ASSESSING ECO-DRIVING PERFORMANCE OF A TRAFFIC PLATOON AT URBAN INTERSECTIONS: AN EXPERIMENTAL STUDY

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ABSTRACT

Eco-driving has been paid increasing attentions for its promising benefits of fuel savings. However, the prevailing eco-driving studies mainly focus on its impacts on individual vehicles but not the performance of the entire traffic flow. In practice, an eco-driver would impede the following vehicles' movement because of its ecological but relatively slow driving behaviours. Consequently, this study is motivated to explore how a traffic platoon would perform with eco-driving. A field experiment was conducted in the Shirosato Driving Test Centre in Japan. This paper reports the field experiment results in terms of queue discharge and fuel consumption performances. Based on the with and without eco-driving analysis, eco-driving is found beneficial to reduce individual vehicles' fuel consumption, whereas the performances of the entire platoon were affected by various factors.

INTRODUCTION

At a time of increasing fuel costs and carbon footprints, an environmentally friendlier driving style which is called "Eco-driving" has become increasingly popular. Different from other strategies, such as developing alternative fuels and optimising engine efficiency, eco-driving promotes a specific approach with which a driver could achieve environmental-friendliness by easily adopting eco-driving advices regardless of vehicle types, vehicle models, vehicles ages and fuel types.

Representative eco-driving includes various driving behaviours, such as maintaining a steady speed, avoiding strong acceleration and deceleration, anticipating the traffic flow ahead to take actions in advance, and minimising idling time. In addition, eco-driving involves vehicle maintenance, such as monitoring tyre pressure, adopting regular service and removing unnecessary weights in trunks.

In literature, it is reported that fuel economy, environment and safety are most obvious advantages of utilising eco-driving (Greene 1985; SenterNovem 2005; CIECA 2007). A Spanish study revealed significant amount of fuel reduction by 13.4% after using eco-driving (SenterNovem, 2005). Accompanying fuel economy benefits, eco-driving is also productive to reduce greenhouse emissions, especially of CO_2. The Swedish National Road Administration assessed the emission performance of a group of drivers before and after providing eco-driving training courses. It reported that the eco-driving participants succeeded in reducing 10.9% of CO_2 emission on average (Johansson 1999). Rafael et al. (2006) investigated the emission patterns for various categorizes of driving styles, and this study revealed the potentials for driving with steady speed and smooth acceleration and brakes. Last but not least, although the safety performance has not been precisely identified in literature, it is expected to be a collateral benefit of eco-driving because of the suggested gentle driving behaviours.

In the past decades, it seems that many of the existing eco-driving studies focus mainly on the performance of individual eco-driving performances but not on the eco-driving impacts from the global perspective of traffic flow performance (Qian and Chung 2011; Olivier 2011). It is questioned whether eco-driving could benefit the traffic flow as a whole. Theoretically, eco-driving, as a gentle and smooth driving behaviour, would not only affect the ecologically-driven vehicle but also the neighbouring vehicles, especially the following vehicles. Therefore, the eco-driving vehicles with relatively slow speed would potentially impede the moving of the followers, ending up with compromising the traffic capacity. In practice, Ando and Nishihori (2011) explored the following behaviours of the drivers after eco-driving vehicles based on a field experiment and they revealed that an eco-driving leader would potentially induce the following drivers who have normal driving behaviours to behave like ecological driver. These facts emphasise the importance of having comprehensive understanding of eco-driving impacts from traffic flow perspective.

Recently, the importance of impacts of eco-driving on traffic flows has been realized. Kobayashi et al. (2007) evaluated an ecological speed control system based on microscopic simulation, and the simulation results revealed that eco-driving had increased the total environmental load (i.e. fuel consumption and CO2 emission of all vehicles in the model) during peak period. Mori et al. (2010) conducted a macroscopic simulation test for an acceleration control system which significantly reduced the vehicle acceleration rates, and they found that the fuel economy of the network had been improved except during the congested period. Qian and Chung (2011) also studied the impacts of eco-driving with moderate acceleration at signalised intersections based on microscopic traffic simulator. The study revealed that the degree of saturation at the intersection and the penetration rates of eco-drivers in a platoon would affect the eco-driving performance. It is interesting to observe that all these studies have found more or less negative impacts after adopting eco-driving. That is to say, in some circumstance, the slow discharge effect at signalized intersections which is caused by eco-driving would quickly negates the benefits of eco-drivers. However, these studies carried out investigations based on traffic simulations which require calibrations of its parameters regarding eco-driving behaviours. The fact is that none of them has comprehensively justified and calibrated the model parameters upon real eco-driving because there is lack of detailed field data of eco-driving behaviours and the interaction between eco-drivers and normal drivers.

This paper reports a field eco-driving experiment which aims to provide insights of eco-driving impacts on traffic flow and details of eco-driving behaviours at urban intersections. The experiments tracked the driving trajectories and fuel consumption of 15 vehicles when they were driving along a replicated urban road with three consecutive signalised intersections. The field collected data was processed for clear understanding and presentation. Before-and-after analysis was conducted with the focus on the queue discharge features and fuel consumption of eco-drivers and traffic platoon.

EXPERIMENT DESCRIPTION

Experiment objective and task

At urban intersections, driving with moderate acceleration would potentially impede the discharge of traffic queue, which could be regarded as a side-effect of eco-driving. The experiment, therefore, mainly aims to study how the side effect would influence traffic performances with following tasks:

- Record details of fuel consumption and behaviours of the entire traffic platoon at signalised intersections
- Explore the effectiveness of eco-driving with gentle acceleration from individual driver perspective
- Assess impacts of eco-driving on fuel consumption from the entire platoon perspective
- Compare difference of queue discharge performance before-and-after having eco-drivers in traffic platoon
- Study the queue discharge behaviours at signalised intersections

Experiment Site

The experiment was conducted in the Shirosato Test Centre of Japan Automobile Research Institute (JARI) on Monday 23rd July and Tuesday 24th July, 2012. The Shirosato Test Centre is located in Higashiibaraki District, Ibaraki, Japan. Figure 1 displays the map of the test centre and the testing area. As highlighted in the map, the selected test road covers approximately 1000 meters of the straight lanes at the outer circuit.

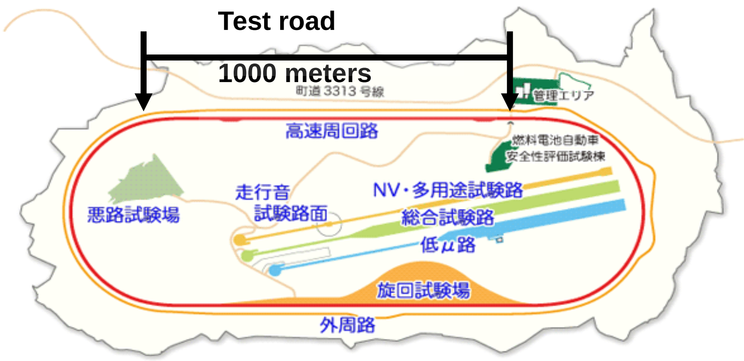


Figure 1: Map of the Shirosato Test Centre (sourced from JARI)

Experiment Setup

As the original road was like racetrack, decorations were prepared to replicate the appearance of urban roads. As shown in Figure 2, portable traffic signals with solar power supply were utilised to control the stop-and-go of the vehicles, and white adhesive tape was applied as stop-lines.

Figure 2: Traffic signal and stop-line

Along the test road, three intersections were employed according to the aforementioned preparation, as shown in Figure 3. The distances between intersections were made sufficient for vehicles to reach desired speeds after stop lines.

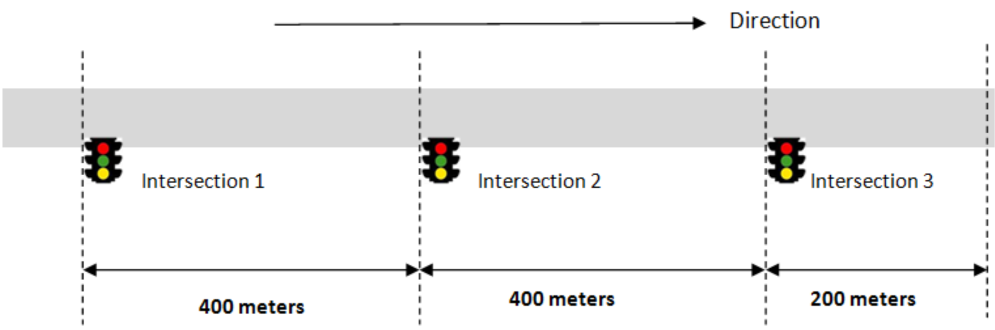


Figure 3: Sketch of the test road

In this experiment, professional drivers are hired to conduct eco-driving. The eco-driving behaviours were carried out according to a specific rule: the maximum acceleration from standstill is approximately 1.11 m/s^2, which makes the vehicle acceleration towards 20 km/h after 5 seconds of start-up, while the normal drivers were not given any specific driving instruction. All the drivers had to obey the maximum speed limit of 50 km/h along the test road, and over-taking was not allowed.

The traffic platoon consisted of 15 vehicles and they were labelled from 1 to 15. Figure 4 illustrates an example of how the vehicles are arranged to stop-and-go at an intersection. Where the queue discharge performance is of interests, the traffic signals were designed to ensure all the test vehicles to stop before the stop-line when the red light is onset, as shown in case A and case B in figure 4. After all the experimental vehicles have fully stopped, green signal would be activated to allow them to discharge in sequences, as shown in case C. Then, the experiment measured the impacts of eco-driving on the queue discharge characteristics, as displayed in Case D. The experiment selected intersection 1 and intersection 3 (shown in figure 2) for queue discharge analysis while the signal of intersection 2 was design to let all traffic pass through without stop.

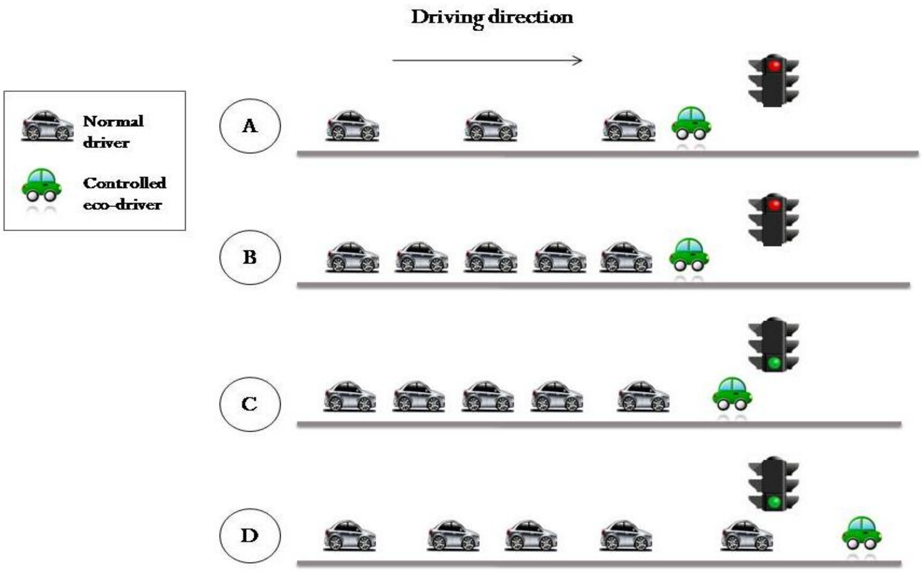


Figure 4: An example of vehicle discharging at the intersection

In total, the experiment conducted 10 different scenarios with respect to eco-driving numbers and eco-driver positions as shown in Table 1. Scenario 1 is used as the base scenario which does not involve any professional eco-driving behaviour. Each scenario was conducted with three runs.

Table 1: List of test scenarios

ID	Scenario	Number of Eco-driver	Position of Eco-driver	Number of replication
1	Scenario 1	0	N/A	3
2	Scenario 2	1	1st vehicle	3
3	Scenario 3	1	5th vehicle	3
4	Scenario 4	1	10th vehicle	3
5	Scenario 5	1	2nd vehicle	3
6	Scenario 6	2	1st and 5th vehicle	3
7	Scenario 7	2	1st and 10th vehicle	3
8	Scenario 8	2	2nd and 5th vehicle	3
9	Scenario 9	2	5th and 10th vehicle	3
10	Scenario 10	2	2th and 10th vehicle	3

Data Collection

To capture the vehicles' trajectory, the study mainly utilises portable GPS units to record the position information. Fuel consumption sensors were also installed on the vehicles. Figure 5 provides the photos of the portable GPS unit and fuel consumption sensor.

Figure 5: Portable GPS unit and fuel consumption sensor

Additional, 16 video cameras were installed on tripods along the 1000 meter test track to capture the vehicle trajectory as backup information. Figure 6 shows the installation of cameras on roadside. At each intersection, additional cameras were set to focus the stop-line for queue discharge behaviour analysis.

Figure 6: Cameras installed on road side

The experiment collected following data:

- Instant speed : km/h
- Latitude : GPS WGS-84
- Longitude : GPS WGS-84
- Altitude : GPS WGS-84
- Engine revolution : revolutions per minute (rpm)
- Engine temperature: ˚C
- Fuel consumption rate: ml/sec
- Throttle :throttle pedal in %
- Brakes: yes/no

The frequency of the GPS data collection is approximate 1 second with deviations. Consequently, the raw data was processed with interpolation techniques to ensure the data was evenly distributed in each second. As there is lack of field data at integer time stamp for interpolation validation and most of the data is close to integer time stamp, linear interpolation was utilised. The interpolation results were compared to the raw data. Figure 7 demonstrates an example of the interpolated and observed trajectory of a vehicle.

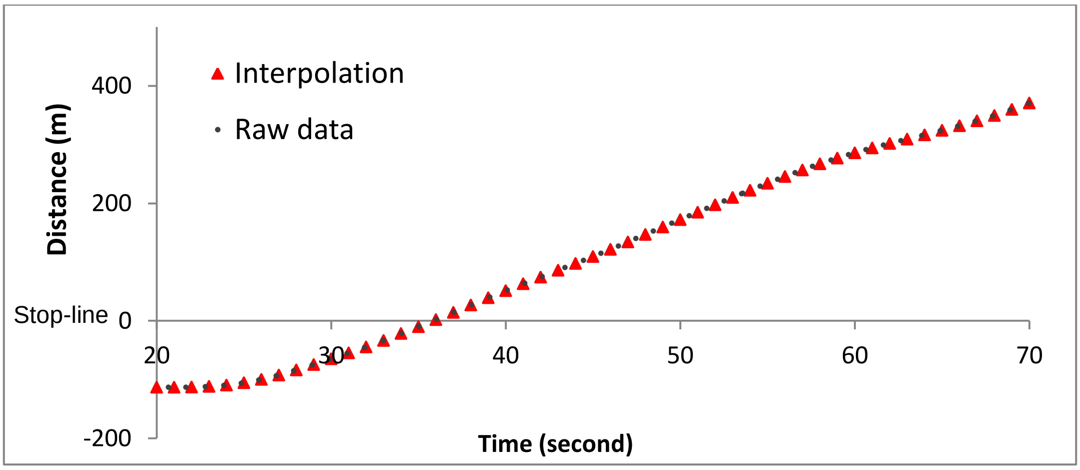


Figure 7 Interpolation of the trajectory of a vehicle at intersection 1

Another treatment has been carried out to reduce the trajectory noises caused by the offset problem of the GPS position equipment. It is found some data has been offset, causing overlap of vehicle on the trajectory plots. To solve this, video data was referenced to adjustment the positions in the traffic platoon.

DATA ANALYSIS

The study collected 30 groups of data for all the replications. Each data group includes vehicle trajectories and fuel consumption. According to the experiment design, each run includes two complete queue discharge procedures. As a result, there are 60 queue discharge dataset available for analysis. This section provides the experiment results. Firstly, fuel consumption performance is explored with respect to individual vehicle and the entire traffic platoon. Then, queue discharge performance of the entire platoon is discussed.

To specify the analytical period of the experiment, the study consider the queue discharge fuel consumption based on following rules:

- For a complete run (i.e., passing through the entire test road): each vehicle's fuel consumption was accumulated from the start of green at the first intersection until it arrived at the destination at 1000 meters away from the first intersection.
- For a queue discharge procedure at an intersection (i.e., at intersection 1 and intersection 3): each vehicle's fuel consumption was accumulated from the start of green at the intersection until it arrived at 200 meters after the intersection.

The rule for a complete run ensures that the fuel consumption data is accumulated right after the queue start to discharge until arrives the experiment destination. The rule for a queue discharge procedure at an intersection focuses only the fuel consumption near an intersection. The distance of 200 meters is selected because all vehicles are able to accelerate to their desired speed before this point.

Fuel Consumption Analysis

Fuel consumption of individual vehicle

Table 2 provides the summary of the fuel consumption performance for each car in the base scenario. As the drivers were asked to utilise the same vehicle throughout the experiment, the results reflect the fuel consumption level of each vehicle with the same driver. The result is used as a benchmark for comparison with eco-driving-related scenarios.

Table 2: Fuel consumption for each car in base scenario

Label / Fuel (ml)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Average	49.68	53.94	120.77	53.28	53.09	56.95	51.53	97.05	53.79	52.46	58.17	48.49	53.22	70.60	61.52
Min	47.39	51.73	110.29	48.77	49.89	53.82	48.98	93.32	53.17	48.60	53.76	45.20	49.53	68.46	58.11
Max	54.11	56.44	133.31	56.30	54.93	60.91	53.78	103.19	54.41	55.99	65.84	51.26	56.02	72.72	68.09

Table 3 demonstrates the average fuel consumption of the two eco-drivers before and after adopting eco-driving. As shown in table 3, Car 14 reduced 2.9% of the fuel consumption while Car 15 significantly saved fuel for about 18.7%. To explore the reason for this difference, the acceleration behaviours after start-up were further examined as displayed in figure 5. It is found the magnitude of driving behaviour change of Car 15 was stronger than Car 14.

This result reveals two facts. Firstly, it qualitatively complies with the findings in many of the eco-driving studies that eco-driving with gentle acceleration is beneficial for fuel economy improvement. According to figure 5, the acceleration pattern of Car 15 has been modified toward a constant acceleration rate. The behaviour changes are expected to contribute to fuel consumption savings as per the eco-driving philosophy. On the contrary, Car 14 was not able to make significant changes in terms of acceleration operations, thus limiting the fuel economy difference before-and-after adopting eco-driving. Secondly, it highlights the importance of understanding the before-and-after behaviour difference while assessing the impacts of eco-driving. The eco-driving comparison results would be validated only if the before-and-after conditions have been clearly verified.

Table 3: Fuel consumption performance of individual driver

Car label	Fuel consumption when normal driving (ml)	Fuel consumption when eco-driving (ml)	Percentage of fuel saving
Car 14	70.6	68.0	2.9%
Car 15	61.5	50	18.7%

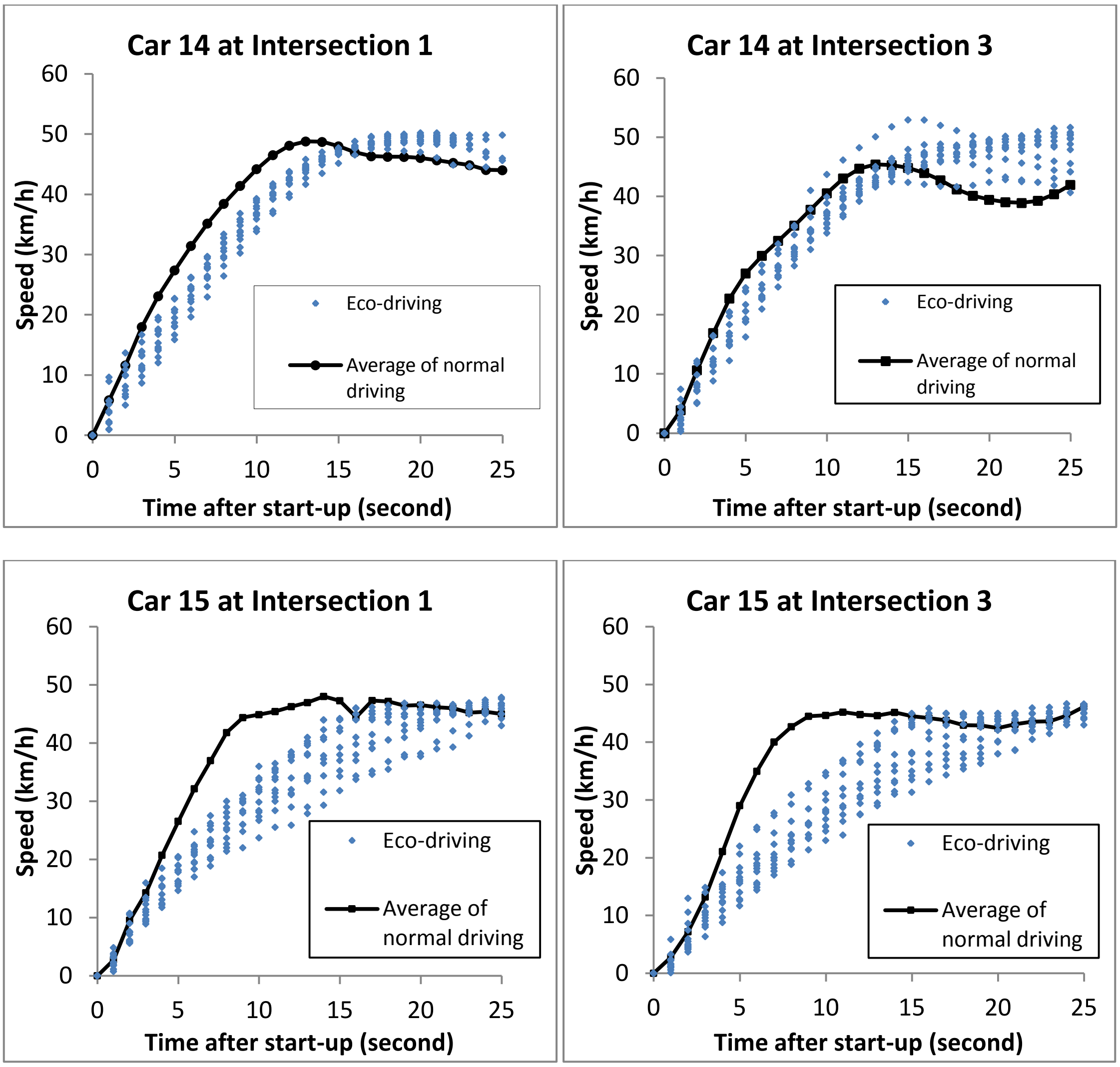


Figure 5: Speed profile comparison of Car 14 and Car 15 at intersections

Fuel consumption of traffic platoon

Then, the study explored the fuel consumption performance from the entire platoon perspective. Table 4 provides the averaged fuel consumption of all the 15 vehicles in terms of number of eco-driver in the platoon. Compared to the eco-driving impacts on individual vehicle, the impacts on the entire traffic platoon is relatively minor, with only 1% and -0.2% for 1 eco-driver scenario and 2 eco-drivers scenario, respectively.

Table 4: Fuel consumption performance with respect to number of eco-drivers

Fuel consumption / Scenario	Average fuel consumption per vehicle (ml)	Percentage of difference to base scenario
No eco-driver	62.27	N/A
1 eco-driver	62.9	+1%
2 eco-drivers	62.11	-0.2%

A paired t-test was performed to determine if the eco-driving was effective from the traffic platoon perspective. By assuming the data has equal variance (a=0.05), Table 5 displays the test results. As in all scenarios, p>a, it could be regarded that there is no obvious difference in the average of fuel consumption. The results tell that the there is no significant difference between the base case and tested scenarios.

Table 5: fuel consumption t-test for different scenario

Scenarios	1st Eco	2nd Eco	5th Eco	10th Eco	1st & 5th Eco	1st &10th Eco	2rd & 5th Eco	2rd & 10th Eco	5th &10th Eco
Two tail p	0.28	0.31	0.69	0.35	0.66	0.87	0.42	0.42	0.72

The performance of each scenario group during complete run is plotted in Figure 6. According to the plots, it is not easy to conclude the relationship between eco-driver position and the fuel consumption. In many of the cases, scenarios with two eco-drivers achieved reduction in fuel consumption, while approximately one-third of the runs seem to have increased fuel consumption from the global point of view.

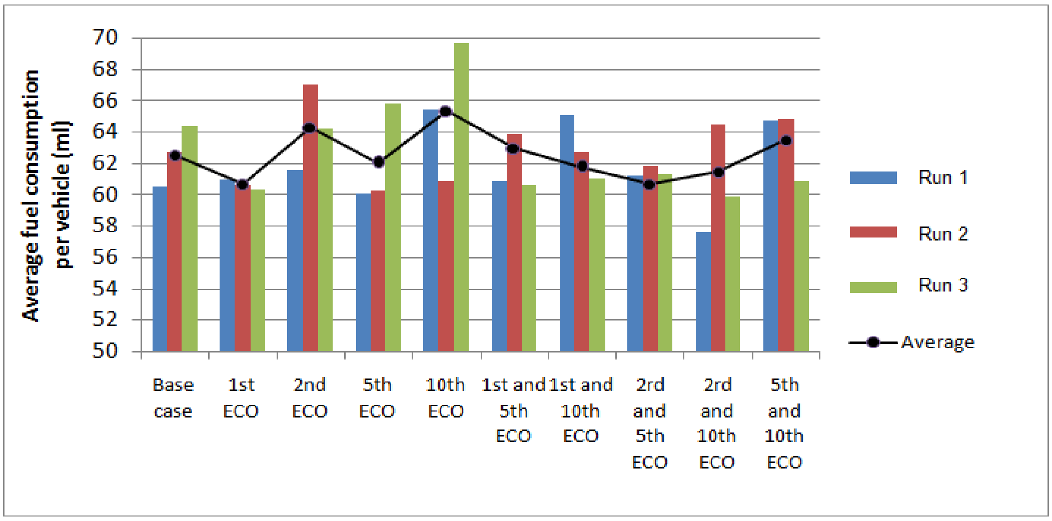


Figure 6: Average fuel consumption per vehicle for entire replication in different scenarios

The fuel performance for queue discharge procedures at a single intersection was also plotted. Figure 7 and Figure 8 give the average fuel consumption performance at intersection 1 and intersection 3, respectively. Similar to the results shown in figure 6, it can be seen that the fuel performance at intersections is also unstable. At intersection 1, 10th ECO scenario and 2nd ECO scenario consumed more fuel than the base case, where as at intersection 2, 2nd ECO scenario consumed more fuel than the base case.

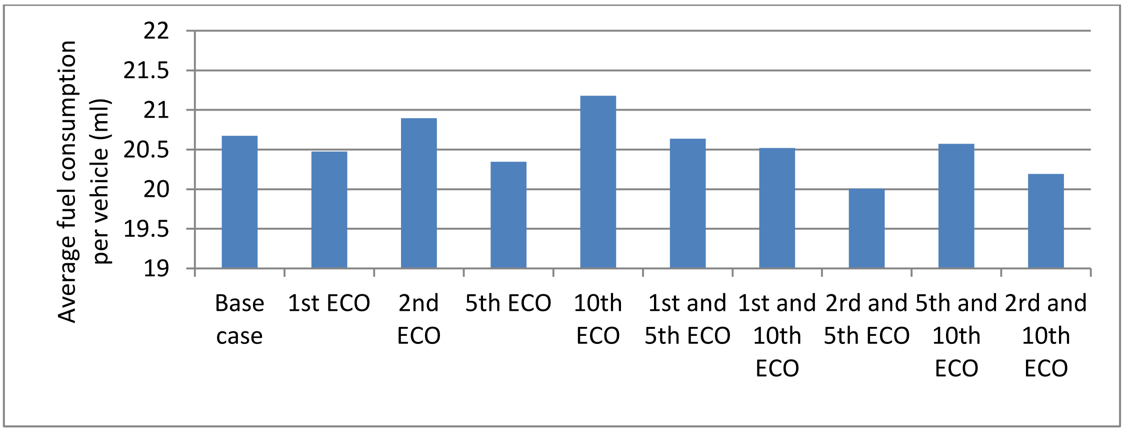


Figure 7: Average fuel consumption per vehicle at intersection 1

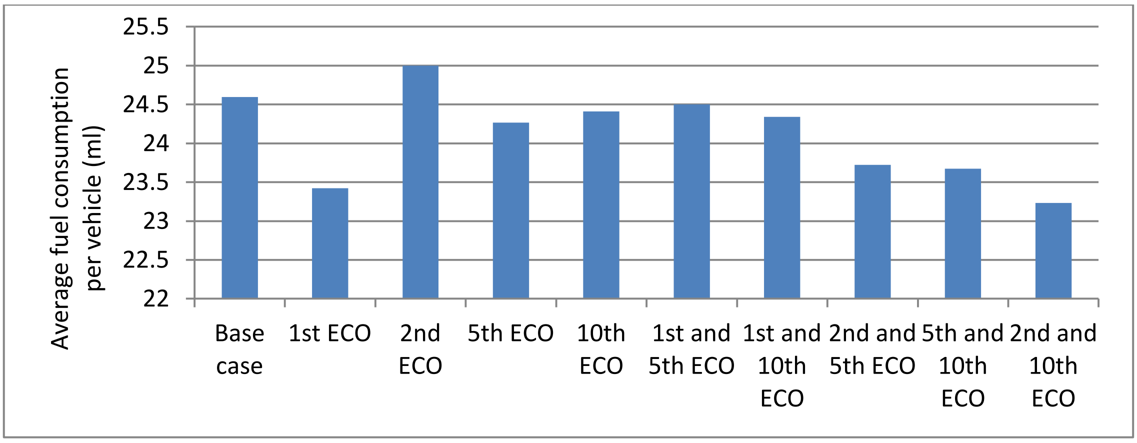


Figure 8: Average fuel consumption per vehicle at intersection 3

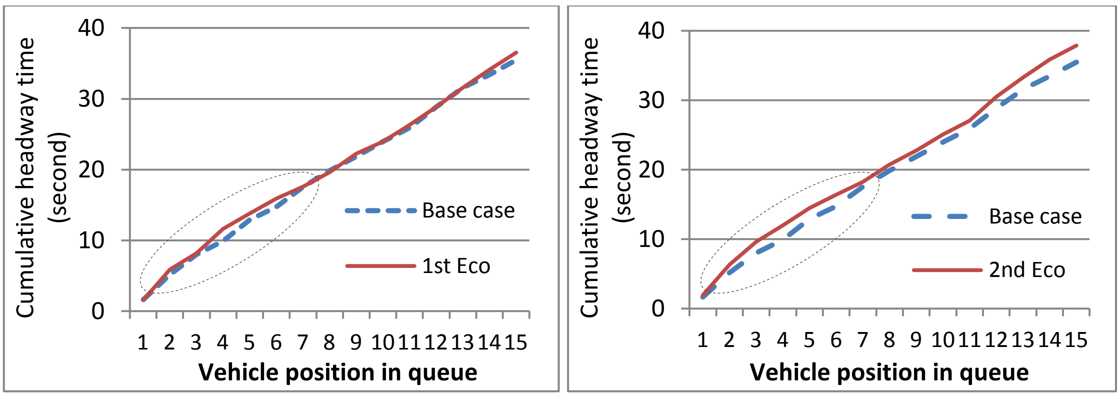
Queue Discharge Analysis

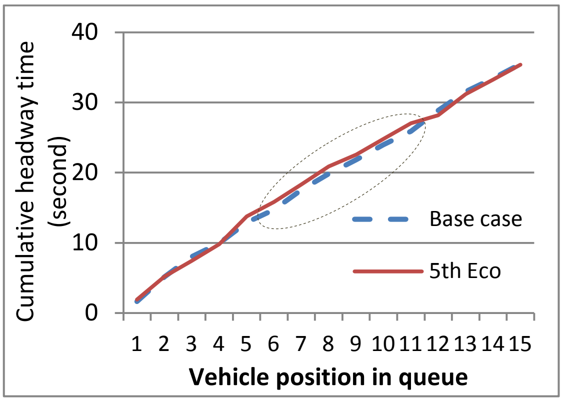
In the last section, it is found that the individual fuel economy is improved whereas the fuel performance of the traffic platoon is unstable. This implies the potential impacts of eco-driving on the other vehicles (i.e., with normal driving behaviour) in the traffic platoon. So the study tried to understand the impacts of eco-driving on the neighbouring vehicles by analysing the queue discharge features.

Queue discharge behaviours determine the capacity of the intersection. In addition, the trajectories of the vehicle start-up procedures reflect the driving aggressiveness (i.e., eco-driving or normal driving). Both capacity and driving aggressiveness have great impacts on fuel consumption, which was assessed in the following parts.

Stop-line headway

Figure 9 gives the cumulative headway time at stop-line in different scenarios. The curves for the base case illustrate the averaged cumulative headway for vehicles in different position of the queue. The cumulative headway time reflect the time needed for the vehicle in a specific position to pass through the stop-line. As shown in figure 9, the impacts of eco-driving on headway features can be observed in the plots that the eco-drivers increased the queue discharge time. The impacts were brought exactly by the eco-driver at its position in queue. In addition, it is found that the increased discharge time were only affect a few (3 to 7) following vehicles as highlighted by dashed circles in figure 9.





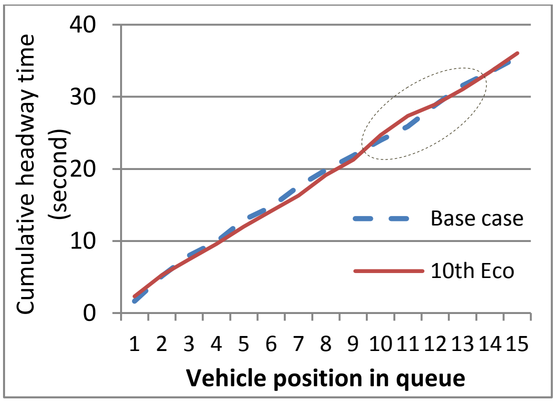


Figure 9: The comparison of the cumulative headway time in different scenarios

As for this study, the signal timing was designed to provide sufficient green time to allow all vehicles to leave the intersections. Hence the impacts of eco-driving on queue discharge time on the ability of the platoon to clear the intersection could not be observed. However, the delay caused by the eco-drivers should not be overlooked.

Saturation discharge analysis

Table 5 presents the average fuel consumption performance and the time for the entire traffic platoon to reach desired speed in different scenarios. The performances are presented by comparison to the base scenarios. The results indicate that the full discharge time has been increased for all scenarios; complying with the assumption that eco-driving would impede queue discharge. Considering the impacts of eco-driving on traffic mobility and environment benefits, two circumstances were found. The first is that eco-driving improved fuel economy while the traffic mobility has been compromises. The second is that eco-driving deteriorated fuel consumption performance of the platoon and queue discharge performance simultaneously.

Table 5: Comparison of fuel consumption and full discharge time (i.e. till free flow speed)

Scenarios	1st Eco	2nd Eco	5th Eco	10th Eco	1st & 5th Eco	1st &10th Eco	2rd & 5th Eco	2rd & 10th Eco	5th & 10th Eco
Average fuel consumption (compared to base case)	-0.95%	1.07%	-1.59%	2.4%	-0.18%	-0.75%	3.24%	-2.33%	-0.5%
Full discharge time (compared to base case)	3.78%	7.3%	0.57%	2.8%	10.8%	8.45%	9.75%	3.64%	2.47%

SUMMARY AND DISCUSSION

The paper has studies the eco-driving performance of traffic platoon based on field experiment. The recorded trajectory data and fuel consumption data were investigated to understand how eco-driving behaviours could affect the performance of traffic flow. The comparative assessment was conducted for fuel consumption and queue discharge features. The following findings and discussion are worth mentioning:

Finding 1

Eco-driving with gentle and constant acceleration is found to be beneficial for fuel economy. However, the performance of the two eco-drivers are quite different. One has achieved 18.7% reduction in total fuel consumption while the other only achieved 2.9% fuel reduction.

Discussion 1

Although vehicle 14 only reveals 2.9% reduction in fuel consumption, it does not indicate that eco-driving is not effective. Most probably, it reflects that the behaviour difference before and after eco-driving is relatively small. For this reason, it highlights the importance to clearly verify the benchmark for eco-driving evaluation.

Finding 2

The performance of the entire traffic platoon is explored with respect to fuel consumption and queue discharge performance. Neither one-eco driver scenarios nor two-eco drivers scenarios has found significant different in fuel consumption from the entire platoon's perspective. Furthermore, the comparison between the various scenarios with respect to the position of eco-driver in platoon reveals no clear clue to provide the relationship between positions of eco-driver in the platoon and the total fuel consumption of the platoon.

Discussion 2

The experiment adopted only two eco-drivers in 15 vehicles, which might explain why the fuel consumption performance of the entire platoon is not significantly different before-and-after introducing eco-driving.

In addition, the number of scenarios and runs are limited in this experiment. This makes it difficult to have a statistical conclusion on the performance. It is recommended for future study to cover more samples.

Finding 3:

Analysis on queue discharge features reveals that the headway at stop line has been compromised by introducing eco-driving. In this experiment, the actual queue discharge performance (throughput) has not been affected because the demand is lower than the intersection capacity.

Discussion 3:

In reality, the impacts of eco-driving on headway should not be overlooked. The delaying of following vehicles by eco drivers might induce the occurrence of congestion when the traffic demand is heavy. Based on the experimental study, the position of eco-driver in the platoon would potentially affect the capacity if the demand is close to capacity.

Finding 4:

Comparison between fuel consumption performance and traffic mobility performance indicted that there is trade-off between fuel consumption and traffic mobility. In most of the scenarios, fuel economy is improved by sacrificing the traffic mobility. In some cases, both fuel economy and mobility are compromised.

Discussion 4:

This finding implies that mobility is the cost for fuel economy. In addition, it reveals the risk of applying eco-driving, because in some cases both fuel and travel time have increased. It is highly recommended taking the risk (e.g., delaying effect or congestion induction) into consideration while evaluating eco-driving strategy.

Overall, this study raises the necessity for evaluating eco-driving impacts from traffic flow perspective and provides some insight about impacts of eco-driving based on the field experiment. For future studies, more experiments are recommended for a further detailed investigation of the eco-driving impacts. Particularly, the impacts caused by different eco-driver positions or penetration rates are of crucial importance. It is also expected to figure how to design better eco-driving strategy from traffic platoon point of view.

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