Renewable and Sustainable Energy Reviews 93 (2018) 596–609

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Eco-driving technology for sustainable road transport: A review

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ARTICLE INFO

Keywords:
Eco-driving
Driving behaviour
Fuel consumption
Emissions
Training and feedback

ABSTRACT

Road transport consumes significant quantities of fossil fuel and accounts for a significant proportion of CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 reduction by 2030 below 2005 levels for the major CO_2 emitting countries [5], together with their shares of global CO_2 emissions in 2015 [6]. These major countries accounted for 80% of global CO_2 emissions in 2015. As shown in Fig. 1, on average, most countries are planning to reduce their CO_2 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 CO_2 emissions, 75% of which are emitted by road transport [7]. Moreover, it is estimated that the energy consumption and CO_2 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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https://doi.org/10.1016/j.rser.2018.05.030
Received 16 August 2017; Received in revised form 16 April 2018; Accepted 13 May 2018
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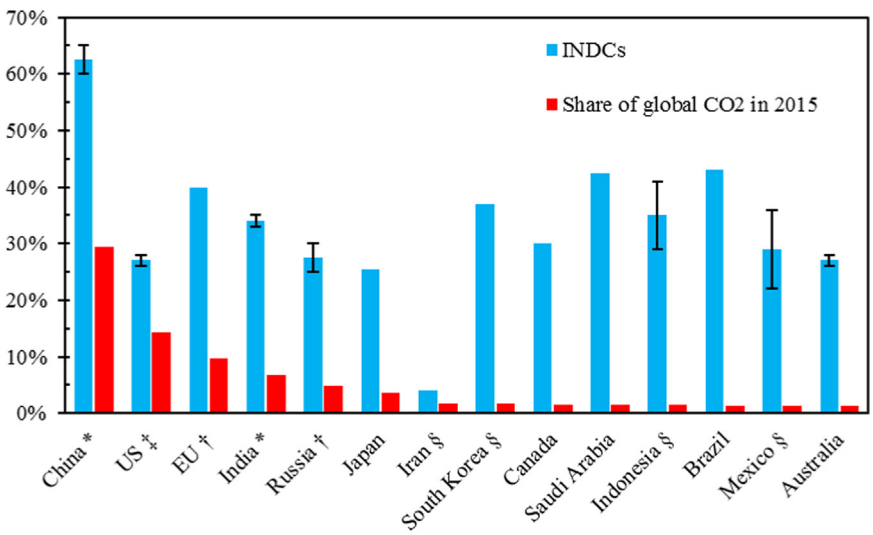

Fig. 1. INDCs as percentages in CO_2 reduction by 2030 below 2005 levels for the major CO_2 emitting countries, as well as their shares of global CO_2 emissions in 2015. Data sources are [5] for INDCs and [6] for shares of CO_2. Error bars indicate the ranges of INDCs. Symbols for INDCs: * per unit of 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 the 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

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