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Evaluating effects of eco-driving at traffic intersections based on traffic micro-simulation

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Abstract

Eco-driving is an initiative driving behavior which aims to reduce fuel consumption and emissions from automobiles. Recently, it has attracted increasing interests and has been adopted by many drivers in Australia. Although many of the studies have revealed considerable benefits in terms of fuel consumption and emissions after utilising eco-driving, most of the literature investigated eco-driving effects on individual driver but not traffic flow. The driving behavior of eco-drivers will potentially affect other drivers and thereby affects the entire traffic flow. To comprehensively assess and understand how effectively eco-driving can perform, therefore, measurement on traffic flow is necessary. In this paper, we proposed and demonstrated an evaluation method based on a microscopic traffic simulator (Aimsun). We focus on one particular eco-driving style which involves moderate and smooth acceleration. We evaluated both traffic performance (travel time) and environmental performance (fuel consumption and CO_2 emission) at traffic intersection level in a simple simulation model. The before-and-after comparisons indicated potentially negative impacts when using eco-driving, which highlighted the necessity to carefully evaluate and improve eco-driving before wide promotion and implementation.

1.0 Introduction

In Australia, the automobile is one of the major sources of greenhouse emissions, and has contributed 69.2 million tons of greenhouse emissions in 2008 with an increase of 26% over the last twenty years (Australian Government Department of Climate Change and Energy Efficiency, 2010). Such a large amount of emissions has created significant environmental stress on communities. Hence, many strategies have been promoted to alleviate environmental problems caused by automobiles. “Eco-driving” is one such strategy, aiming to reduce exclusive fuel consumption and greenhouse emissions by modifying or optimizing drivers’ behavior. Compared with hardware-based strategies, such as using high-efficiency engines and green energy, eco-driving is especially advantageous as it can be applied to all kinds of vehicles on the road immediately. As a result, eco-driving is receiving increasing popularity among the drivers and the authorities are rolling out a variety of eco-driving programs.

Representative eco-driving involves various driving behaviors, such as maintaining a steady speed, avoiding heavy acceleration and deceleration, well anticipating the traffic flow ahead, and minimising idling time. These behaviors will tend to smooth vehicle movements and avoid unnecessary fuel consumption, thereby reducing greenhouse emissions. In addition, eco-driving involves vehicle maintenances, such as monitoring tyre pressure, adopting regular service and avoiding unnecessary weights. Based on proper maintenances, the vehicles can secure optimal mechanical conditions, thus improving fuel efficiency from the respective of engine operations. The benefits of employing proper vehicle maintenances can be easily recognised because the vehicle condition is internally predefined regardless of the vehicle operations on roads. However, the benefits from adopting particular eco-driving behavior will involve somewhat uncertainty because the vehicle operations on road are subject to the complexity of traffic conditions. For instance, under congestion, steady speed is absolutely not easy to maintain. Therefore, emphasis should be paid on whether a particular eco-driving behavior will be able to benefits the environments under different scenarios and how such the behavior will affect traffic conditions on roads.

To this day, advantages of eco-driving dominate the evaluation results among the majorities of the existing studies. Hornung (2004) used a driving simulator to collect the drivers' behavior and fuel consumption data before and after an eco-driving training course. The fuel consumption was found to be 17% lower after adopting eco-driving among a group of seventy-nine participants. SenterNovem (2005) uncovered the 5-10% fuel saving on average that can be achieved according to the field test results and real experience from a wide spread eco-driving project (TREATISE[1]) conducted in Europe. An Australian eco-driving trail also reported that a 27% reduction in fuel consumption was able to be achieved by fully trained eco-drivers (Symmons et al., 2009).

Although the results from existing studies indicated eco-driving as an effective strategy to save fuel consumption and reduce greenhouse emissions, most of the current studies are conducted under specified testing environment and constrains, such as vehicle type, time of day, driving router, design of evaluation, etc. (Symmons et al., 2009). Evaluations subject to local and limited conditions are difficult to provide substantial evidence for a nationwide promotion and implementation.

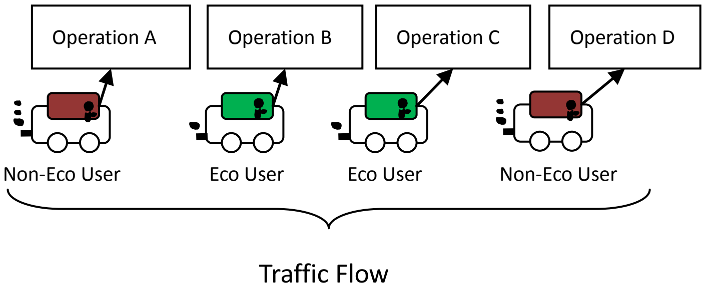
More critical, litter literature has investigated the impacts of eco-driving on traffic flow. The common design of eco-driving studies focuses on before-and-after comparison with respect to only individual vehicle. On the basis of an individual vehicle, the performance of eco-driving is quite deterministic because the core of eco-driving is to efficiently operate the vehicle. However, when considering traffic flow with a mix of driving behavior, in fact the situation will be much more complicated. Eco-driving will affect not only the eco users but also the other drivers in the traffic flow because the vehicles are inter-related. As shown in Figure 1, assuming two typical driving styles on the road, i.e. normal driving and eco-driving, because of the interactions between different driving styles, the actual vehicle operations will be different with regard to not only the driving style itself but also the position in the traffic flow. This implies the importance of evaluating eco-driving on the basis of traffic flow.

Hence this paper will introduce an evaluation method to investigate impacts of eco-driving on traffic flow, which is expected to provide useful information to improve existing eco-driving strategies, to identify where and when to implement eco-driving, and to cooperate with other

[1] Training programme for local energy agencies and actors in transport and sustainable energy actions

traffic control strategies. In section two, the applicability of using microscopic traffic simulator is explored by an example of simulation model. In this example, a particular eco-driving behavior, moderate and smooth acceleration, is studied. The impacts of eco-driving in the example is concluded by measuring both traffic performance (travel time) and environmental performance (fuel consumption and CO_2 emission). In section three, the evaluation results and potential implementations of this study are discussed.

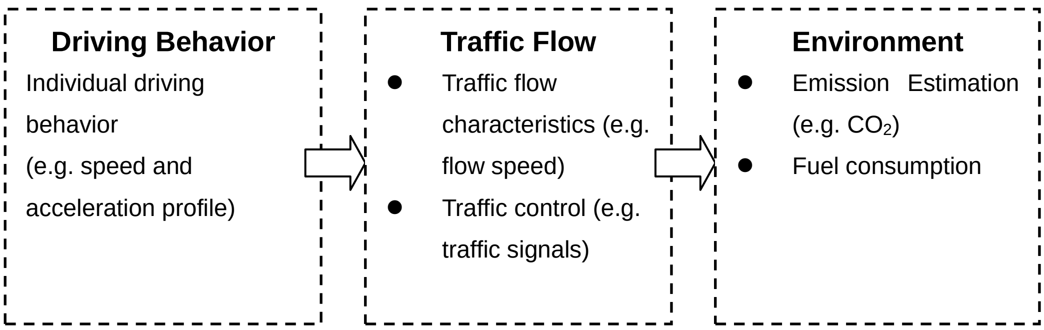
Figure 1: Potential driving operations with normal driving and eco-driving in a traffic flow



2.0 Evaluating eco-driving based on traffic micro-simulation

Summarised by Smit et al. (2010), evaluating eco-driving involves quantification of driving behavior and its corresponding impacts on vehicle performances (i.e. the fuel consumption and greenhouse emissions). As this paper will consider the impacts on traffic flow, an extra component, traffic flow characteristics, must be added on. The framework to quantify driving behaviors, traffic flow and environmental performance are shown in Figure 2. The driving behavior is the basic unit which physically determines the environmental performance from respective of individual vehicle. The traffic flow is composed by individual driving behavior but it is subject to various conditions, such as the flow speed and traffic signal control. Consequently, the performance of the traffic flow is the product of driving behavior and traffic flow conditions.

Figure 2: the framework to quantify effects of eco-driving



Generally, there are two approaches to assess the impacts of driving behaviors; they are field tests and traffic simulations. When considering the impacts on traffic flow, traffic simulations have obvious advantages over field tests. Traffic simulations are able to replicate various traffic conditions in computers, while the field measurements will be labor-intense and time-consuming in testing different scenarios. In addition, a traffic simulation can generate substantial traffic within a large network but a field test is hard to cover a large sample size that can be substantially representative for the whole network. Therefore, traffic simulation can be an appropriate tool to assess eco-driving complying for the proposed approach. To further demonstrate the applicability of this approach, we evaluated one particular eco-driving style, moderate and smooth acceleration.

2.1 Moderate acceleration at traffic intersections

It is important to highlight the “acceleration operation” especially at traffic intersections. When driving on urban roads, the traffic intersections are the places where some of the drivers have to stop and wait for the right of way. The procedure of the stop-and-go involves numerous acceleration operations. It is found that acceleration operations have a significant effect on emissions and strong acceleration tends to generate high instantaneous emission rates and produce high levels of pollution (Carlock, 1992; Rakha et al., 2000). So, automobiles will have more possibility to contribute to excessive fuel consumption and emissions near traffic intersections. Overall, this situation implies that eco-driving with a moderate acceleration has great potential to reduce fuel consumption and emissions at traffic intersections.

Nevertheless, at intersections, eco-driving with moderate acceleration needs to be applied with care. Before stop lines, moderate acceleration will slow down the average speed of start-up after the green light onset, thereby reducing the discharge flow rate of queuing vehicles. Reduced discharge flow rate tends to cause congestion and hence increase fuel consumption and emissions. Mori et al. (2010) conducted a macroscopic simulation test for an acceleration control system which reduces the acceleration rate of all the vehicles in the network and they found that acceleration reduction will increase the congestion level during peak hours. Similarly, Kobayashi et al. (2007) used a microscopic traffic simulation model to test a speed control system which is relevant to moderate acceleration and they uncovered that eco-driving increases environmental load when it is congested. In these studies, the negative impacts on traffic flow caused by congestion (both original congestion and subsequent congestion caused by eco-driving) overweigh the total benefits obtained from each eco-driver. Such a trade-off between individual eco-driving gain and traffic flow loss must be carefully identified, and is necessary and worthwhile investigating before implementation.

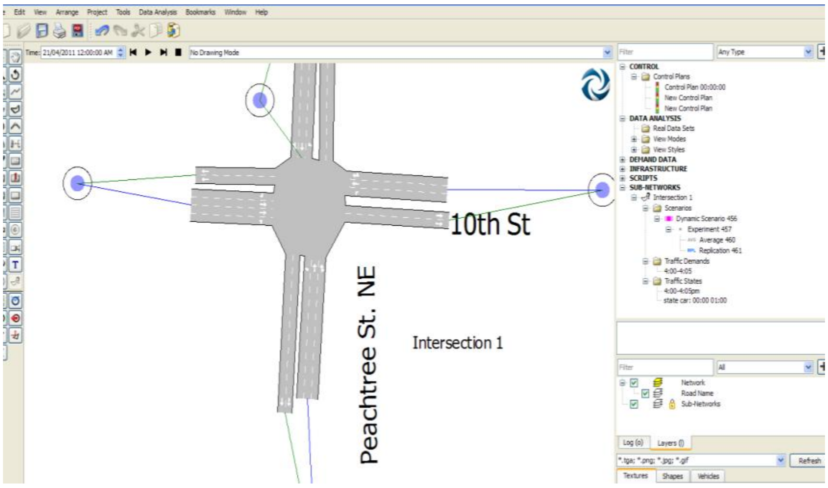
2.2 Simulation of driving behavior

Before using simulation for evaluation purpose, it is important to ensure that the simulator can identically describe the real driving behavior and traffic flow characteristics. Hallmark et al. (1999) studied the difference between real traffic data and simulation output and it was found that a specific traffic simulator (NETSIM) does not adequately mimic instantaneous vehicle activity in some circumstances. The variance between real driving behavior and simulation output will lead to further errors in measure of performance. As such, while simulating eco-driving, the capability of the simulator (or simulation model) to replicate the interested situations must be confirmed. As the acceleration operations of queuing vehicles at intersections contribute significant fuel consumption and emissions before stop lines, the emphasis is on mimicking the acceleration operations based on simulations. Once the acceleration pattern of the vehicles can be correctly represented, the environmental performance can be correspondingly estimated.

In this paper, we propose to use the “Aimsun” microscopic traffic simulator (TSS, 1997). The “Aimsun” microscopic traffic simulator consists of a car-following model and a lane changing model, which is able to generate detail speed-acceleration profile by fraction of time. “Aimsun” software package also provides environment assessment functions that can estimate fuel consumption and emissions. The fuel consumption and emission models embedded take advantage of the speed-acceleration profile to calculation environmental performances (Panis et al., 2006).

In order to verify the applicability of the Aimsun simulator, we use real world speed-acceleration profile data obtained from the “Next Generation Simulation Program (NGSIM)” to build the benchmark model. NGSIM is an open source database which consists of high-quality traffic and trajectory data for the purpose of traffic simulation. The dataset of Peachtree Street in the Midtown neighborhood of Atlanta, Georgia in USA was sourced. Figure 3 illustrates the geometrics of the intersection in the simulation interface. Particularly, the speed-acceleration data of the northbound middle through lane was collected to calibrate the acceleration behavior of queuing vehicles, because there is sufficient queuing vehicles in the though lane during red traffic signal.

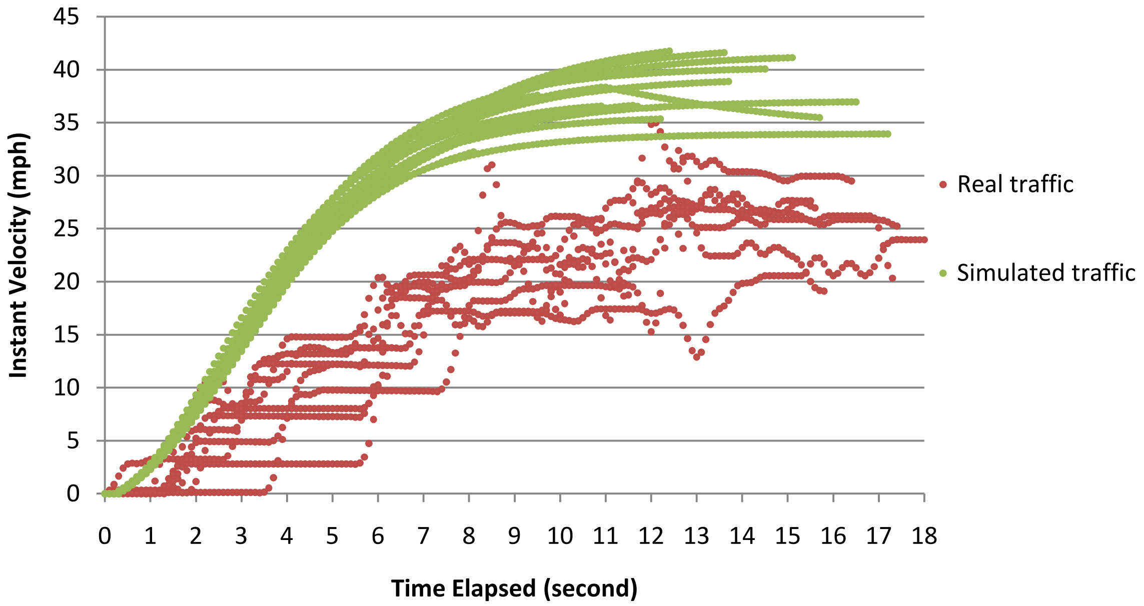
Figure 3: the 10th Avenue-Peachtree Street intersection



Firstly, the real acceleration data of the queuing vehicles at intersections are collected and plotted. Then an uncalibrated microscopic simulation model (i.e., with the default parameters of the simulator) was executed with random seeds of demand. Figure 4 provides the example for the comparison between real acceleration operations and simulated acceleration operations just after the green onset.

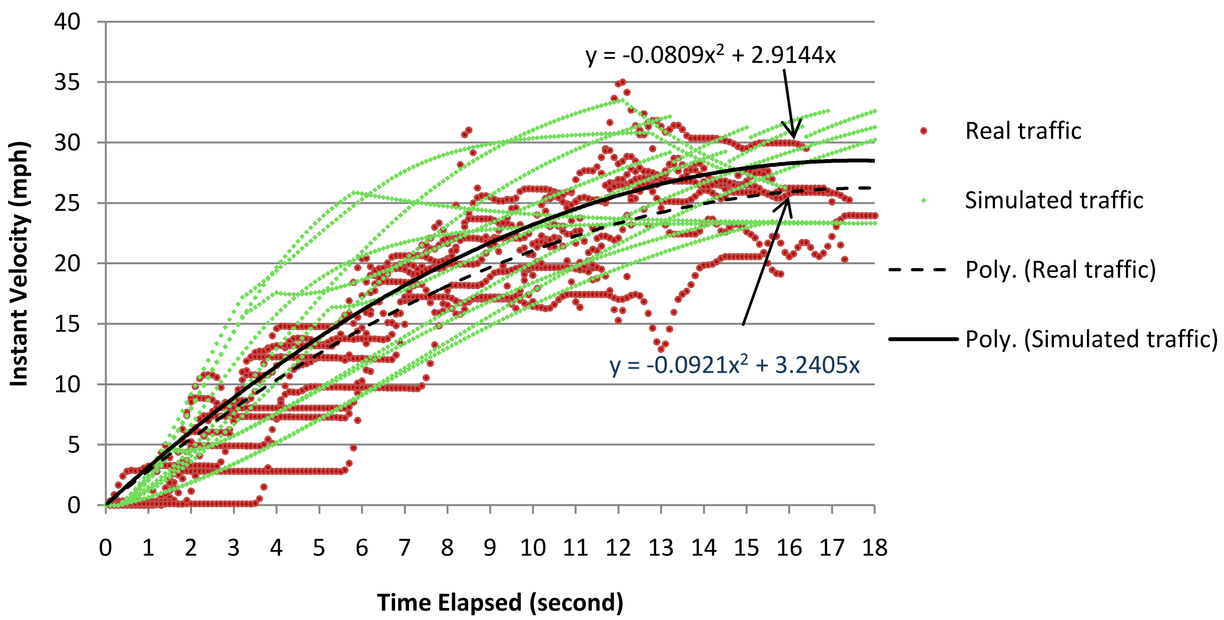
The plots delivered two important messages. The first is that the “Aimsun” simulator is able to generate similar acceleration-speed patterns for discharging vehicles at intersection. As shown in Figure 4, both simulated and real traffic started to move with a relatively higher acceleration just after the green light onset, and then smoothed the acceleration while approaching the desired speed. This phenomenon demonstrates the capability of the Aimsun traffic simulator in generating detail and reasonable speed-acceleration profile. Secondly, the high variances between the real and the simulated curve imply that a further calibration is needed.

Figure 4: Real discharge velocity and the simulated discharge velocity (before calibration)



To emulate the real speed profile, we imported the speed profile during acceleration operations derived from the real data into the vehicle characteristics in the simulation model, and then executed the simulation model again. Figure 5 displays the outputs of the calibrated model. The calibrated model generated approximately close tendency to the real data in terms of instant speed value versus time, indicating that the speed-acceleration profile generate by the calibrated simulation model can be recognized as a similar replication of real driving behaviors.

Figure 5: Real discharge velocity and the simulated discharge velocity (after calibration)



2.3 Evaluation of eco-driving

This part we will showcase an example of evaluation results based on the calibrated acceleration patterns. To simplify, the evaluation model consists of a single through lane and a signalised intersection (the same geometry as the northbound middle through lane in Figure 3). The traffic signal design includes 30 seconds green light followed by 20 seconds red light. We executed the simulations for one hour with five random replications for each scenario. The scenarios with respect to a variety traffic conditions on roads are categorized as following:

- Different traffic pressure: This aims to determine the performances of moderate acceleration under various traffic conditions. The flow rates per lane tested here are: 300 vehicles per hour, 600 vehicles per hour and 1000 vehicles per hour. Note, the flow rate of 1000 veh/ hour is slightly over the capacity regarding the signal timings. As a result, the flow rates applied reflect low, medium and high traffic demands.
- Increasing penetration rate of eco-drivers: A mixed driving style tends to generate different traffic flow with a uniform driving style, especially at intersections where stop-and-go occurs frequently. The tested penetration rates of eco-drivers includes: 0%, 25%, 50% and 100%.
- Different acceleration rates: The value and variation of acceleration rate adopted by drivers directly affects the traffic performance. There are two styles of eco-driving tested in the simulation, the normal eco-driver and the active eco-driver that adopts 10% and 20 % reduction in maximum acceleration rate, respectively.

We selected and computed "average individual fuel consumption" and "average individual CO_2 emission" as the measure of environmental performance, and "average individual travel time" as the measure of traffic performance. Note the measures of performance are collected within the intersection level and all vehicles generated by the simulation were counted in the measures of performance. We define the results from normal driving behavior (i.e. the real acceleration operations) as the benchmark and denote the benchmark value as one in all cases. Then we compared the eco-driving performances with the benchmarks. The results are shown in Figure 6-8.

Figure 6 shows that under normal traffic condition moderate acceleration is beneficial to the environment accompanying little impact on travel time. However, when the traffic is heavy (i.e., the traffic flow rate is 1000veh/hour) moderate acceleration significantly increased all the measures of performance.

Figure 7 reveals the performances with different percentages of eco-drivers under normal traffic condition. It is found that except the scenario of 25% eco-drivers all the scenarios achieved positive environmental benefits by comparing with the normal driving. The negative impacts found in 25% scenarios imply that the eco-drivers might impede the normal drivers on the roads and break down the smooth driving patterns of the normal drivers, leading to the excessive fuel consumption and emissions. With the increasing percentage of the eco-drivers, the driving behavior in the traffic flow will tend to be homogenous, thereby reducing the disruption between different driving behaviors and improving the performances. It is also obvious in Figure 7 that more travel time were consumed by eco-drivers.

Figure 8 indicates the impacts of different acceleration rates adopted. It is found that moderate and smooth acceleration has great potentials in fuel saving without major increase in travel time under normal traffic condition. For instance, an 11% fuel saving was achieved by adopting active eco-driving while the increase of travel time was only 3%. This result qualitatively complies with the benefits revealed by existing studies.

Figure 6: the impacts of moderate acceleration with different demands

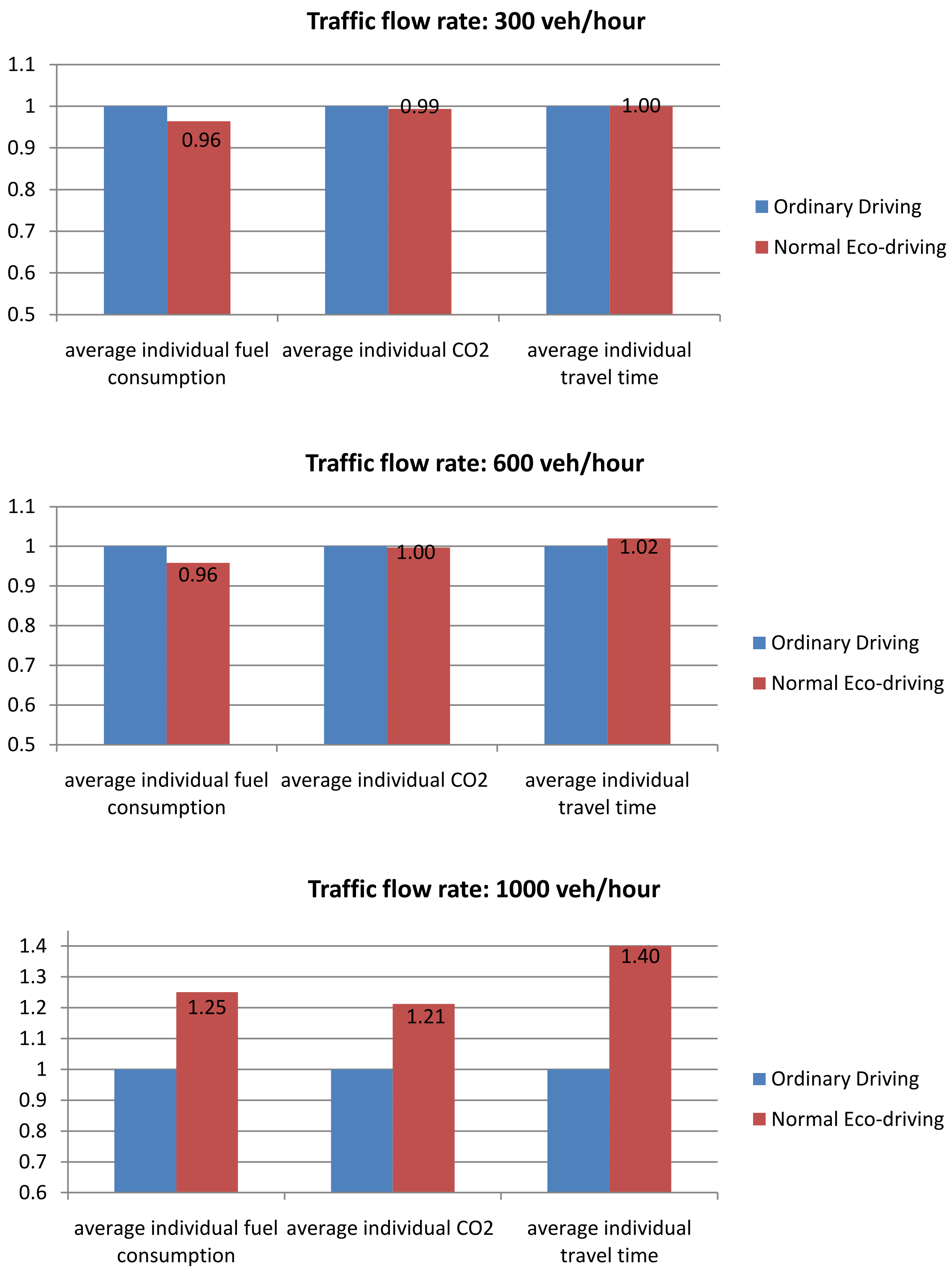


Figure 7: the impact of eco-driving with different penetration rates

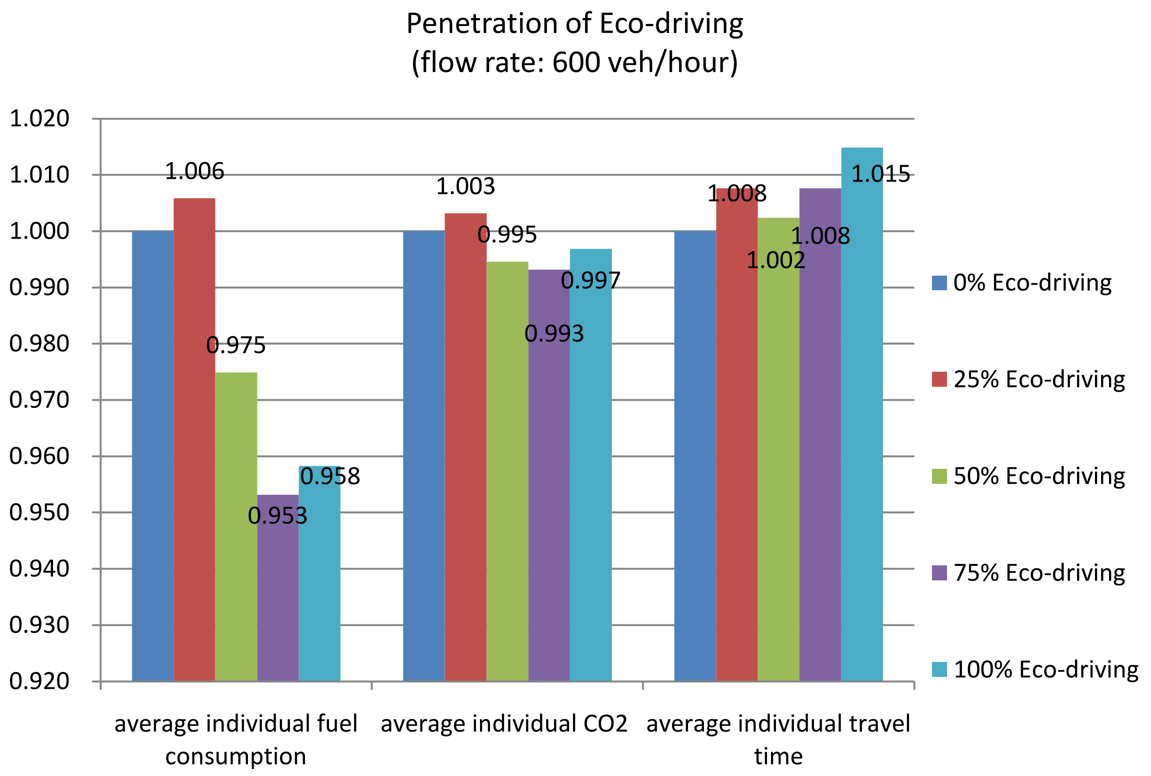
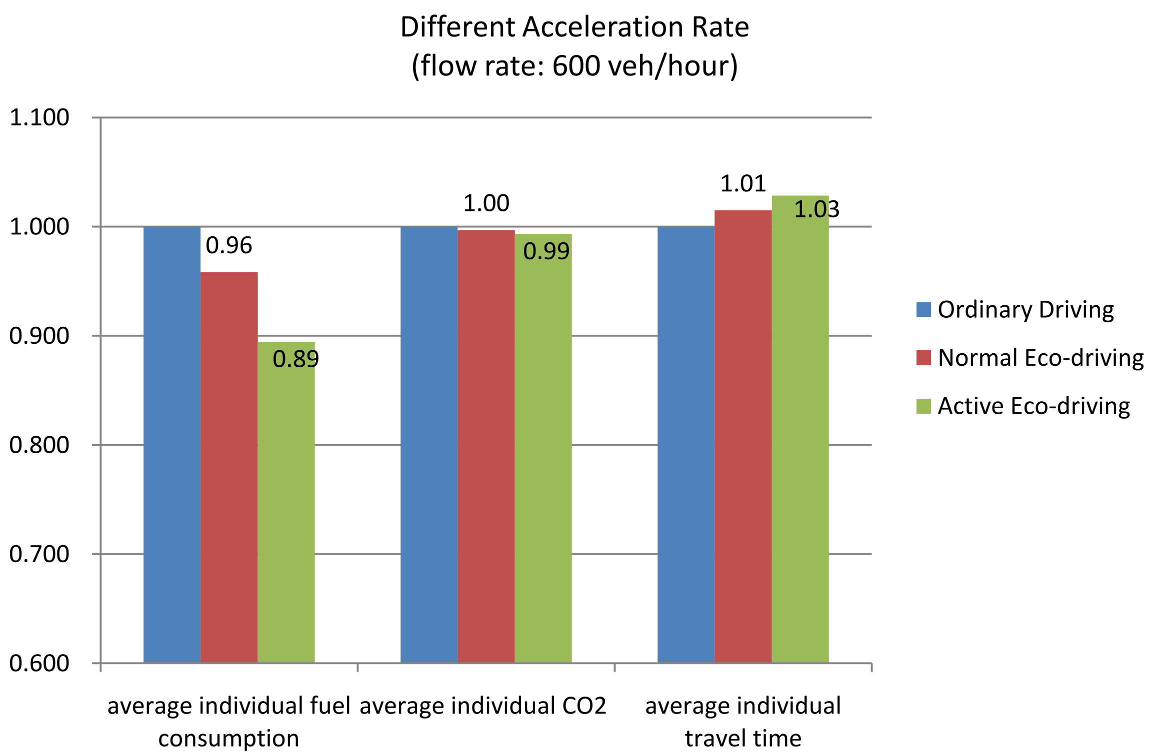


Figure 8: the impact of eco-driving with different acceleration rates



3.0 Discussion and conclusion

The test results aforementioned revealed some critical issues while implementing eco-driving:

- Traffic condition has significant impact on the performance of eco-driving. It is found that when the traffic was congested negative effects were produced by eco-driving.
- The changes in the penetration rates of eco-drivers have an obvious impact on environmental performances. It is interesting to find a mix of driving behavior might have negative environmental effects.
- Different acceleration rates generate different performance. This implies the potential to reduce fuel consumption and emission by changing driving behavior.

This paper introduced an approach to evaluate the effects of eco-driving on the basis of traffic flow by using traffic micro-simulation model. An example on traffic intersection level showcased the applicability of this approach. The evaluation results revealed negative impacts on environment which demonstrated that eco-driving will affect not only traffic performances but also environmental performances. This highlighted the necessity to comprehensively understand how eco-driving will affect the traffic before wide promotion and implementation.

Further study will be conducted to extend the research scope to arterial roads with several intersections, which will have possibly significant contribution to eco-driving strategy development. By comprehensively evaluating eco-driving, it is expected to provide the information on how to optimise environmental benefits of eco-driving in accordance with various scenarios.

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