Faculty of Engineering and IT

Eco-driving Technology for Logistics Transport Fleet to Reduce Fuel Consumption and Emissions

UTS Final Project Report

Project Title: Eco-driving Technology for Logistics Transport Fleet to Reduce Fuel Consumption and Emissions

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Project Objectives

The specific objectives of this project were:

- Find the most effective eco-driving skills.
- Evaluate the effectiveness of the eco-driving skills and programs.
- Identify the knowledge gap in eco-driving technology.

Work Outline

The following works were conducted to achieve the objectives presented above:

- Recent publications on eco-driving were collected.
- The collected publications were reviewed.
- A technical report was prepared (this report).

Materials and Data

The following materials/data were used for this work:

- Over 200 journal/conference papers and technical reports on eco-driving were collected from the UTS library and other open resources.

Deliverables/Results/Outputs

- A technical report for the client (this report).
- A journal academic paper for the broader research community (the paper has been submitted to the Journal of *Renewable & Sustainable Energy Reviews* (2016 impact factor = 8.050, ranked 5/92 in the field of Energy & Fuels). It is under the second round review process now and a final print will be provided once accepted).

Executive Summary

Road transport consumes a large amount of fossil fuel and contributes to a significant proportion of CO_2 and pollutant emissions worldwide. The driver is the last major and often overlooked factor that determines vehicle performance. Eco-driving is a relatively low-cost and immediate measure to reduce fuel consumption and emissions significantly. This project reviews the factors and implementation methods 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, an immediate and significant reduction in fuel consumption and CO_2 emissions was 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. This implies the necessity of developing quantitative eco-driving suggestions and integrating them into vehicle hardware 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 CO_2 reduction of individual vehicles, but ignore the pollutant emissions and the impacts on network levels. Finally, the challenges and research gaps of eco-driving technology are elaborated.

1. Introduction

Road transport is the single largest contributor to air pollution in cities and have serious health impacts to their inhabitants [1-3]. The 2016 World Health Organization (WHO) fact sheet showed that 92% of the world population was living in places where air pollution exceeded the WHO air quality guideline levels and caused about three million premature deaths globally [4]. The public and commercial transport fleets (e.g., logistics transport) consume a large amount of fossil fuel and exhaust huge pollutant emissions.

Eco-driving is a new technology aiming to change drivers' inefficient driving behaviours that could reduce both fuel consumption and emissions. The implementation of eco-driving is relatively low-cost and immediate, and the improvement in fuel efficiency can be up to 45% [5]. It does not need to invest on fleet retrofit, but just a simple change in the driving style. A recent eco-driving training project for 86 drivers in a Germany logistics company showed an average reduction of 5% in fuel consumption [6]. Eco-driving training for 29 Helsinki Finland bus drivers showed 11.6% of fuel savings immediately after the training and 16.9% when 6 months later [7]. Eco-driving is an initiative which has seen worldwide adoption and investigation. However, the eco-driving skills adopted vary significantly between programs, and their effectiveness varies greatly as well. Therefore, it is needed to review the recent global eco-driving programs and identify the most effective eco-driving skills/experience suitable for Sydney logistics transport fleet.

The aim of this project is to review and analyse the published studies on eco-driving technology. Specifically this project will cover the (1) factors, (2) implementation, and (3) challenges and research gaps of eco-driving.

2. Factors of eco-driving

Eco-driving involves a number of factors and has different definitions or scope in the literature. 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 the these driving behaviours could lead to significantly higher reductions in fuel consumption and emissions than other behaviours such as better maintenance practices [8].

2.1. Driving speed

Constant speed is the optimal speed profile for fuel consumption under various road conditions [9, 10]. Therefore using cruise control when possible is commonly recommended for eco-driving [5, 11, 12]. 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 speeds due to increased friction losses [13]. As a result, the fuel consumption-driving speed curve shows a U-shape. This efficiency-speed curve also applies for hybrid and electric vehicles. The optimal speeds for hybrid vehicles are in similar ranges as ICE vehicles, but much lower for electric vehicles [14]. Studies showed that the optimal cruising speed is usually in the range of 50-90 km/h [12, 15-18]. 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 [11].

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 [19]. In addition, reducing speed limit would also achieve reductions of other pollutants, in particular NOx 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 for 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 take into account the speed limit, travel time, road grade, traffic signals and traffic flow [20]. Therefore, eco-driving speed is usually recommended at or safely below the speed limit [14, 21, 22]. Many studies have been carried out to estimate the optimal driving speed profile under various real-world traffic conditions, such as congestion levels [23], road grades [24, 25], car-following scenarios [26], signalized roads [27-30], and hybrid electric vehicles [31].

2.2. Acceleration/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 significantly and have no consensus [14, 32]. Most eco-driving programs recommend smooth driving and minimising acceleration and braking [11, 12]. The US Department of Energy [12] suggested that aggressive driving could lower fuel economy by roughly 15-30% at highway speeds 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 [33]. However, a few studies [34, 35] 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 deteriorated the passengers' comfort [36].

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. Aggressive driving style not only consumed more fuel, but also produced more pollutant emissions such as CO, HC and NOx [15, 37-39]. Berry [40] 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 speeds on highways. The greatest fuel saving could be attained if the most aggressive drivers drove with lower acceleration.

Efforts have been devoted to find the optimum acceleration/deceleration values or strategies under various road conditions. The most efficient use of gears and acceleration strategy was low engine speed and moderate throttle position (50%) for both petrol and diesel cars [33]. Birrell et al. [21] 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 the engine brake (without changing down through gears) for smooth deceleration and minimising the use of the foot brake where appropriate. A few acceleration/deceleration (or speed smoothing) schemes have proposed for various driving situations, e.g., road intersections [41], hilly roads [42] and vibrotactile accelerator pedal [43].

2.3. Idling

Idling should be minimised because every vehicle achieves zero fuel efficiency (0 km/L) when idling [14]. An idling vehicle consumes 0.6-5.7 L/h fuel depending on the vehicle type, engine size, fuel type and load [44]. It was estimated that idling wasted about 22.7 billion litres fuel in the US annually, half of which was contributed by personal vehicles [45]. Eliminating unnecessary idling of personal vehicles would be the same as taking five million vehicles off the road in terms of saving fuel and reducing emissions [45]. Idling also produces high pollutant emissions of CO, HC, NOx and PM [46].

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 [45]. 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 [11, 45]. However, a survey showed that the average total idling time of American drivers was 16.1 min per day [47]. 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 behaviours was generally low [48]. Therefore, like the concept of eco-driving, changing people's idling behaviours 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 periods before driving or stopping, and turning the engine off in drive-through queues or while waiting for passengers. However, drivers usually have less control over idling in traffic and it may be inconvenient or even unsafe to turn off the engine. This kind of idling can be reduced or avoided by more efficient speed, accelerating, decelerating and routing behaviours. By looking ahead at the changes in traffic flow or signals, idling time in congested traffic or intersections could be reduced by reducing the driving speed earlier and more smoothly (releasing the throttle and using the engine brake rather than foot brake) and avoiding unnecessary accelerating and hard braking again, which save fuel during both driving and idling [49-51]. Idling time at intersections, congestions and accidents can be reduced or avoided by eco-routing devices [52, 53]. New engine technologies can also help reduce idling in traffic, such as stop-start technology [54-56].

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 [57-59]. 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 [60]. 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), 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 the travel time, distance and fuel consumption [61-63].

Road type and grade could influence fuel economy and emissions significantly. Road type determines the average driving speed and the 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 [5]. Choosing a flat and constant speed limit road is not only safer, but also saves fuel [38, 59, 64, 65]. 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 light [41, 52, 53, 58]. Some studies reported that the amount of fuel savings on the chosen eco-route was dependent on vehicle type [52, 53, 59, 66].

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 [67]. 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% [68]. Experiments at the Oak Ridge National Laboratory showed that a small passenger car consumed more fuel with maximum cooling than with windows-down when cruising speed was between 64-113 km/h [69]. 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 speeds (e.g. on city streets) but air conditioner becomes more efficient at high speeds (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 cab
and seat heating, headlights, entertainment systems and cigarette lighters, also increases f
consumption. Conservative use of these features is recommended [14]. 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 [5, 11, 12, 14, 33]. Vehicle weight should be minimised by removing unnecessary items [8, 12]. Proper maintenance can reduce fuel [5]. Aerodynamic drag should be minimised (e.g., external cargo boxes and windows) [11, 12, 14]. However, drivers usually do not have much control over these factors during a trip and the chance of implementing these skills is relatively low.

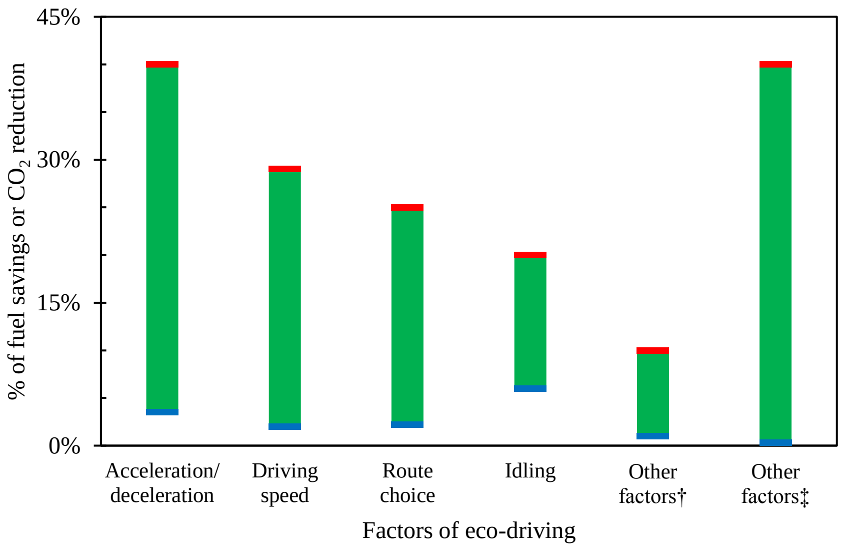


Fig. 1. Ranges of percentages of fuel savings or CO_2 reduction contributed by each eco-driving factor. Data are derived from [12, 15, 38, 42] for acceleration/deceleration, [11, 12, 19, 24-30] for driving speed, [5, 49-51, 56] for idling, [5, 52, 58-63, 65, 70] for route choice, [8, 12, 68] for other factors† that drivers have control over and [5, 11, 12, 14] for other factors‡ that drivers have no control.

2.6. Comparison of eco-driving factors

Fig. 1 compares the ranges of percentages of fuel savings or CO_2 reduction contributed by each eco-driving factor. Savings in fuel consumption are taken from experimental or numerical studies for a given origin-destination trip. Some data indicating the potential benefits of a single factor in ideal or extreme conditions are not comparable and thus excluded. It should also be noticed that eco-driving factors are not independent and mostly overlap with each other. As shown in Fig. 1, the primary eco-driving factor is acceleration/deceleration, contributing to 3.5-40% fuel savings or CO_2 reduction. This justifies the effectiveness of avoiding aggressive driving behaviours that are commonly recommended in eco-driving programs. Driving spee[redacted] and route choice could contribute to 2-29% and 2.2-25% fuel savings, respectively. They a[redacted] followed by idling reduction behaviours (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.

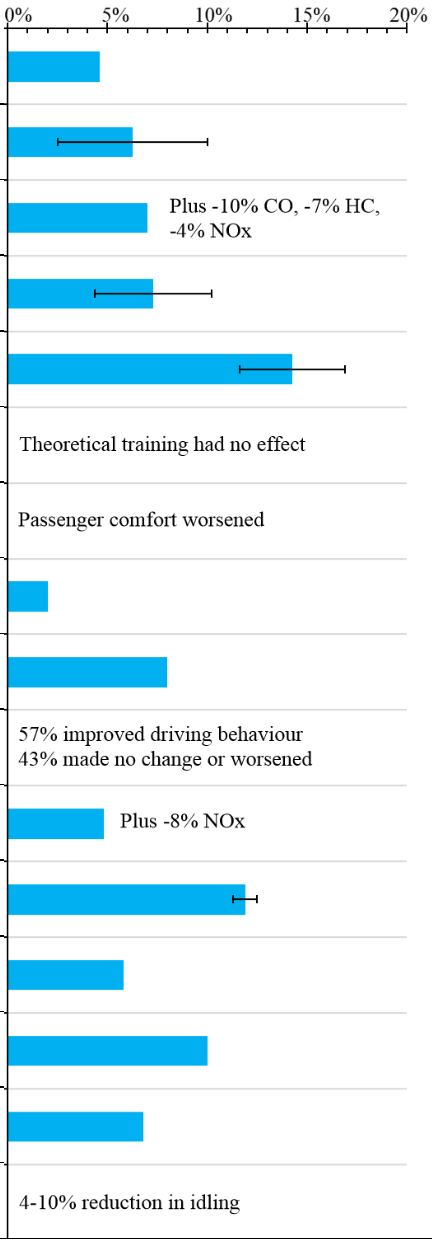
3. Implementation of eco-driving

3.1. 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 1 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 1, the percentage of fuel savings is generally in the range of 2-15%, varying significantly between programs and 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 [71] 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. [72] 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 [73] 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. [74] reported that purely theoretical training had no effect in either the short-term or long-term, indicating the necessity of practical training elements.

Table 1 Summary of eco-driving training programs.

Programs	Training strategies and study periods	Fuel savings or CO_2 reduction*
Queensland Australia [72]	5 interventions with increasing intensity 6-week before and 12-week after training	
Quebec Canada [75]	6h theoretical and practical training 2-month before and 6-10-month after training	
Queensland Australia [76]	Simple theoretical training Immediately before and after training	Plus -10% CO, -7% HC, -4% NOx
Athens Greece [77]	Theoretical and practical training 1.5-month before, immediately and 2-month after training	
Helsinki Finland [7]	7h eco-driving (or first-aid) course (driving simulator) Immediately before and after, and 6-month after training	
Germany [74]	Incentives and half-day theoretical training 12-month before and 6-month after training	Theoretical training had no effect
Uppsala Sweden [36]	Theoretical and practical training (stronger acceleration) 3-month short-term study	Passenger comfort worsened
Uppsala Sweden [78]	Theoretical and practical training (stronger acceleration) Several years before and one year after training	
Ontario Canada [79]	Tailored courses based on pre-training data 10-month before and 6-month after training	
California USA [80]	Being asked to visit EcoDrivingUSA website 4-month survey study	57% improved driving behaviour 43% made no change or worsened
Portugal [81]	4h eco-driving education and individual report 2-3-month before and after training	Plus -8% NOx
France [71]	Eco-driving training and simple eco-driving advice Immediately before and after training	
Belgium [82, 83]	4h theoretical and practical course Several months before and after training	
Singapore [84]	Theoretical and practical training Immediately before and after training	
Sweden [73]	In-vehicle feedback system and personal training 3-week before and after training	
Calgary Canada [85]	Tailored course based on pre-training data (focus on idling) 1-month before and after training	4-10% reduction in idling



** Error bars indicate the minimum-maximum values.*

Generally programs that assessed the effectiveness immediately after training demonstrated obvious improvements in fuel consumption, emissions and driving behaviours [76, 81, 82, 84, 85], while long-term studies showed that the training impact faded over time [75, 78, 83]. 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. [7] 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 [83]. When taking this into consideration, the conclusion of an eco-driving training program changed from “effect was stable over time [82]” to “effect was grad[redacted] lost [83]”. In addition, the training effect was highly heterogeneous between individuals [75][redacted] large percentage of trainees would exhibit no change or even become worse after training [80, 82]. A survey study showed that eco-driving interventions were more effective with high levels of pre-intervention motivation or supervisor support [86]. Studies also showed that eco-driving training was more effective under city conditions than highway conditions [75], and was more effective for manual transmission cars than automatic cars [75, 76]. A main challenge of eco-driving training programs is the fair evaluation of the effectiveness [87]. 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 (e.g., several drivers many share one vehicle and one driver may drive different vehicles in a company or family context) [7].

The above programs were all for the existing licenced/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 [88]. 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 [89, 90]. 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 [91]. Strömberg et al. [92] investigated the effect of the introduction of eco-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.

3.2. 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 [93]. The type of feedback also varies greatly, such as visual versus auditory versus haptic [94], real-time versus delayed [95], continuous versus intermittent [96], and general versus personalised [97]. 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.

Safety

Safety is the most important concern in a driving task. Generally, eco-driving largely overlaps with safe-driving [98]. 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 [99, 100]. Staubach et al. [101] 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. [96] reported that intermittent visual eco-driving information had shorter dwell time than continuous information did. Stahl et al. [102] 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 [103]. Jamson et al. [104] 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. [93] 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 divers might have up to 50% spare attentional capacity during normal driving [99]. 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 [105, 106]. These guidelines apply for both the original (Phase 1) [105] and portable and aftermarket electronic devices (Phase 2) [106] that are operated by the driver through visual and manual means.

Acceptance

Acceptance of in-vehicle eco-driving devices largely determines their effectiveness. Although most drivers are willing to adopt eco-driving skills [107, 108], 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 [109]. It has been clearly shown that different drivers had very different preferences on the type of information and th majority preferred simple and clear information [110]. 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 [111]. Therefore, a personalised feedback could increase drivers' acceptance and motivation [111, 112]. Regarding the feedback type, auditory feedback, alone or in any combination with visual or haptic feedback, was not well accepted [113] and haptic systems were more acceptable than visual or auditory systems [101, 114].

Effectiveness

Table 2 shows the effectiveness of various types of in-vehicles eco-driving devices. As shown in Table 2, 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 [115, 116] or after a certain period (e.g., weekly) [95]. Experiments using field trials and driving simulators showed that real-time feedback was more effective than delayed feedback [95, 115, 117]. Real-time feedback was usually either visual, auditory, haptic or their combination. As shown in Table 2, 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 [114]. Auditory feedback required less cognitive efforts and could be complementary to visual devices [93, 114]. 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 feedback [94, 101, 110, 118]. Haptic feedback provided drivers with advice through the accelerator pedal by either extra force, increased stiffness or vibration when over acceleration occurred [94, 119, 120]. Haptic feedback was effective for speed control and collision avoidance [118, 119, 121] while the limitation was that it only provided feedback on the use of the accelerator pedal. Table 2 also shows that the fuel savings of field trials are typically lower than those of driving simulators and modelling. It has been well confirmed that in-vehicle devices were more effective in urban and congested traffic than in rural and highway traffic [122-125]. 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 [125]. In-vehicles devices were also significantly more effective for aggressive drivers than normal or mild drivers [116, 124]. As shown in Table 2, 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% [123, 124, 126, 127]. However, longer term studies (several weeks or months) showed much lower fuel savings (< 8%) [95, 128-132]. This indicates that in-vehicle devices have the same limitation as training programs. That is, the effectiveness attenuates over time.

Table 2 Effectiveness of in-vehicle eco-driving devices.

Feedback type	Testing method	Study period	Fuel savings	Sources
Delayed	Driving simulator	3 runs	3.43%	[115]
Delayed	Field frails	3 months	0%	[95]
Real-time visual	Driving simulator	6 runs	16%	[122]
Real-time visual	Driving simulator	2 runs	9-15%	[125]
Real-time visual-haptic	Driving simulator	3 runs	15.9-18.4%	[101]
Real-time auditory	Driving simulator	3 runs	5.45%	[115]
Real-time haptic	Driving simulator	7 runs	12%	[120]
Real-time visual + delayed	Modelling	N/A	19.47-30.33%	[116]
Real-time visual	Modelling	several runs	37.3%	[123]
Real-time visual	Field trails	several runs	13%	[123]
Real-time visual	Test track (no traffic)	3 runs	30%	[126]
Real-time visual	Field trails	2 days	4.4-25.3%	[124]
Real-time auditory-visual	Field trails	90 runs	11.04%	[127]
Real-time visual-auditory	Field trials	14-22 days	7.61%	[128, 129]
Real-time visual vs delayed	Field trails	37 weeks	3-6%	[130]
Real-time auditory	Field trails	2633 h/bus	0.3-2%	[131]
Real-time visual	Field trails	1 month	4.4%	[132]

3.3. 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 [133] and its amendment Commission Directive 2012/36/EU [91] 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 [91]. These criteria correspond to the five golden and eight silver eco-driving rules [88]. Other legislative actions on eco-driving is the Engine Idling Laws in the US [45, 134] and Hong Kong [135], 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 outside the European Union.

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 [6] 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 [136] 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 [137] 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 [117, 138, 139]. 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 [140, 141], Progressive's Snapshot Program [142] and OnStar's Smart Driver Program [143].

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 [47]. Drivers also usually put a lower priority on fuel saving than time saving and convenience [109, 144], making excessive speed common on highways and reducing speed limit being extremely unpopular [19, 22]. 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 [12], Australia [11], Europe [90], Japan [145] and China [146]. 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.

4. Challenges and research gaps

Road transport consumes a large amount of fossil fuel and emits significant CO_2 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 Section 3, 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 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 sa[redacted] 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 CO_2 emissions, but did not cover pollutant emissions such as CO, HC, NOx and PM. Trade-offs may be needed between fuel economy, pollutant emissions and travel time [147]. Different eco-driving strategies may be required for different purposes.
- Current eco-driving studies mostly focus on individual's driving behaviours, but lacks consideration on 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.

5. 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. An immediate and significant reduction in fuel consumption and CO_2 emissions can be 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 on network levels should also be considered.

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