell can be climatically controlled (i.e. ambient temperature and humidity) to simulate driving under a wide range of climatic conditions. The operator has full control of all the engine parameters. Thus, engine dynamometer testing can be conducted to investigate the impacts of driving styles and ambient conditions on emissions and fuel consumption. Furthermore, the engine driveshaft is directly connected to the dynamometer so the results are not affected by transmission and driveline power losses. Therefore, the accuracy and repeatability of engine dynamometer test are relatively high. The limitations of engine dynamometer testing are that it does not fully represent the performance of a complete vehicle and the range of test conditions is limited although real-world engine load test cycles can be run on modern engine test benches by simulating the vehicles on-road driving dynamics [86]. Furthermore, the fuel consumption and emissions of entire vehicle fleets cannot be represented by engine dynamometer testing as usually only a few engines in each vehicle type are tested.

3.1.2. Chassis dynamometer

Chassis dynamometers enable operators to simulate the resistive load on vehicle wheels. They consist of three main components, namely the load cell (absorption unit), the roller set and the power and torque indication system. During chassis dynamometer testing, the vehicle is tied down and placed on a set of rollers which are coupled to the dynamometer load cell or a belt drive system. Thus, load can be applied to the vehicle to simulate real-world driving resistance. The driving cycles and load can be controlled by operators, which are mainly transient cycles such as the New European Driving Cycle (NEDC) and Federal Test Procedure (FTP). These cycles are pre-defined driving profiles that operators have to attempt to emulate during testing. Operators must anticipate and follow the speed within ± 2 km/h and time within ± 1 s [87]. The vehicle fuel consumption and exhaust emissions are continuously measured and recorded along with driving parameters. As chassis dynamometers are built in laboratory and designed to meet regulatory standards, the testing results are highly precise and reliable. Moreover, test cycles, road resistance and climate conditions can be fully controlled by operators, thus the test results are not affected by real-world driving factors and the repeatability is relatively high. Chassis dynamometer testing can evaluate the impacts of driving behaviours on emissions and fuel economy, which will be analysed for further development of eco-driving technology. On the other hand, the range of test conditions such as steep road gradients are limited in chassis dynamometer testing. Thus, chassis dynamometer testing cannot represent real driving. Furthermore, driving resistance that simulates road load is generated from vehicle coast down test under artificial conditions. So that vehicle emissions and fuel consumption are

lower when compared to real driving results [88].

3.1.3. Driving simulator

Driving simulators are mainly built in laboratory to study driving behaviours, to provide eco-driving training, and to evaluate new eco-driving training programs and in-vehicle devices. A driving simulator mainly consists of a fixed-base car mock-up with a steering wheel, acceleration and brake pedals and indicators. Road scenarios are displayed on a screen, which provide the road environment and traffic information to the driver. Driving behaviours are continuously monitored and fuel consumption and emissions are calculated accordingly. The major advantage is that driving simulators offer a safe and effective method for examining various factors on the driver performance [89]. Safety issues and traffic accidents are not a concern in a laboratory driving simulator study. The driving behaviours are recorded and used to improve the performance of individual drivers. Real-time driving information are displayed on the screen to drivers so that they can well understand the impacts of their behaviours on emissions and fuel consumption during the experiment. The limitation of driving simulators is that road and traffic conditions are pre-defined and fixed. Eco-driving studies on driving simulators usually only have a few runs to test the introduction of new training programs or in-vehicle devices. Real-world traffic and road conditions are not included. Furthermore, the results are highly dependent on the simulator program which calculates the emissions and fuel consumption corresponding to different vehicle operation conditions. The use of driving simulators may also cause simulator sickness mostly due to an incongruity of sensory input with conflicting signals from simulated and actual motion [90].

3.2. On-road experiments

Emissions and fuel consumption measurements under on-road conditions provide valuable data for the actual driver performance of eco-driving. On-road experiments are typically less accurate and repeatable than laboratory testing [91]. Moreover, on-road experiments are highly affected by the uncertainties in traffic conditions, driver behaviours and transient operation due to the absence of standard testing cycles [86]. The commonly used on-road research methods for eco-driving include portable emissions measurement system (PEMS), data logger, odometer reading and fuel use, and surveys.

3.2.1. PEMS

A PEMS is a mobile emission measurement instrument that is used on-board the target vehicle to test under real driving conditions. A PEMS integrates advanced emission analysers, an exhaust flow metre, a weather station and a GPS system, and connects with the on-board diagnostics (OBD) system of the vehicle to acquire the driving parameters such as vehicle and engine speeds. A PEMS is installed either in the cabin or in the trunk of the test vehicle. Heated sample lines and exhaust flow measurement system are directly connected to the

tailpipe. The sampling line is pre-heated to 190 °C to avoid the condensation of HC. Exhaust emissions, flow rate and temperature can be monitored in real-time together with the engine, vehicle and ambient parameters. A PEMS is well utilised and developed because the upcoming Euro-6c regulation will include Real Driving Emissions (RDE) as a new and additional type approval test for new vehicles [92]. The major advantage is that a PEMS can provide second-by-second emissions and fuel consumption data during real-world driving. It can be installed into different categories of vehicles to build up a large database under a wide range of driving conditions for further development of eco-driving technology. The effect of driving style on fuel consumption and emissions can be analysed. In addition, the impacts of road grade can be investigated [48], which would be difficult to replicate in laboratory testing. On the other hand, a PEMS usually measures a limited range of pollutants which are less comprehensive than laboratory testing can achieve. The total weight of a PEMS including accessories is about 100–500 kg which can affect the measurement results, especially for light weight vehicles (e.g. 45 kg of extra weight could increase fuel consumption by 1–2% [16,22]). Moreover, the repeatability and accuracy of PEMS measurements are lower than laboratory testing due to the traffic conditions, driving behaviours and ambient conditions in a real driving.

3.2.2. Data logger

Data loggers are designed to collect the vehicle state and driver operation data under real driving conditions. Data loggers are plugged into the OBD II or control area network (CAN) of a vehicle to collect the vehicle speed, engine speed, fuel consumption, GPS and emissions data. OBD II is a standard port to provide real-time data of driving parameters and has been adopted by the US EPA since 1996 [93]. The major advantage of data loggers is that they can be simply connected with an OBD II or CAN and collect data during normal driving. They can minimise the effect of the added device mass on the measured results compared to a PEMS. Most vehicles manufactured after 1996 should have OBD II ports. The data collected can be used to investigate the impacts of driving behaviours on emissions and fuel consumption. In addition, data loggers can be used on a large number of vehicles during long-term normal daily driving at a low cost. On the other hand, the data available from OBD II or CAN differs by manufacturer, vehicle model and type. Not all driving parameters are available as some may not be found in OBD II or CAN data stream.

3.2.3. Odometer reading and fuel use

Eco-driving has been already implemented in normal daily driving. To evaluate its effectiveness, fuel consumption can be manually logged by paper forms, fuel cards and company records (how frequently and how much fuel is refilled) and vehicle usage can be recorded via the odometer readings. The advantage of this method is that it is relatively simple and inexpensive. It is applicable to a large number of vehicles and feasible for long-term studies. In addition, this method does not have impact on the driving behaviours. However, the limitation is that human errors may occur in recording the fuel use and mileage, and drivers may forget to record the data at gas stations. Another limitation is that the data available is very limited, mainly the fuel use and mileage. The calculated fuel consumption rates are only mean values in certain periods.

3.2.4. Surveys

Surveys are assigned to drivers after they are involved in eco-driving programs. The levels of fuel savings and emissions reduction are strongly dependent on drivers' motivation, attitude, acceptance, knowledge and behavioural change. Surveys are aimed to understand these factors. Surveys are relatively simple and inexpensive. Furthermore, the feedback of drivers' experience can be used to improve the eco-driving training programs and in-vehicle devices. The major limitation of surveys is that the information collected is very

limited and no quantitative data on fuel consumption or emissions is available.

3.3. Numerical modelling

Numerical modelling is widely used to evaluate the performance of new eco-driving and eco-routing algorithms. Numerical models predict the fuel consumption and emissions as a result of different driving behaviours. Based on transparency, Zhou et al. [13] classified fuel consumption models into white-box, grey-box and black-box models, with ascending simplicity and descending accuracy. By comparing the model efficiency and accuracy, the grey-box models are recommended for eco-driving and eco-routing systems [13]. The major advantage is that numerical modelling can investigate the effectiveness of new eco-driving strategies or algorithms without conducting field experiments, saving greatly in both research time and cost. However, the limitation is that the results are less accurate and reliable than those of laboratory and on-road experiments. A model may only consider a few driving parameters (input variables) and ignore others that also have impacts on driver performance. In addition, the results are limited as well. Some models may only predict fuel consumption [25,94–96] while some may be able to predict a few common emissions (mostly CO₂, CO, HC and NO_x) [51,52,70,72].

3.4. Comparison of research methods and their applications

Table 2 summarises the mechanisms, advantages and limitations of the research methods used for eco-driving. As shown in Table 2, each method has its own advantages and disadvantages, which determine their applications in eco-driving research. Engine and chassis dynamometers are highly accurate and repeatable. They are commonly used for type-approval or inspection and maintenance (I/M) programs. Engine and chassis dynamometer testing results are also valuable for developing numerical models. Driving simulator is a safe and effective method to design and evaluate new eco-driving training strategies and in-vehicle devices. A PEMS measures second-by-second fuel consumption and emissions data, along with the driving, vehicle and ambient parameters under real-world driving. This dataset enables detailed analysis to be performed on the effect of each driving parameter on driver performance, thus to identify fuel-efficient and low-emission behaviours for developing more effective eco-driving strategies. Data loggers are suitable for evaluating the effectiveness of eco-driving training programs or in-vehicle devices during normal driving in the long-term and at large-scale due to the low-cost, simple setup and limited maintenance/supervision required. Odometer readings and fuel records are also suitable for long-term and large-scale studies. The cost is lower while the data collected is much more limited compared to data loggers. Surveys are used to understand drivers' attitude, knowledge, motivation and acceptance of eco-driving training programs and in-vehicle devices, which cannot be acquired by other methods. Numerical modelling is usually used to design and evaluate new eco-driving and eco-routing algorithms without performing field tests, which helps reduce both the research time and cost.

4. Implementation of eco-driving

4.1. Training programs

The purposes of eco-driving training programs are to provide drivers with the knowledge (theoretical training) and skills (practical training) to drive more fuel efficiently. Table 3 summaries the published eco-driving training programs which compared the fuel consumption before and immediately after (or a certain period after) training. Some studies also included a control group to better assess the training effects. As shown in Table 3, the percentage of fuel savings is generally in the range of 2–15%, varying significantly between programs and

Table 2
Comparison of eco-driving research methods.

Method	Mechanism	Advantages	Disadvantages
Engine dynamometer	Measures engine operation parameters by applying simulated load via dynamometer	High accuracy and repeatability Climatically controlled Full control on engine	Not real-world data Not a complete vehicle Small scale studies High cost
Chassis dynamometer	Measures vehicle operation parameters by applying simulated resistive load via chassis roller	High accuracy and repeatability Climatically controlled Large degree of control	Not real-world data Limited road gradient Small scale studies High cost
Driving simulator	Records driver behaviours and performance data in driving simulator system	No safety issues Low cost	Driving conditions are pre-defined Not real-world data Simulator sickness Short-term studies
PEMS	Measures vehicle operation parameters by carrying instrument on-board the target vehicle	Acceptable accuracy Real-world data Wide driving and ambient conditions	Added weight may bias results Limited repeatability Small-scale and short-term studies
Data logger	Reads vehicle and engine operation parameters from OBD II or CAN	Low cost, fast and easy setup Long-term and large-scale studies	Limited accuracy and repeatability Available data is limited and differs by vehicle model
Odometer reading and fuel record	Records odometer reading and fuelling frequency by drivers or company	No impact on driver performance Real-world data Low cost and simple Long-term and large-scale studies No impact on driver performance Real-world data	May miss some records (human factors) Very limited information recorded Low accuracy and repeatability
Survey	Receives feedback from drivers after eco-driving programs	Low cost and simple Large scale studies Understands drivers' knowledge, attitude, motivation and acceptance	No quantitative data on fuel consumption and emissions
Numerical modelling	Predicts effect of driving behaviours on fuel consumption and emissions by numerical models	Low cost Shortens research cycle	Not real-world data Low accuracy and reliability Limited factors considered Limited output data

individuals. Eco-driving programs usually included theoretical training, practical training or their combination. The training results have not reached a consensus and sometimes may be even conflicting. This is because each program varies greatly in eco-driving strategies, vehicle categories, trainees and driving conditions. Andrieu and Pierre [97] compared the effects of simple advice and eco-driving training on driving behaviours. Their results showed that the average fuel consumption decreased by providing simple advice (12.5%) was slightly higher than that by training (11.3%). However, the routes and vehicles used for the two methods were different. Jeffreys et al. [98] compared the effectiveness of five eco-driving interventions with increasing intensity, including (1) 1 h on-line learning and hardcopy brochure, (2) intervention 1 plus 2 h classroom lesson, (3) intervention 1 plus 50 min driving lesson, (4) interventions 1, 2 and 3, and (5) intervention 1 plus a half-day workshop. The results showed that all the five interventions had apparent fuel savings and there was no statistically significant difference between them. Strömberg and Karlsson [99] compared the effects of two eco-driving strategies, namely an in-vehicle feedback system and feedback coupled with personal training. The results showed that both strategies showed 6.8% in fuel savings and no difference was observed between the two strategies. However, Schall et al. [100] reported that purely theoretical training had no effect in either the short-term or long-term, indicating the necessity of practical training elements.

Generally programs that assessed the effectiveness immediately after training demonstrated obvious improvements in fuel consumption, emissions and driving behaviours [101–105], while long-term studies showed that the training impact faded over time [106–108]. This was because the driving habits developed through many years of practice were engrained and thus hard to change in short training programs. An exception was reported by Sullman et al. [109] who found that the fuel savings 6 months after training (16.9%) were even larger than that immediately after training (11.6%). It should be noted

that many factors could influence fuel consumption and thus the training results. For example, higher ambient temperature results in lower fuel consumption [108]. When taking this into consideration, the conclusion of an eco-driving training program changed from “effect was stable over time [103]” to “effect was gradually lost [108]”. In addition, the training effect was highly heterogeneous between individuals [106]. A large percentage of trainees would exhibit no change or even become worse after training [103,110]. A survey study showed that eco-driving interventions were more effective with high levels of pre-intervention motivation or supervisor support [111]. Studies also showed that eco-driving training was more effective under city conditions than highway conditions [106], and was more effective for manual transmission cars than automatic ones [101,106]. A main challenge of eco-driving training programs is the fair evaluation of the effectiveness [112]. There are many variables in a real-driving task and some would be out of control during experiments, such as changes in routes, traffic and road conditions, weather, number of passengers, and turn-over of drivers (several drivers many share one vehicle and one driver may drive different vehicles in a company or family context) [109].

The above programs were all for the existing licensed/experienced drivers while few studies were for learner drivers. One training program for learner drivers was the ECOWILL project carried out during May 2010 to April 2013 in 13 European countries. ECOWILL provided eco-driving seminars for both learner (level 1) and licensed (level 2) drivers [113]. The level 1 project integrated five golden and eight silver eco-driving rules into driving school curricula and driver tests, aiming to educate 10 million learner and novice drivers with a sustainable lasting effect [114,115]. The project was turned out to be very successful. By the end of the project, the Commission Directive 2012/36/EU made eco-driving a mandatory element of the driver test in all 28 European countries, which entered into force on 19 January 2013 [116]. Strömberg et al. [117] investigated the effect of the introduction of eco-

Table 3
Summary of eco-driving training programs.

Programs	Training strategies, trainees and study periods*	Fuel savings or CO ₂ reduction*
Queensland Australia [98]	5 interventions with increasing intensity 853 (EG) + 203 (CG) private drivers 6-week before and 12-week after training	0% 5% 10% 15% 20%
Quebec Canada [106]	6h theoretical and practical training 45 (EG) + 14 (CG) car drivers 2-month before and 6-10-month after training	
Queensland Australia [101]	Simple theoretical training 13 drivers using one automatic car Immediately before and after training	Plus -10% CO, -7% HC, -4% NOx
Athens Greece [174]	Theoretical and practical training 3 bus drivers 1.5-month before, immediately and 2-month after training	
Helsinki Finland [109]	7h eco-driving (or first-aid) course 29 (EG) + 18 (CG) bus drivers using a simulator Immediately before, immediately and 6-month after training	
Germany [100]	Incentives and half-day theoretical training 91 logistics drivers (<1/3 CG) 12-month before and 6-month after training	Theoretical training had no effect
Uppsala Sweden [44]	Theoretical and practical training (stronger acceleration) 350 bus drivers + CG 3-month short-term study	Passenger comfort worsened
Uppsala Sweden [107]	Theoretical and practical training (stronger acceleration) 350-400 bus drivers, 249 EG Several years before and one year after training	
Ontario Canada [175]	Tailored courses based on pre-training data 64 drivers 10-month before and 6-month after training	
California USA [110]	Being asked to visit EcoDrivingUSA website 51 (EG) + 53 (CG) drivers 4-month survey study	57% improved driving behaviour 43% made no change or worsened
Portugal [102]	4h eco-driving education and individual performance report 9 (EG) + 11 (CG) drivers 2-3-month before and after training	Plus -8% NOx
France [97]	Eco-driving training and simple eco-driving advice 20 (simple advice) + 19 (training) drivers Immediately before and after training	
Belgium [103, 108]	4h theoretical and practical course 10 private drivers Several months before and after training	
Singapore [104]	Theoretical and practical training 116 drivers Immediately before and after training	
Sweden [99]	In-vehicle feedback system and personal training 54 bus drivers including CG 3-week before and after training	
Calgary Canada [105]	Tailored course based on pre-training data (focus on idling) 200 drivers trained, 15 examined 1-month before and after training	4-10% reduction in idling

*EG: experimental group. CG: control group. Error bars indicate the minimum-maximum values. The references cited in this table are [44, 97-110, 174, 175].

driving into driving school curriculum in Sweden. They found that new drivers' understanding of eco-driving was at an operational level and had been clearly shaped by their driving education, while experienced drivers' understanding was broader and included strategic and tactical decisions.

4.2. In-vehicle devices

In-vehicle eco-driving devices are an important complement to the training programs whose impacts may attenuate over time. In-vehicle devices can continuously monitor driving and provide drivers with feedback. The parameters monitored usually include fuel consumption, speed, acceleration, deceleration, idling, and road and traffic conditions. Feedback on driving performance and advice on improving it are provided to drivers based on monitoring. There are a variety of in-

vehicle devices, including dashboard, smartphone applications, GPS navigation system, offline feedback system, dedicated aftermarket feedback system and haptic pedals [118]. The type of feedback also varies greatly, such as visual versus auditory versus haptic [119], real-time versus delayed [120], continuous versus intermittent [121], and general versus personalised [122]. Regardless of the types of devices and feedback, there are mainly three factors considered on in-vehicle devices' design and research, namely safety, acceptance and effectiveness.

4.2.1. Safety

Safety is the most important concern in a driving task. Generally, eco-driving largely overlaps with safe-driving [123]. Eco-driving recommends avoiding excessive speed and aggressive driving which are highly linked with crash risk and severity. However, the introduction of

in-vehicle devices will inevitably draw some attention away from the driving task. These devices often present feedback visually. Investigations showed that a driver would spend 4–8% of the time looking at the eco-driving displays, with an average glance duration of 0.43–0.60 s and none or a few glances longer than 2 s [124,125]. Staubach et al. [126] found that the distraction was initially very high (glance > 2 s) but reduced over time when introducing a new in-vehicle device. The critical time-to-collision (< 15 s) situations, hard braking and speeding were reduced by the device. Different types of in-vehicle devices would cause different distractions for drivers (e.g. visual, manual and cognitive). Studies were conducted to investigate their effects on safety. Kircher et al. [121] reported that intermittent visual eco-driving information had shorter dwell time than continuous information did. Stahl et al. [127] found that both attentional and interpretational in-vehicle displays could improve anticipatory performance for novice drivers but not for experienced drivers. Attentional display would be better for novice drivers because it had shorter and less frequent glances. Experiments on a driving simulator showed that the distraction risk caused by eco-driving task was lower than navigator and CD changing tasks which required cognitive and manual demands [128]. Jamson et al. [129] reported that continuous real-time visual feedback was the most effective but obviously reduced attention to the forward view and increased subjective workload, while haptic feedback had little effect on workload but was less effective than visual feedback. Gonder et al. [118] suggested that auditory feedback might be preferable from a driver distraction point of view and the information provided should be made as simple as possible to understand to minimise the cognitive effort required to process it. It was estimated that drivers might have up to 50% spare attentional capacity during normal driving [124]. Therefore, the distraction caused by in-vehicle devices could be minimised if the attention needed is obtained from this spare capacity. Long glances (> 2 s) away from the forward road scene at one time are associated with an increased risk of crash or near crash. The US Department of Transportation required that in-vehicle devices be designed so that a task can be completed by the driver with a glance away from the roadway in ≤ 2 s and a cumulative glance time in ≤ 12 s [130,131]. These guidelines apply for both the original (Phase 1) [130] and portable and aftermarket electronic devices (Phase 2) [131] that are operated by the driver through visual and manual means.

4.2.2. Acceptance

Acceptance of in-vehicle eco-driving devices largely determines their effectiveness. Although most drivers are willing to adopt eco-driving skills [132,133], acceptance depends strongly on the design of the system, such as the type, content, complexity and presentation of information, which should be considered seriously from an ergonomics perspective [134]. It has been clearly shown that different drivers had very different preferences on the type of information and the majority preferred simple and clear information [135]. It was found that using a display with historical feedback and incorporating learning elements increased the acceptance for learning oriented drivers, while performance oriented drivers might prefer comparative feedback and game elements [136]. Therefore, a personalised feedback could increase drivers' acceptance and motivation [136,137]. Regarding the feedback type, auditory feedback, alone or in any combination with visual or haptic feedback, was not well accepted [138] and haptic systems were more acceptable than visual or auditory systems [126,139].

4.2.3. Effectiveness

Fig. 3 shows the effectiveness of various types of in-vehicles eco-driving devices. As shown in Fig. 3, most of the studies used real-time (also referred as dynamic or online) feedback devices and only a few used delayed (also referred as static or offline) feedback. Both feedback types monitored the driving parameters during a trip using various data sources, such as CAN, OBD, GPS, sensors, map data or the internet. Real-time devices evaluated the driving performance and provided the feedback on improving fuel efficiency to drivers in real-time. In contrast, delayed devices provided a feedback report after the trip was completed [140,141] or after a certain period (e.g. weekly) [120]. Experiments using field trials and driving simulators showed that real-time feedback was more effective than delayed feedback [120,140,142]. Real-time feedback was usually either visual, auditory, haptic or their combination. As shown in Fig. 3, the majority of studies used visual feedback devices. Visual feedback was effective to deliver detailed instructions on eco-driving while the disadvantage was that it would distract drivers and increase cognitive workload [139]. Auditory feedback required less cognitive efforts and could be complementary to visual devices [118,139]. However, a main drawback of auditory feedback was that drivers could not ignore it unless turning it off and might be annoyed by its prolonged use, making it the least accepted

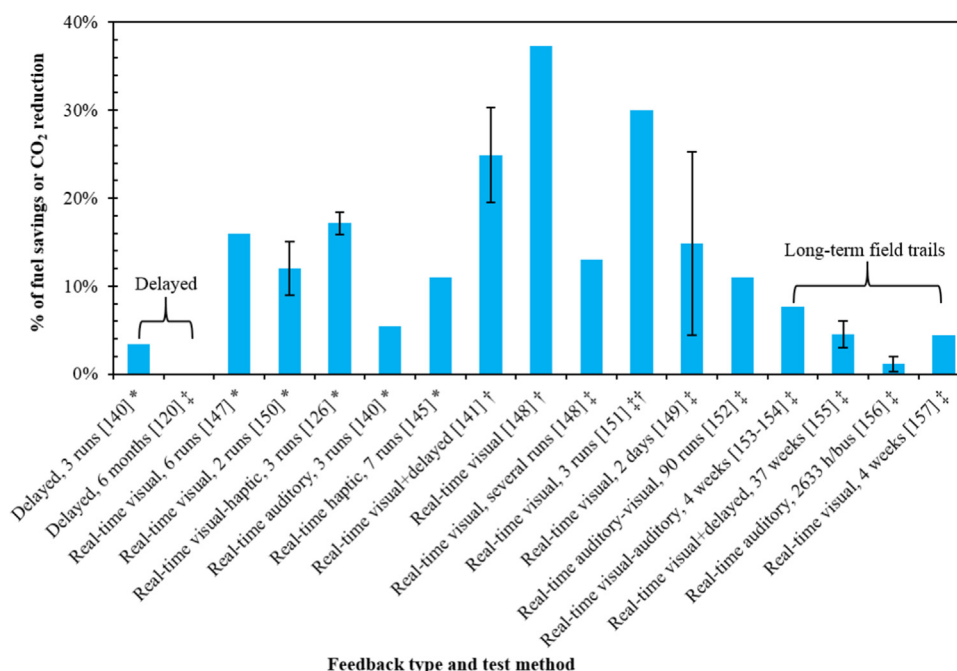


Fig. 3. Effects of feedback type and test methods on percentages of fuel savings or CO₂ reduction. Error bars indicate the minimum-maximum values reported in the studies. Symbols indicate the testing methods: * Driving simulator, † Modelling, ‡ Field trials, †† Test track with no traffic. The references cited in this figure are [120,126,140,141,145,147–157].

feedback [119,126,135,143]. Haptic feedback provided drivers with advice through the accelerator pedal by either extra force, increased stiffness or vibration when over acceleration occurred [119,144,145]. Haptic feedback was effective for speed control and collision avoidance [143,144,146] while the limitation was that it only provided feedback on the use of the accelerator pedal. Fig. 3 also shows that the fuel savings of field trials are typically lower than those of driving simulators and modelling. It was often reported that in-vehicle devices were more effective in urban and congested traffic than in rural and highway traffic [147–150]. However, a driving simulator study showed that the effectiveness of in-vehicle devices was not affected by traffic complexity in either rural or urban situations [150]. In-vehicles devices were also significantly more effective for aggressive drivers than normal or mild drivers [141,149]. As shown in Fig. 3, the majority of studies were carried out in very short periods (a few runs in one or two days) and their percentages of fuel savings were typically higher than 10% [148,149,151,152]. However, longer term studies (several weeks or months) showed much lower fuel savings (< 8%) [120,153–157]. This indicates that in-vehicle devices have the same limitation as training programs. That is, the effectiveness attenuates over time.

4.3. Regulations, incentives and social marketing

Mandatory regulations can greatly promote the implementation of eco-driving. The most important one would be the Directive 2006/126/EC [158] and its amendment Commission Directive 2012/36/EU [116] of the European Parliament and of the Council, which made eco-driving a mandatory element in driving schools and driver tests in all 28 European countries. One of the marking criteria in the driver test is driving economically and in a safe and energy-efficient way by considering the engine speed, gear changing, braking and accelerating [116]. These criteria correspond to the five golden and eight silver eco-driving rules [113]. Other legislative actions on eco-driving is the Engine Idling Laws in the US [56,159] and Hong Kong [160], which restrict unnecessary idling time. Vehicles in special or emergency conditions (e.g. congestion, ambulance, fire and police) are usually exempted. Although eco-driving has attracted much attention in research globally, few regulations have been issued.

Financial incentives can be used to encourage eco-driving. Such incentives could be awards for fuel-efficient public drivers or eco-driving based insurance for private drivers. Schall and Mohnen [161] investigated the effects of monetary and tangible non-monetary incentives on eco-driving in a Germany logistics company. The results showed an average reduction of 5% in fuel consumption due to non-monetary incentive and 3.5% due to monetary incentive. Lai [162] reported a more than 10% reduction in fuel consumption after introducing a monetary reward system to bus drivers. Moreover, the benefit showed no decline over time and the money saved from fuel reduction was much more than the rewards given. Liimatainen [163] developed an eco-driving incentive system using fuel consumption data for heavy-duty vehicle drivers. The pay-as-you-drive (PAYD) or usage-based insurances (UBI) could be used to encourage eco-driving [142,164,165]. Several car insurance companies have adopted these schemes by using telematics to monitor people's driving behaviours and offer a discount depending on how they drive, such as Admiral's Black Box Insurance [166,167], Progressive's Snapshot Program [168] and OnStar's Smart Driver Program [169].

It is also important to increase people's awareness and understanding on eco-driving by social marketing and advertising. For example, many drivers still believe that it is better to idle their cars several minutes before they drive or stop, which wastes a large amount of fuel [58]. Drivers also usually put a lower priority on fuel saving than time saving and convenience [134,170], making excessive speed common on highways and reducing speed limit being extremely unpopular [18,28]. However eco-driving does not increase travel time in urban situations and only increases slightly in rural situations, and

slower driving gains safety as well. To address these barriers, social marketing and advertising of eco-driving are necessary. The eco-driving skills and benefits have been given on many governments' websites, such as US [22], Australia [21], Europe [115], Japan [171] and China [172]. However, only the motivated drivers would visit these websites and implement the eco-driving tips provided. So far very few efforts have been made for the general public.

5. Challenges and future research directions

Road transport consumes a large amount of fossil fuel and emits significant CO₂ and pollutant emissions. Driving behaviours are considered as the last major factors that determine vehicle fuel efficiency and emissions. Eco-driving is a relatively low-cost and immediate measure to significantly improve fuel efficiency. As reviewed in Section 4, it has attracted worldwide investigation and adoption in recent years. However, the effectiveness of eco-driving varies greatly due to their different research scopes, methods and factors. The following challenges should be considered and investigated as future perspectives.

- The effects of both eco-driving training programs and in-vehicle devices were significant in the short term, but faded over time. Efforts are needed to design more effective and lasting training programs and in-vehicle devices.
- The benefits claimed by modelling and laboratory testing were usually much greater than those of field trials. Efforts are needed to convert the potential benefits of eco-driving from research studies into practical driving.
- The many variables in a real-world driving task make it difficult to accurately and fairly evaluate the effect of eco-driving on fuel consumption and emissions. Better experimental design is needed to focus on key variables with the most significant effects on fuel savings and emissions reduction.
- Current eco-driving skills are mostly qualitative. Investigations are needed to provide quantitative suggestions that could be integrated into hardware to generate more constant and uniform improvements.
- Most studies mainly investigated the effect of eco-driving on reducing fuel consumption and CO₂ emissions, but did not cover pollutant emissions such as CO, HC, NO_x and PM. Trade-offs may be needed between fuel economy, pollutant emissions and travel time [173]. Different eco-driving strategies may be required for different purposes.
- Current eco-driving studies mostly focus on individual's driving behaviours, but lacks consideration at network levels. The recommended eco-driving styles may be constrained by surrounding vehicles or may even be unrealistic under real-driving conditions.
- Current eco-driving studies are mainly for licensed or experienced drivers, while fewer studies have been carried out for learner or novice drivers. Investigations on how eco-driving can shape and improve new drivers' driving performance are needed.

6. Conclusions

Eco-driving technology has been critically reviewed based on extensive scientific articles. It is found that eco-driving is a relatively low-cost and immediate measure to reduce fuel consumption and emissions significantly. The major factors influencing fuel consumption and emissions that a driver has control over during driving are acceleration/deceleration, driving speed, route choice and idling. Training programs and in-vehicle feedback devices are commonly used to implement eco-driving skills. Immediate and significant reductions in fuel consumption and CO₂ emissions have been observed with a slightly increased travel time. However, the impacts of both methods can attenuate over time due to the ingrained driving habits developed over the years. This implies the necessity of developing quantitative eco-driving suggestions

and integrating them into vehicle hardware to generate more constant and uniform improvements. Efforts on developing more effective, sustainable and lasting training programs and in-vehicle devices are needed for drivers. Future studies on the effect of eco-driving on pollutant emissions are required as road transport continues to be the single largest contributor of air pollution in urban areas. The effect of eco-driving on fuel consumption and emissions at network levels should also be considered.

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