Advancing Eco-driving Strategies for Drivers and Automated Vehicles Traveling within Intersection Vicinities

Final Report

TranLIVE

Peijia Tang, M.S.

Mehdi Azimi, Ph. D., P.E.

Fengxiang Qiao, Ph.D.

and

Lei Yu, Ph.D., P.E.

January 2016

DISCLAIMER

1. Report No. TranLIVE/TSU/16/02	2. Government Accession No.	Recipient's Catalog No.

4. Title and Subtitle Advanced Eco-driving Strategies for Drivers and Automated Vehicles Traveling within Intersection Vicinities	5. Report Date January 2016
	6. Performing Organization Code
7. Author(s) Peijia Tang, Mehdi Azimi, Fengxiang Qiao, and Lei Yu	
	8. Performing Organization Report No. TransLIVE/TSU/16/02
9. Performing Organization Name and Address Department of Transportation Studies Texas Southern University 3100 Cleburne Avenue Houston, TX 77004	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTRT12GUTC17/KLK900-SB-002
12. Sponsoring Agency Name and Address Tier 1 University Transportation Center TranLIVE Office of the Assistant Secretary for Research and Technology U. S. Department of Transportation 1200 New Jersey Avenue, SE. Washington, DC 20590	13. Type of Report and Period Covered Research Report 01/01/12 - 01/31/16
	14. Sponsoring Agency Code

15. Supplementary Notes

100% Matching Fund from Texas Southern University.

16. Abstract

Vehicle emissions occupy a considerable share of emission inventories in the United States. One of the approaches taken to minimize vehicle emissions is eco-driving. Supported by advanced ITS technologies, it is available to provide the real-time eco-driving advice/suggestions to drivers and to automated vehicles. In order to examine the most effective eco-driving advising strategies for drivers, and evaluate potential emission mitigations of eco-driving for automated vehicles. Real-time eco-driving models for drivers and for automated vehicles were developed respectively. The eco-driving model for drivers was programmed in a high-fidelity driving simulator. Different eco-driving advising strategies with regard to the types (audio vs. visual) and the frequencies of the suggestions were designed and tested by thirty-one driver participants. On the other hand, the eco-driving model for automated vehicles was applied in a VISSIM simulation platform under different traffic conditions. The automated vehicles in the simulation environment could adjust their driving behaviors second-by-second according to the eco-driving model. Finally, the MOVES' method was used to estimate vehicle emissions for both driving simulator tests and VISSIM simulations. It is found that all of the eco-driving scenarios for drivers are effective in emission reducing. The audio eco-driving strategy with a 10-second interval is the most effective strategy to reduce emissions. However, eco-driving scenario spent more travel time. Meanwhile, real-time eco-driving suggestions for automated vehicles saved 20% CO2. However, vehicle emissions are dependent on traffic condition.

17. Key Words Eco-driving, Vehicle Emissions, Automated Vehicles, Traffic Simulation, Driving Simulator, VISSIM, MOVES	18. Distribution Statement No restriction. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161

19. Security Classify (of this report) Unclassified	20. Security Classify (of this page) Unclassified	21. No. of Pages 95	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

NOTICE

ACKNOWLEDGMENT

The authors would like to thank the research assistants at Texas Southern University (TSU) in data processing and scripting in VISSIM. Also the authors would like to express thanks to all personnel who have directly or directly contributed to this project or have provided various assistances.

ABSTRACT

Vehicle emissions occupy a considerable share of emission inventories in the United States. One of the approaches taken to minimize vehicle emissions is eco-driving. Supported by advanced ITS technologies, it is available to provide the real-time eco-driving suggestions to drivers and to automated vehicles.

In order to examine the most effective eco-driving advising strategies for drivers, and evaluate potential emission mitigations of eco-driving for automated vehicles. Real-time eco-driving models for drivers and for automated vehicles were developed respectively. The eco-driving model for drivers was programmed in a high-fidelity driving simulator. Different eco-driving advising strategies with regard to the types (audio vs. visual) and the frequencies of the suggestions were designed and tested by thirty-one driver participants. On the other hand, the eco-driving model for automated vehicles was applied in a VISSIM simulation platform under different traffic conditions. The automated vehicles in the simulation environment could adjust their driving behaviors second-by-second according to the eco-driving model. Finally, the MOVES' method was used to estimate vehicle emissions for both driving simulator tests and VISSIM simulations. It is found that all of the eco-driving scenarios for drivers are effective in emission reducing. The audio eco-driving strategy with a 10-second interval is the most effective strategy to reduce emissions. However, eco-driving scenario spent more travel time. Meanwhile, real-time eco-driving suggestions for automated vehicles saved 20% CO_2. However, vehicle emissions are dependent on traffic condition.

EXECUTIVE SUMMARY

The transportation sector consumes a large amount of energy, and has become the second largest source of carbon dioxide (CO_2) emissions in the United States. In 2013, among all of the modes of transportation available, light-duty vehicles shared the biggest slice of the pie, generating 56.59% of CO_2. Moreover, vehicles are the main source of carbon monoxide (CO), oxide of nitrogen (NO_x) and other emissions, which pose a major threat to human health and our living environment. One of the approaches taken to minimize vehicle emissions is eco-driving, which refers to a range of driving actions, associated with driving behavior and driving habits that can reduce vehicle emissions and fuel consumption. Typical eco-driving suggestions include but are not limited to maintaining a steady speed, anticipating the traffic flow, avoiding sudden acceleration, avoiding abrupt braking, avoiding unnecessary idling, checking the tire pressure frequently, and performing a regular maintenance on the car. Supported by advanced ITS technologies, it is available to provide the real-time eco-driving advice/suggestions to drivers and to automated vehicles.

Real-time eco-driving suggestions are usually provided to drivers through in-vehicle audio or visual system. However, both of the audio and visual systems could be distracting, and the frequencies of providing eco-driving suggestions may influence drivers' reactions. On the other hand, existing studies on eco-driving for automated vehicles simplified the driving behavior when queuing, which do not duplicate the real world.

This report intends to examine the most effective eco-driving advising strategies for drivers and evaluates potential emission mitigations of eco-driving for automated

vehicles. Real-time eco-driving models within intersection vicinities for drivers and for automated vehicles were developed respectively, which were based on real-time data such as, traffic signal phase and timing, distance from the vehicle location to the intersection stop bar, queue length at the intersection upstream, travel speed, and speed limit, etc. The eco-driving model for drivers evaluated drivers' potential to cruise to pass, accelerate to pass, or decelerate to pass the intersection at the intersection upstream; and evaluates drivers' potential to avoid speeding, slightly accelerate or maintain their speed at the intersection downstream. The proposed model was programmed in a high-fidelity driving simulator. The outcome of the model was provided via an in-vehicle device, which could provide audio or visual suggestions to drivers. Different eco-driving advising strategies with regard to the types (audio vs. visual) and the frequencies of the suggestions were designed and tested by thirty-one driver participants.

On the other hand, the eco-driving model for automated vehicles classified deeper of the driving behaviors in passing the intersection at upstream. Six situations and their corresponding real-time eco-driving strategies were built. The six situations were Cruise, Accelerate and Pass, Decelerate and Pass, Decelerate and Stop at the Stop Line, Decelerate due to the Queue and Follow the Leading Vehicle, and Decelerate and Stop at the Queue. The proposed model was applied in VISSIM simulation software, where Visual Basic were scripted to pick up automated vehicles, make eco-driving decisions, and implement real-time eco-driving guidance. Further, different traffic conditions with a v/c ratio changing from 0.3 to 0.8 were simulated. Finally, the MOVES' method was used to estimate vehicle emissions for both driving simulator tests and VISSIM simulations. It is found that all of the eco-driving scenarios for drivers are effective in emission reducing. The audio eco-driving strategy with a 10-second interval is the most effective strategy to reduce emissions. However, eco-driving scenario spent more travel time. Meanwhile, real-time eco-driving suggestions for automated vehicles saved 20% CO_2. However, vehicle emissions are dependent on traffic condition.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Symbol	Unit	Definition
a_{ac}	m/s^2	Expected acceleration rate for the vehicle to reach the stop line
aa_{ta}	m/s^2	Targeted instantaneous acceleration rate based on the eco-driving instruction for automated vehicles approaching the intersection
a_{de}	m/s^2	Expected deceleration rate for automated vehicles to reach the stop line
a_{ded}	m/s^2	Constant deceleration rate for the vehicle traveling a given distance
a_{det}	m/s^2	Constant deceleration rate for the vehicle whose speed decreases to zero within the time period
a_{max}	m/s^2	Maximum acceleration rate
a_t	m/s^2	Instantaneous acceleration/deceleration rate
C	S	Cycle length of the traffic signal
d_{max}	m/s^2	Maximum deceleration rate
d_{sp}	M	Actual distance of the space from the vehicle to its leading vehicle
d_{ts}	M	Distance from the time when making judgments to the stop line (or end of queue, if any)
DS_{dn}	-	Driving situation at the downstream of intersections
DS_{up}	-	Driving situation at the upstream of intersections
E_i	G	Estimated total amount of emission type (CO$_2$, CO, NO$_x$, or HC) for a single vehicle
$E_{i,k}$	G	Average amount of emissions of eco-driving vehicles for emission type i and v/c ratio k
e_{range}	m/s	Acceptable deviation from the speed limit when traveling within the intersection vicinity
Er_{ij}	g/s	Emission rate for the emission type i in OpModeID j
g	S	Effective green time

i	-	Type of emissions (CO_2, CO, NO_x, or HC)
j	-	Operation Mode ID (OpModeBin)
l_{fmax}	M	Maximum distance for car following
l_q	M	Queue length at the upstream, which is from the end of queue to the stop line
$N_{i,k}$	G	Average amount of emissions of non-eco-driving vehicles for emission i and v/c ratio k
p_j	1	Frequency of OpModeBin j
q	1	Number of OpModeBin
$RE_{i,k}$	%	Emission mitigation rate of eco-driving vehicles for emission i (CO_2, CO, NO_X, or HC) and v/c ratio k
sig	-	State of the signal (0 represents red, and 1 represents green)
t	S	Instantaneous time spent after making the eco-driving decisions
T	S	Total time spent for the automated vehicle passing the stop line
T_a	S	Total time spent for the automated vehicle approaching to the stop line or the end of the queue
t_{ac}	S	Expected time of accelerating to reach the stop line
t_c	S	Expected time of cruising from the time when making the judgment to the stop line
t_{de}	S	Expected travel time of deceleration
t_{ded}	S	Time spent for the vehicle traveling a given distance
t_{def}	S	Final suggested time of deceleration
t_{det}	S	Time spent for the vehicle whose speed decreases to zero within the time period
T_f	S	Total time spent for car following until the automated vehicle passes the stop line
t_{lg}	S	Remaining time for the green interval within a signal cycle
t_{lr}	S	Remaining time for the red interval within a signal cycle

t_{pa}	S	Time passed from the beginning of the signal cycle when making the eco-driving decisions
T_{re}	S	Time remaining after the automated vehicle reaches the stop line until the signal turns to green
v_{ft}	m/s	Instantaneous speed of the automated vehicle when following its leading vehicle
v_{limit}	m/s	Speed limit
v_{max}	m/s	Upper bound of the acceptable speed for traveling within the intersection vicinity
v_{min}	m/s	Lower bound of the acceptable speed for traveling within the intersection vicinity
v_t	m/s	Instantaneous speed of the vehicle v_{ta}
m/s		Targeted instantaneous speed

CHAPTER 1

INTRODUCTION

1.1 Background

The transportation sector consumes a large amount of energy, and has become the second largest source of carbon dioxide (CO_2) emissions in the United States ("Annual Energy Outlook 2015 with projections to 2040," 2015). In 2013, among all of the modes of transportation available, light-duty vehicles shared the biggest slice of the pie, generating 56.59% of CO_2. Moreover, vehicles are the main source of carbon monoxide (CO) ("Carbon Monoxide," n.d.), oxide of nitrogen (NOx) ("Nitrogen Oxides," n.d.) and other emissions, which pose a major threat to human health and our living environment.

Driving behavior is one of the main factors that influence vehicle emissions. Early studies have proved that aggressive driving behaviors generate significantly higher levels of emissions than normal driving behaviors (Vlieger, 1997; Sierra Research, 2001). In addition, intersections are the main areas where vehicles generate emissions due to frequent stops and accelerations (Xu, 2011). In order to reduce vehicle emissions, it is important to improve the driving behaviors in the vicinities of intersections. In order to mitigate vehicle emissions, eco-driving has been promoted for decades as one of the approaches to improve driving behaviors. It is gaining worldwide attention. Eco-driving refers to a range of driving actions, associated with driving behavior and driving habits that can reduce vehicle emissions and fuel consumption. Typical eco-driving suggestions include but are not limited to maintaining a steady speed, anticipating the traffic flow, avoiding sudden acceleration, avoiding abrupt braking, avoiding unnecessary idling, checking the tire pressure frequently, and performing a regular maintenance on the car

(“ECOWILL,” n.d.).

Eco-driving suggestions can be classified into two categories. One is “traditional eco-driving” that includes the advice provided to drivers through websites, brochures, or classroom training programs before the driving begins. Those suggestions are a variety of conceptual rules for drivers to form good habits of driving. The Japanese campaigns: “Soft Acceleration, e-Start” (Shinpo, 2007), "Eco-Drive Promotion Month" (Ministry of Economy, Trade and Industry of Japan, 2014), and European campaign ECO-DRIVING (“ECODRIVEN,” n.d.) are all examples of early-launched traditional eco-driving projects.

Another category of eco-driving is the “advanced eco-driving,” which involves a variety of advices and feedback communications during the driving practice (Boriboonsomsin et al., 2011). In this method, vehicles can obtain and share real-time information about traffic signals, traffic conditions, and driving behaviors through dedicated short-range communications (DSRC) (“DSRC Service,” n.d.) between vehicles to infrastructures (V2I), infrastructures to vehicles (I2V), and vehicles to vehicles (V2V).

Advanced eco-driving suggestions are classified into two sub-categories depending upon whether the drivers or the vehicles receive the eco-driving advice, and how they react to the advice accordingly. The first suggestion is the advice given to the drivers, while driving, through human-machine interfaces (HMIs) in order to entice the drivers to follow the advice. Many HMI-based eco-driving suggestions are provided through in-vehicle audio or visual systems, such as Radio Frequency Identification (RFID) based Drivers’ Smart Assistance System (Qiao et al., 2014) and Smartphone based warning messages (Rahman et al., 2015; Qiao et al., 2016). Many on-road tests as well as driving simulator lab experiments have demonstrated that the audio warning messages are able to guide drivers to drive smoothly, thereby significantly reducing vehicle emissions caused by excessive acceleration (Li et al., 2016a; Li et al., 2015). However, it takes time for drivers to read/hear the HMIs massages before taking a corresponding reaction, which distracts drivers' attention to the roads. Therefore, both the audio or visual systems could be distractive to drivers. Furthermore, drivers may find it difficult to follow high-frequency advice when driving. On the other hand, drivers may ignore low- frequency eco-driving advice and perform their normal driving behaviors, which make the eco-driving advice ineffective. Hence, the effectiveness of eco-driving advising strategies might vary depending on the frequency of providing eco-driving suggestions to drivers.

The second sub-category is the eco-driving advice applied in automated vehicles (partially automated, highly automated, or fully automated vehicles), whose longitudinal and lateral controls are taken over by the vehicle system automatically with limited or no driver controls (Shladover, 2012). Today, partial-automated or high-automated vehicles are a topic of popular emerging research in transportation and engineering. Those vehicles are considered to be equipped with dedicated devices, which are assumed to be able to follow the eco-driving advice exactly (Wu et al., 2014). However, the traffic conditions within the intersection vicinities are complicated. It is common for vehicles joining in a queue and wait for the traffic signal when approaching the intersections, needless to mention the fact that. Before automated vehicles are implemented, the technologies of connected vehicle and autonomous vehicles have to be highly mature in the market. There is a need to analyze the eco-driving strategies applied in automated vehicles approaching the intersections under different traffic conditions.

1.2 Objectives of the Study

The background of the research presented above provided the context for defining the objectives of this research. The research objectives are summarized as follows:

1. Developing real-time eco-driving algorithms to be used in normal vehicles to advise drivers behavior, and to be applied in automated vehicles traveling within intersection vicinities,
2. Examining the most effective eco-driving advising strategies among audio and visual in-vehicle systems at different frequencies for drivers, and
3. Evaluating potential emission mitigations of eco-driving strategies for automated vehicles approaching intersections under different traffic conditions

Through achieving the aforementioned objectives, the possible achievements of the study will occur in the following two aspects:

1. The eco-driving algorithms will provide methods for the automobile industry and also for in-vehicle device manufacturers to contribute to reducing vehicle emissions either by means of providing the eco-driving advice to the drivers, or by adjusting the automated vehicle systems, and
2. The recommended eco-driving advising strategies for drivers will provide a reference for manufacturers to develop human-machine interfaces that are accepted by drivers and are effective in reducing emissions.

1.3 Outline of the Study

In documenting the achievement of the research objectives, this report is comprised of six chapters. The first chapter provides an overview of the problem, the research objectives, and the outline of the study. The second chapter presents an overview of the existing achievements on the study of eco-driving, as well as the vehicle emission estimation approaches. The third chapter describes the design of the study by building real-time eco-driving models for drivers and automated vehicles, respectively. The eco-driving models for drivers are studied by conducting driving simulator tests through audio or visual in-vehicle advising systems, and the eco-driving models for automated vehicles are studied in VISSIM traffic simulation platform. The fourth chapter presents the results of the driving simulator tests and VISSIM simulation outcomes. Finally, the fifth chapter provides the study conclusions and also recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

The literature review is conducted from three perspectives in order to establish the context for the proposed research. First, the existing efforts on eco-driving will be presented. Second, typical approaches of vehicle emission estimations will be reviewed. Finally, the limitations of the existing studies will be discussed.

2.1 Existing Efforts on Eco-driving

The concept of eco-driving has developed for decades. This section will first introduce the general development of eco-driving studies. Then advanced eco-driving applications and state-of-art advanced eco-driving in research will be reviewed.

2.1.1 Development of Eco-driving

It has been proved that traditional eco-driving is effective in reducing emissions within uninterrupted corridors (without any intersection or junction). Vlieger (1997) demonstrated that vehicle emissions when driving aggressively are up to four times higher than those of normal driving behaviors. The study also showed that fuel consumption increases by 12% to 40%. Sierra Research, Inc. (2001) found that the most aggressive driving might only represent 2% of the entire travel time but generates about 40% of the total emissions. In a study conducted by Beusen et al. (2009), the average fuel consumption decreased by 5.8% in four months according to the records of driving behaviors and fuel consumption after the drivers took traditional eco-driving courses.

Due to frequent acceleration, deceleration, and idling, intersection vicinities may produce more emissions compared to uninterrupted corridors. Rouphail (2001) showed that, during control delays, the vehicle emissions were approximately twice as much as without delays. Tang et al. (2014) found that a gentler behavior of approaching (or departing from) an intersection would generate less CO and NO_X emissions.

Contrary to the positive results of the above-mentioned studies, Kobayashi et al. (2007) demonstrated that eco-driving increased the total amount of CO_2 within a network. Qian et al.'s (2011) research results produced a similar conclusion. However, both studies only used moderate acceleration for all vehicles in the simulation software. Meanwhile, their studies did not focus on the driving behaviors of individual vehicles.

Existing studies indicate that the driving environment at intersections is more complicated than that in uninterrupted facilities (Li and Qiao, 2014; Li et al., 2016b). It is difficult to tell whether traditional eco-driving could reduce emissions at intersections. Furthermore, traditional eco-driving suggestions are not channelized for specific situations. They cannot be updated in real time when the driving situation changes.

Along with the recent advancements in the field of ITS technologies, eco-driving has been gaining popularity in both research and vehicle technology deployment. Advanced eco-driving is a level of the eco-driving technology that applies Vehicle-to- Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Infrastructure-to-Vehicle (I2V) communications to transfer and share information regarding the signal timings, traffic flows, and driving behaviors of nearby vehicles. Meanwhile, on-board diagnostics (OBD) monitors, global positioning system (GPS) receivers, or other systems can be utilized to collect the instantaneous driving behavior data. By processing and integrating the data, and applying eco-driving algorithms into the in-vehicle system, it is possible to make eco-driving judgments based on the instantaneous driving situations. Ultimately, eco-driving suggestions are to be put into effect by either applying them to the drivers through the in-vehicle audio or visual system, or providing them directly to the vehicle control system.

2.1.2 Advanced Eco-driving Applications in Market

There are several vehicles' on-board systems designed by auto manufacturers, which provide real-time eco-driving advice to drivers. For example, the SmartGauge with EcoGuide, designed by Ford, provides real-time fuel efficiency information via an LCD monitor in the vehicle ("Next-Generation SmartGauge with EcoGuide," n.d.). The on-board system displays lusher green leaves and vines for more efficient driving behavior. In the Honda Eco Assist system, fuel-saving behaviors, such as smooth acceleration and braking, cause the on-board display to show a green color. In contrast, less fuel-efficient behaviors trigger the display to turn blue (Cogan R, 2014). Eco-driving applications developed on-board are supported by the built-in sensors in the car, and do not require extra hardware. However, such applications are limited to a small group of car models or upgrade-featured cars. In addition, those applications emphasize fuel consumption or driving behaviors rather than vehicle emissions.

Taking advantage of the growing penetration of smartphones in the world market and the convenience of designing a mobile application, developers have designed many eco-driving mobile applications all over the world. BMW M Power Meter is an app that provides real-time information about drivers' lateral and longitudinal acceleration, speed, and travel time (BMW Group, 2015). A Glass of Water, a smartphone app, applies an animation of a glass of water to indicate the aggressiveness of the driving behavior. The app begins with a full glass of water, and the more aggressive driving, the more water pours out of the glass, resulting less water left in the glass ("A Glass of Water," n.d.). Many smartphone applications collect data by using Global Positioning System (GPS) or accelerometer sensors. These data actually represent the movement of the smartphones, and do not directly refer to the drivers' driving behaviors. However, the accuracy of the GPS data depends on the signals received from the satellites, which is a limitation of the GPS technology. Furthermore, those apps are not capable of collecting the data on fuel consumption and emissions.

In addition, instantaneous data related to driving behavior and fuel consumption can be collected more accurately via vehicle OBDII connectors by using plug-in monitoring systems. The Fiat eco:Drive system relies on its plug-in devices to collect driving behavior data when driving, and it provides detailed feedbacks to drivers via its software application after the car stops (Fiat, 2010). However, the results from the Fiat eco:Drive system is not in real-time, as drivers have to connect the devices to computers to check their results.

2.1.3 Advanced Eco-driving in Research

Real-time eco-driving suggestions are usually provided to drivers through in-vehicle audio or visual systems. Xia et al. (2012) programmed a system to display information regarding the traffic signal phase and timing (SPaT), and to recommend a speed for the vehicles driving through intersection vicinities. The system was supported by a Controller Area Network (CAN bus), a 4G/LTE cellular network, and a cloud-based server. Zhao et al. (2015) developed a smartphone driving behavior application based on the value of Vehicle Specific Power (VSP). When the VSP was beyond the threshold, the app would warn the driver with a beep and a visual image. Hallilhan et al. (2011) found that the real-time animations of eco-driving advice could help drivers accelerate less, but the drivers would spend a longer time without looking back at the road ahead. Staubach et al. (2014) designed an in-vehicle eco-driving system that gave the driver visual indications of efficient driving behaviors, signal timings, and curve information ahead. The results showed that the eco-driving system could save 15.9% to 18.4% in fuel. The research of Daun et al. (2013) indicated that a real-time eco-driving system could save 12.2% in fuel. Their system provided both audio and visual eco-driving advice. Hiraoka et al. (2011) displayed both the real and target value of the fuel economy on the vehicle dashboard every minute. However, the target value of the fuel economy was calculated based on the values from the past 10 minutes. Wu et al. (2010) found that fuel consumption and CO_2 emissions could be reduced by up to 40% after applying the advanced driving alert system (ADAS). Rakha et al. (2011) established a framework to enhance the fuel consumption efficiency for the vehicles approaching a signalized intersection. Kamalanathsharma et al. (2012) proposed an eco-cooperative adaptive cruise control (ECACC) system to compute the most fuel-efficient vehicle trajectory. The optimized speed profiles reduced the fuel consumption by 30% in the proximity of signalized intersections. Sun et al. (2013) developed and implemented a dynamic eco- driving speed guidance strategy (DESGS) on a driving simulator to seek the most fuel/emission-optimal trajectory. Wu et al. (2014) implemented the eco-approach/ departure application via HMIs and partial automation vehicle. The results showed that the efficiency of the HMIs application was degraded due to the delays in drivers' reaction.

Current studies have shown that since the advanced eco-driving can provide real-time eco-driving advice to drivers or vehicles, it is much more advantageous to be applied to vehicles within intersection vicinities compared to others. Studies on real-time eco-driving advice for drivers via in-vehicle audio or visual systems have been proved to be effective. However, none of the studies compared the methods in providing the eco-driving advice i.e. audio vs. visual systems. In fact, when receiving the eco-driving advice, drivers might have to listen to or move their eyes towards the in-vehicle system. This action may present a burden on the performance of the driving or cause distraction. Furthermore, high frequency of eco-driving advice may make it difficult for drivers to follow it. On the other hand, studies on real-time eco-driving instruction in automated vehicles were focused on ideal conditions under which individual vehicles travel in a free-flow condition. However, in reality, driving behaviors are influenced to a great extent by traffic conditions. Vehicles may have to join queues or follow the leading vehicles. Wu et al. (2014) indirectly utilized the delay time to calculate emissions for queuing. But in fact, the driving behaviors during the queuing process are not limited only to idling. Vehicles may follow the leading vehicles or stop when queuing. Using the delay time only simplifies the issue but does not replicate real world condition. Kamalanathsharma et al. (2012, 2014) applied the equation of Marshall and Berg to estimate the time for queue dissipation. However, the model requires constant arrival and discharge flow rates (Marshall et al., 1997), which simplified the problem.

2.2 Emission Estimation Models

Vehicle emission models are important for estimating the effectiveness of eco-driving strategies. Typical vehicle emission models for the micro-scale level of studies are Comprehensive Modal Emission Model (CMEM), Virginia Tech Microscopic Energy and Emission Model (VT-Micro), and Motor Vehicle Emission Simulation (MOVES).

2.2.1 CMEM

CMEM is a power-demand model (Scora, et al., 2006). The emission estimation process is broken down into six modules that correspond to the physical phenomena associated with the vehicle operation and the productions of vehicle emissions (An, et al., 1997). The six modules and the general processes of the model are shown in Figure 1.

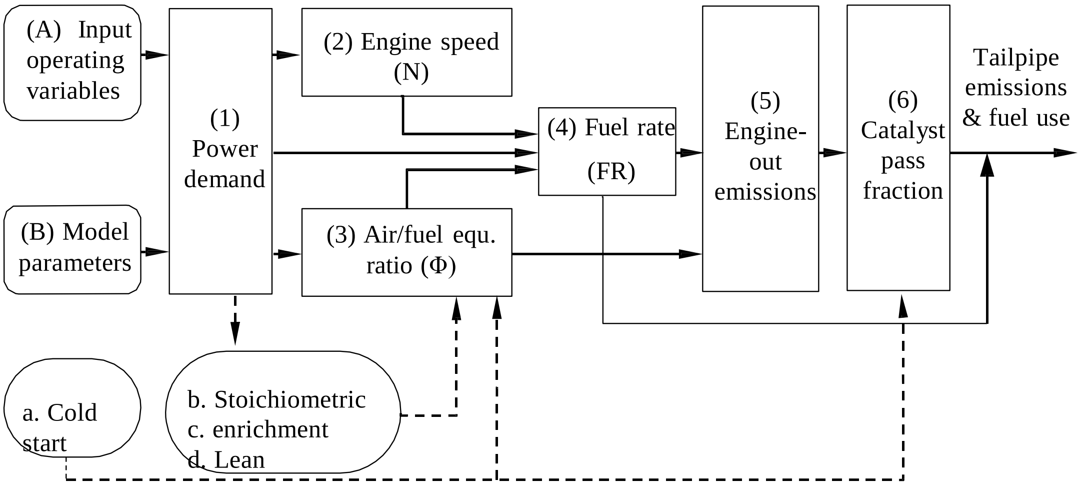


Figure 1 Model Architecture of CMEM (An, et al., 1997).

As Figure 1 demonstrates, the power demand is calculated according to the driving operation variables and parameters of the vehicle model. Then, the fuel rate is determined by considering the power demand, engine speed, and air/fuel ratio. Furthermore, the carbon-balance method is applied to calculate the engine-out emission. Finally, the pipeline emissions are determined by taking the catalyst pass fraction into consideration.

CMEM describes the internal processes of how to generate pipeline emissions in detail. However, its parameters and algorithms are complicated, which is the main limitation of this model.

2.2.2 VT-Micro

The VT-Micro emission model is a nonlinear regression model that utilizes a multi-dimensional polynomial model structure. The independent variables are namely the instantaneous speed and acceleration. The emission algorithm is shown in Equation (1).

$$\mathbf{ln}(\mathbf{MOE_e}) = \begin{cases} \sum_{i=0}^{3}\sum_{j=0}^{3}\left(\mathbf{L}_{i,j}^{e} * \mathbf{u}^{i} * \mathbf{a}^{j}\right) \mathbf{a} \geq \mathbf{0} \\ \sum_{i=0}^{3}\sum_{j=0}^{3}\left(\mathbf{M}_{i,j}^{e} * \mathbf{u}^{i} * \mathbf{a}^{j}\right) \mathbf{a} < \mathbf{0} \end{cases} \tag{1}$$

where MOE_e is the emission rate (mg/s); $L_{i,j}^{e}$ is the regression coefficient for emission type e at speed power i and acceleration power j when the accelerations are positive; $M_{i,j}^{e}$ is the model regression coefficient for emission type e at speed power i and acceleration power j when the value of accelerations is negative; u is the instantaneous speed (km/h); and a is the instantaneous acceleration (km/h/s) (Rakha, et al., 2004).

The VT-Micro model has fewer parameters than CMEM. The accuracy of the results only depends on the speed and acceleration, which is much easier to use. However, the model does not consider any physical principles about the generation of the vehicle emissions. Therefore, it is less convincible.

2.2.3 MOVES

MOVES is a power-demand-based model. It utilizes the variable VSP as one of its main parameters. VSP is the instantaneous tractive power per unit vehicle mass. The instantaneous power generated by the engine is used to overcome the rolling resistance and aerodynamic drag, and to increase the kinetic and potential energies of the vehicle (Jimènez-Palacios, 1998). The equation for VSP is shown as follows.

$$VSP = v \cdot [(1 + \varepsilon)a + g \cdot \mathrm{grade} + g \cdot C_R] + \frac{0.5\rho_a \cdot C_D \cdot A \cdot v \cdot (v + v_m)^2}{m} \quad (2)$$

where VSP is the vehicle specific power (kw/t); v is the vehicle speed (m/s); a is the vehicle acceleration (m/s^2); ε is the mass factor, which is the equivalent translational mass of the rotating components (wheels, gears, shafts, etc.) of the powertrain; g is the acceleration of gravity (9.8m/s^2); grade is vertical rise/slope length; C_R is the coefficient of rolling resistance; ρ_a is the ambient air density (1.207 kg/m^3 at 20 °C or 68 °F); C_D is the drag coefficient; A is the frontal area of the vehicle (m^2); and v_m is the headwind into the vehicle (m/s).

For a light-duty vehicle, the value of $C_D A/m$ is around 0.0005, and the value of ε is 0.1. Referring to a typical urban highway, the value of C_R is 0.0135. Assuming that the values of the grade and v_m are both 0, the equation of VSP for a light-duty vehicle driving on a flat urban highway is simplified in Equation (3).

$$VSP = v(1.1a + 0.132) + 0.000302v^3 \quad (3)$$

In MOVES, the vehicle emission rate is determined by the Operation Mode (OpModeID), which is refined by the ranges of VSP and speeds, except for idling and braking. The definition of each OpModeID in MOVES is shown in Table 1 (Office of

Transportation and Air Quality, 2010).

Table 1 Definition of MOVES Operating Mode Attributes

OpModeID	*Operating Mode Definition*
0	Braking: Acceleration ≤ -2 mph/s, or < -1 mph/s for 3 consecutive seconds
1	Idling: -1 ≤ Speed < 1
11	Low Speed Coasting: VSP < 0; 1 ≤ Speed < 25
12	Cruise/Acceleration: 0 ≤ VSP < 3; 1 ≤ Speed < 25
13	Cruise/Acceleration: 3 ≤ VSP < 6; 1 ≤ Speed < 25
14	Cruise/Acceleration: 6 ≤ VSP < 9; 1 ≤ Speed < 25
15	Cruise/Acceleration: 9 ≤ VSP < 12; 1 ≤ Speed < 25
16	Cruise/Acceleration: 12 ≤ VSP; 1 ≤ Speed < 25
21	Moderate Speed Coasting: VSP < 0; 25 ≤ Speed < 50
22	Cruise/Acceleration: 0 ≤ VSP < 3; 25 ≤ Speed < 50
23	Cruise/Acceleration: 3 ≤ VSP < 6; 25 ≤ Speed < 50
24	Cruise/Acceleration: 6 ≤ VSP < 9; 25 ≤ Speed < 50
25	Cruise/Acceleration: 9 ≤ VSP < 12; 25 ≤ Speed < 50
27	Cruise/Acceleration: 12 ≤ VSP < 18; 25 ≤ Speed < 50
28	Cruise/Acceleration: 18 ≤ VSP < 24; 25 ≤ Speed < 50
29	Cruise/Acceleration: 24 ≤ VSP < 30; 25 ≤ Speed < 50
30	Cruise/Acceleration: 30 ≤ VSP; 25 ≤ Speed < 50
33	Cruise/Acceleration: VSP < 6; 50 ≤ Speed
35	Cruise/Acceleration: 6 ≤ VSP < 12; 50 ≤ Speed
37	Cruise/Acceleration: 12 ≤ VSP < 18; 50 ≤ Speed
38	Cruise/Acceleration: 18 ≤ VSP < 24; 50 ≤ Speed
39	Cruise/Acceleration: 24 ≤ VSP < 30; 50 ≤ Speed
40	Cruise/Acceleration: 30 ≤ VSP; 50 ≤ Speed

It is noted that, for two-digit OpModeID, the first digit represents the range of the speed, and the second digit represents the range of VSP. In previous studies the OpModeIDs were defined based on only 17 specific modes as shown in Table 2 (Koupal et al., 2004). According to Table 2, the maximum range of VSP was equal and larger than

12, which was represented by #6. In subsequent studies, VSP was classified into more bins. As it is demonstrated in Table 1, the range of VSP is classified into 12 to 18, 18 to

24, 24 to 30, and equal and bigger than 30, which are represented by #7, #8, #9, and #0, respectively. Since the new ranges of #7, #8, #9, and #0 have already covered the previous range of #6, there is no #6 to stand for a range of VSP in Table 1. This is why there are OpModeID 27, 28, 29, 37, 38, 39, and 40, but no OpModeID 26 or OpModeID 36 in Table 1.

Table 2 Definition of MOVES Operating Mode Attributes in Previous Studies

OpModeID	*Operation Mode Description*	*VSP (kw/t)*	*Speed (mph)*	*Acceleration (mph/s)*
0	Deceleration/Braking	-	-	Acceleration ≤ -2 or Acceleration < -1 for 3 consecutive seconds
1	Idling	-	-1 ≤ Speed < 1	-
11	Cruise/Acceleration	VSP < 0	0 ≤ Speed < 25	-
12	Cruise/Acceleration	0 ≤ VSP < 3	0 ≤ Speed < 25	-
13	Cruise/Acceleration	3 ≤ VSP < 6	0 ≤ Speed < 25	-
14	Cruise/Acceleration	6 ≤ VSP < 9	0 ≤ Speed < 25	-
15	Cruise/Acceleration	9 ≤ VSP < 12	0 ≤ Speed < 25	-
16	Cruise/Acceleration	12 ≤ VSP	0 ≤ Speed < 25	-
21	Cruise/Acceleration	VSP < 0	25 ≤ Speed < 50	-
22	Cruise/Acceleration	0 ≤ VSP < 3	25 ≤ Speed < 50	-
23	Cruise/Acceleration	3 ≤ VSP < 6	25 ≤ Speed < 50	-
24	Cruise/Acceleration	6 ≤ VSP < 9	25 ≤ Speed < 50	-
25	Cruise/Acceleration	9 ≤ VSP < 12	25 ≤ Speed < 50	-
26	Cruise/Acceleration	12 ≤ VSP	25 ≤ Speed < 50	-
33	Cruise/Acceleration	VSP < 6	50 ≤ Speed	-
35	Cruise/Acceleration	6 ≤ VSP < 12	50 ≤ Speed	-
36	Cruise/Acceleration	12 ≤ VSP	50 ≤ Speed	-

Each OpModeID relates to an emission rate for a specific type of emissions. On the other hand, VSP is calculated by the instantaneous speed and acceleration, which represents the vehicle driving behavior. That is to say, VSP bridges the driving behaviors and the vehicle emissions. In addition, the process of gathering the driving behavior data and the process of estimating the vehicle emissions are independent, which makes

MOVES much easier to apply.

2.3 Summary

Based on the advanced ITS technologies, providing real-time eco-driving advice to drivers or to automated vehicles has a greater potential to reduce the vehicle emissions within the intersection vicinities compared to traditional eco-driving advice. Many real-time eco-driving suggestions are provided to drivers through in-vehicle audio or visual systems. When receiving the eco-driving advice, drivers might listen to the advice or move their eyes towards the in-vehicle systems. It may introduce a burden to the performance of driving or cause distractions. Furthermore, it might be difficult for drivers to follow the eco-driving advice provided in high frequency. Meanwhile, drivers may ignore low-frequency eco-driving advice while driving. However, few existing studies have compared the strategies of providing eco-driving advice (i.e. audio system vs. visual system) at different frequencies.

On the other hand, the existing studies on the real-time eco-driving for the automated vehicles have been concentrated on ideal conditions under which the individual vehicles travel in a free-flow condition. However, in the real world, driving behaviors are highly influenced by the traffic conditions. Vehicles may have to join queues or follow the leading vehicles. Some previous studies have indirectly utilized the delay time to calculate emissions for the queuing process. In fact, the vehicles may follow the leading vehicle or stop when they are in the queuing process. Driving behaviors in a queue is varied. However, current studies only simplify the issue but do not replicate the real world.

Emission estimation approaches are essential to evaluating eco-driving strategies.

There are several micro-level emission estimation models. As an EPA standard tool for estimating vehicle emissions, MOVES has combined the driving behavior and the vehicle emission rates by VSP and operation mode binning method. Parameters in MOVES are easy to obtain. Hence, the VSP and the operation mode binning method will be utilized in this report.

CHAPTER 3

DESIGN OF THE STUDY

In order to examine the most effective eco-driving advising strategies for drivers and evaluate the potential emission mitigations of eco-driving advice for automated vehicles, the real-time eco-driving models for the drivers and the automated vehicles will be built. The logics of the two models and corresponding algorithms will be included in the proposed eco-driving models. Then, the eco-driving model for the drivers will be tested in the driving simulator environment by using different audio and visual advising strategies. Furthermore, the eco-driving model for the automated vehicles will be applied in a VISSIM simulation platform under the different traffic conditions. After conducting the driving simulator tests and the VISSIM simulations, MOVES vehicle emissions estimation method will be used to estimate the vehicle emissions for driving simulator tests and VISSIM simulations. The design of the study is shown in Figure 2.

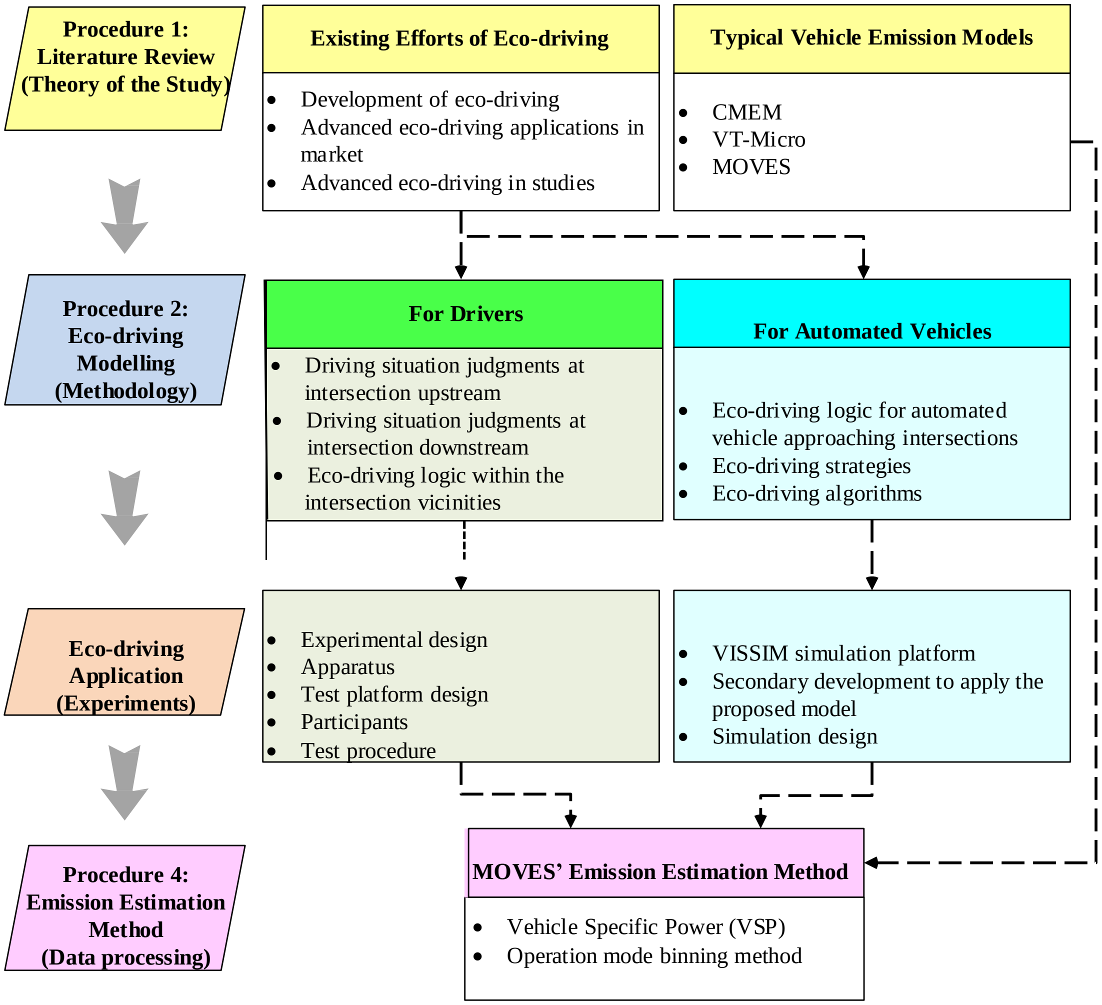


Figure 2 Design of the Study.

3.1 Eco-driving Strategies for Drivers

In order to examine the most efficient real-time eco-driving strategies to drivers, eco-driving models for drivers traveling at the intersection upstream and downstream will be first established. Then, the proposed model will be programmed in the HyperDrive software and be applied in the audio and visual in-vehicle systems of the driving simulator.

3.1.1 Eco-driving Modeling for Drivers

The eco-driving modeling is conducted in two parts depending on the position of the vehicle within the vicinity of intersection. The first part is for driving at the intersection upstream, which is defined from the entrance of the intersection vicinity to the stop line. The other is for driving at the intersection downstream, which is from the stop line to the exit of the intersection vicinity. It is noted that the intersection vicinity is defined due to the area that is sufficient for drivers to react to the eco-driving suggestions.

Driving Situation Judgments at the Intersection Upstream. The expected cruising time to reach the stop line is calculated by Equation (4).

$$t_c = \frac{d_{ts}}{v_t} \tag{4}$$

where t_c is the expected time of cruising from the time when making the judgment to the stop line (s), d_{ts} is the distance from the time when making the judgment to the stop line (or end of queue, if any) (m), and v_t is the instantaneous speed of the vehicle when making the judgments (m/s).

According to the expected time of cruising to the stop line and the traffic signal phase and timing, driving situations at the upstream are categorized into four groups, shown in Equation (5). For each group, a typical eco-driving instruction will be provided to drivers.

$$DS_{up} = \begin{cases} 1\text{ , when } sig = 0, \text{ and } t_c > t_{lr} \\ 2\text{ , when } sig = 1, \text{ and } t_c \le t_{lg} \\ 3\text{ , when } sig = 0, \text{ and } t_c \le t_{lr} \\ 4\text{ , when } sig = 1, \text{ and } t_c > t_{lg} \end{cases} \tag{5}$$

where DS_{up} is the driving situation at the upstream of the intersection; sig is the state of the signal (0 represents red, and 1 represents green); t_{lr} is the remaining time for the red interval (s), and t_{lg} is the remaining time for the green interval (s).

In situations 1 and 2, drivers could pass the intersection by cruising at the current speed. An instructing message of "MAINTAIN YOUR SPEED" will be delivered to the drivers. In Situations 3 and 4, the vehicles will not be able to cruise in order to pass the intersection. A message of "SLOW DOWN" will be delivered to the drivers. Furthermore, when the signal turns to green and the vehicle is still at the intersection upstream, a message of "SLIGHTLY ACCELERATE" will be delivered to drivers.

Driving Situation Judgments at the Intersection Downstream. Drivers traveling within an intersection downstream are encouraged to drive neither too slow nor too fast. Driving too slow will cause longer travel time, which is unnecessary and inefficient. Driving too fast is against the traffic law and may also lead to higher emission rates. The acceptable range of speed is defined by defining the upper and lower bounds in Equation (6).

$$\begin{cases} v_{max} = v_{limit} + e_{range} \\ v_{min} = v_{limit} - e_{range} \end{cases} \tag{6}$$

where v_{max} is the upper bound of the acceptable speed for traveling within the intersection vicinity (m/s), v_{min} is the lower bound of the acceptable speed for traveling within the intersection vicinity (m/s), v_{limit} is the speed limit (m/s), and e_{range} is the acceptable deviation from the speed limit (m/s).

Based on the speed at the present time of the vehicle and the acceptable ranges of traveling speed at the downstream, driving situations at the downstream are categorized into three groups, as shown in Equation (7). For each group, a typical eco-driving suggestion will be provided to drivers.

$$DS_{dn} = \begin{cases} 1, when\ v_t > v_{max} \\ 2, when\ v_t \in [v_{min}, v_{max}] \\ 3, when\ v_t < v_{min} \end{cases}$$

(7)

where DS_{dn} is the driving situation at the downstream of intersections.

Situation 1 indicates that the vehicle is speeding. An instructional massage of “AVOID SPEEDING” will be delivered to drivers. Situation 2 shows that the vehicle is driving within the acceptable range of speed. Then, a massage of “MAINTAIN YOUR SPEED” will be delivered to drivers. Situation 3 represents the case that the speed is too low. In this case, a message of “SLIGHTLY ACCELERATE” will be delivered to drivers.

Eco-driving Logic for Drivers within the Intersection Vicinities. Combining the driving situation judgments both upstream and downstream, the entire logic of the eco-driving model for drivers is illustrated in Figure 3.

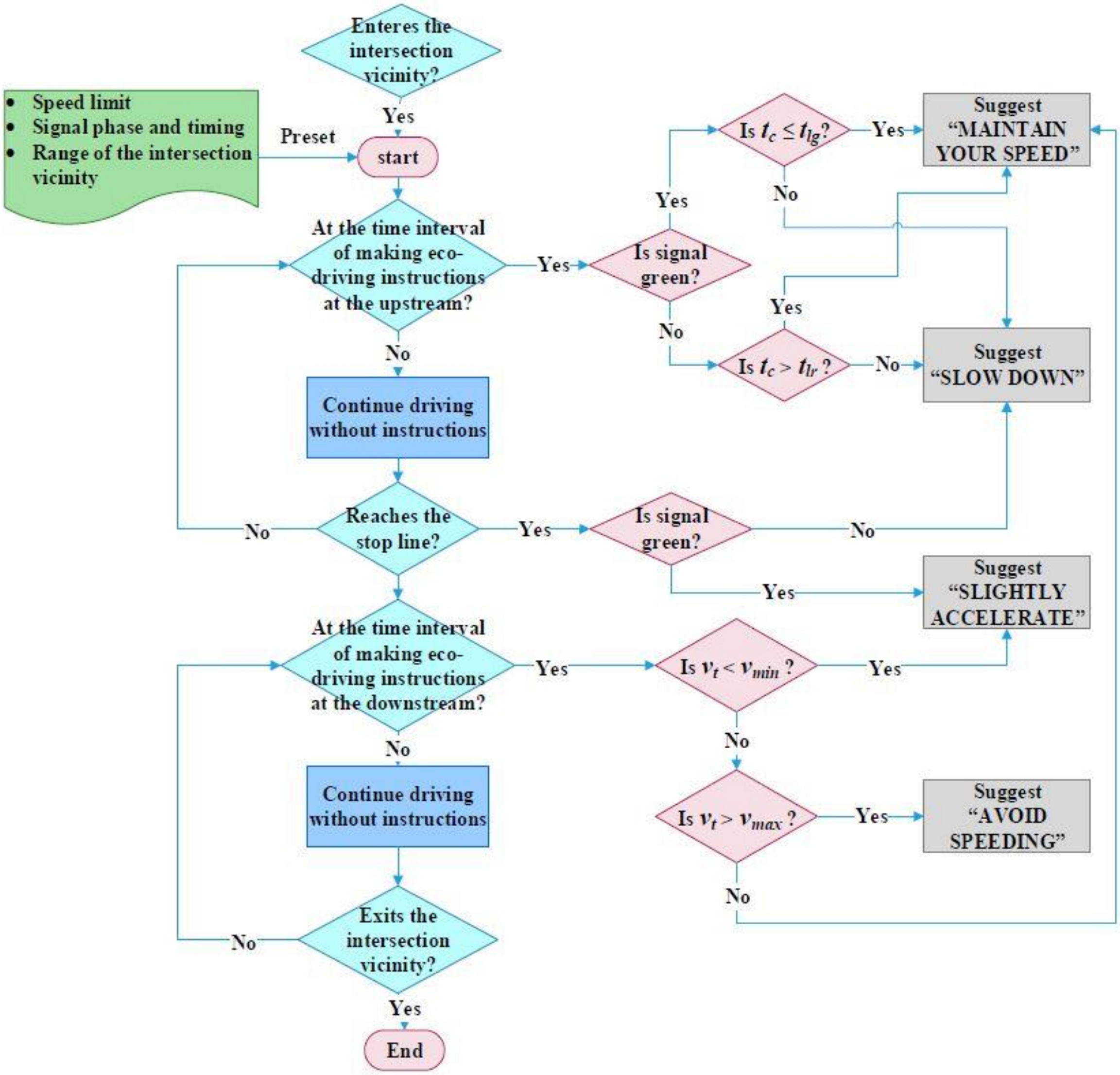


Figure 3 Eco-driving Logic for Drivers Driving within the Intersection Vicinities.

3.1.2 Eco-driving Application on Driving Simulator

Experimental Design. The test experiments are designed into three scenarios: 1) normal driving without any eco-driving advice (this is considered as a base scenario), 2) audio eco-driving advice, and 3) visual eco-driving advice. Both of the audio and visual eco-driving scenarios have three sub-scenarios, with different advising frequencies: provision of audio/visual eco-driving advice at an interval of 5 seconds, 10 seconds, or 15 seconds. Therefore, the design includes a total of seven scenarios.

Apparatus. The test experiments were conducted using a high fidelity passenger-car driving simulator supported by DS-600c hardware, as shown in Figure 4. The driving simulator is a partial Ford Focus Cab with a full-width front interior and standard automatic transmission driver controls. Its mode orders are park (P)-rear (R)- neutral (N)- drive (D)-low (L) (“DS-600c,” n.d.). An 180° wraparound display presents the virtual driving environment in front of the cab. A previous study has proven the high feasibility of using the driving simulator to examine vehicle emissions by comparing the emission related outcomes from driving simulator tests with those from field tests (Li, et al., 2015).

Tool Command Language (TCL) was scripted to build the test platforms of different driving scenarios. During the test experiments, the instantaneous speed, acceleration, distance travelled, and other measurements were collected on a second-by- second basis.

Figure 4 DS-600c Driving Simulator.

Test Platform. As is shown in Figure 5, three intersections were designed in the driving simulator environment. Each approach had two lanes. The speed limits were 30 mph (48.27km/h). And the traffic conditions were free flow. A total of 600 meters were designed for each intersection, namely 300 meters for the upstream and the downstream respectively. Before each intersection, a 100-meter uninterrupted road was designed. In addition, an additional 100-meter uninterrupted road was designed as the preparation area for drivers to start the driving simulator and accommodate themselves to the speed limit.

The signal phases and timing plans were exactly the same for all three intersections. Once the vehicle entered the intersection vicinity, a new signal cycle would be started with 30 seconds in red followed by 15 seconds in green. The eco-driving suggestions were provided through the in-vehicle system, as is shown in Figure 6, which offered audio and visual functions. The suggestions were provided at the vicinities of the first, second, and third intersections at 15-second, 5-second, and 10-second intervals, respectively. In addition, the system also advised drivers to avoid speeding when their speeds are higher than the permitted speed. However, there was no advice given to drivers for the base scenario (scenario of normal driving).

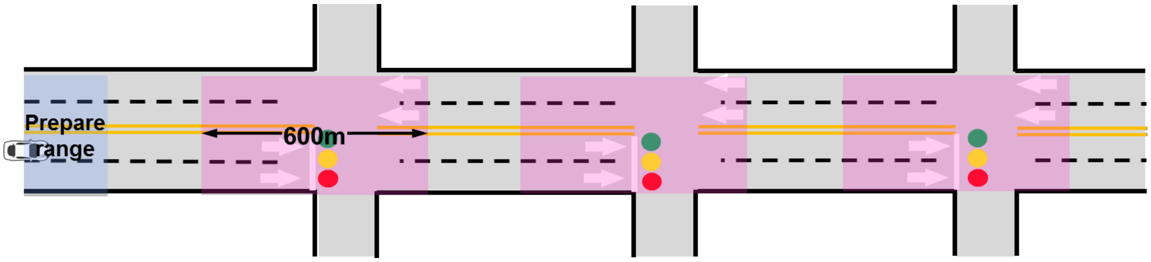


Figure 5 Driving Simulator Test Platform.

Figure 6 In-vehicle Devices Applied in the Driving Simulator Test.

Test Procedure. There were four phases in the test. The first phase was the warming up stage, which enables drivers to familiarize themselves with the driving simulator and the virtual environment. Before testing, drivers were told to drive as if they were driving a real vehicle in the real world. They could drive at any speed according to the speedometer on board. However, they were urged to pay attention to the speed limit signs, avoid running a red light, take a straight path and do not take left or right turn at intersections, since the whole test path was set on a straight route. In the first phase, the system did not record any data.

The second phase would not begin until drivers had already been familiarized with the system. In this phase, the base scenario (scenario of normal driving) was tested, and the system began to record the data. The above-mentioned instructions were given to drivers before the test.

The third phase was for testing the eco-driving scenarios. Participants were trained on the concept of eco-driving, each type of audio/visual eco-driving advice, and frequencies of the real-time eco-driving advising before the test. The scenarios of audio and visual eco-driving were carried out for each participant after the drivers understood the procedure completely. The sequence of the two scenarios of eco-driving (i.e. audio and visual) was arranged based on a permutation plan. Each participant drove through each scenario once.

After the tests, a questionnaire survey (shown in Appendix A) was conducted for each participant to collect drivers' demographics information, their knowledge about eco-driving before the test, and their experiences during the test.

Participants. Thirty-one volunteers were randomly selected at Texas Southern University. All of the participants had valid drivers' licenses with sufficient driving experiences.

3.2 Eco-driving Strategies for Automated Vehicles

In order to evaluate the potential emission mitigations for automated vehicles in more realistic traffic conditions, the driving situations and the corresponding eco-driving strategies will be first analyzed by considering more conditions, such as accelerating to pass the intersection at the upstream and decelerating to join a queue. Then, the proposed eco-driving model will be applied on a VISSIM simulation platform. Finally, traffic simulations will be conducted in the various traffic conditions.

3.2.1 Eco-driving Modeling for Automated Vehicles

The eco-driving model aims to prevent the automated vehicles, which are approaching intersections, from the abrupt acceleration, sudden deceleration, unnecessary stopping, and idling at the stop line of the intersections as much as possible. That will be achievable by generating and updating smooth speed profiles instantaneously for vehicles, and finally resulting in optimal-emission driving behaviors.

Eco-Driving Logic for Approaching Intersections. Assuming a vehicle approaching an intersection with a pre-timed signal control system, the combination of the instant signal information, the vehicle speed, the queue information at the intersection upstream, and the distance to the end of the queue or the stop line will form different driving situations. Based on a decision-tree method, the eco-driving logic is established, as shown in Figure 7.

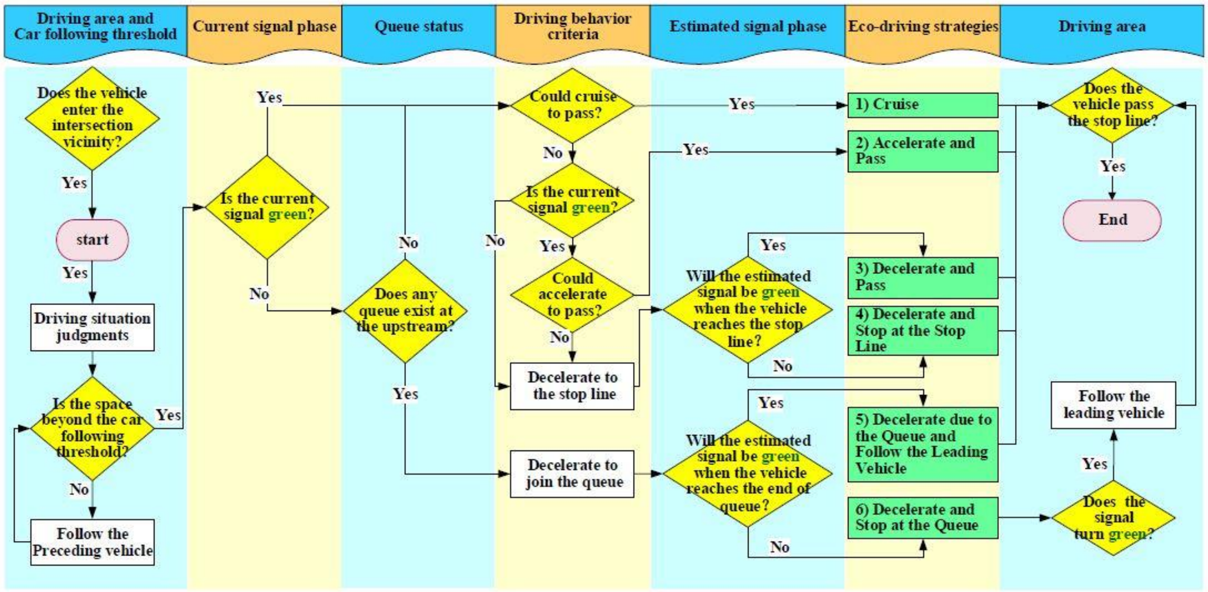


Figure 7 Decision-Making Logic for Automated Vehicles Based on Eco-driving.

Eco-Driving Strategies for Approaching Intersections. According to Figure 7, vehicles may face six typical situations when approaching intersections. A specific eco-driving strategy is promoted for each driving situation. The six driving strategies are listed as follows:

1) Cruise: The vehicle has the opportunity to cruise in order to pass the intersection.

2) Accelerate and Pass: If the vehicle cruises, it reaches the intersection at the red phase of the traffic signal. Instead, it can accelerate to pass the intersection before the green phase ends. In this case, the maximum speed should not exceed the speed limit.

3) Decelerate and Pass: The vehicle does not have the opportunity to proceed through the intersection if it cruises or accelerates (at a speed within the speed limit). Therefore, instead of reaching the stop line at the current red phase of the traffic signal, it reduces its speed so that it can pass the intersection during

the next green phase of the traffic signal without the need to stop and wait at the intersection.

4) Decelerate and Stop at the Stop Line: The vehicle does not have the opportunity to proceed through the intersection if it cruises or accelerates to pass the intersection at the current green phase, or even reduces its speed to pass the intersection at the next green phase without the need to stop. Therefore, the vehicle has to stop at the stop line and waits for the next green phase of the signal.

5) Decelerate due to the Queue and Follow the Leading Vehicle: This is a situation in which the traffic signal is red and there is a queue at the intersection. However, the signal turns to green when the vehicle reaches the back of the queue. Therefore, the vehicle follows the leading vehicle and does not wait for the signal.

6) Decelerate and Stop at the Queue: This is a situation during which the traffic signal is red, and there is a queue at the intersection. When the vehicle reaches the tail of the queue, the signal is still red. In this case, the vehicle has to stop and wait for the preceding vehicle to start moving after the signal turns green.

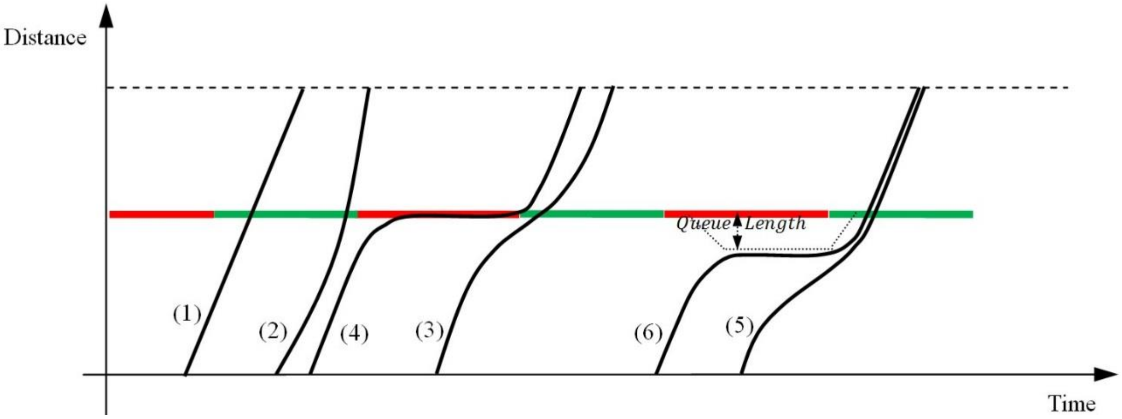


Figure 8 Time-space Diagram of Eco-driving Strategies for Automated Vehicles.

Figure 8 shows the time-space diagram for a vehicle approaching an intersection with the six eco-driving strategies. The eco-driving decision-making is based on four assumptions provided the following:

a) The vehicles do not change their lanes within the intersection vicinity.

b) The traffic condition is under-saturated flow, which means the queue will be dissipate during green phases. Thus the driving behavior of joining a queue during the green phase is considered.

c) The spacing between the automated vehicle and the leading vehicle is beyond the car-following spacing threshold when the automated vehicle system is making eco-driving decisions. If the space is within the car-following spacing threshold, the automated vehicle has to follow the leading vehicle.

d) The eco-driving decisions are made instantaneously (in every moment of the time) based on the position of the automated vehicle, the traffic signal, and the availability of other vehicles queuing at the stop line, and the eco-driving strategies are updated accordingly.

<u>Eco-Driving Algorithms for Approaching Intersections.</u> According to the aforementioned eco-driving decision-making logic, eco-driving algorithms will be developed to define each typical driving situation and its corresponding strategy in a mathematical approach. First, the driving behavior thresholds will be defined. Then, the decision target and the decision condition for each of the six eco-driving strategies will be established.

1. Driving Behavior Thresholds

Based on the assumption that the acceleration and deceleration rates are constant in this study, four thresholds are defined for identifying the driving situations for the vehicle.

Threshold 1: Expected time of cruising to the stop line. Assuming the vehicle has the opportunity to pass the intersection if it cruises, the expected travel time is calculated by Equation (4).

Threshold 2: Expected acceleration to reach the stop line. Assuming the vehicle does not have the opportunity to pass the intersection if it cruises, the vehicle could accelerate to pass the intersection within the current green phase in order to avoid stopping at the stop line and waiting for the next green phase. The vehicle can take a constant acceleration for the remainder of the green phase, which is supposed to be the smoothest accelerating behavior. The expected travel time and acceleration rate are calculated by Equation (8).

$$\begin{cases} \boldsymbol{t_{ac}} = \boldsymbol{t_{lg}} \\ \boldsymbol{a_{ac}} = \dfrac{2(\boldsymbol{d_{ts}} - \boldsymbol{v_t} \times \boldsymbol{t_{lg}})}{\boldsymbol{t_{lg}}^2} \end{cases} \tag{8}$$

where $\boldsymbol{t_{ac}}$ is the expected time of accelerating to reach the stop line (s) and $\boldsymbol{a_{ac}}$ is the expected acceleration rate to reach the stop line (m/s^2).

Threshold 3: Expected time of decelerating to reach the stop line or the end of the queue. Assuming the vehicle does not have the opportunity to pass the intersection if it cruises or accelerates, the vehicle has to decelerate to reach the stop line or the end of the queue, if available. There will be two criteria to identify the deceleration rate for a given period of time, as shown in Equation (9). The first one relies on the time. The deceleration rate is calculated considering that the speed of the vehicle decreases to zero within a given time period. The second criterion depends on the distance. The deceleration rate is calculated considering that the speed of the vehicle decreases to zero by traveling a given distance.

$$\begin{cases} a_{det} = \dfrac{v_t}{t_{det}} \\ a_{ded} = \dfrac{2\left[v_t \times t_{ded} - (d_{ts} - l_q)\right]}{{t_{ded}}^2} \end{cases} \tag{9}$$

where a_{det} is the constant deceleration rate for the vehicle whose speed decreases to zero within the time period (m/s^2), a_{det} is the given time for the speed decreasing to zero (s), a_{ded} is the constant deceleration rate for the vehicle traveling a given distance (m/s^2), t_{ded} is the time spent for traveling a given distance (s), and l_q ^{l_q} is the queue length at the upstream, which is from the end of the queue to the stop line (m).

If $a_{ded} < a_{det}$, the speed of the vehicle with the deceleration rate at a_{ded} will not be zero when it reaches the stop line or the end of the queue. As a result, this situation will not be acceptable due to the safety issue, because the traffic signal is still red or the leading vehicle is in a stop position. If $a_{ded} > a_{det}$, the vehicle with the deceleration rate at a_{ded} will stop before reaching the stop line (or the end of the queue). In other words, it will not reach the stop line or reach the end of the queue when the speed of the vehicle reaches zero. This situation will not be acceptable for eco-driving, because later the vehicle has to accelerate to pass the remaining distance, which is unnecessary. Setting $a_{ded} = a_{det}$ and considering that the vehicle with a constant deceleration rate reaches the stop line or the end of the queue while its speed also decreases to zero, the expected deceleration rate and the travel time are calculated by Equation (10).

$$\begin{cases} a_{de} = a_{ded} = a_{det} = \dfrac{{v_t}^2}{2(d_{ts} - l_q)} \\ t_{de} = \dfrac{2(d_{ts} - l_q)}{v_t} \end{cases} \tag{10}$$

where a_{de} is the expected deceleration rate (m/s^2), and t_{de} is the expected decelerating time (s).

Considering the signal indication and the availability of the queue at the stop line, there will be four scenarios for a vehicle decelerating to approach the intersection:

Scenario 1: $t_{de} \geq t_{lr}$ and there is no queue at the stop line. The vehicle has the opportunity to pass the intersection without a stop. The gentlest driving behavior is the final suggested time of deceleration (t_{def}) equals to t_{lr}. This scenario is corresponding to the Eco-driving Strategy 3.

Scenario 2: $t_{de} > t_{lr}$ and there is no queue at the stop line. The vehicle has to stop at the stop line and wait for the next green phase of the signal. The gentlest driving

behavior would be $t_{def} = t_{de}$. This scenario corresponds to the Eco-driving Strategy 4.

Scenario 3: $t_{de} \geq t_{lr}$ and there is a queue at the stop line when the vehicle is approaching the intersection. The vehicle has to follow the leading vehicle to pass the stop line after reaching the tail of the queue. The gentlest driving behavior would be $\boldsymbol{t_{def}} = \boldsymbol{t_{lr}}$. This scenario corresponds to the Eco-driving Strategy 5.

Scenario 4: $\boldsymbol{t_{de}} < \boldsymbol{t_{lr}}$ and there is a queue when the vehicle is approaching the intersection. The vehicle has to stop at the end of the queue, wait for the next green phase of the signal, and then follow the leading vehicle to pass the stop line. The gentlest driving behavior would be $\boldsymbol{t_{def}} = \boldsymbol{t_{de}}$. The scenario corresponds to the Eco-driving Strategy 6.

Threshold 4: Spacing Threshold for Car Following. The maximum distance between the automated vehicle and its leading vehicle for car following, $\boldsymbol{l_{fmax}}$, is set to be 50 meters in this study (Ahn, et al., 2014). If the actual distance of the space from the automated vehicle to its leading vehicle is shorter than this value (i.e. $\boldsymbol{d_{sp}} < \boldsymbol{l_{fmax}}$), the vehicle has to follow the leading vehicle. The six eco-driving strategies will not be applicable until the spacing is beyond the spacing threshold.

2. Eco-driving Decision Targets and Conditions

The target and condition for each of the six eco-driving strategies are established one-by-one, as demonstrated as follows.

Strategy 1 - Cruise to pass the intersection: The decision target for this strategy is defined by Equation (11).

$$\begin{cases} aa_{ta} = 0 \\ v_{ta} = v_t \\ T_a = \dfrac{d_{ts}}{v_t} \\ T = T_a \\ t \in [0, T_a] \end{cases}$$

(11)

where aa_{ta} is the targeted instantaneous acceleration based on the eco-driving advising (m/s^2), v_{ta} is the targeted instantaneous speed (m/s) t is the instantaneous time spent after making the eco-driving decisions (s), T_a is the total time spent for the vehicle approaching to the stop line or the end of the queue (s), and T is the total time spent for the vehicle passing the stop line, (s).

Based on the eco-driving logic, this eco-driving strategy includes two cases. In case 1, the signal is green when the in-vehicle system makes the eco-driving decisions, and the vehicle can cruise to pass the stop line during the current green phase. In case 2, the signal is red when making the decisions, but the vehicle can cruise to pass the stop line in the coming green phase. Therefore, the decision condition for cases 1 and 2 is given by Equations (12) and (13), respectively.

$$\begin{cases} t_{pa} \in [0, g) \\ t_c < t_{lg} \\ v_t \le v_{limit} \\ d_{sp} \ge l_{fmax} \end{cases}$$

(12)

where T_{pa} is the time passed from the beginning of the signal cycle when making the eco-driving decisions, assuming that the signal cycle begins with the green phase (s), C is the cycle length of the traffic signal (s), and g is the effective green time (s).

$$\begin{cases} t_{pa} \in [g, C\,) \\ t_c \geq t_{lr} \\ l_q = 0 \\ v_t \leq v_{limit} \\ d_{sp} \geq l_{fmax} \end{cases} \tag{13}$$

<u>Strategy 2 - Accelerate and Pass:</u> The decision target for this strategy is defined by Equation (14). The decision condition is defined by Equation (15).

$$\begin{cases} T_a = t_{ac} = t_{lg} \\ aa_{ta} = a_{ac} \\ v_{ta} = v_t + aa_{ta} \times t \\ T = T_a \\ t \in [0, t_{lg}) \end{cases} \tag{14}$$

$$\begin{cases} t_{pa} \in [0, g) \\ aa_{ta} \in [0, a_{max}] \\ v_{ta} \leq v_{limit} \\ t_c \geq t_{lg} \\ t_{ac} < t_{lg} \\ d_{sp} \geq l_{fmax} \end{cases} \tag{15}$$

where a_{max} is the maximum acceleration rate, set as 3m/s^2.

<u>Strategy 3 - Decelerate and Pass:</u> The decision target for this strategy is defined by Equation (16).

$$\begin{cases} t_{def} = t_{lr} \\ aa_{ta} = \dfrac{2[v_t \times t_{def} - (\,d_{ts} - l_q)]}{{t_{def}}^2} \\ v_{ta} = v_t - aa_{ta} \times t \\ T_a = t_{def} \\ T = T_a \\ t \in [0, t_{def}) \end{cases}$$

(16)

According to the eco-driving logic (see Figure 7), this eco-driving strategy includes two cases. In case 1, the signal is green when the vehicle system is making the eco-driving decisions; however, the vehicle can neither cruise nor accelerate to pass the stop line. In case 2, the signal is red when the vehicle system is making the eco-driving decisions; and there is no queue at the stop line. If the vehicle continues cruising, it will reach the stop line before the red phase ends, and it cannot pass. Therefore, the vehicle system should choose to maintain a minimum deceleration from the decision point instead of cruising followed by a sudden deceleration at the stop line. The decision condition for cases 1 and 2 is defined by Equations (17) and (18), respectively.

$$\begin{cases} t_{pa} \in [0, g) \\ aa_{ta} \in [0, d_{max}] \\ v_t \leq v_{limit} \\ t_c \geq t_{lg} \\ t_{ac} \geq \mathrm{t_{lg}} \\ t_{de} \geq \mathrm{t_{lr}} \\ d_{sp} \geq l_{fmax} \end{cases}$$

(17)

where d_{max} is the maximum deceleration rate, set as 4m/s^2.

$$\begin{cases} t_{pa} \in [g, C) \\ aa_{ta} \in [0, d_{max}] \\ v_t \leq v_{limit} \\ l_q = 0 \\ t_c < t_{lr} \\ t_{de} \geq t_{lr} \\ d_{sp} \geq l_{fmax} \end{cases}$$

(18)

Strategy 4 - Decelerate and Stop at the Stop Line: The decision target for this strategy is defined by Equation (19).

$$\begin{cases} t_{def} = t_{de} \\ aa_{ta} = a_{de} \\ v_{ta} = v_t - aa_{ta} \times t \\ T_a = t_{def} \\ T_{re} = \mathrm{t_{lr}} - t_{def} \\ T = T_a + T_{re} \\ t \in [0, T_a) \end{cases} \tag{19}$$

where T_{re} is the time remaining after the automated vehicle reaches the stop line until the signal turns to green (s).

This eco-driving strategy also includes two cases (see Figure 7). In case 1, the signal is green when making the eco-driving decisions. In case 2, the signal is red when the driver is making the eco-driving decisions. The decision condition is defined by Equations (20) and (21), respectively.

$$\begin{cases} t_{pa} \in [0, g) \\ aa_{ta} \in [0, d_{max}] \\ v_t \leq v_{limit} \\ t_c \geq t_{lg} \\ t_{ac} \geq t_{lg} \\ t_{de} < \mathrm{t_{lr}} \\ d_{sp} \geq l_{fmax} \end{cases} \tag{20}$$

$$\begin{cases} t_{pa} \in [g, C) \\ aa_{ta} \in [0, d_{max}] \\ v_t \leq v_{limit} \\ l_q = 0 \\ t_c < \mathrm{t_{lr}} \\ t_{de} < \mathrm{t_{lr}} \\ d_{sp} \geq l_{fmax} \end{cases} \tag{21}$$

Strategy 5 - Decelerate due to the Queue and Follow the Leading Vehicle: For this strategy, the decision target for the vehicle to decelerate and join the end of the queue is as Equation (16). The decision target for car following is defined by Equation (22).

$$\begin{cases} v_{ta} = v_{ft} \\ T_f = \min_{\forall t_f \in \{1,2\ldots\}} \left\{ \sum_{t=1}^{t_f} v_{ft} > l_q \right\} \\ t \in [0, T_f) \end{cases}$$

(22)

where v_{ft} is the instantaneous speed of the automated vehicle when following its leading vehicle (m/s), and T_f is the total time spent for car following (s).

It is noted that for this strategy, the total time spent for the automated vehicle passing the stop line is $T = T_a + T_f$. The decision condition for the automated vehicle before it starts following the leading vehicle is defined by Equation (23).

$$\begin{cases} t_{pa} \in [g, C) \\ aa_{ta} \in [0,\ d_{max}] \\ v_t \leq v_{limit} \\ l_q > 0 \\ t_{de} \geq t_{lr} \\ d_{sp} \geq l_{fmax} \end{cases}$$

(23)

Strategy 6 - Decelerate and Stop at the Queue: For this strategy, the decision target for the vehicle decelerating to the end of the queue is as Equation (19). The decision target for the vehicle following the leading vehicle is as Equation (22). It is noted that, for this strategy, the total time spent for the automated vehicle passing the stop line is $T = T_a + T_{re} + T_f$. The decision condition for the automated vehicle is shown by Equation (24).

$$\begin{cases} t_{pa} \in [g, C) \\ aa_{ta} \in [0,\ d_{max}] \\ v_t \le v_{limit} \\ l_q > 0 \\ t_{de} < t_{lr} \\ d_{sp} \ge l_{fmax} \end{cases} \tag{24}$$

3.2.2 Eco-driving Application on Traffic Simulation Software

Simulation Platform Design. VISSIM simulation software was used to implement the proposed eco-driving model for automated vehicles. The simulation network was a four-leg intersection. The intersection vicinity was the area including each intersection approach located within 200 meters from the center of the intersection. All the approaches within the intersection vicinity were assumed to be flat, and the approaches have four 12-feet lanes, two lanes in each direction.

The traffic signal was operated under two-phase pre-timed control with a cycle length of 120 seconds, including 57 seconds of green and 3 seconds of yellow. The speed limit on all approaches was 65 km/h. Passenger cars were the only vehicle types selected for the simulation study. The automated vehicles, whose driving behavior would be adjusted according to the eco-driving model, were generated on the northbound approach of the intersection. To avoid any interference with lane-changing movements, only through movements were designed in southbound and northbound.

The look-ahead distance, defined as the distance for a vehicle to react to the vehicles nearby (PTV, 2011), was set to be 50 meters. The function of the look-ahead distance was as a spacing threshold for the car following. By defining the look-ahead distance in VISSIM, all of the simulated vehicles would follow their leading vehicles when the spacing was within the look-ahead distance.

Secondary Development in VISSIM to Apply the Proposed Model. The additional module in VISSIM, the Microsoft Component Object Model (COM), is a programming interface that connects external programming environments, such as Visual Basic, C#, and Python, to automate certain tasks that could not be pre-designed in VISSIM directly (PTV, 2011). In order to apply the eco-driving model for automated vehicles, Visual Basic for Application (VBA) was scripted through the VISSIM COM. The general process of the scripting is shown in Figure 9.

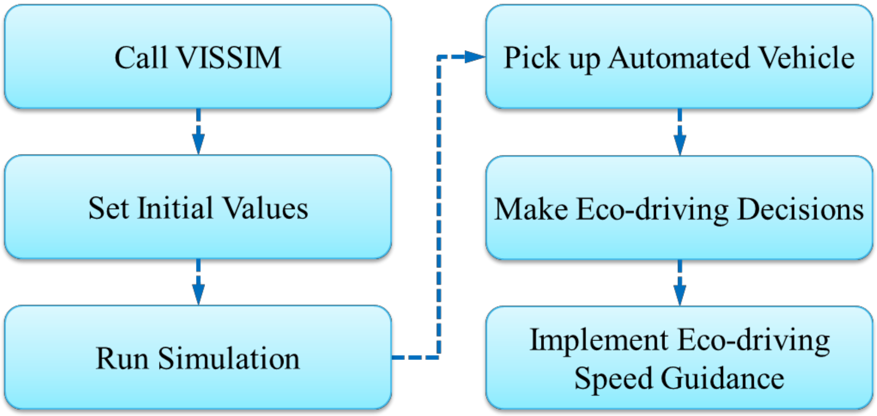


Figure 9 General Process of Applying Eco-driving Strategies for Automated Vehicles through the Module of COM in VISSIM.

As shown in Figure 9, the first step was to open the VISSIM platform, then set initial values for important parameters in the simulation. In order to avoid interference between automated vehicles, the automated vehicle with the eco-driving behaviors was selected in such a way that only one vehicle was qualified at a time. The other vehicles driving within the network are all normal vehicles. The driving behaviors of normal vehicles were defaulted by VISSIM. A second automated vehicle was selected after a random period of time from the moment that the prevailing automated vehicle had left the intersection vicinity. The random time interval ranged from 0 to 60 seconds. During the automated vehicle approaching the intersection, eco-driving decisions were made on a second-by-second basis, and the driving behaviors were adjusted accordingly. The VBA scripting is shown in Appendix B.

Simulation Design. The simulation was conducted under six traffic conditions with the v/c ratio equal to 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 respectively. The simulation resolution was set to be one time step (s) per simulation second. Different random seeds were set for each traffic condition to represent the stochastic behavior in the simulation.

3.3 Emission Estimation Method

MOVES were used to estimate the emissions for both of the driving simulator tests and VISSIM simulations. For light-duty vehicles on a flat road, VSP is calculated by Equation (3).

All of the vehicles involved in this research were assumed to be 5-year-old gasoline passenger cars. From MOVES' database, the average emission rates for the selected type of vehicles in each OpModeID for CO_2, CO, NO_x, and HC are shown in Table 3 (Office of Transportation and Air Quality, 2011; Park et al.'s research, 2015; Choi et al.'s, 2011). Therefore, the emission summation is calculated by Equation (25).

Table 3 Emission Rates of 5-year-old Gasoline Passenger Cars for Each OpModeID

OpModeID	Operation Mode Description		Default Average Emission Rate (g/s)			
			CO_2	CO	NO_X	HC
0	Braking		3.529	0.00514	0.00023	0.00019
1	Idle		3.265	0.00089	0.0001	0.00005
11	VSP < 0	1 < Speed < 25	5.134	0.01769	0.00034	0.00013
12	0 ≤ VSP < 3		7.089	0.02888	0.00052	0.0001
13	3 ≤ VSP < 6		9.852	0.02662	0.00122	0.00019
14	6 ≤ VSP < 9		12.449	0.0382	0.00215	0.00026
15	9 ≤ VSP < 12		14.845	0.05539	0.00381	0.00036
16	12 ≤ VSP		17.93	0.09347	0.00794	0.00058
21	VSP < 0	25 < Speed < 50	6.985	0.02305	0.00067	0.0002
22	0 ≤ VSP < 3		7.95	0.03055	0.00109	0.00018

23	$3 \le VSP < 6$		9.683	0.03928	0.00165	0.0002
24	$6 \le VSP < 9$		12.423	0.05742	0.00279	0.00038
25	$9 \le VSP < 12$		16.578	0.06517	0.00391	0.00037
27	$12 \le VSP < 18$		21.855	0.09787	0.00616	0.00059
28	$18 \le VSP < 24$		29.459	0.23924	0.01354	0.00384
29	$24 \le VSP < 30$		40.359	0.50667	0.02378	0.00681
30	$30 \le VSP$		50.682	1.77951	0.03129	0.01125
33	$VSP < 6$	$50 \le Speed$	9.951	0.01731	0.00144	0.00019
35	$6 \le VSP < 12$		15.956	0.02956	0.00396	0.00027
37	$12 \le VSP < 18$		20.786	0.04351	0.00554	0.00034
38	$18 \le VSP < 24$		27.104	0.21928	0.0115	0.00259
39	$24 \le VSP < 30$		36.102	0.23137	0.01712	0.00376
40	$30 \le VSP$		46.021	0.67999	0.02156	0.00492

$$E_i = \sum_{j=1}^{q} (Er_{ij} \times p_j) \tag{25}$$

where E_i is the estimated total amount of emission type i (CO_2, CO, NO_x, or HC) for a single vehicle (g), q is the number of OpModeID, p_j is the frequency of OpModeID j, and Er_{ij} is the emission rate for the emission type i in OpModeID j (g/s).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results from the Driving Simulator Test

In order to seek the most efficient real-time eco-driving suggestions to drivers, vehicle emissions, trajectory VSP distributions, instant driving behavior parameters, and travel time of each eco-driving audio/visual testing scenarios, as well as the basic scenario that without any suggestions were compared.

4.1.1 Emissions

In this study, the averages of the total CO_2, CO, NO_X, and HC emissions were estimated for all testing scenarios based on 31 driving experiments. Figures 10 to 13 show the total CO_2, CO, NO_X, and HC emissions for the base, audio eco-driving, and visual eco-driving scenarios for three processes, respectively. The first process deals with the case in which the vehicle travels within the upstream. The second process includes the case in which the vehicle travels within the downstream. The third process summarizes the other two cases, which include the case in which the vehicle travels within the whole vicinity of the intersection.

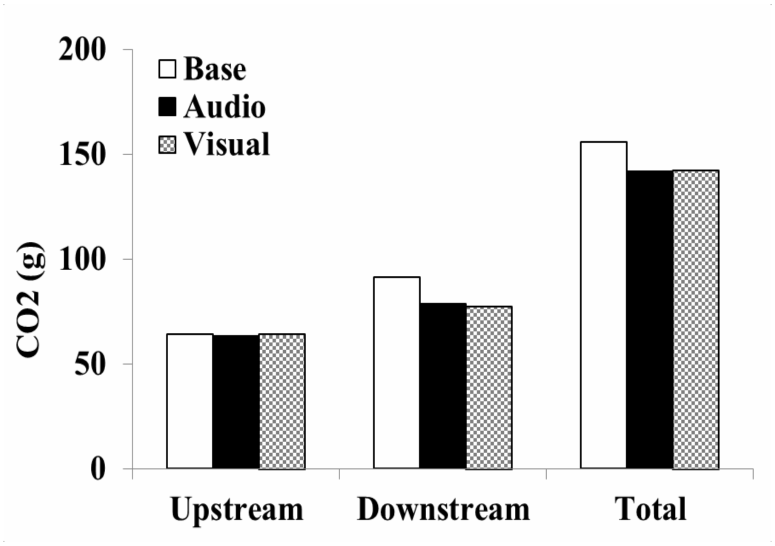


Figure 10 CO_2 Emissions of the Base Scenario and Audio and Visual Eco-Driving Scenarios.

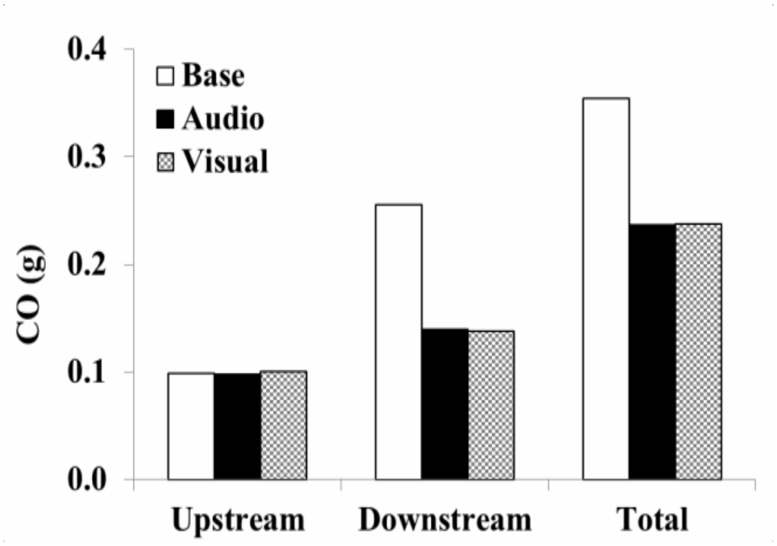


Figure 11 CO Emissions of the Base Scenario and Audio and Visual Eco-Driving Scenarios.

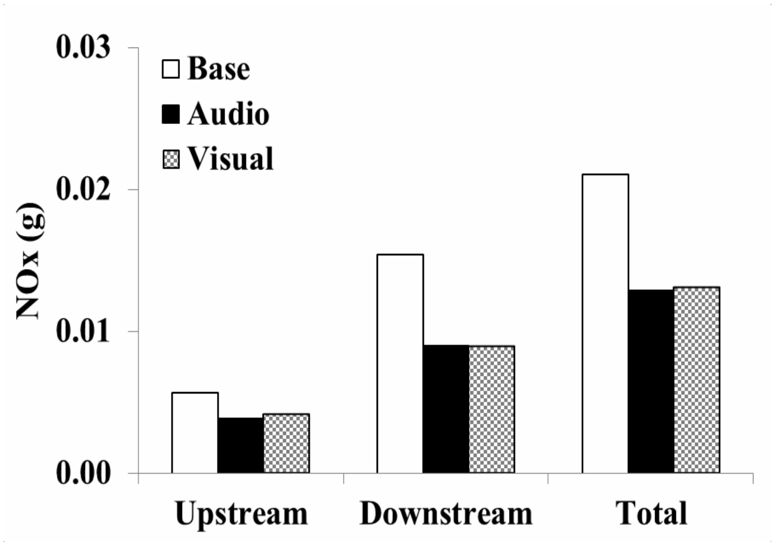


Figure 12 NO_X Emissions of the Base Scenario and Audio and Visual Eco-Driving Scenarios.

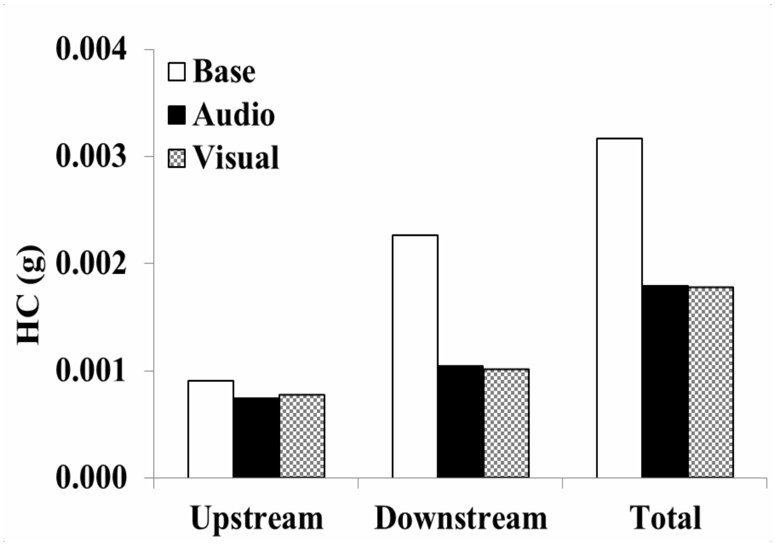


Figure 13 HC Emissions of the Base Scenario and Audio and Visual Eco-Driving Scenarios.

Figures 10 to 13 illustrate that the majority of the emission mitigations are within the intersection downstream. The eco-driving strategies reduce emissions of CO_2, CO, NOx, and HC at the intersection downstream by 14.96%, 45.50%, 42.06%, and 55.52%, respectively when compared to the base scenario. The emissions generated within the upstream for the base scenario and audio and visual eco-driving scenarios are comparable. We hypothesize that such a phenomenon may occur due to two reasons. First, the drivers had already become familiarized with the driving scenarios and the driving simulator environment before starting the main test. Moreover, the signal timing, the range of the intersection vicinities, and the traffic conditions were similar for all of the intersections. Therefore, some drivers might have applied gentler driving behaviors at the upstream based on their already gained experience in the previous scenarios. The second reason is that the possibility of accelerating at the upstream in order to pass the intersection had not been considered in the eco-driving model. Therefore, the eco-driving decision options at the upstream were limited, and the drivers had less freedom in choosing diverse driving behaviors at the upstream.

The average emissions of CO_2, CO, NO_X, and HC generated in the base scenario and audio and visual eco-driving scenarios with different instruction frequencies, i.e. at 5-second, 10-second, and 15-second intervals, are illustrated in Figures 14 to 17 for the three aforementioned processes. Considering the process of traveling within the whole vicinity of the intersections, the audio eco-driving scenario with 10-second interval advising generates the least amount of CO_2, NO_X, and HC emissions. This scenario reduces 10.20% of CO_2, 33.08% of CO, 42.76% of NO_X, and 46.86% of HC compared to the base scenario. However, the differences in total emissions among all of the eco- driving scenarios are not significant.

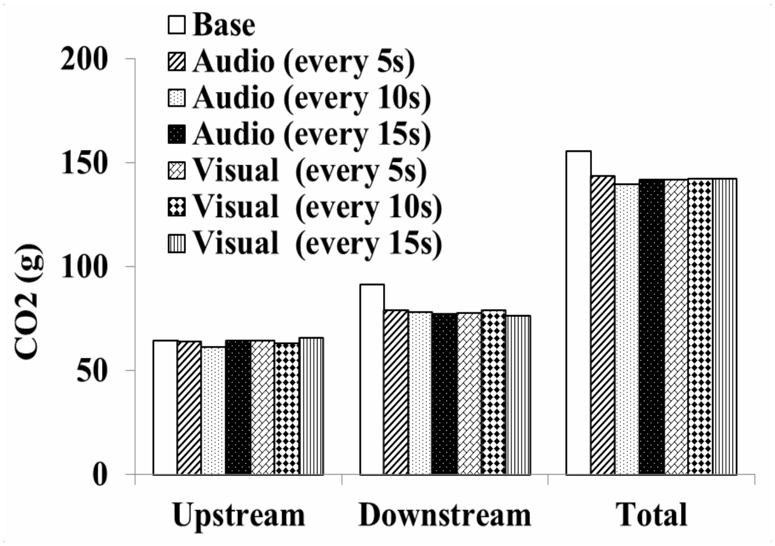


Figure 14 CO_2 Emissions of the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising.

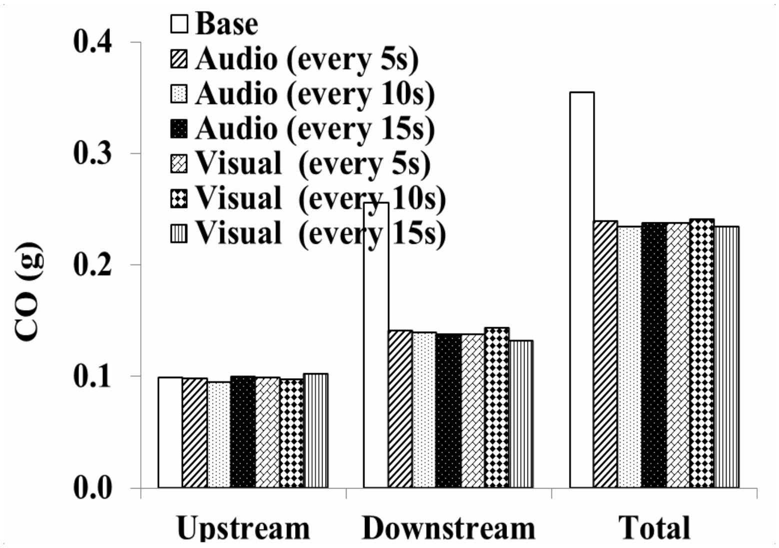


Figure 15 CO Emissions of the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising.

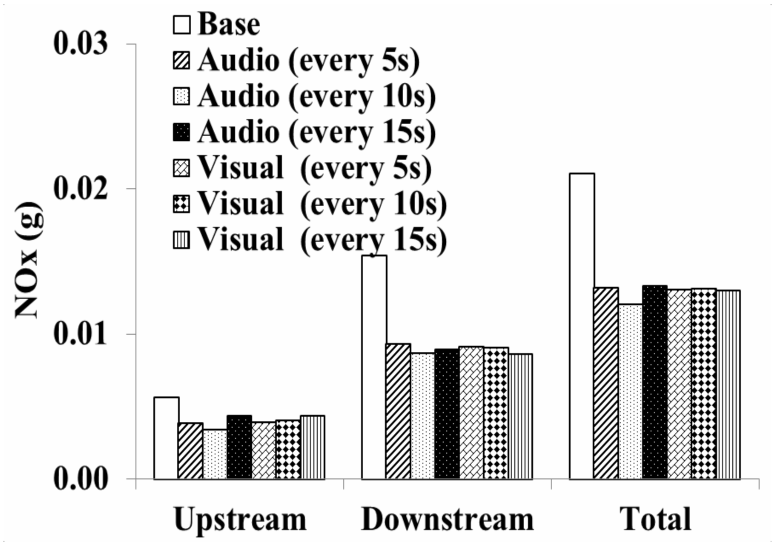


Figure 16 NO_X Emissions of the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising.

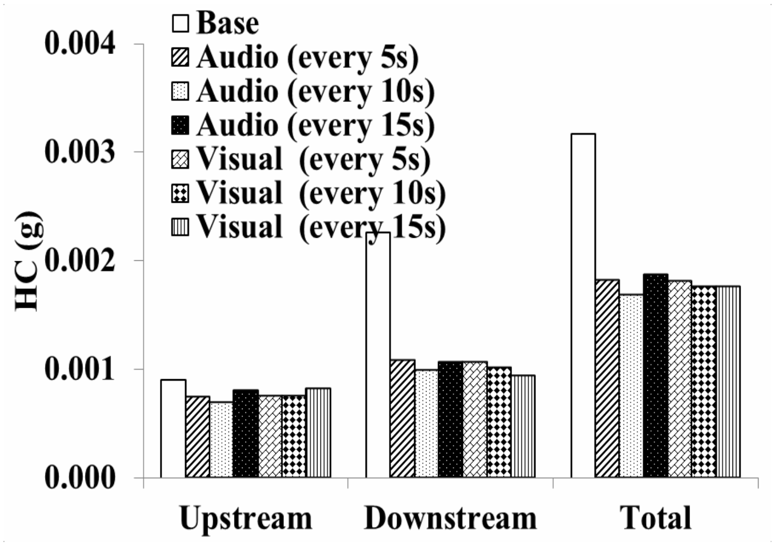


Figure 17 HC Emissions of the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising.

4.1.2 Distributions of VSP

Figure 18 illustrates the distribution of the instantaneous VSP for each scenario. The results show bell-shaped charts for the base scenario and audio and visual eco-driving scenarios. By increasing the number of VSB bins, the frequency of high bins in the base scenario becomes higher than that of the eco-driving scenarios. This is a possible reason why the base scenario generates more emissions than eco-driving scenarios. As shown in Table 3, a larger VSP bin relates to a higher emission rate for the same range of speed.

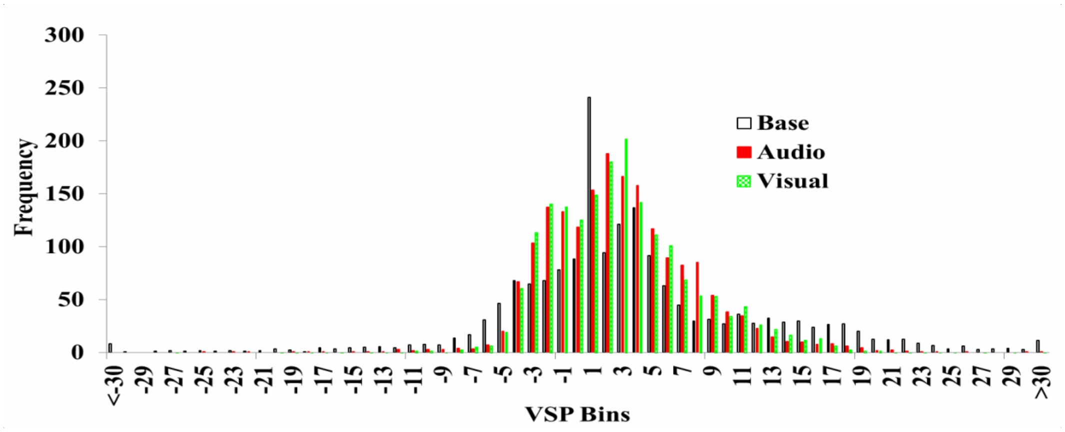


Figure 18 Distributions of the Instantaneous VSP for the Base Scenario and Audio and Visual Eco-Driving Scenarios.

In addition, the distributions of VSPs for audio and visual eco-driving scenarios are very similar. The distributions of the instantaneous VSP for each sub-scenario with different frequencies of advising also show similar results, as shown in Figure 19.

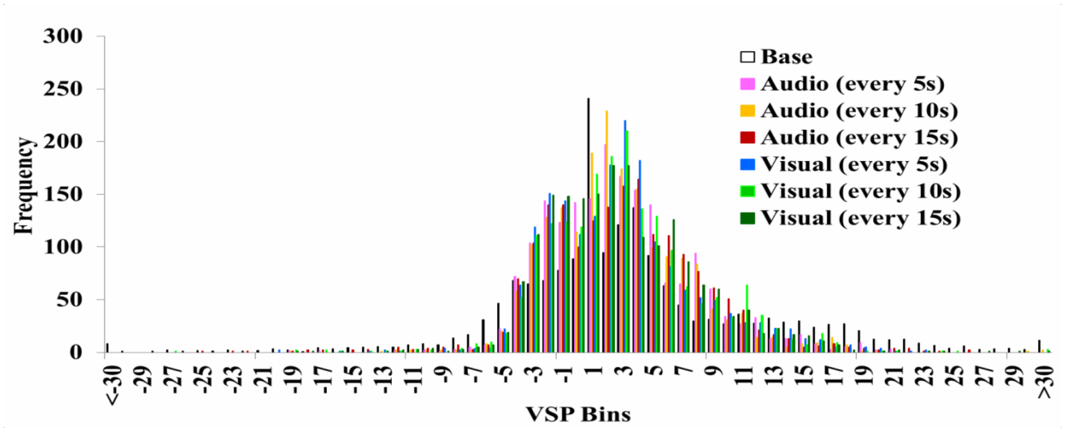


Figure 19 Distributions of the Instantaneous VSP for the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising.

4.1.3 Instantaneous Speed and Acceleration

The instantaneous speed and acceleration were calculated at an one-meter interval within the vicinity of intersections. Figure 20 illustrates the speed-distance diagrams for each scenario. The speed-distance diagrams show that the initial speed of the vehicle when entering the intersection vicinity in the base scenario is higher than the speed in the eco-driving scenarios. The main reason for is that, for eco-driving scenarios, real-time eco-driving suggestions have already been provided to the drivers before reaching and entering the vicinity of the intersection. Those real-time eco-driving suggestions for driving on un-interrupted road mainly focus on speed. Once the driver exceeded the maximum acceptable speed, the in-vehicle system would give the drivers warnings to avoid speeding. However, the drivers, in the base scenario, did not receive any suggestions or warnings.

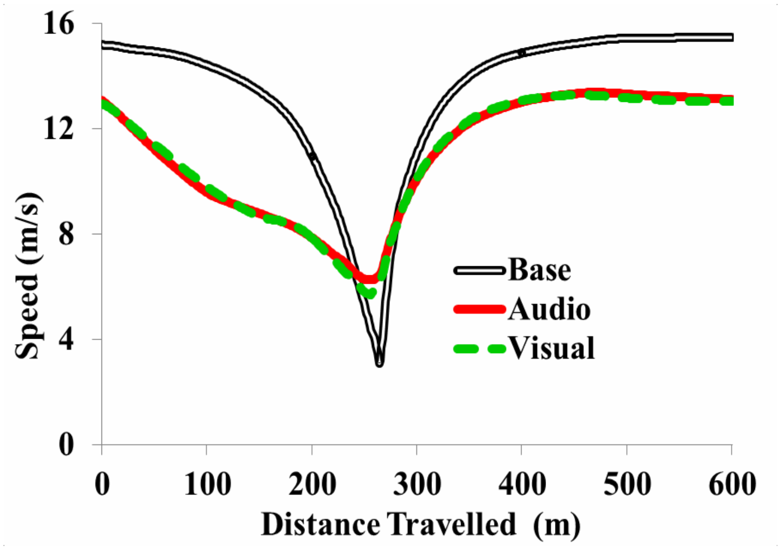


Figure 20 Speed-distance Diagrams for the Base Scenario and Audio and Visual Eco-Driving Scenarios.

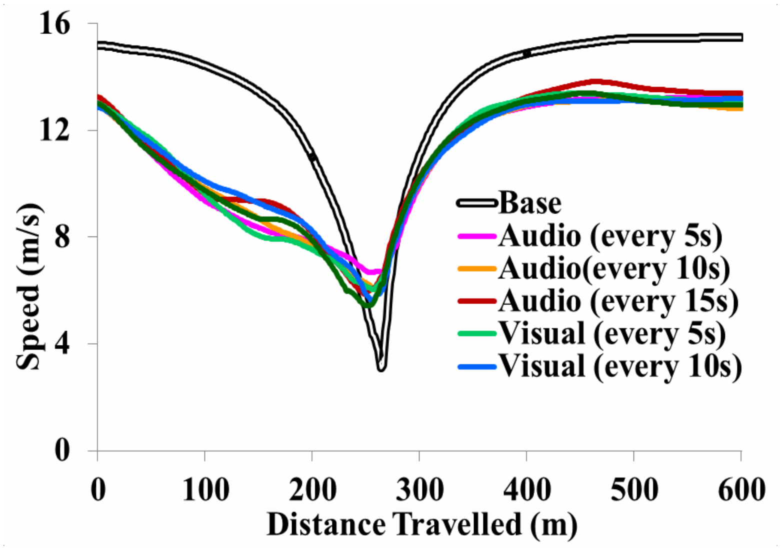


Figure 21 Speed-distance Diagrams for the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising.

It should be noted that, since Figure 20 is based on the average results of 31 participants, there is no value of zero for the average of the instantaneous speed. This is due to the fact that some participants had already made good judgments and were driven ecologically in the base scenario without any suggestions. They had lower speeds in the intersection vicinities. Hence, they were able to pass the intersections during the green interval, instead of hitting the red light and stopping at the stop line. As a result, the average of the instantaneous speed of 31 participants is non-zero. More detailed information on the instantaneous speed for each sub-scenario is shown in Figure 21. The speed-distance diagrams for the scenarios of audio eco-driving and visual eco-driving are similar.

Figure 22 illustrates the acceleration-distance diagrams for each scenario. It is shown that drivers, in the base scenario, drove more aggressively at the upstream compared to the eco-driving scenarios. The acceleration-diagrams show that drivers, in the eco-driving scenarios, begin to decelerate as soon as they enter the intersection, and they maintain a slight deceleration when they reach the stop line. However, in the base scenario, drivers began to decelerate at around 100 meters after they had already passed the entrance of the intersection vicinities.

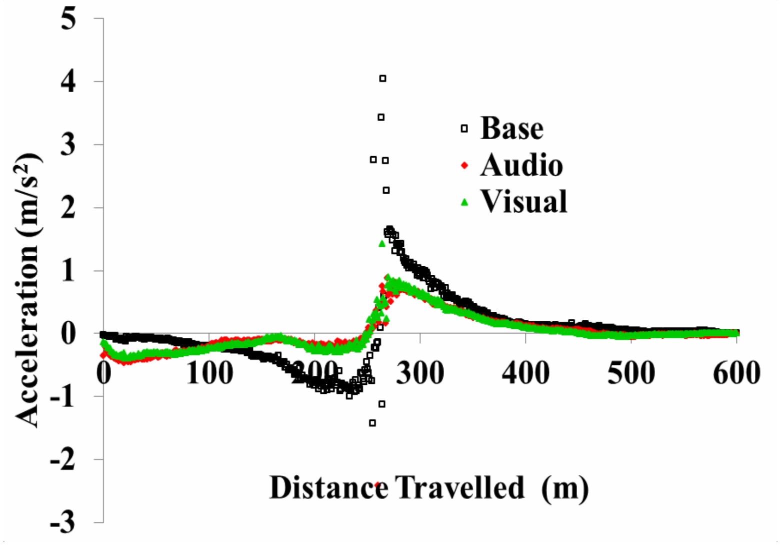


Figure 22 Acceleration-distance Diagrams for the Base Scenario and Audio and Visual Eco-Driving Scenarios.

In the base scenario, it is observable that drivers have severe accelerations when leaving the intersection at the downstream. The acceleration-distance diagrams for the base scenario show multiple records that are even greater than 3.0 m/s^2, whereas in the eco-driving scenarios, the acceleration rates are less than 2.0 m/s^2. More detailed information on the instantaneous acceleration for each sub-scenario is shown in Figure 23. The acceleration-distance diagrams for the sub-scenarios of audio eco-driving and visual eco-driving are similar.

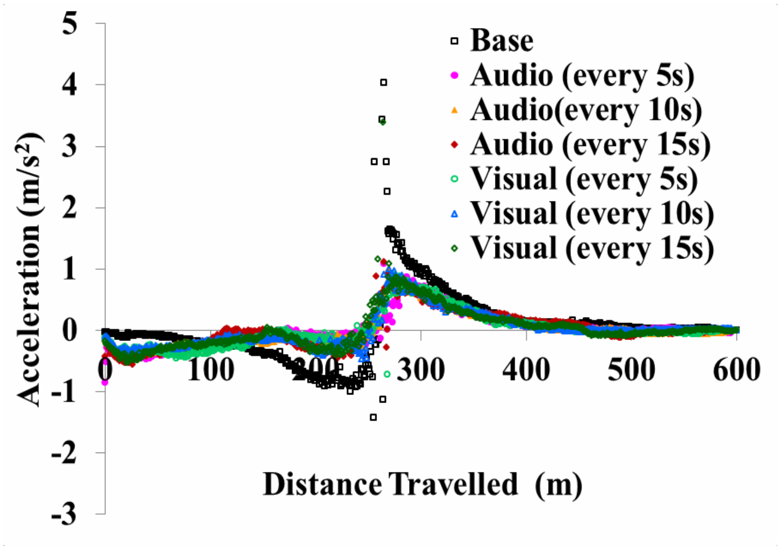


Figure 23 Acceleration-distance Diagrams for the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising.

The box-and-whisker plots of the instantaneous speed and acceleration for the whole process of passing the intersection vicinities are shown in Figures 24 and 25. The speed variance from the base scenario is larger than that from the eco-driving scenarios. The range of speed for the base scenario is 3.1 m/s to 15.48 m/s, while it is 6.28 m/s to 13.38 m/s for the audio eco-driving scenario and 5.70 m/s to 13.29 m/s for the visual eco-driving scenario.

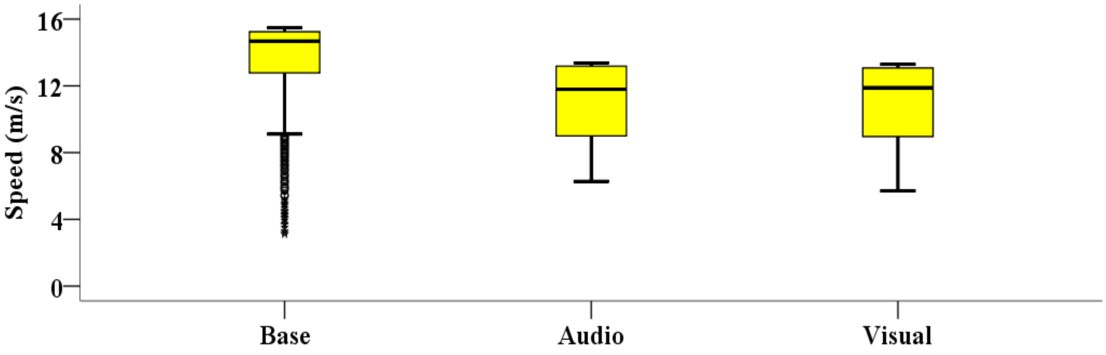


Figure 24 Box Plot of the Instantaneous Speed for the Base Scenario and Audio and Visual Eco-Driving Scenarios.

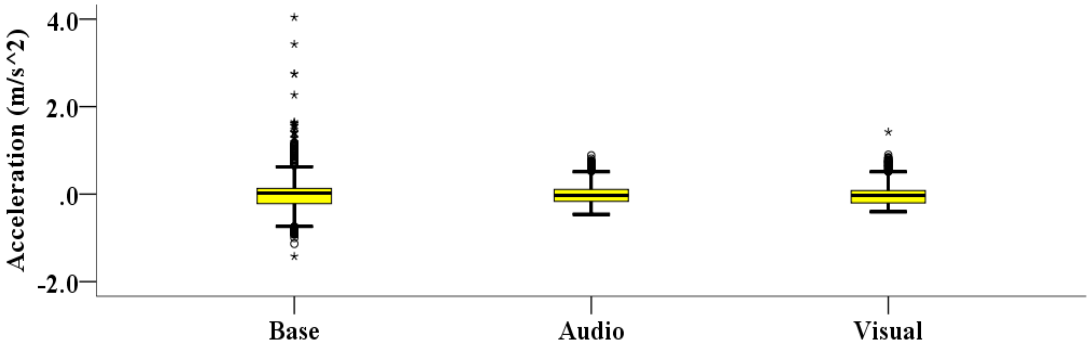


Figure 25 Box Plot of the Instantaneous Acceleration for the Base Scenario and Audio and Visual Eco-Driving Scenarios.

In addition, many records of the instantaneous speed in the base scenario fall beyond the inner fence, while all of the records of eco-driving scenarios fall within the inner fence. The results indicate that it was more often travelling in low speeds in the base scenario. Furthermore, more records of the instantaneous acceleration in the base scenario fall beyond the inner fence compared to the eco-driving scenarios, which implies that aggressive accelerations were experienced more frequently in the base scenario. More detailed information on the distributions of the instantaneous speed and instantaneous acceleration for each sub-scenario are shown in Figures 26 and 27. Overall, there is no major difference among all the eco-driving sub-scenarios.

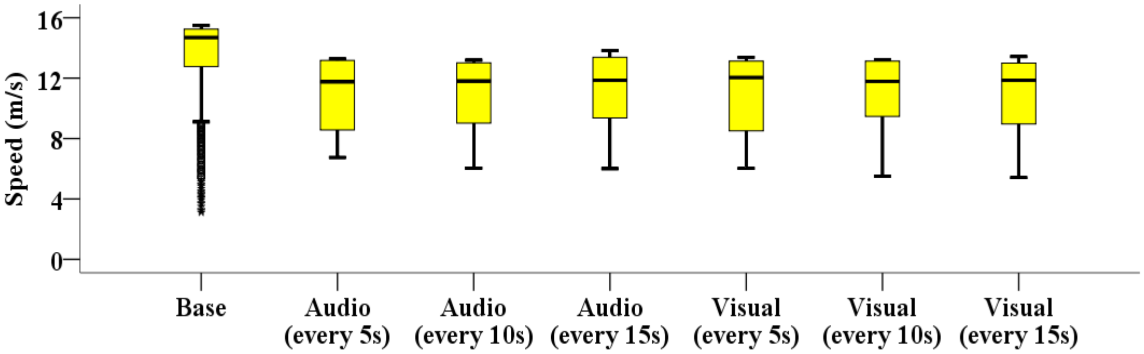


Figure 26 Box Plot of the Instantaneous Speed for the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising

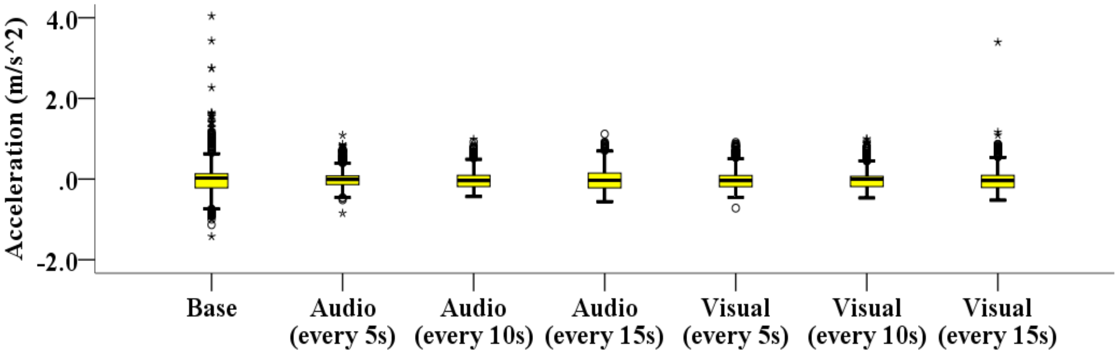


Figure 27 Box Plot of the Instantaneous Acceleration for the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising

4.1.4 Travel Time

Four time-related indexes, including the total travel time, time percentage of idling, time percentage of speeding, and time percentage of braking, were analyzed for each scenario. As shown in Figure 28, it takes a longer time for vehicles in both the audio and visual eco-driving scenarios to pass the intersection vicinities compared to the base scenario. The main reason for this phenomenon is that drivers drove more abruptly after passing the stop line. In contrast, drivers in eco-driving scenarios were instructed to slow down to avoid speeding. The travel time spent in the eco-driving scenarios was 9.56% to 12.84% greater than the time spent in the base scenario.

The statistics shows that the idling, speeding, and braking happened more frequently in the base scenario than the eco-driving scenarios. The idling, speeding, and braking respectively account for 10.41%, 12.32%, and 9.40% of the total time travelled for the base scenario. On the other hand, the time percentages of idling, speeding, and braking are less than 2%, 2.5%, and 3%, respectively, for the eco-driving scenarios. More detailed information of the four time-related indexes for each sub-scenario is shown in Figure 29.

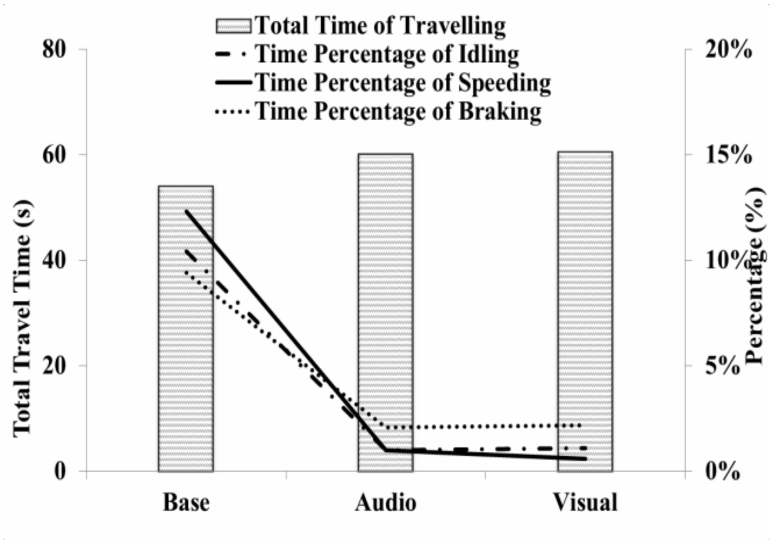


Figure 28 Total Travel Time, Time of Idling, Time of Speeding, and Time of Braking for the Base Scenario and Audio and Visual Eco-Driving Scenarios.

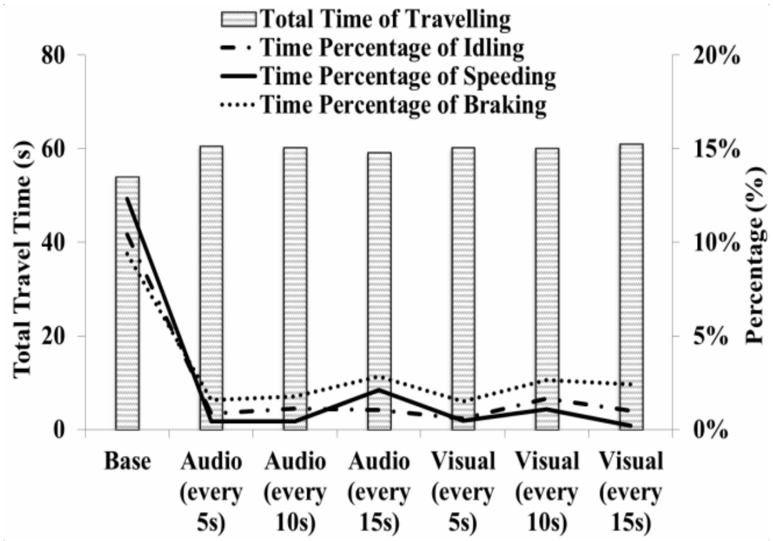


Figure 29 Total Travel Time, Time of Idling, Time of Speeding, and Time of Braking for the Base Scenario and Audio and Visual Eco-Driving Scenarios with Difference Frequencies of Advising.

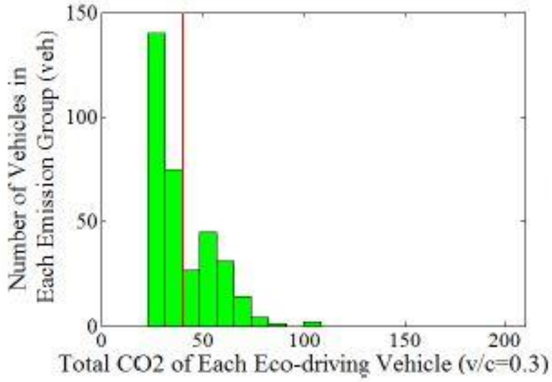
4.2 Results from the VISSIM Simulation

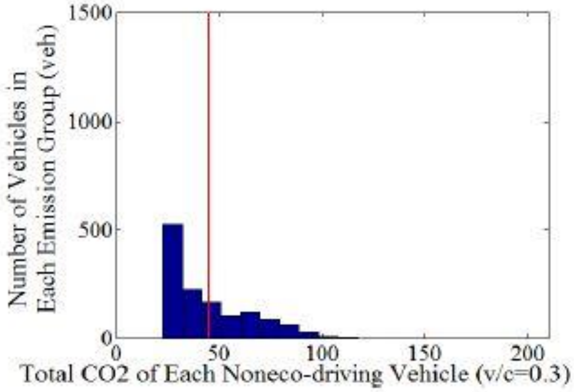
In order to analyze the emission effects of eco-driving behaviors, the estimated total emissions emitted by automated vehicles (eco-driving vehicles) and normal vehicles (non-eco-driving vehicles) were calculated. The automated vehicles (eco-driving vehicles) were the vehicles with eco-driving behaviors based on the developed eco-driving model in this research. The normal vehicles (non-eco-driving vehicles) were the other vehicles traveling within the vicinity of intersection in the same direction of the eco-driving vehicles. The non-eco-driving vehicles followed the default driving behavior in VISSIM.

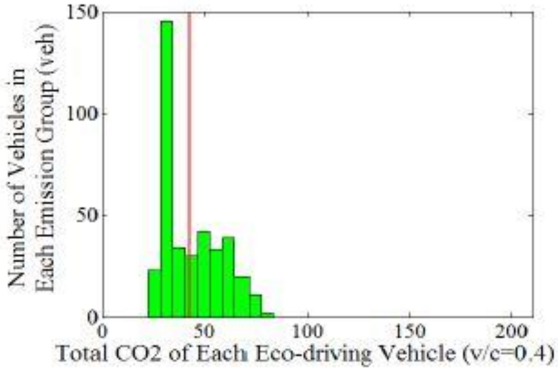
4.2.1 Distributions of Total Emissions

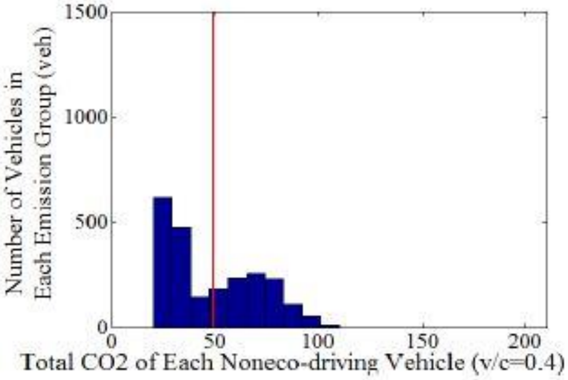
The emissions were analyzed in MATLAB, and categorized into sub-ranges for each group of eco-driving and non-eco-driving vehicles. The number of vehicles in each group and sub-range were counted, and the distributions of total CO_2 emissions for a single vehicle in different traffic conditions were shown in Figure 30.

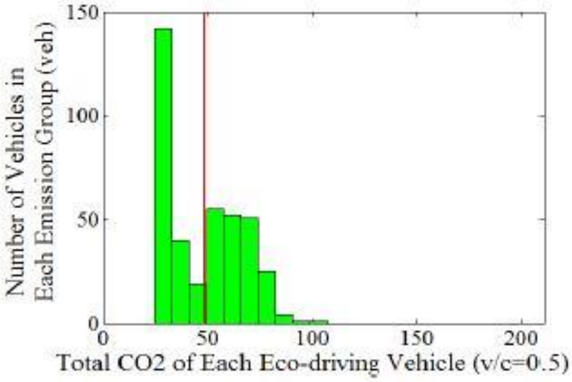
For each graph in Figure 30, the horizontal axis represents the range of total CO_2 emitted by a single eco-driving (or non-eco-driving) vehicle. The vertical axis represents the frequency (number) of the vehicles whose emissions are within the sub-ranges. The vertical red solid line in each graph shows the average amount of CO_2 emissions for all of the eco-driving or non-eco-driving vehicles. The figure illustrates that, for the same v/c ratio, the distribution of the emissions of eco-driving vehicles is more concentrated around the low-value sub-ranges, while emissions of non-eco-driving vehicles have been spread out in a wider range. The average emission of eco-driving vehicles for the same v/c ratio is lower than those of non-eco-driving vehicles. For the low v/c ratios (0.3 and 0.4), the emission distribution shapes of the eco-driving vehicles are right-skewed, peaking in the range of 20 to 40 grams. The distributions are bi-modal when v/c ratios are bigger than 0.4. One of the peaks remains in the range of 20 to 40 grams, and the other peak appears in the range of 60 to 80 grams. The second peak rises by the growth of the v/c ratio. The graphs show that, for the same v/c ratio, eco-driving vehicles could generate fewer amounts of emissions than non-eco-driving vehicles. However, the emissions of eco-driving vehicles are influenced by traffic conditions.

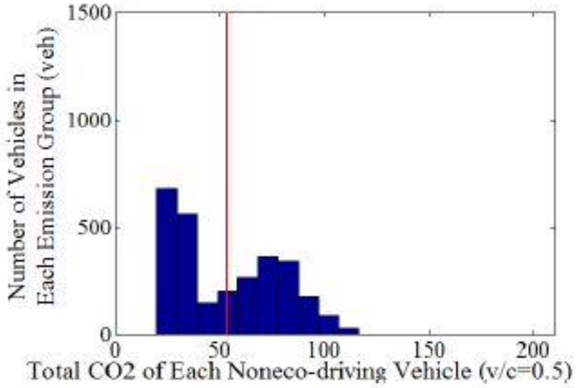


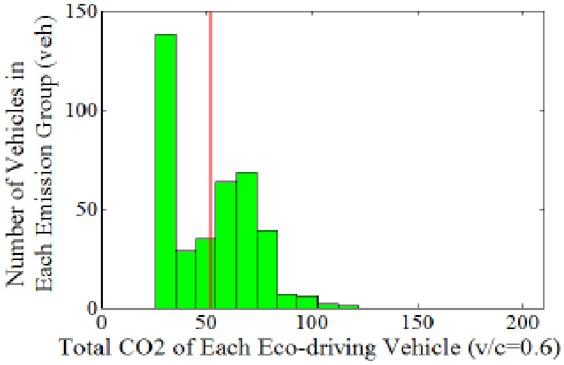


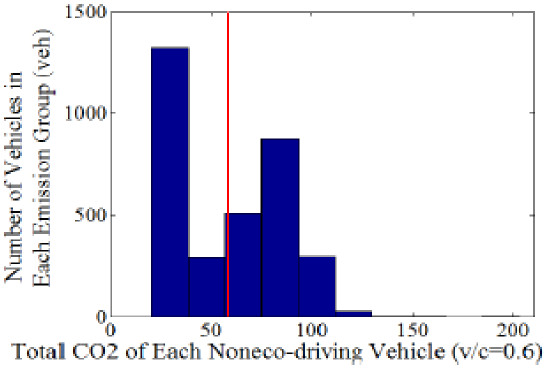












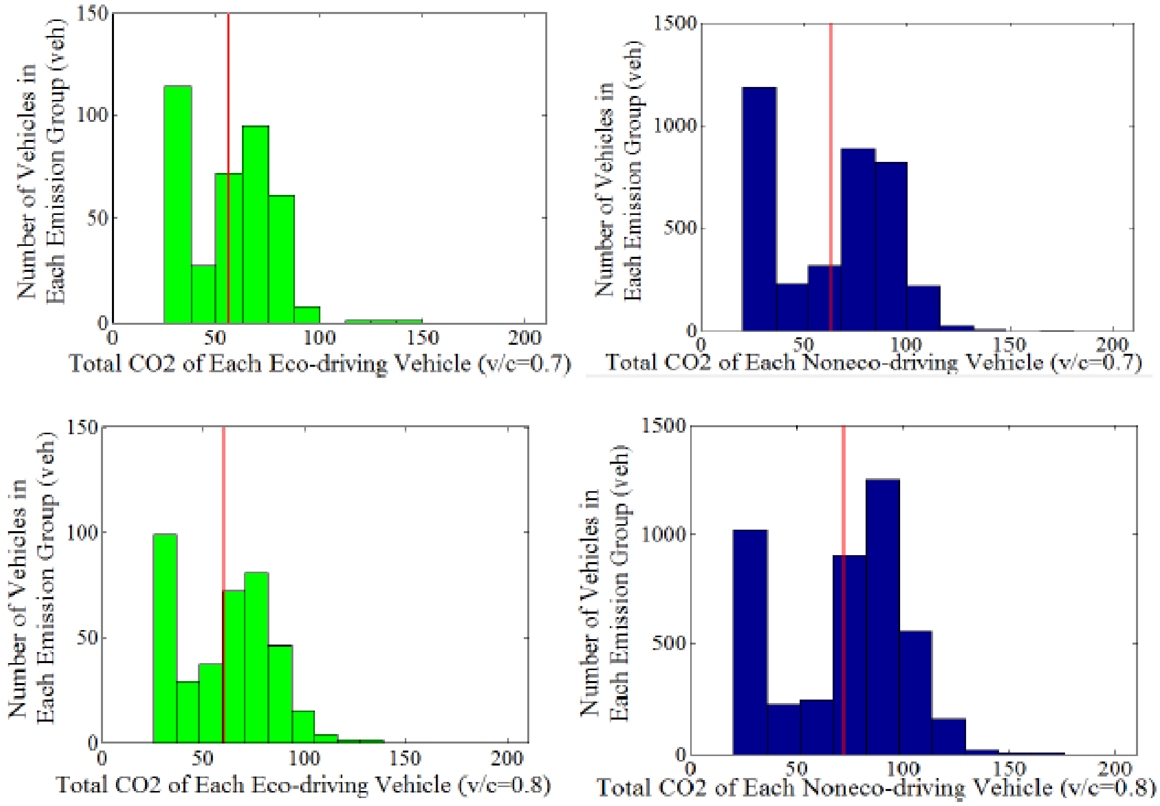


Figure 30 Distribution of Total CO_2 and Average CO_2 of Eco-driving Vehicles and Non-eco-driving Vehicles in Different Traffic Conditions.

4.2.2 Emission Mitigation Rate

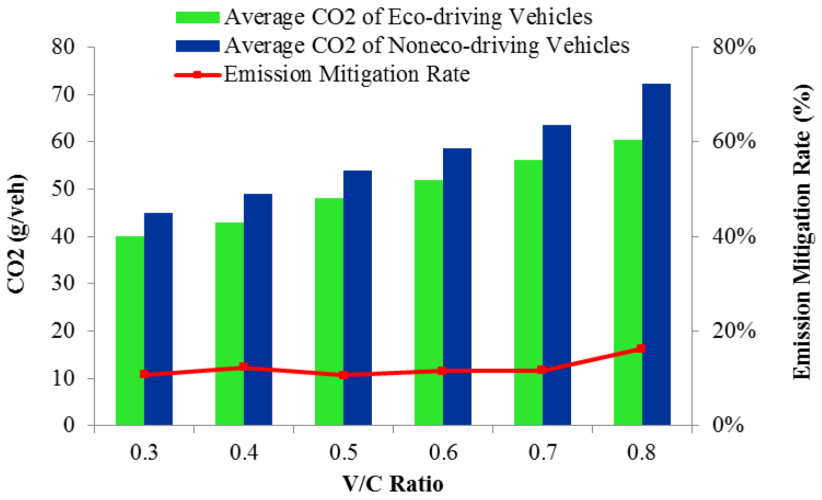
To further study the effectiveness of eco-driving strategies, the emission mitigation rate of eco-driving vehicles in light of non-eco-driving vehicles was calculated by Equation (26).

$$RE_{i,k} = \frac{|E_{i,k} - N_{i,k}|}{N_{i,k}} \times 100\%$$

(26)

where $RE_{i,k}$ is the emission mitigation rate of eco-driving vehicles for emission i (CO_2, CO, NO_X, or HC) and v/c ratio k, $E_{i,k}$ is the average amount of emissions of eco-driving vehicles for emission i and v/c ratio k (g), and $N_{i,k}$ is the average amount of emissions of non-eco-driving vehicles for emission i and v/c ratio k (g).

Figure 31 illustrates the emission amounts and emission mitigation rates of eco-driving for various traffic conditions. The figure shows that the average amounts of CO_2, CO, NO_X, and HC emissions are highly bounded up with the level of traffic conditions. When the v/c ratio is 0.3, the eco-driving vehicles produce the least amount of emissions. However, the emission amounts of both eco-driving vehicles and non-eco-driving vehicles increase by the growth of the v/c ratio. This phenomenon may be due to the fact that, when the v/c ratio increases, it is more frequent for vehicles joining a queue and waiting at the intersection upstream. They have to spend more time approaching the intersection. Therefore, more emissions are generated. In addition, the emission mitigation rates increase by the growth of v/c ratio for the four types of emissions. The results show that eco-driving could save around 20% CO_2, and around 60% of CO, NO_X, and HC.



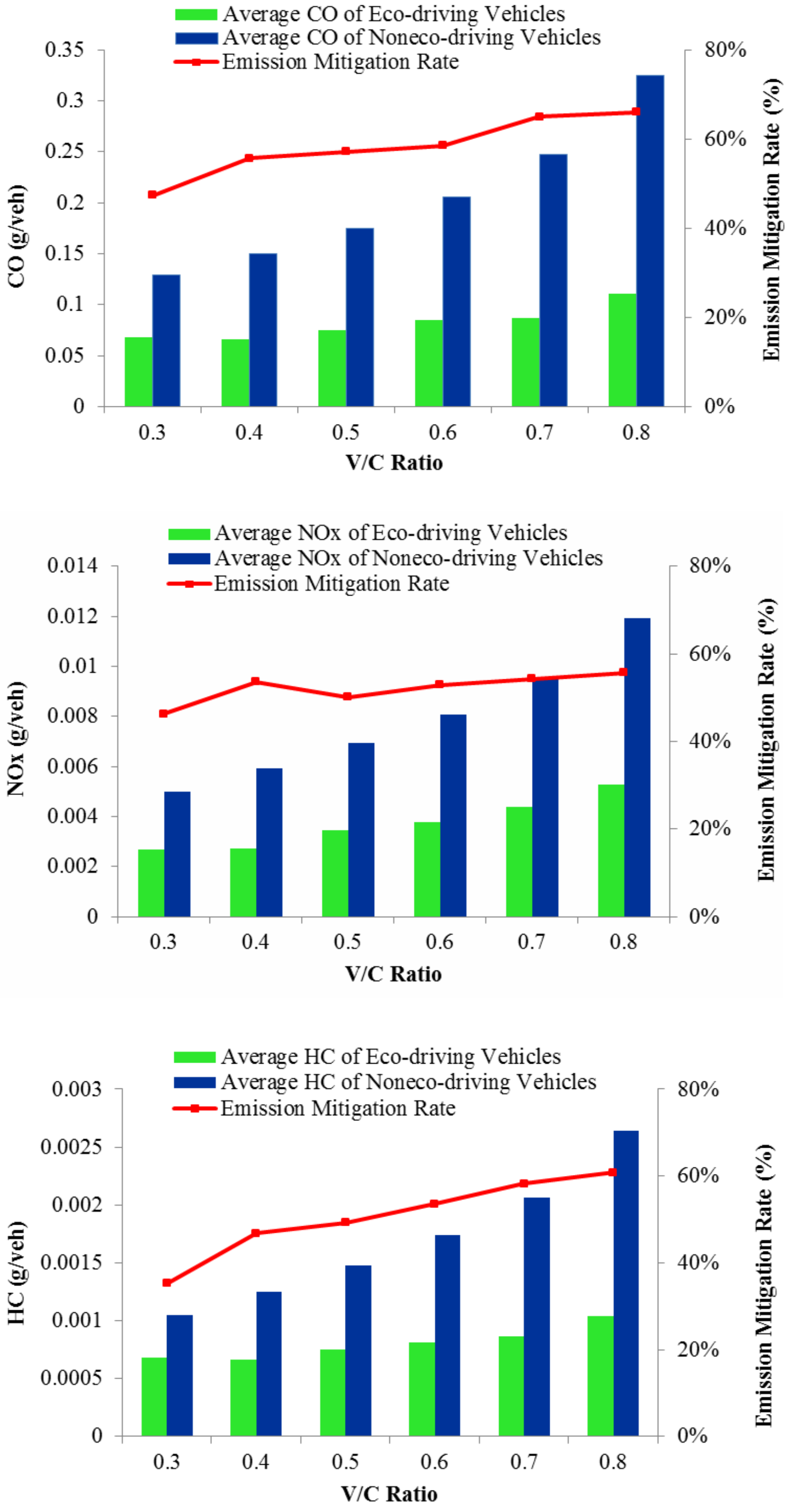


Figure 31 Average Emission Amounts and Emission Mitigation Rates of Eco-Driving Vehicles in Different Traffic Conditions.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Individual real-time eco-driving models for drivers and for automated vehicles were developed in this study in order to examine the most effective eco-driving advising strategies for drivers and to evaluate the potential emission mitigations of eco-driving advice for automated vehicles. The eco-driving models for drivers were programmed in the in-vehicle system of a high-fidelity driving simulator. Audio and visual real-time eco-driving advising strategies with different frequencies were tested in the driving simulator environment. Also, the eco-driving models for automated vehicles were applied in a VISSIM simulation platform under different traffic conditions. The automated vehicles in the simulation environment could make eco-driving decisions on a second-by-second basis and adjust their driving behaviors accordingly. Finally, the MOVES' method was used to estimate vehicle emissions for both driving simulator and VISSIM simulation tests. Several conclusions can be drawn from the study:

1. Real-time audio and visual eco-driving strategies could reduce around 10% of CO_2, and over 30% of CO, NO_x, and HC by comparing to without any suggestion. Furthermore, the trajectories of traveling within the intersection were smoother in eco-driving scenarios than in the base scenario. However, eco-driving scenarios took more total travel time, which reduces the efficiency of mobility.
2. On average, the audio eco-driving saves more emissions than the visual eco-driving. In particular, the scenario of providing the audio eco-driving advising at a 10-second interval generates the least emissions. However, the difference between the 10-second interval audio eco-driving strategy and other audio/visual

eco-driving strategies are not significant.

3. Real-time eco-driving suggestions are effective for automated vehicles. Under the same v/c ratio, automated vehicles could generate fewer amounts of emissions than normal vehicles. The eco-driving could save around 20% of CO_2 and over 60% of CO, NO_X, and HC.
4. The emissions from automated vehicles are influenced by the growth of the v/c ratios. This phenomenon may be due to the fact that when the v/c ratio increases, it is more likely and more frequent for a vehicle to join a queue and wait at the intersection upstream. Thus, they have to spend a longer time approaching the intersection. Therefore, more emissions are generated.

Further research is recommended to focus on the following issues:

1. The best eco-driving strategy for drivers may be influenced by the signal cycle length, the green to cycle ratio (g/c), the traffic condition, and the possibility of accelerating to pass the intersection. It is recommended that future study take these factors into consideration.
2. More samples of participants with a variety of ages, genders, driving experiences, and eco-driving background knowledge should be involved in the driving simulator test. In addition, the sequences to test the sub-scenarios of audio and visual eco-driving strategies should be changed to avoid the drivers becoming familiarized with the test sequences, in order to make the test results more convincible.
3. Lane changing within the intersection vicinity was not considered in the VISSIM simulation in this study. In fact, it avoided the possible interferences between the

automated vehicles and the normal vehicles nearby, except the leading vehicle. However, the lane changing is indeed a phenomenon that commonly happens within the intersection vicinity. It is suggested that future studies consider the lane changing and the other possible interferences with other vehicles in the future studies.

4. Instead of only considering the upstream of the intersections, it is suggested that future studies integrate the intersection upstream and downstream, and consider the process of passing the intersection vicinity as a whole.

APPENDIX

A. Driving Simulator Test Survey for the Eco-driving Strategies to Drivers

I. Demographic information

1)	Your age	18-25	26-35	36-45	46-60	Over 60
		○	○	○	○	○
2)	Race/Ethnicity	White	Black	Hispanic	Asian	Others
		○	○	○	○	○
3)	Education Level	High school or less	College	Bachelor’s degree	Master’s degree or more	others
		○	○	○	○	○
4)	Do you have any hearing of vision disabilities?	Have hearing disability	Have vision disability	Have hearing and vision disabilities	Don’t have hearing or vision disabilities	
		○	○	○	○	
5)	How long is your driving experience?	< 1 year	1-3 years	3-10 years	Over 10 years	
		○	○	○	○	

II. About the test

6)	Had you ever heard about Eco-driving concepts or advice before doing this test?	Yes		No		
		○		○		
7)	In your opinion, how much is driving in simulator similar different from your real-world driving experience?	Very different		Median		Very
		1	2	3	4	5
		○	○	○	○	○
8)	Was the **audio** eco-driving advice during the test **understandable**?	Difficult to understand		Median		Clearly understandable
		1	2	3	4	5
		○	○	○	○	○
9)	Was the **visual** eco-driving advice during the test **understandable**?	Difficult to understand		Median		Clearly understandable
		1	2	3	4	5
		○	○	○	○	○

The last two scenarios of driving simulator test, which you took, had been designed in such a way that the eco-driving advice were provided within different time intervals (i.e. once every 15 seconds for intersection No. 1, once every 5 seconds for intersection No. 2, and once every 5 seconds for intersection No. 3.)

10) Which **frequency** of **audio** devices did you prefer in the test	Advice once every 15s	Advice once every 5s	Advice once every 10s	No preference	Didn't notice/don't remember
	○	○	○	○	○

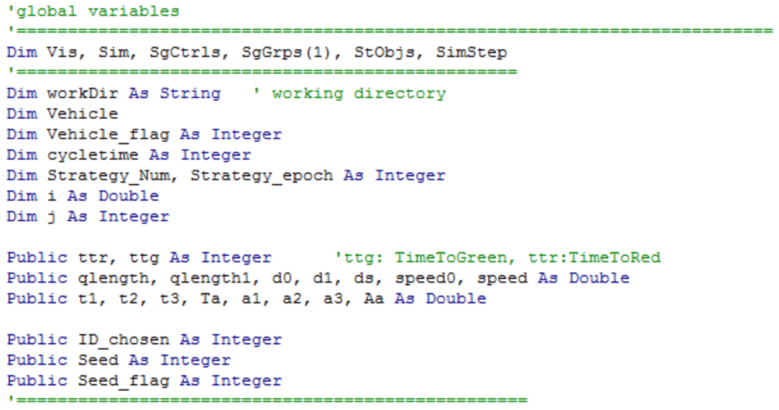
11) Which **frequency** of **visual** devices did you prefer in the test	Advice once every 15s	Advice once every 5s	Advice once every 10s	No preference	Didn't notice/don't remember
	○	○	○	○	○

12) Which type of eco-driving Advice do you prefer? Why? Please provide a reason for you answer, if possible.	Audio	Visual
	○	○

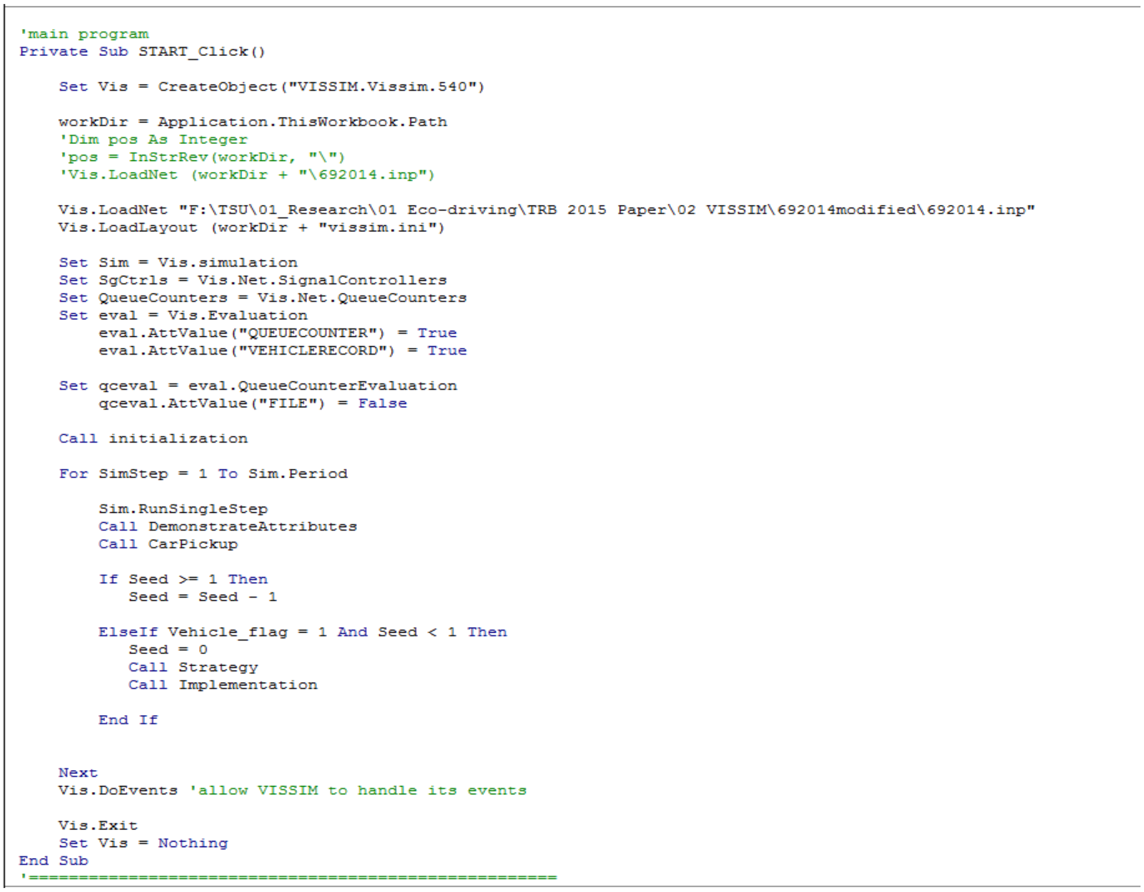
III. More recommendations and comments

If you have any comment or recommendation, please write it down.

B. Visual Basic Scripts of Applying the Eco-driving Model into VISSIM Platform

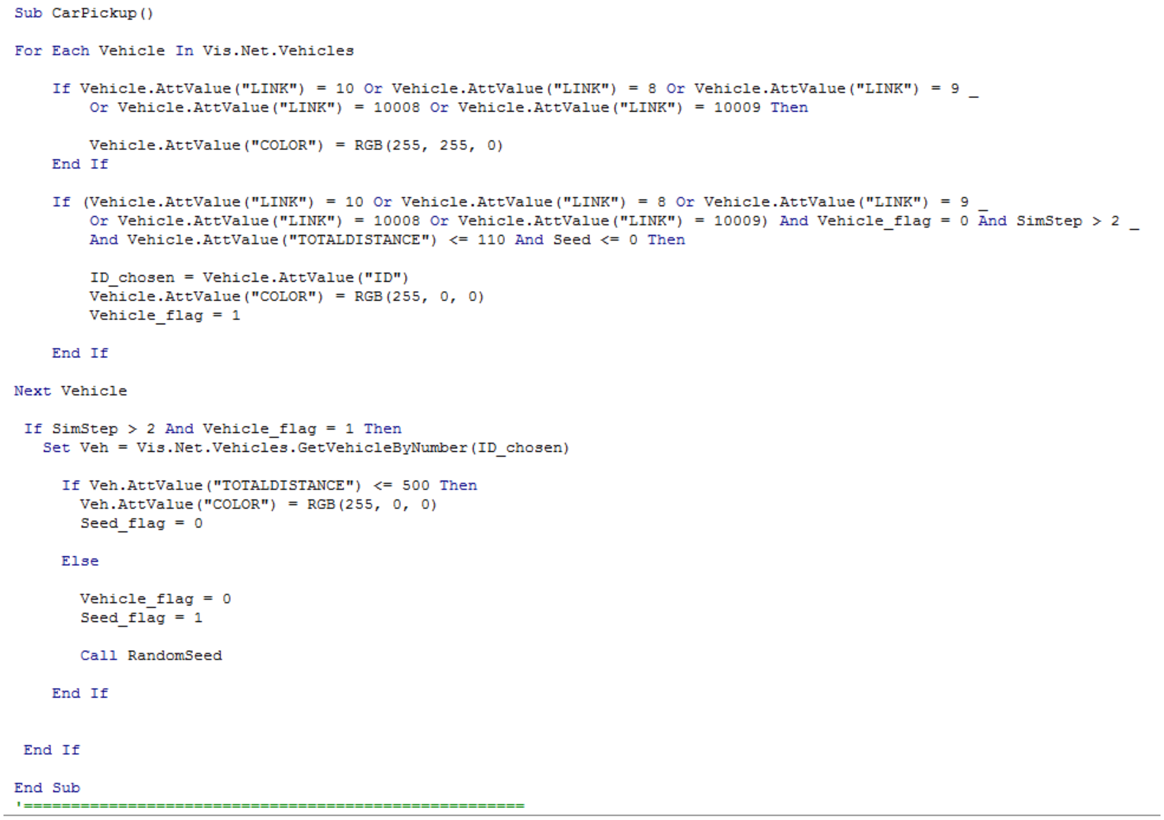


```
'global variables
'===========================================================================
Dim Vis, Sim, SgCtrls, SgGrps(1), StObjs, SimStep
'==================================================
Dim workDir As String   ' working directory
Dim Vehicle
Dim Vehicle_flag As Integer
Dim cycletime As Integer
Dim Strategy_Num, Strategy_epoch As Integer
Dim i As Double
Dim j As Integer

Public ttr, ttg As Integer      'ttg: TimeToGreen, ttr:TimeToRed
Public qlength, qlength1, d0, d1, ds, speed0, speed As Double
Public t1, t2, t3, Ta, a1, a2, a3, Aa As Double

Public ID_chosen As Integer
Public Seed As Integer
Public Seed_flag As Integer
'===================================================
```

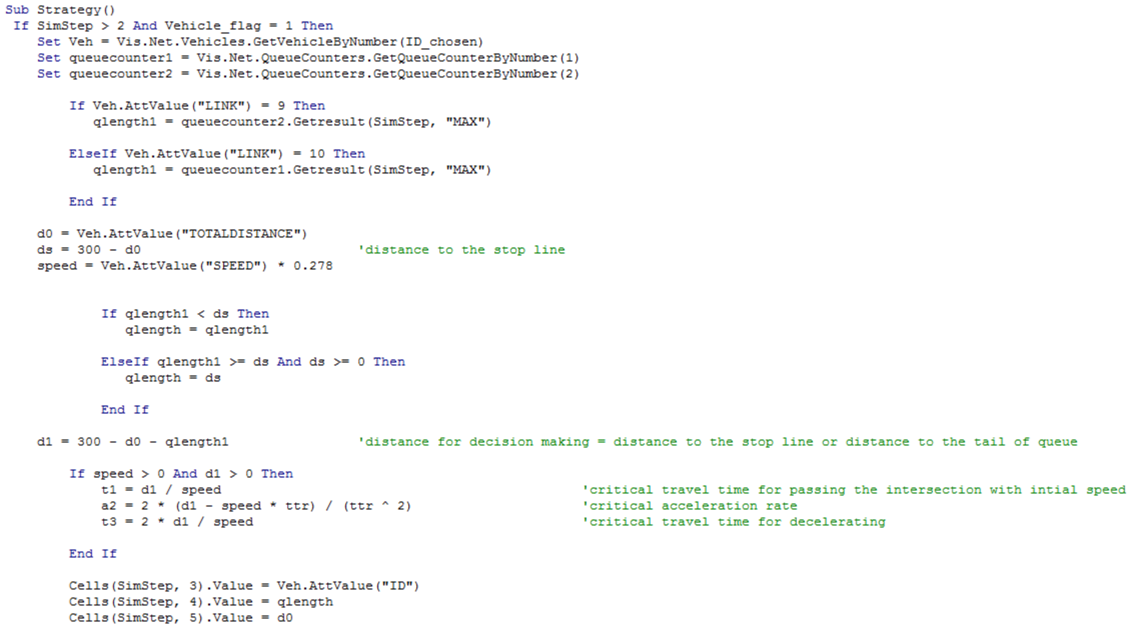


```
'main program
Private Sub START_Click()

    Set Vis = CreateObject("VISSIM.Vissim.540")

    workDir = Application.ThisWorkbook.Path
    'Dim pos As Integer
    'pos = InStrRev(workDir, "\")
    'Vis.LoadNet (workDir + "\692014.inp")

    Vis.LoadNet "F:\TSU\01_Research\01 Eco-driving\TRB 2015 Paper\02 VISSIM\692014modified\692014.inp"
    Vis.LoadLayout (workDir + "vissim.ini")

    Set Sim = Vis.simulation
    Set SgCtrls = Vis.Net.SignalControllers
    Set QueueCounters = Vis.Net.QueueCounters
    Set eval = Vis.Evaluation
        eval.AttValue("QUEUECOUNTER") = True
        eval.AttValue("VEHICLERECORD") = True

    Set qceval = eval.QueueCounterEvaluation
        qceval.AttValue("FILE") = False

    Call initialization

    For SimStep = 1 To Sim.Period

        Sim.RunSingleStep
        Call DemonstrateAttributes
        Call CarPickup

        If Seed >= 1 Then
           Seed = Seed - 1

        ElseIf Vehicle_flag = 1 And Seed < 1 Then
           Seed = 0
           Call Strategy
           Call Implementation

        End If


    Next
    Vis.DoEvents 'allow VISSIM to handle its events

    Vis.Exit
    Set Vis = Nothing
End Sub
'=====================================================
```

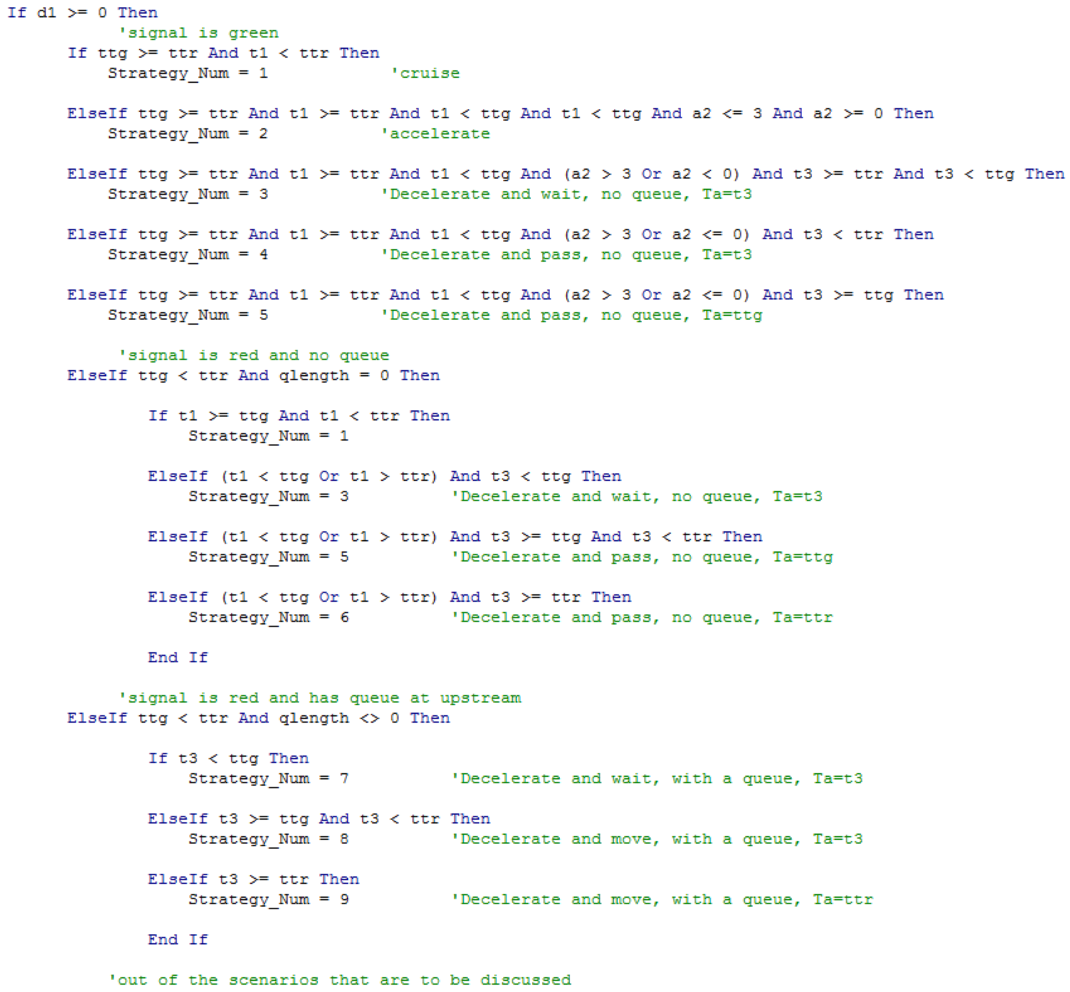
```
Sub RandomSeed()

If Seed_flag = 1 Then
    Seed  = Int(Rnd()   60 +  1)   ' 60 SEC

Else
    Seed    0

End If

End Sub

Sub initialization()

    Vehicle_ flag = 0
    Strateqy_Num = 0
    Seed  flag = 0
    Seed  = 1

    qlength  = 0
    qlength1    0
    qlength2 = 0

    al    0
    a2    0
    a3    0
    Aa    0
    tl    0
    t2    0
    t3    0
    Ta    0

End Sub

Sub DemonstrateAttributes()

    'sl.gnal.
    Se  SgGrps(l.) = SgCerl.s.GeeSiqnal.Conerol.l.erByNumber(1).Siqnal.Groups.GeeSiqnal.Group3yNumber(2)

    cycletime = SimStep  Hod  120 + 1          'CYCLE length
    Cells(SimStep, 2).Value = cycletiree


    If cvcletiree >= 1 And cvcletime  <= 60 Then

       ttr    60 - cycletime + 1
       I.L.y    l..l...L' T 60

    Elseif cycletime  > 60 And cycletiree <= 117  Then

        ttg   120   cyc et me + 1
        eer   eeg  1 60

    Elseif cycletime  > 117 And cycletioce <= 120 Then

        L.L.y   120 - y l. L.iw    T  1
        r.r.r   r:r.cr + no

    End If

End Sub
```



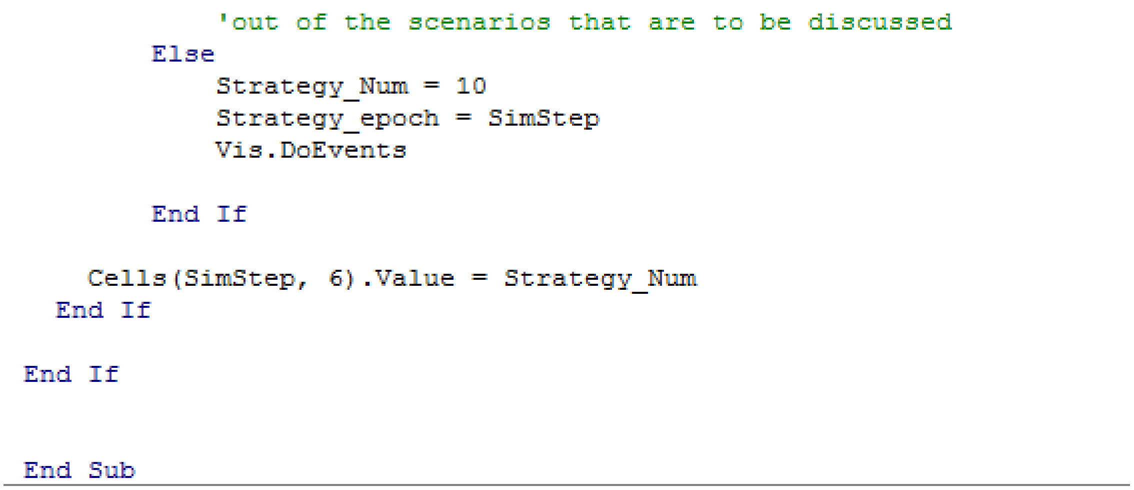
```
Sub CarPickup()

For Each Vehicle In Vis.Net.Vehicles

    If Vehicle.AttValue("LINK") = 10 Or Vehicle.AttValue("LINK") = 8 Or Vehicle.AttValue("LINK") = 9 _
        Or Vehicle.AttValue("LINK") = 10008 Or Vehicle.AttValue("LINK") = 10009 Then

        Vehicle.AttValue("COLOR") = RGB(255, 255, 0)
    End If

    If (Vehicle.AttValue("LINK") = 10 Or Vehicle.AttValue("LINK") = 8 Or Vehicle.AttValue("LINK") = 9 _
        Or Vehicle.AttValue("LINK") = 10008 Or Vehicle.AttValue("LINK") = 10009) And Vehicle_flag = 0 And SimStep > 2 _
        And Vehicle.AttValue("TOTALDISTANCE") <= 110 And Seed <= 0 Then

        ID_chosen = Vehicle.AttValue("ID")
        Vehicle.AttValue("COLOR") = RGB(255, 0, 0)
        Vehicle_flag = 1

    End If

Next Vehicle

 If SimStep > 2 And Vehicle_flag = 1 Then
   Set Veh = Vis.Net.Vehicles.GetVehicleByNumber(ID_chosen)

     If Veh.AttValue("TOTALDISTANCE") <= 500 Then
       Veh.AttValue("COLOR") = RGB(255, 0, 0)
       Seed_flag = 0

     Else

       Vehicle_flag = 0
       Seed_flag = 1

       Call RandomSeed

    End If


 End If

End Sub
'======================================================
```



```
Sub Strategy()
 If SimStep > 2 And Vehicle_flag = 1 Then
    Set Veh = Vis.Net.Vehicles.GetVehicleByNumber(ID_chosen)
    Set queuecounter1 = Vis.Net.QueueCounters.GetQueueCounterByNumber(1)
    Set queuecounter2 = Vis.Net.QueueCounters.GetQueueCounterByNumber(2)

        If Veh.AttValue("LINK") = 9 Then
           qlength1 = queuecounter2.Getresult(SimStep, "MAX")

        ElseIf Veh.AttValue("LINK") = 10 Then
           qlength1 = queuecounter1.Getresult(SimStep, "MAX")

        End If

    d0 = Veh.AttValue("TOTALDISTANCE")
    ds = 300 - d0                           'distance to the stop line
    speed = Veh.AttValue("SPEED") * 0.278


            If qlength1 < ds Then
               qlength = qlength1

            ElseIf qlength1 >= ds And ds >= 0 Then
               qlength = ds

            End If

    d1 = 300 - d0 - qlength1                'distance for decision making = distance to the stop line or distance to the tail of queue

        If speed > 0 And d1 > 0 Then
            t1 = d1 / speed                                      'critical travel time for passing the intersection with intial speed
            a2 = 2 * (d1 - speed * ttr) / (ttr ^ 2)              'critical acceleration rate
            t3 = 2 * d1 / speed                                  'critical travel time for decelerating

        End If

        Cells(SimStep, 3).Value = Veh.AttValue("ID")
        Cells(SimStep, 4).Value = qlength
        Cells(SimStep, 5).Value = d0
```



```
If d1 >= 0 Then
           'signal is green
      If ttg >= ttr And t1 < ttr Then
          Strategy_Num = 1            'cruise

      ElseIf ttg >= ttr And t1 >= ttr And t1 < ttg And t1 < ttg And a2 <= 3 And a2 >= 0 Then
          Strategy_Num = 2           'accelerate

      ElseIf ttg >= ttr And t1 >= ttr And t1 < ttg And (a2 > 3 Or a2 < 0) And t3 >= ttr And t3 < ttg Then
          Strategy_Num = 3           'Decelerate and wait, no queue, Ta=t3

      ElseIf ttg >= ttr And t1 >= ttr And t1 < ttg And (a2 > 3 Or a2 <= 0) And t3 < ttr Then
          Strategy_Num = 4           'Decelerate and pass, no queue, Ta=t3

      ElseIf ttg >= ttr And t1 >= ttr And t1 < ttg And (a2 > 3 Or a2 <= 0) And t3 >= ttg Then
          Strategy_Num = 5           'Decelerate and pass, no queue, Ta=ttg

           'signal is red and no queue
      ElseIf ttg < ttr And qlength = 0 Then

              If t1 >= ttg And t1 < ttr Then
                  Strategy_Num = 1

              ElseIf (t1 < ttg Or t1 > ttr) And t3 < ttg Then
                  Strategy_Num = 3           'Decelerate and wait, no queue, Ta=t3

              ElseIf (t1 < ttg Or t1 > ttr) And t3 >= ttg And t3 < ttr Then
                  Strategy_Num = 5           'Decelerate and pass, no queue, Ta=ttg

              ElseIf (t1 < ttg Or t1 > ttr) And t3 >= ttr Then
                  Strategy_Num = 6           'Decelerate and pass, no queue, Ta=ttr

              End If

           'signal is red and has queue at upstream
      ElseIf ttg < ttr And qlength <> 0 Then

              If t3 < ttg Then
                  Strategy_Num = 7           'Decelerate and wait, with a queue, Ta=t3

              ElseIf t3 >= ttg And t3 < ttr Then
                  Strategy_Num = 8           'Decelerate and move, with a queue, Ta=t3

              ElseIf t3 >= ttr Then
                  Strategy_Num = 9           'Decelerate and move, with a queue, Ta=ttr

              End If

          'out of the scenarios that are to be discussed
```



```
      'out of the scenarios that are to be discussed
    Else
      Strategy_Num = 10
      Strategy_epoch = SimStep
      Vis.DoEvents

    End If

  Cells(SimStep, 6).Value = Strategy_Num
 End If

End If


End Sub
```

```
Sub Implementation()

 If SimStep > 2 And Vehicle_flaq = 1 And  (Strateqy_Num = 1 Or Strateqy_Num = 2
 Or Strategy_Num  3 Or Strategy_Num  4 Or Strategy_Num  5 Or Strateqy_Num  6
 Or Strategy_Num = 7 Or Strategy_Num = 8 Or                   9) Then
 Strategy_Num


    Set Veh = Vis.Net.Vehicles.GetVehicleByNumber(ID_cbosen)

    If dO <= 300 And d1 >= 0 Then

            Select Case  Strategy_Num

            Case  1
                    Aa    0
                    Ta    t1
            Case  2
                    Aa    a2
                    Ta    ttr
            Case  3
                    Aa    -speed ^ 2 /  (2 • d1)       'a3
                    Ta    t3
            Case  4
                    Aa    -speed ^ 2 /  (2 • d1)       'a3
                    Ta    t3
            Case  5
                    Aa    2 •  (d1 - speed  • ttq) / ttq ^ 2
                    Ta    ttq
            Case 6
                    Aa    2 •  (d1 - speed * ttr) / ttr ^ 2
                    Ta    ttr
            Case  7
                    Aa    -speed ^ 2 /  (2 • d1)       'a3
                    Ta    t3
            Case 8
                    Aa    -speed ^ 2 /  (2 • d1)       'a3
                    Ta    t3
            Case 9
                    Aa    2 •  (d1 - speed * ttr) / ttr ^ 2
                    Ta    ttr

            End Select

                    If Cells(SimStep - 1, 7) = "" Then
                        i = speed
                        Cells(SimStep, 7).Value = i
                    Else
                        i = Cells(SimStep - 1, 7).Value + Aa
                        Cells(SimStep, 7).Value = i
                    End If


    El::tcl ▼ d1 < 0 Or /O > 30•) Ih n
            Vi.DoEv nt                    'owf th =  donc  for deciioakino
          Ao - V:h.Atl;\e.lue(..!:;PEEI>")  .. 0.270 - Cell.:=iitep -    1. 0).Velue          'acceleration unit: (m/s^2)
          V!'"h . :.LLVl m•1 ''T)F.:<I TR FT>= PFF.T>")    - l'i!':
    n: T-

      ''faranel:ere tor checlo:Ln;
      I"U..!s1::>.1m!:>te?, 8) .\'alue = \'e..:t':Va.lue("!iVl!!!:J.)") 1( 0. 2' 8      •speea unu: (m/ s)
      t:e.Us•::> m::>eep, 9) ,\'alue = Aa

      t:e.Us1::>.1m::>eep, 1U; . 'Jal.ue  t.:ell.s(.Sllll!:ep,  . 'Jal.ue  ,. 11. 1 ,.. -::eU.e(.Sl.ll:>ep,  i:i; .vaLue + U.1J-;. _
                                    1 0.0•)0302 .. Ccll:(Sin :p,  81 . V:1lu = '' 3
      C ll:ISimSec-:,  11: . Vulu = - Ccll:(Sin :p, 81 . V:1lu =  Z.Z3';  1:1'CCCd unh: (m::h)
      C ll:.•5im!:iee'0, 12: . Volu = - Cell(;j p,     91 . Ve.lu = '"  -.23';          •e.cc l:::eion unit:  (ml'h/1
Cnd If
```

REFERENCES

A Glass of Water. (n.d.). Retrieved from www.aglassofwater.org/

Ahn, K., and Rakha, H. (2014). Ecolane Applications: Preliminary Testing and Evaluation. *Transportation Research Record: Journal of the Transportation Research Board*, (2427), 41-53.

An, F., Barth, M., Norbeck, J., and Ross, M. (1997) Development of comprehensive modal emissions model: operating under hot-stabilized conditions. *Transportation Research Record: Journal of the Transportation Research Board*, (1587), 52-62.

Annual Energy Outlook 2015 with projections to 2040. (2015, April). (DOE/EIA-0383 (2015)). Retrieved from U.S. Energy Information Administration (EIA) website. http://www.eia.gov/forecasts/aeo/

Beusen, B., Broekx, S., Denys, T., Beckx, C., Degraeuwe, B., Gijsbers, M., Scheepers, K., Govaerts, L., Torfs, R., and Panis, L. I. (2009, October). Using On-board Logging Devices to Study the longer-term Impact of an Eco-driving Course. *Transportation Research Part D: Transport and Environment*, 14 (7), 514–520.

BMW Group. (2015). BMW M Power Meter. Retrieved from iTunes Preview website itunes.apple.com/us/app/bmw-m-power-meter/id344494968?mt=8

Boriboonsomsin, K., Barth, M., and Vu. A. (2011). Evaluation of Driving Behavior and Attitude towards Eco-Driving: A Southern California Limited Case Study. In *Transportation Research Board 90th Annual Meeting* (No. 11-0151).

Carbon Monoxide. (n.d.). Retrieved from U.S. Environmental Protection Agency website, http://www.epa.gov/cgi-bin/broker?polchoice=CO&_debug=0&_service=data&_program=dataprog.national_1.sas

Choi, D. and J. Koupal. (2011, June). MOVES Validation. In *MOVES Workshop*. Office of Transportation and Air Quality.

Cogan R. (2014, January). Honda’s Eco Assist Makes You a More Efficient Driver. Retrieved from Cars of Changes website, carsofchange.com/top-stories/hondas-eco-assist-makes-you-a-more-efficient-driver/

Daun, T. J., Braun, D. G., Frank, C., Haug, S., and Lienkamp, M. (2013). Evaluation of Driving Behavior and the Efficacy of a Predictive Eco-driving Assistance System for Heavy Commercial Vehicles in a Driving Simulator Experiment. 16th International IEEE Conference on Intelligent Transportation Systems (ITSC), The Hague, Netherlands (pp. 2379-2386).

Dedicated Short Range Communications (DSRC) Service. (n.d.). Retrieved from Federal Communications Commission website, http://wireless.fcc.gov/services/index.htm?job=service_home&id=dedicated_src

Driving Simulator. (n.d.). Retrieved from Department of Transportation Department of Texas Southern University website. http://transportation.tsu.edu/NTSCE/NTECE_htm/facilities.htm

ECOWILL. (n.d.). Retrieved from Intelligent Energy Europe website. http://www.ecodrive.org/en/what_is_ecodriving-/the_golden_rules_of_ecodriving/#golden rules

European Campaign On improving DRIVing behaviour, ENergy-efficiency and traffic safety (ECODRIVEN). (n.d.). Retrieved from Intelligent Energy Europe website, https://ec.europa.eu/energy/intelligent/projects/en/projects/ecodriven

Fiat. (2010, Feburary). *Eco-driving Uncovered*. Retrieved from http://www.ecodriver-project.eu/library/other-documents/ecodriving-uncovered/

Hallihan, G., Mayer, A., Caird, J., and Milloy, S. (2011). Effects of Hybrid Interface on Ecodriving and Driver Distraction. *Transportation Research Record: Journal of the Transportation Research Board*, (2248), 74-80.

Hiraoka, T., Nishikawa, S., and Kawakami, H. (2011). Driver-Assistance System to Encourage Spontaneous Eco-Driving Behavior. In Process: *ITS World Congress*, (Vol. 2011).

Jimènez-Palacios, J. L. (1998). *Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing* (Doctoral dissertation, Massachusetts Institute of Technology).

Kamalanathsharma, R., and Rakha, H. (2012, September). Agent-based Modeling of Eco-Cooperative Adaptive Cruise Control Systems in the Vicinity of Intersections. *15th International IEEE Conference on Intelligent Transportation Systems (ITSC), Anchorage, Alaska, USA.*

Kamalanathsharma, R., and Rakha, H. (2014) Agent-Based Simulation of Ecospeed-Controlled Vehicles at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, (2427), 1-12.

Kobayashi, I., Tsubota, Y., and Kawashima, H. (2007) Evaluation of Eco-driving within a Network Using Traffic Simulation. *WIT Transport on the Built Environment* (Vol. 96).

Koupal, J., Landman, L., Nam, E., Warila, J., Glover, E., and Giannelli, B. (2004). MOVES2004 Energy and Emissions Inputs. *EPA document number: TBD.*

Li, Q. and Qiao, F. (2014). How Drivers' Smart Advisory System Improves Driving Performance? A Simulator Imitation of Wireless Warning on Traffic Signal under Sun Glare. LAMBERT Academic Publishing. ISBN-13: 978-3-659-57193-0. Saarbrucken, Germany.

Li, Q., F. Qiao, and L. Yu. (2016b). Vehicle Emission Implications of Drivers Smart Advisory System for Traffic Operations in Work Zones. Journal of Air & Waste Management. DOI:10.1080/10962247.2016.1140095. ISSN: 1096-2247 (Print) 2162-2906 (Online) Journal. Online access: http://www.tandfonline.com/doi/pdf/10.1080/10962247.2016.1140095.

Li, Q., Qiao, F., and Yu, L. (2015). Will Vehicle and Roadside Communications Reduce Emitted Air Pollution? International Journal of Science and Technology, Vol. 5, No. 1, 2015. 17-23. http://ejournalofsciences.org/archive/vol5no1/vol5no1_3.pdf.

Li, Q., Qiao, F., Wang, X., and Yu, L. (2016a) Drivers Smart Advisory System Improves Driving Performance at STOP Sign Intersections. Journal of Traffic and Transportation Engineering (English Edition). In Press.

Li, Z., Yu, L., Qiao, F., and Wang, J. (2015). Feasibility Study of Using Driving Simulator to Develop Operating Mode Distributions for Emission Analysis. In *Transportation Research Board 94th Annual Meeting* (No. 15-1437).

Ministry of Economy, Trade and Industry of Japan. (2014, January). *November is Eco-Drive Promotion Month!* Retrieved from www.meti.go.jp/english/press/2012/1031_01.html

Next-Generation SmartGauge with EcoGuide. (n.d.). Retrieved from Ford website, www.ford.com/cars/cmax/features/Feature4/#page=Feature3

Nitrogen Oxides. (n.d.). Retrieved from U.S. Environmental Protection Agency website, http://www.epa.gov/cgi-bin/broker?polchoice=NOX&_debug=0&_service=data&_program=dataprog.national_1

Office of Transportation and Air Quality. (2011, August). *Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator (MOVES2010) Final Report*. (EPA-420-R-11-011), pp 14.

Park, S., Ahn, K., Rakha, H. A., & Lee, C. (2015). Real-Time Emission Modeling with EPA MOVES: Framework Development and Preliminary Investigation. In *Transportation Research Board 94th Annual Meeting* (No. 15-2604).

PTV. (2011). *VISSIM 5.40 User Manual.* Karlsruhe, Germany.

Qian, G., and Chung, E. (2011). Evaluating Effects of Eco-driving at Traffic Intersections Based on Traffic Micro-simulation. *Australasian Transport Research Forum 2011 Proceedings* (pp.28-30).

Qiao, F., Jia, J., Yu, L., Li, Q., and Zhai, D. (2014) Drivers' Smart Assistance System Based on Radio Frequency Identification. In Transportation Research Record: Journal of Transportation Research Board, No. 2458, Transportation Research Board of the National Academies, Washington, DC, 2014, pp. 37-46.

Qiao, F., Rahman, R., Li, Q., and Yu, L. (2016) Identifying Smartphone Based Intelligent Messages for Worker's Crossing in Work Zone. Special Issues on ITS, Journal of Transportation Technologies, ISSN Online: 2160-0481. In Press.

Rahman, R., Qiao, F., Li, Q., Yu, L., and Kuo, P.-H. (2015). Smart Phone Based Forward Collision Warning Message in Work Zones to Enhance Safety and Reduce Emissions. DOI: 10.13140/RG.2.1.2867.8169. Presentation and Publication in the 94th Transportation Research Board Annual Meeting, National Academy of Sciences, Washington, DC, January 11-15, 2015.

Rakha, H., Ahn, K., El-Shawarby, I., and Jang, S. (2004, April). Emission model development using in-vehicle on-road emission measurements. In *Annual Meeting of the Transportation Research Board, Washington, DC* (Vol. 2).

Rakha, H., and Kamalanathsharma, R. (2011). Eco-driving at signalized intersections using V2I communication. *14th International IEEE Conference on Intelligent Transportation Systems (ITSC), Washington, DC* (pp. 341-346).

Rouphail, N., Frey, H., Colyar, J., and Unal, A. (2001). Vehicle Emissions and Traffic Measures: Exploratory Analysis of Field Observations at Signalized Arterials. In *80th Annual Meeting of the Transportation Research Board, Washington, DC*.

Scora, G., and Barth, M. (2006, June). Comprehensive Modal Emission Model (CMEM). Version 3.01. Center for Environmental Research and Technology. University of California at Riverside.

Shinpo, K. (2007, November). *Japanese Eco-driving Initiative*. Retrieved from http://www.internationaltransportforum.org/Proceedings/ecodriving/1-04Japan.pdf

Shladover, S. E. (2012, July). Automated Vehicles: Terminology and Taxonomy. *2012 Road Vehicle Automation Workshop. Irvine, California.*

Sierra Research. US Environmental Protection Agency, Washington, DC. (2001). *Development of Speed Correction Cycles*. (Report No. M6.SPD.001. EPA420-R-01-042).

Staubach, M., Schebitz, N., Köster, F., and Kuck, D. (2014). Evaluation of an Eco-driving Support System. *Transportation Research Part F: Traffic Psychology and Behaviour*, 27, 11-21.

Sun, J., Niu, D., Chen S., and Li, K. (2013, January). Development and Investigation of a Dynamic Eco-Driving Speed Guidance Strategy for Signalized Highway Traffic. In *Transportation Research Board 92nd Annual Meeting* (No. 13-2272).

Tang, P., Yu, L., and Song, G. (2014). Effect of Driving Behaviors on Emissions in Eco-Driving at Intersections. In *Transportation Research Board 93rd Annual Meeting* (No. 14-0648).

U.S. Environmental Protection Agency, Washington, DC. (2010). *Motor Vehicle Emission Simulator (MOVES) User Guide for MOVES2010b*. Retrieved from http://www3.epa.gov/otaq/models/moves/documents/420b12001b.pdf

Vlieger, D. (1997). On Board Emission and Fuel Consumption Measurement Campaign on Petrol-driven Passenger Cars. *Atmospheric Environment*, 31 (22), 3753–3761.

Wu, G., Boriboonsomsin, K., Xia, H., and Barth, M. (2014). Supplementary Benefits from Partial Vehicle Automation in an Eco-Approach/Departure Application at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, (2424), 66-75.

Wu, G., Boriboonsomsin, K., Zhang, W., Li, M., and Barth, M. (2010). Energy and Emission Benefit Comparison of Stationary and In-Vehicle Advanced Driving Alert Systems. *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington, DC, (2189) 98-106.

Xia, H., Boriboonsomsin, K., Schweizer, F., Winckler, A., Zhou, K., Zhang, W. B., and Barth, M. (2012). Field Operational Testing of ECO-approach Technology at a Fixed-time Signalized Intersection. *15th International IEEE Conference on Intelligent Transportation Systems (ITSC), Anchorage, Alaska, USA. (pp. 188-193).*

Xu, Y. (2011). *Vehicle Operating Mode Distribution Model for Emission Evaluation on Traffic Networks*. (Doctoral dissertation. Beijing Jiaotong University)

Zhao, Q., Zhu, S., Yu, L., and Qiao, F. (2015). Experimental Development and Testing of a Smartphone Eco-driving App. In *Transportation Research Board 94th Annual Meeting* (No. 15-3211).