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MICROSCOPIC SIMULATION STUDY OF ECO-DRIVING PERFORMANCE AT URBAN INTERSECTIONS

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ABSTRACT

Eco-driving, which refers to an ecological way of driving, has been found to have great potential to reduce fuel consumption and greenhouse emissions in general. However, in urban areas, one particular eco-driving style, called "gentle acceleration" is under debate. The "gentle acceleration" may interrupt the queue discharge rate at signalised intersections. To explore this issue, this study firstly reviewed the existing eco-driving assessment methods. Based on the review, the paper suggests using microscopic simulation as an evaluation tool. The paper discusses three challenges for study of the eco-driving performance based on microscopic simulation approach. They are:

- Simulate realistic eco-driving acceleration behaviour
- Consider variation in response time to green onset
- Assess penetration rates of eco-drivers

Keywords: eco-driving, microscopic simulation, fuel consumption, CO2 emission, queue departure

INTRODUCTION

At a time of increasing fuel costs and carbon footprints, road transport sectors keep seeking appropriate strategies for sustainable development. Eco-driving is one of the available approaches that aims to reduce fuel consumption and CO2 emissions. Different from other strategies, such as developing alternative fuels and cutting-edge engines, eco-driving only focuses on improving driving behaviours. It promotes an effective way of driving which could be easily adopted by drivers regardless of vehicle classes, vehicle ages and fuel types.

In the literature, eco-driving is denoted as a special way to use vehicles, with the fundamental objective to improve energy efficient and environmental friendliness (Beusen et al., 2009; Barth and Boriboonsomsin, 2009; eco-drive.org, 2012; SenterNovem, 2005). Typically, eco-driving covers, but is not limited to, the following topics:

- For manual transmission, shift gear up as soon as possible (e.g., shift up before approximately 2500RPM for petrol cars)
- Accelerate and decelerate smoothly
- Anticipate traffic flow (e.g., look ahead and anticipate to surrounding traffic and situations)
- Maintain a steady speed
- Switch off the engine at long stops, such as stopping at railway crossing
- Avoid unnecessary weighs
- Maintain a vehicle in good condition (e.g. vehicle maintenance)
- Check tyre pressures regularly
- Use fuel-consuming/emission indicator
- Use real-time driving assistant equipment (e.g. GPS, eco-indicator or advanced driving guidance system)

It has been widely agreed that eco-driving has considerable benefits in terms of fuel economy, safety, and environment. Since the early eco-driving project, the number of 5-10% average fuel saving has been recognised in many studies (Greene 1985; SenterNovem 2005; CIECA 2007). A Spanish study revealed a significant fuel reduction of 13.4% after using eco-driving (SenterNovem, 2005). Accompanying fuel economy benefits, eco-driving is also productive to reduce greenhouse emissions, especially of CO2. The Swedish National Road Administration assessed the emission performance of a group of drivers before and after providing eco-driving training courses. It is discovered that all the eco-driving participants succeeded in reducing 10.9% CO2 emission on average (Johansson 1999). Rafael et al. (2006) investigated the emission patterns for various categories of driving style, which implied the potential benefits of an eco-driving style with steady speed and smooth acceleration and brakes. Although the safety performance has not been precisely identified in the literature so far, it is also expected to be a collateral benefit of eco-driving.

However, it seems that many of the existing eco-driving studies haven't comprehensively justified the impacts of eco-driving. It is not only because they are conducted under specified testing environments and constrains, such as vehicle type, time of day, driving routes, etc. (Symmons et al., 2009), but also because the common design of eco-driving evaluation lacks a global perspective on traffic flow performance (Qian and Chung 2011; Olivier 2011).

A particular eco-driving tactic (i.e. adopting soft acceleration at intersections) is now under debate. If a driver accelerates gently for the purpose of fuel saving, the slow moving vehicle may retard the discharge speed of its following vehicles. This causes discussion as to whether the eco-driving would bring negative impacts onto non-eco-users. Also, if the saturation flow rate is compromised due to the ecological but slow moving vehicles, the subsequent reduction of the intersection capacity would tend to cause congestion. In that situation, the excessive fuel consumption and emissions generated by the congested vehicles would soon negate the benefits obtained from the eco-vehicles.

This study, therefore, aims to seek an appropriate approach to explore the aforementioned debate. The paper is arranged as follows. The next section provides a brief review about the existing eco-driving assessment methods. It is recommended to follow the microscopic simulation approach for eco-driving study. Then the basic framework of a microscopic simulation is introduced, followed by the discussion of three challenges to simulate eco-driving behaviours. A brief conclusion is provided in the last section

ECO-DRIVING ASSESSMENT METHODS

As the popularity of eco-driving has increased, assessing the effectiveness of the aforementioned tactics has gained lots of attention. Considering there is an ordinary traffic system which has normal drivers and traffic performance as the input and output respectively, introducing eco-driving becomes a new input to the system. Then, the eco-driving evaluation task becomes similar to a control problem, in which researchers are interested in figuring out the relationship between the input (i.e. eco-driving) and the output (i.e. corresponding performance). As concluded by Smit et al. (2009), the most important and difficult part of eco-driving assessment is to quantify the input and its corresponding performance. In the literature, there are three types of evaluation methods (i.e. field experiment, driving simulator and traffic simulation).

Field experiments are among the most popular approaches in the literature (SenterNovem, 2005; Smit, 2010; Symmons et al., 2009). It directly compares before-and-after performance based on real drivers on real road environments. As the performance, such as driving speed, fuel consumption and CO2 emission are normally measured by high-resolution sensors. It is able to precisely represent the output of eco-driving. However, it has some weak points. Firstly, this type of assessment is labour-intense and time-consuming because it requires all inputs and outputs to be based on real driving experience. In addition, it is almost impossible to ensure before-and-after comparison to stand on the same benchmark. The common design of field experiment is to conduct tests under similar traffic conditions, such as unique driving routes and at the same time of day, which would neglect complexity and variation of many microscopic traffic features. For instance, the delay time caused by traffic signal control at a certain intersection would be simply different in two test cases. Last but not least, it is difficult to completely interpret the output results, because much information, such as how a driver understands a specific eco-driving tactic and to what extent an eco-driving instruction has been followed, is sometimes unavailable or unable to be quantified in the field experiment. Then, these parts of the information are usually smoothed in the averaged output with little explanation, which does not reflect the real impacts of eco-driving (Symmons et al., 2009).

Driving simulators have been increasingly implemented for environment-related studies (Hornung, 2004). A typical driving simulator displays the virtual environment and has a driving controller which could be either a full-sized vehicle or simply a steering wheel. This approach could effectively reduce the experiment cost, especially in developing a variety of scenarios. As the scenarios are repeatable, this approach ensures the before and after test-bed could be equally compared. However, as the driving environment is virtually replicated, the outputs, including driving behaviour and traffic performance, would highly rely on the fidelity of the simulator. Also, it is required to ensure that drivers understand and conduct eco-driving correctly before the experiment is carried out.

The rapid development of computing technology has boosted the spread of traffic simulation. This approach relies on all virtual environments, including virtual roads, simulated drivers and replicated traffic controls, which could significantly reduce the labour involved in eco-driving studies. As simulation adopts modelled driving behaviours and virtual roads, the flexibility of scenarios could be further extended. That is to say, traffic simulation is able to provide a variety of test-beds (either real or not real) with relatively less cost. The key task to follow this approach is to properly replicate driving behaviour and corresponding performance. Under this circumstance, the input (i.e. eco-driving) could follow the desired behaviour closely for better representing eco-driving strategy. However, this approach requires much more data for test-bed calibration and validation than using filed experiment or traffic simulator. Particularly, providing realistic eco-driving behaviours are of crucial importance.

As discussed above, in order to investigate eco-driving from a global point of view, traffic simulation could be a good choice in terms of cost-benefits and its capability to mimic eco-driving behaviours. Therefore, the study proposes a general framework for eco-driving study based on microscopic simulation as shown in Figure 1. The driving behaviour module is used to replicate driving behaviours, including normal driving and eco-driving. The traffic flow module is composed by individual driving behaviours with consideration of the traffic flow characteristics. The span between individual driving behaviour and traffic flow features usually relies on particular driving models, such as car-following model and lane-change model. Furthermore, the environment module utilise the flow features and the individual driving performance for environmental evaluation by use of fuel consumption models and emission models.

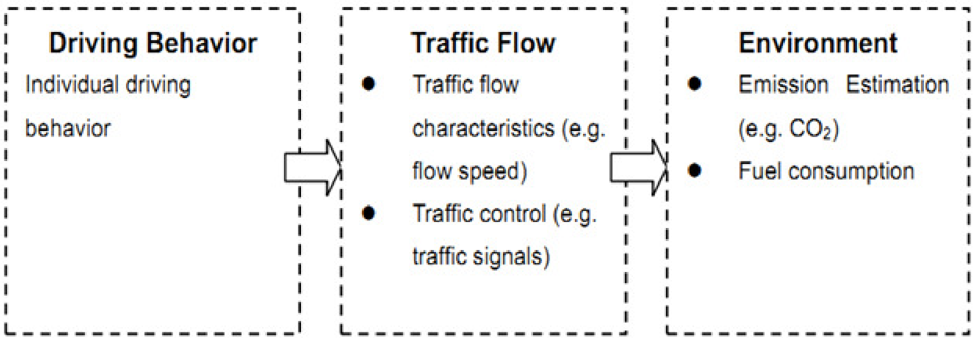

Figure 1 an example of a simulation-based eco-driving assessment framework

The design of the framework has great potential to provide comprehensive analysis of eco-driving performance. However, like all the simulation studies, it is vital to ensure that traffic simulation is able to describe the real driving behaviour and traffic flow characteristics before carrying out tests. A small difference between a real driver and the simulated driving unit could lead to significant difference in traffic flow characteristics, ending up with large error while estimating the network performance. The following sections will discuss several important issues for simulating eco-driving behaviours, which would be beneficial to improve the credibility of a simulation study.

ACCELERATION OPERATIONS

At urban intersection, stop-and-go manoeuvres are unavoidable and dominating in the traffic flow movements. Figure 2 illustrates a typical example of queue departure trajectories. When the traffic light turns to green, each vehicle will response and accelerate towards their desired speeds. Then, traffic flow characteristics, such as saturation flow speed and headway, could be measured accordingly. However, the ideal trajectories as shown in Figure 2 are not always available in reality. When there are various driving behaviours in a traffic flow (e.g. sportive driving and normal driving) the traffic flow will not be homogenous. Therefore, it is important and challenging to replicate reasonable acceleration operations and corresponding traffic flow features.

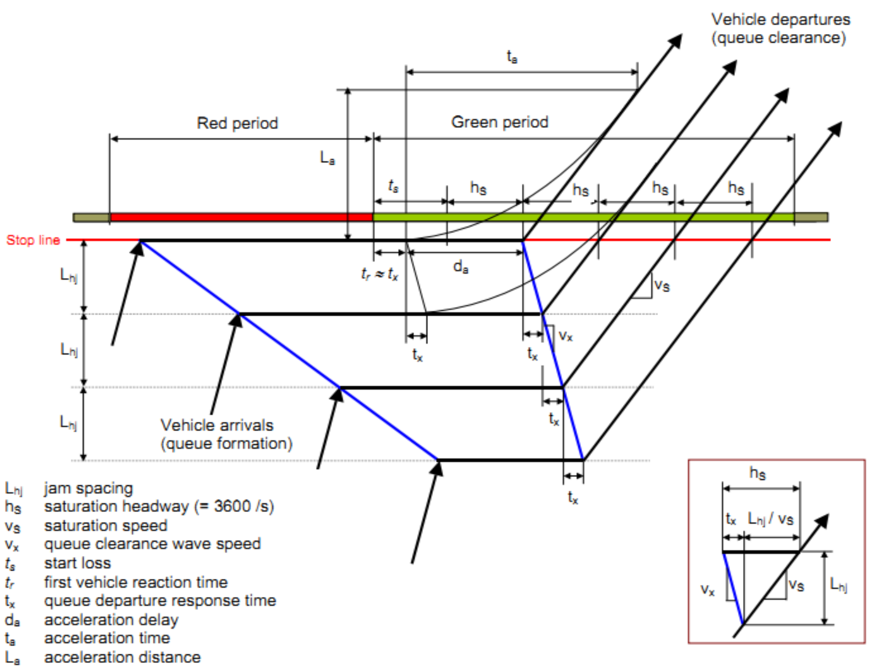

Figure 2 Queue discharge at a signalised intersection (source: Queue discharge flow and speed models for signalised intersections (Akcelik and Besley, 2002))

A common method to replicate eco-driving operation is to use the summarised speed or acceleration features collected from real driving behaviour data. Kobayashi et al. (2007) utilised the relationship between speed and acceleration rates collected from real eco-drivers as the input of eco-driving behaviours in the simulation networks. Qian and Chung (2011) also attempted to use the driving speed profile collected from real driving trajectories to mimic eco-driving behaviours. The collected eco-performance (i.e. speed and acceleration) is used to represent eco-driving. As long as the driving operations of the eco-drivers in a simulation model are properly calibrated against the observed features, it is reasonable to think that the eco-driving operations are mimicked. However, one shortcoming of this method is that only the statistical features of the eco-driving behaviours are interpreted and performed in the simulation studies. The simulated eco-driving only represents the macroscopic features of eco-driving, which usually covers only the averaged eco-driving speeds or acceleration rates. In other words, applying macroscopic features of eco-driving behaviour does not fully take advantage of the powerful capability of microscopic simulation in terms of replicating detailed driving operations.

Moreover, using statistical measurements of eco-driving behaviours seems to overlook the fact that the field-collected eco-driving acceleration or speed profile is the consequence of eco-driving as well as the traffic flow conditions. For example, the nature of intersection geometrics, experimental routes, traffic conditions and even the changes of driving behaviour within a driving trail, would affect eco-driving characteristics in reality. By using the eco-driving performance based on specific situation without detailed justification of the condition, it would further raise the debate on the credibility of the simulation test-bed.

Consequently, a potential solution is to have comprehensively understanding of the ecological driving behaviours and interpret corresponding behaviours in simulation environment with respect to the eco-mechanism but not the eco-performance.

Besides the eco-driving behaviours, the behaviours of normal drivers also need careful investigations. A normal driver that is following an eco-driver would be affected by the ecological driving style. Figure 3 displays an example of the queue discharge trajectories of two groups of vehicles at an intersection. The trajectory data is obtained from a real eco-driving experiment under signalised intersection environment (Qian et al., 2013). The dotted lines represent a group of four normal drivers, while the dashed lines display a group of vehicles that composed of an eco-driver at the first position and three normal drivers following the eco-leader. It can be seen in figure 3 that the “slowly-moving” impact of the eco-leader has been delivered from the eco-leader to the fourth vehicle in the queue, which implies the importance of interaction between eco-drivers and normal drivers.

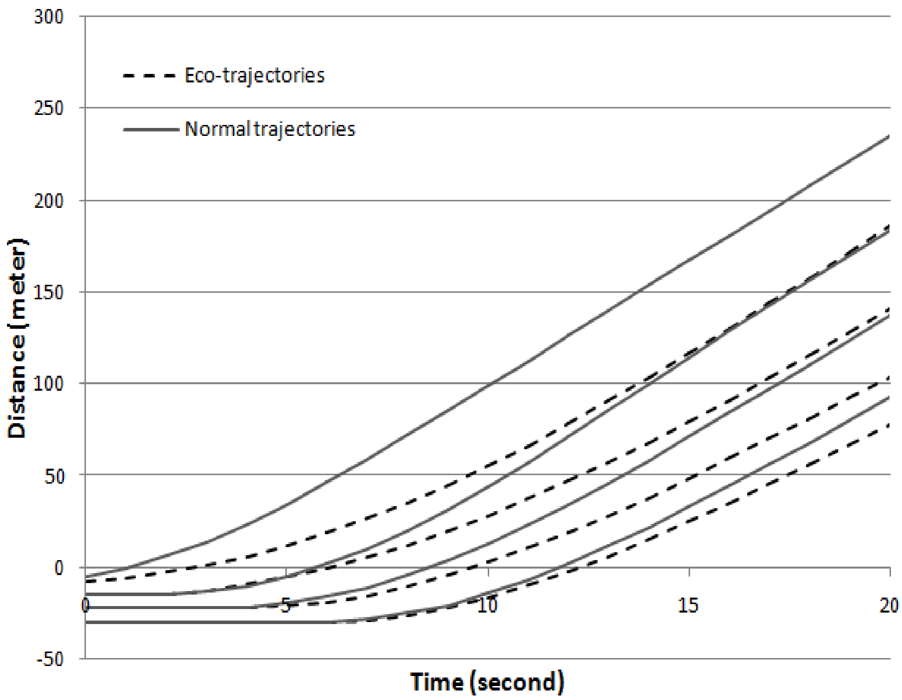

Figure 3 Normal trajectories and eco-trajectories at an intersection from an eco-driving experiment (Qian et al., 2013)

RESPONSE TIME BEFORE STOP-LINES

According to Figure 2, the response time of a driving unit might also influence the queue discharge behaviours at urban intersections. However, many of the car-following models embedded in microscopic simulators are lack of consideration on response variation at stop-lines with respect to certain driving behaviours.

By definition, most car-following model control driver's longitudinal driving behaviours with respect to the preceding conditions. This notion could be expressed as Eq. (1).

$$F_t = f[L_{t-1},\ F_{t-1}] + \beta \quad (1)$$

Where

F_t is the follower's driving behaviour at time t
L_{t-1} is the leader's driving behaviour at time (t-1)
f denotes a specific car-following philosophy
β is the error term

This car-following design regulates drivers' behaviours in a "reactive" approach. That is to say a driver will make decision to move vehicle in accordance with the traffic condition changes. As a result, applying car-following for queue discharge situation would generate a rule that a following vehicle would not start until the preceding vehicle start to move. This type of queue discharge behaviour might neglect some acceleration behaviours in reality. For example, after the green traffic light onset, a following vehicle with fast response may move immediately in a traffic queue if there is sufficient space ahead, while its leaders still keep standstill. This phenomenon has been spotted in the Peachtree St traffic trajectory dataset from the "Next Generation Community Program" (NGSIM Community, 2012). Figure 4 illustrates an example of the quick response. The third vehicle in queue started to move before the second vehicle started to accelerate. This phenomenon, however, is hard to replicate if a traditional car-following philosophy is applied.

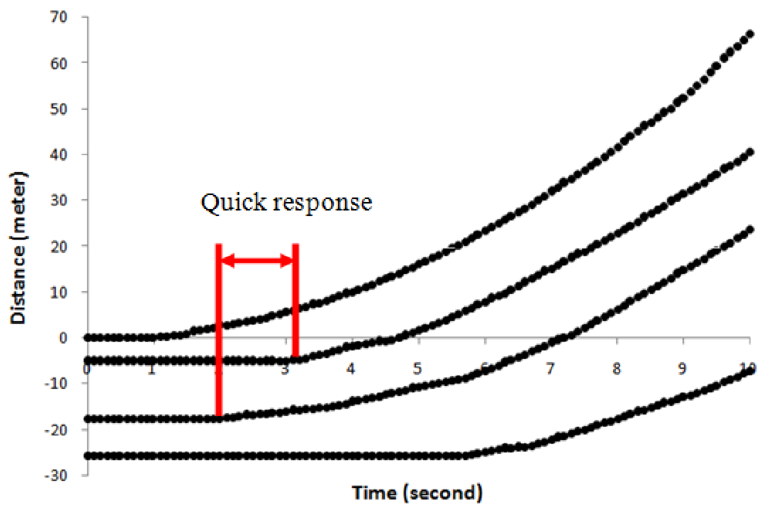

Figure 4 Quick response of a following driver

Moreover, Figure 4 indicates that the response times of individual vehicles are various. However, many of the car-following applications tend to use pre-distributed stop–line response time values without specification to any driving behaviours (i.e. conservative driving, normal driving and sportive driving). Considering a driver who adopts soft acceleration, it is highly possible that the response time would be different from a normal driver. This is because a driver with soft acceleration may be well aware of the slow moving features of his/her behaviour to for start-up decision-making.

PENETRATION RATES OF ECO-USERS

When evaluating eco-driving from traffic flow perspective, penetration rate of eco-drivers is another important factor that would affect the net performance. In simulation, it is not difficult to emulate different penetration rates, but how to investigate and interpret the impacts caused by different penetration rates is challenging. The study conducted a simple simulation test with the purpose to have some brief understanding of this impact.

The study selects a particular intersection on Peachtree St, in Atlanta Georgia, U.S. The data is sourced from the “Next Generation Community Program” (NGSIM Community, 2012). The dataset consists of detailed trajectories, traffic flow information and signal timing operations for a period of 30 minutes on November 8th, 2006. The test bed is developed with Aimsun simulator version 6 (TSS, 2010). The study only uses the northbound through lane traffic for modelling and analysis. The simplification is made because other movements in this intersection did not include sufficient queuing vehicles during the analysis period. In the test-bed, the demand of the through lane is configured as 548 vehicles per hour, which compiles with the observed traffic flow from NGSIM dataset. The traffic signal timing is set according to the observed timing operations which utilised fixed signal timing control during the analytical period. The cycle time is 100seconds, and the green split for the northbound through traffic is 40 seconds.

According to the aforementioned discussion, it is important to simulate the driving behaviours and queue discharge characteristics at intersections. The selected simulator, Aimsun, adopts a safety distance based car follow model which was developed by Gipps (1981). The model classifies the driving actions as free moving or following. Therefore, for intersection studies, vehicle parameters (i.e. accelerations rates) should be adjusted in accordance with the observed data for both the leaders and the followers. Figure 5 shows the calibrated simulation speed profiles against the observed speed profiles of a preceding vehicle and a following vehicle, respectively. The observations are plotted based on the NGSIM trajectory date, while the simulated speeds are outputted from the Aimsun simulator. The solid lines represent the observed speed profiles just after the vehicle starts to move, while the dotted lines describe the simulated speed profiles. According to figure 6, a normal leader accelerates to approximately 30km/h in the first 5 seconds, while a normal follower accelerates to about 25 km/h in the first 5 seconds. The start-up procedure is completed with the desired speed of about 45km/h after 10 seconds. The calibration of normal drivers' acceleration speed profiles leads to a close approximation of realistic driving operations in the simulation test-bed.

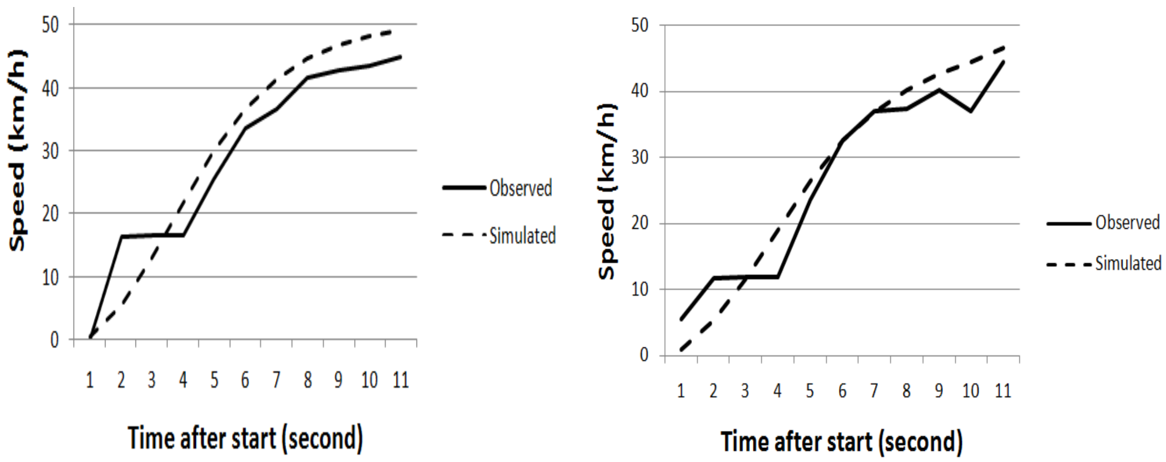

Figure 5 speed profile of normal leading driver (left); and speed profile of a normal following driver(right)

Regarding eco-driving behaviours, the study adopted a roughly soft acceleration behaviour recommended by the Association for Promotion of Eco-driving (2012), which is to accelerate to the speed of 20km/h for 5 seconds after starting. Figure 6 shows eco-driving speed profiles from the test-bed. The solid line shows an eco-leader in a queue while the dotted line shows the eco-follower in a traffic queue. As seen in figure 6, an eco-follower has relatively gentle acceleration operations than eco-leader. This is because a vehicle in the queue is also affected by the preceding vehicles while an eco-leader is able to freely accelerate. In general, both eco-leaders and eco-followers adopt near-linear acceleration speeds while departing an intersection.

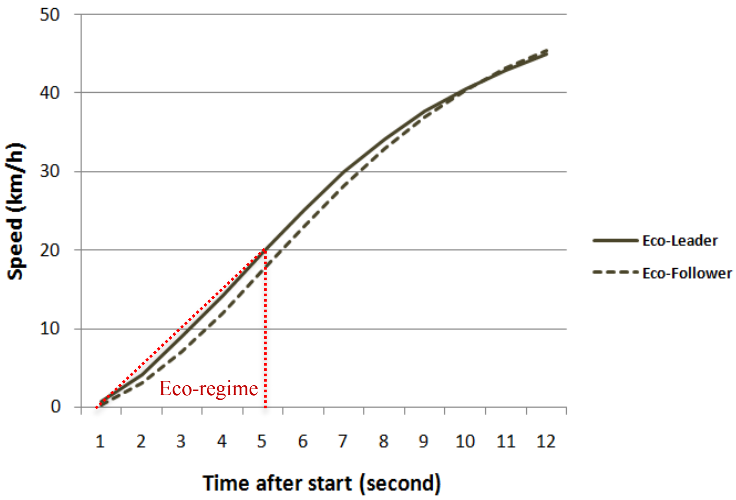

Figure 6 speed profiles of eco-leaders and eco-followers

To analyse different penetration rates of eco-driving, the study developed 20 scenarios that covers penetration rates from 0% to 100%. The 0% scenario represents the base test-bed that only involves normal driving at the intersections, while 100% scenario represents all drivers adopting eco-driving. Although 100% of eco-driving is hardly achievable in practice, the study considers this situation to provide homogeneous driving behaviours to compare with non-eco situations. Each scenario has 10 replications with random seeds. The simulation period is 30 minutes for each replication. A 30-second warming-up time has been used to fill the intersection with vehicles, which is not included in the performance analysis.

The study measures the average travel time for passing through the intersection, total fuel consumption and CO2 emission within the intersection. The fuel consumption and emission are estimated by the speed-and-acceleration based environment models which have been already embedded in the Aimsun simulator (Panis et al., 2006). All the results are presented with the average of 10 replications for each scenario. The scenario with all normal drivers is used as the benchmark, while all other scenarios are compared to the base case.

Figure 7 shows the travel time performance. As seen in figure 7, the travel time only has slight changes for all the eco-driving percentage scenarios. When the penetration rate is less than 35%, travel time performance stands at a steady level which is close to the base scenario. Although the average travel time increases when the penetration rate is over 35%, the growth rate is not significant, with the maximum of only 5% increase. The fluctuations of the tendency reflect the randomness of driving behaviour characters that are set in the Aimsun simulator. It could be concluded that gentle acceleration would affect the mobility of traffic flows when the eco-driving penetration rates is high.

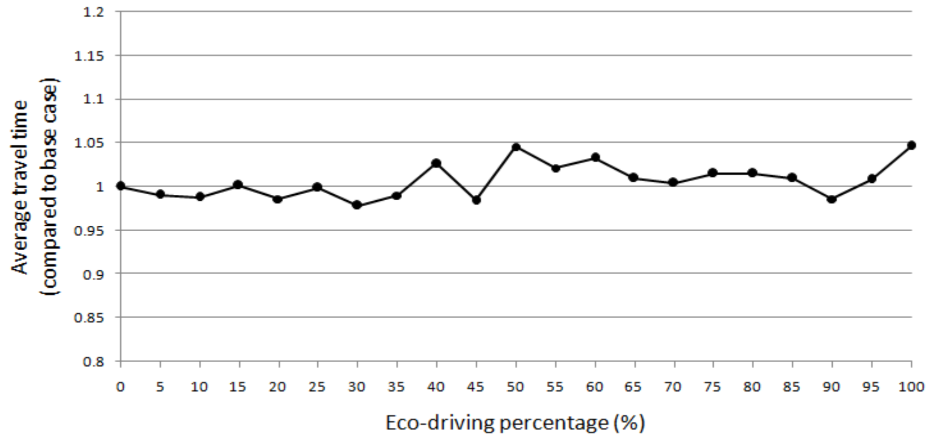

Figure 7 travel time performances with different penetration rates

Figure 8 illustrates the fuel consumption performance for queue discharge at the intersection. With the increasing penetration rates, the fuel consumption tends to decrease with some fluctuations. The minimum fuel consumption is 90% of the base case, which is achieved in the 100% eco-driving scenario. The quantity of the fuel consumption has never overweighed that of the base case.

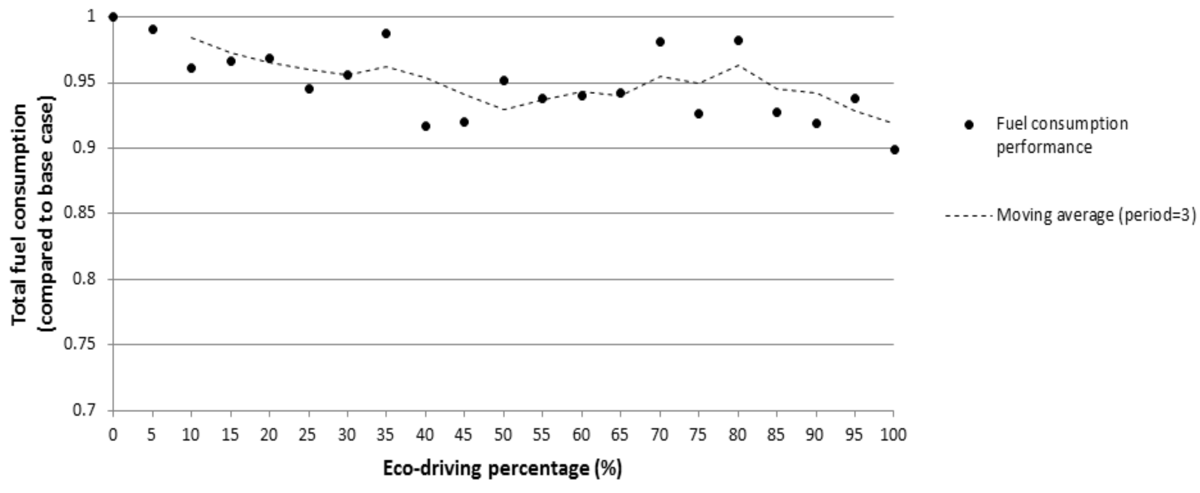

Figure 8 fuel consumption performances with different penetration rates

Figure 9 provides the CO_2 emission performance for queue discharge procedures at intersections. The overall tendency of CO_2 emission drops with the increasing eco-driver penetration rates. It can be seen that there are some occurrences that traffic with eco-driving generated more CO_2 than the base scenario. However, the quantity of the negative impact is relatively minor, with less than 2% over the base case. When the penetration rate is 100%, eco-driving has been found significant benefits on CO_2 emission reduction.

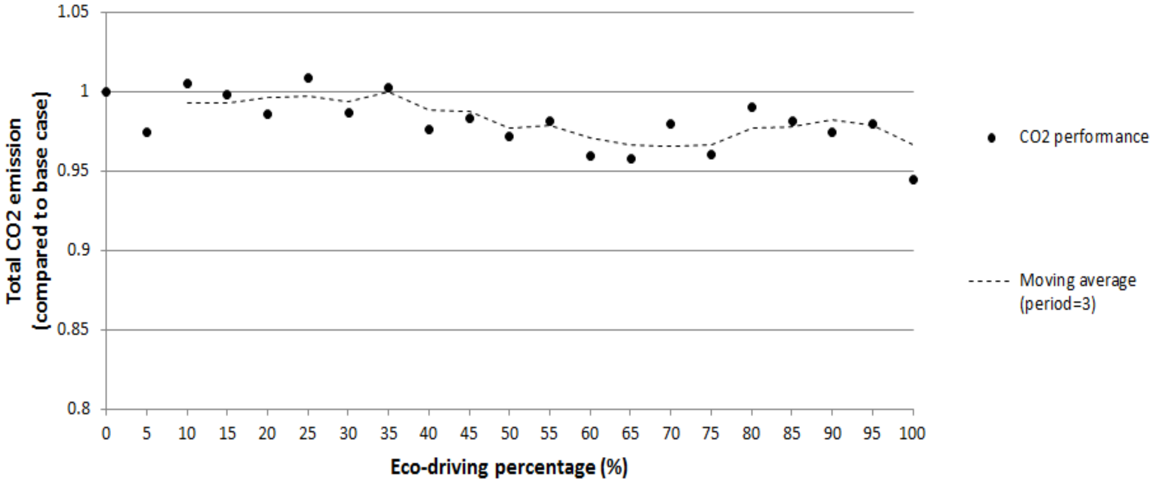

Figure 9 CO2 emission performances with different penetration rates

In addition, both figure 8 and figure 9 show some fluctuations in the scenarios of different penetrations rates. It implies that other impacts might also affect the performance of eco-driving. For example, the homogeneity of driving behaviour has obvious impact on the stability of the traffic system. As seen in figure 8 and figure 9, when all drivers adopt eco-driving, the optimal environmental performance has been achieved, while with mixed driving behaviours the performance reflects a certain variation.

Overall, the above simulation study reveals the following:

- Penetration rates of eco-driving would be an important factor to the performances but
- Results show that they are not linear-related
- 100% eco-driver reveals potential environmental benefits with relatively small trade-off in travel time performance
- Other impacts, such as eco-driver positions and degree of saturation at the intersection, need to be considered in future studies.

CONCLUSION

This paper presents discussions of the simulation approach to assessing the impact of eco-driving behaviours at urban intersections. It is highlighted that assessing eco-driving from a traffic flow perspective is necessary and important. The discussion of three challenges to eco-driving simulation study has revealed that eco-driving simulation studies are far more than just simulating eco-driving behaviour. The understandings of “how eco-driving would perform in a traffic flow”, “how eco-drivers interact with normal drivers”, “how different penetration rates of eco-drivers would affect the traffic system” are some of the key questions for eco-driving evaluation studies. Although this paper hasn’t fully addressed the aforementioned questions, it demonstrated the advantages of applying microscopic simulation to studying eco-driving for traffic platoon.

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