A critical review of Eco-driving and CO_2 Emissions modelling to facilitate Eco-routing

Md. Saniul Alam
PhD Researcher
Trinity College Dublin

Dr. Aonghus McNabola
Assistant Professor
Trinity College Dublin

ABSTRACT

The main goals of Eco-Driving comprise environmental protection, air pollution remediation and road safety improvements. To achieve these goals, Eco-Driving can be achieved through several methods such as the addition of advanced vehicle technology (e.g. controlling/limiting acceleration) and/or the energy efficient choice of route (Eco-routing) or transport mode (i.e. less vehicle idling, less time in traffic congestion, or lower emissions intensity). Incorporating any of these methods or any of their combinations into a trip clearly indicates that less emission should be caused by the trip compared to a normal trip with the same origin and destination.

This paper presents a review of available literature on Eco-Driving identifying the opportunities and challenges facing this emissions reduction tool. The reported benefits and possible disadvantages of Eco-Driving are outlined as are the reported methodologies of implementing Eco-Driving. Finally, the research on modelling of Eco-Driving trips in terms of trip by trip emissions estimation and prediction with the goal of providing carbon footprint information to road users to is also reviewed. Eco-routing requires information on the environmental impacts of such choices (i.e. route A or B, mode A or B) to be communicated to road users prior to their departure. Therefore, Eco-Driving behaviour in this context requires emissions models to be developed which are capable of predicting emissions on a trip by trip basis. Armed with information on the predicted CO_2 emissions of taking route A or B, using mode A or B etc, individuals may make more environmentally informed decisions on their travel behaviour.

1. INTRODUCTION

Vehicle Emission is the subject of wide concern among government agencies worldwide, for its known negative environmental impacts, including human health [1] and climate change [2]; [3]. It was noted [4] that transport emissions comprise 26% of the overall CO_2 emissions in EU. This is a cause for concern due to the high traffic demand growth rate, estimated to increase by 50% for freight and 35% for passengers between 2000 and 2020 [5]. In response to this and the emission of green house gases in other sectors, many countries have committed to reducing their total emissions by set percentages over the coming years to combat climate change and improve environmental health [6]. As a result, governments are intensifying efforts to reduce CO_2 emissions across all sectors, including transport through various initiatives.

In the transport sector, these initiatives include improvements in vehicle technology and the implementation of policy tools to combat climate change. These tools cover a wide range of areas such as direct interventions on vehicle movement, e.g. fuel tax, congestion pricing, parking pricing policies, overall system management, etc. Others include improvements in public and sustainable transport, technological improvements, carbon tax systems [7]; [8], subsidy provision for Eco-Driving [9] and raising public awareness of carbon footprints. Increasing the awareness of individuals about the impact of their activities on the global environment has the potential to reduce CO_2 emissions. It was argued [10] that achieving policy targets for individual carbon emissions reduction will require measures to improve the individual's decision-making, practices, and structural engagement simultaneously. Thus, policies aiming to reduce CO_2 emissions from a bottom-up approach like Eco-Driving presents an interesting subject for critical examination.

This paper presents a review of the available literature on Eco-driving policies and tools, identifying the opportunities and challenges facing this emissions reduction strategy. The reported benefits and possible disadvantages of Eco-Driving are outlined as are the reported methodologies of implementing Eco-Driving. Finally, the research on modelling of Eco-Driving trips in terms of emissions estimation and prediction with the goal of providing carbon footprint information to road users to facilitate Eco-Driving or Eco-routing is also reviewed.

2. ECO-DRIVING

2.1 Policy

Eco-Driving policy is a growing concern worldwide. Several European countries such as Austria, the Netherlands, Spain, and Germany have incorporated Eco-Driving policy within their national CO_2 reduction or climate change strategies. It has also been reported that Eco-Driving in the United States has been abandoned at the national level.

It was reported [12] that the European Union has mandated the fitting of Gear Shift Indicators (GSI), which display shifting up or down signs on the instrument panel to ensure optimal gear changing and thereby improved fuel efficiency, in all new cars from 2012. In 2001, Eco-Driving Europe began to accelerate the establishment of Eco-Driving in Europe by providing guidance to the drivers. In individual EU countries such as Ireland, national policy has been developed which recognises that driver behaviour (Eco-Driving) can significantly affect the amount of energy and emissions from a single vehicle (Smarter Travel policy paper 2009-2020). According to the policy paper [13], efficient driving can reduce emissions by up to 10%, with lower savings in the long-term, through driving more moderately, using on-board fuel monitors and avoiding rapid acceleration and excessive braking. Under this policy action, it was recommended that research on on-board technology should be a focus for public vehicles to reinforce Eco-Driving behaviour and promote efficient driving in the haulage industry.

In the Netherlands an Eco-Driving government programme resulted from the Kyoto agreement and from national policy documents targeting CO_2 emission reductions from transport. In 2006 it was shown that a CO_2 emissions reduction of 0.3 t and 0.6 t were directly and indirectly related to these Eco-Driving activities [14]. Eco-driving as a government policy has also been in place in Japan since 2003. Government grants have been available to subsidise Eco-Driving Management Systems (EMS) since 2005, and all of the relevant ministries and agencies were engaged in promoting Eco-Driving [15]. Similarly, in Switzerland a subsidy for the promotion of Eco-Driving has been provided as part of the Swiss Energy Action Plan in order to promote fuel savings of between 10% and 15%, as well as fewer accidents, less wear and tear of vehicles, and greater protection of the environment [9]. Korea and New Zealand have also recently commenced Eco-Driving policies since April 2010 and March 2009 respectively [12]. Thus, Eco-driving is a growing area of policy focus worldwide but, the underlying limitations and critical examination of Eco-Driving are often neglected.

2.2 Methods and Practices

The claimed benefits of Eco-Driving across a number of different studies include: general claims about reduction of fuel consumption by 10% [11]; reduced fuel consumption by 5 to 15% in different European Eco-Driving programs [16]; potential fuel savings of 10–15 % due to modern engine technology, i.e. smart, smooth and safe techniques [17]; etc. Such savings in fuel have subsequently resulted in monetary savings, for example, an estimation of 10.2% in fuel saving during an Eco-Driving training session of bus drivers in Athens estimated savings of €6,630,000 per annum [16].

Several different strategies have been developed to facilitate Eco-Driving, including training courses, driving contests, driving assistance tools (e.g. displays communicating suggestions on vehicle speed or route choice) and tools for acceleration control (e.g. an active acceleration pedal). Among these, driver learning has been shown to have a lower impact in the long term. It was found that most drivers show an immediate improvement in fuel consumption with Eco-Driving training that was stable over time, but some tended to revert back into their original driving habits over time [18]. Driver training and the addition of vehicle control devices for Eco-Driving have received significant attention amongst Eco-Driving investigations. However, Eco-Route choice has received little attention in contrast.

The control of driving to reduce CO_2 emissions can be achieved through maintaining constant speeds, controlling acceleration and gear ratio. Researchers [19] developed a model of optimal driving strategy for the assessment of Eco-Driving; here vehicle speed and gear ratio were identified as influencing variables. An investigation was [20] conducted at a signalized road where vehicles were equipped with dynamic Eco-Driving technology and found that there were indirect network-wide energy and emissions benefits to overall traffic, even at low penetration rates (5% to 20%) of those vehicles. This was due to the influence of Eco-Driving vehicles on the behaviour of the following vehicle in a line of traffic, i.e. the following vehicle(s) are also forced to reduce hard acceleration and braking.

As the evidence suggests, controls on driving may cause a reduced individual impact on the environment when considered in isolation but at the level of an entire traffic network this may interfere with traffic performance. A group of researchers [21] used micro-simulation at intersections and found that Eco-Driving based on moderate and smooth acceleration can cause negative environmental impacts (with higher total emission). The changes in behaviour of a single Eco-Driver may cause unusual driving behaviour in the following drivers in the traffic, thus affecting both traffic performance and environmental performance in the link/intersection. Therefore, it must be noted that if Eco-Driving was a widespread practice that traffic as a whole may be slower to progress through the network. The introduction of speed based Eco-Driving behaviour may reduce the signalized intersection capacity by allowing fewer numbers of vehicles to pass at an intersection for a given period of time. Thus, speed control based Eco-Driving is a debatable topic and requires further investigation. It may be concluded that widespread Eco-Driving could result in an increase in traffic congestion time and as a result CO_2 emissions. However, this point is unclear and requires further research as signal timings may be adopted to accommodate such changes in driver behaviour. Furthermore Eco-Driving on longer distance journeys in the absence of congested city centre type traffic would clearly not suffer from this complication.

Investigations have also shown that an Eco-Driving car only impacts the following cars driving behaviour and has a little impact on other cars behind in the same lane. It was also reported that Eco-Driving may also increase the number of the overtaking cars, i.e. drivers overtaking an Eco-Driver resulting in increased emissions and road safety risks [22].

It has been estimated that the choice of route, using a fuel consumption and emission models, can result in energy savings of up to 23%, if motorists choose lower emissions routes (Eco-Routing) [23]. An investigation was conducted in Sweden to analyse fuel consumption and CO_2 emission using a navigation system where optimization of route choice was based on the lowest total fuel consumption. It was found that 46% of trips, which were the result of a drivers' spontaneous choice of route, were not the most fuel-efficient. These trips could save, on average, 8.2% of fuel by using a fuel-optimized navigation system. This corresponded to a 4% fuel reduction for all journeys [24]. The available evidence therefore suggests that significant fuel and CO_2 emissions savings could be achieved through the adoption of Eco-Routing behaviours and technologies in single trips.

However, it could be also argued that if Eco-Routing information was disseminated widely to road users this may make a suggested route no longer the eco-friendly choice if all drivers choose that route. Such criticism could be eliminated if the selection of Eco-Route is based on real-time data rather than the current practice of static or average value models. It must also be recognised that the widespread adoption of Eco-Routing would ideally result in an equilibrium state in terms of CO_2 emissions between available route choices. Therefore the fuel and emissions savings found in previous investigations based on controlled experiments may overestimate the ultimate savings achievable using this technique.

In addition, Eco-routing may have other limitations in real world practice as Eco-Route preference is generally based on emission/fuel consumption, which often carries less importance compared to the journey time of a route choice to the drivers [25]. However, a pilot study in the United States [16] found that Eco-Driving practices are highly elastic and that existing eco-drivers, which were about 40%, could reach 95% with oil price increases.

3. EMISSIONS MODELLING

3.1 Current Practices and Limitations

Static emissions modelling for Eco-Driving is widely available; however, existing models have limitations in terms of predicting the trip by trip emissions precisely. Most of the available tools are either capable of predicting emissions for a given route/trip, based on average vehicle trajectory data or the average emission rate, but none take account of real time traffic information. Emissions can also be estimated in real time capturing instantaneous engine data by using additional data capturing devices. Sometimes specific navigation or display devices are necessary to get real-time or predictive emission information.

Of the generally used models capable of estimating individual carbon footprints, models can be classified into aggregated data, personal diaries, and trip-by-trip cases [26]. The latter case is suitable for the promotion of Eco-Driving and can be further classified by mobile phone application based or online based models. There are also some other models whose usability is limited to within the research arena. The limitations of all of these models can be discussed in the following categories: 1. Additional device use; 2. Methodological accuracy of the application/suitability for Eco-Driving, and 3. Timing of application: prediction, real time, or post trip. First two limitations are more applicable for real time emission calculation models.

1. A study [27] reported on the development of a system whereby some devices were added to vehicles to assist drivers in Eco-Driving/safe driving in Japan. Assisting devices displayed instantaneous fuel rate and CO_2 emissions information, also advising on acceleration/braking rates. An application of a similar study [28] used this approach, which also required a device to be installed in a vehicle to obtain data from the engine in real time. Similar to this approach, another study [18] evaluated the long-term impact of an Eco-Driving training course where GPS measurements were used to monitor the position and speed of vehicles and a device was used to obtain electronic engine data. A group of researchers [29] developed a navigation tool to assist drivers in choosing a route based on energy and emissions. The inherit challenge for the widespread use of using these approaches was the requirement to use additional devices whether as a display device or as a data capturing device for each vehicle/user.

2. Real time emission calculation in existing practice does not often consider basic modelling issues. These limitations can be categorized as omitting second by second vehicle trajectory as model input data, capability of the models for instantaneous calculation of emission in online mode, and overlooking classical methodological issues. The following discussed models used GPS and/or accelerometers, however, did not consider second-by second vehicle trajectories. [30] used accelerometer data (avoiding use of GPS data) and used inbuilt engine parameters to calculate fuel consumption and emission. [26] used accelerometer for mode detection (e.g. walk or car) and used GPS to compute total distance travelled as an input for the CO_2 emissions calculation. [31] reported that their smartphone application detected transportation mode, in real-time, by studying the speed, position and pattern of the movement using GPS data, GSM Cell Tower location and the phones sensors. However, carbon footprint for a journey is calculated by multiplying travelled distance with travel mode based emission multiplier.

Few models have been developed with a strong theoretical backup but these may not be suitable for online calculation of emission for real-time trip-by-trip cases. These models are either designed for accepting simplified input data for analysis e.g. link based approach or based on driving cycles. The link based approach often takes account of average value whereas driving cycle based modes have the criticism of using either smooth acceleration profile (e.g. European Driving Cycle) or not representing actual driving condition and thus underestimate the emission [32].In these circumstances, the following three methodologies may not be suitable for real time application. Researchers [33] outlined the development of an Eco-Driving model that accounted for engine stress and Vehicle Specific Power (VSP is the sum of external forces opposing vehicle motion multiplied by vehicle speed and divided by vehicle mass) to characterise six primary driving patterns for links which was subsequently applied to estimate the fuel consumption and emissions for the links. An application [34] can be mentioned here that calculates emissions (per second for CO_2, CO, NO_x, HC and PM) and fuel consumption (based on few assumptions: flat terrain, 'normal' driving and gear change assumptions etc.) made by a vehicle during a defined 'drive-cycle' which was generated, based on instantaneous (one Hz) speed data from the GPS receiver. Researchers [35] developed an eco-friendly route model using eco-drive cycles through the use of the dynamic programming optimization method for a vehicle in off-line simulation which may not be suitable for real time situation due to high computational cost and use of driving cycle concepts.

Second by second vehicle trajectories are important because during a hard acceleration period the engine load increases. [36] indicated that during periods of high engine load CO is the main output reducing CO_2 discharge as fuel to air ratio is not sufficient. Other important methodological limitations for existing real time applications are omission of road grade and hot and cold emission factors. A number of studies reported that the CO emission rate increases as road grade increases for light-duty gasoline vehicles [37, 38]. Therefore emission factors vary for CO and CO_2 significantly in these cases.

3. Post trip evaluated information [39] seems to have less impact on eco-driving compared to on-route information. Thus, it can be argued that both the prediction and estimation of emissions are necessary for on route or pre-trip decision making if the aim is to reduce the carbon foot prints of individuals. The discussed Eco-Driving tools clearly have a limitation as none of the tools can provide real-time calculation and prediction simultaneously. It is obvious that predicting emission/fuel consumption for a future trip should be based on route segments rather than vehicle trajectories as later is impossible to predict. Many previous investigations have predicted route based emissions/fuel consumption; however, these have not taken account of real-time traffic information. Rather those models are based on very basic distanced based analysis (e.g. [40], [41]). In many cases, the emphasis has been given on sharing past travel data/historic data for eco-route choice [42]. Therefore, trip-by-trip emission prediction modelling based on real time traffic is not still well established.

3.2 Emission models for eco-driving/routing

A system developed for assisting Eco-Driving behaviour should include both real time estimation and prediction applications for emission. Real time emission can be predicted for a desired route to understand the environmental impact of travel from emission point of view. The most critical argument here we discussed for modelling is that the data use for model development and input data for analysis should be spatially referenced. In other words, the data collected must take account some of the local characteristics (e.g. road grades) and location of the routes must be identified by the models.

Modal modelling [43] for real time emission calculation considers instantaneous second by second vehicle trajectories (e.g., speed and acceleration from GPS [44]). It will also consider congestion [43] and high emission from aggressive driving [45]. An algorithm may be developed using Neural networks for internal combustion engines [46, 47] which will take account of VSP [48, 49] derived from vehicle trajectories. To train the neural network, portable emission monitoring system data; speed and acceleration data (from GPS); and road grade data (from GIS) should be collected to convert into VSP in discrete bins. A switch in the neural network can be used for selecting a hot and cold emissions model based on the driving phase or length of driving performed.

Emission can be predicted for different routes and an optimal route can be selected based on the associated emissions. Alternatively, emissions can be considered as a cost component of route choice to find the optimal one as carried out by [33]. A simplistic model should be used to calculate emissions where improved speed or travel time link data will be the modelling input. Three possible approaches can be discussed for use of data for predicting emissions, either by: i) obtaining floating car speed data as input (as discussed earlier- 2-3% cell phone penetration equivalent to traffic flow velocity, [50]); ii) by applying a NN for forecasting volume from historical loop detector data and using speed vs. volume curves; iii) or building a deriving cycle generation tool capable of working online based on real time variables [51]. But an inherit problem with these techniques is that such models will not react to sudden fluctuations in traffic, for instances the situation will be worse if most of the drivers choose the Eco-friendly route as suggested by the model. To avoid this limitation, it is necessary to connect the model with real time traffic signalling systems (SCOOT, SCATS or UTOPIA) in the local area. The loop detector occupancy data, a by product of the traffic signalling system, should be used to calculate the speed of the links. The point here is that many investigations have been carried out on freeways to calculate speed from loop detector data, but such attempts are absent for signalized urban areas where a single loop detector provides information in a link. This has been thus identified as a key component of the research for emission prediction models in this context. Further improvement of the prediction can be possible using Excess cold start emission per start.

4. CONCLUSION

This study notes that Eco-Driving is often promoted worldwide without any rigorous level of assessment about suitability of methods and their possible impact at the total network level. Thus, a critical examination was carried out on Eco-Driving methods and concluded that Eco-Routing has much potential over other methods.

The paper also pointed out that an eco-routing tool should have two parts: prediction and real time estimation. Thus, the paper discussed possible benefits of considering modal model and identifies areas of improvement for a trip by trip emission modelling for eco-routing. In addition, an outline has also been drawn for predicting emission for the eco-routing purpose.

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