Network-wide Assessment of Eco-Cooperative Adaptive Cruise Control Systems on Freeway and Arterial Facilities

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ABSTRACT (ACADEMIC)

The environmental impact of a transportation system is critical in the assessment of the transportation system performance. Eco-Cooperative Adaptive Cruise Control (Eco-CACC) systems attempt to minimize vehicle fuel consumption and emission levels by controlling vehicle speed and acceleration levels. The majority of previous research efforts developed and applied Eco-CACC systems on either freeway or signalized intersections independently on simple and small transportation networks without consideration of the interaction among these controls.

This thesis extends the state-of-the-art in Eco-CACC evaluation by conducting a comprehensive evaluation on a complex network considering Eco-CACC control on both freeways and arterials individually and simultaneously. The goal of this study is to compare Eco-CACCs on arterial facilities (Eco-CACC-A), freeway facilities (Eco-CACC-F) and both facilities (Eco-CACC-F+A). The effects of Eco-CACC are evaluated considering various Measures of Effectiveness (MOEs), including: average vehicle delay, fuel consumption, and emission levels using simulated results from INTEGRATION, a microscopic traffic assignment and simulation software, considering different freeway speed limits, traffic demand levels and system market penetration rates. In total, 19 traffic scenarios for each of the four different cases (Eco-CACC-A, Eco-CACC-F and Eco-CACC-F+A plus a base no control case) were tested. In total 760 simulation runs were conducted (4 cases × 19 scenarios ×10 repetitions). T-tests and pairwise mean comparison (Tukey's HSD) were conducted to identify any statistical differences between control cases and the base case from the simulation results. This thesis shows that arterial and freeway Eco-CACCs can work well together and their effects will be largely influenced by network characteristics.

ABSTRACT (PUBLIC)

Environment issues have gradually become extremely significant in economy development all over the world. Transportation, as one of the main sector in economy, is a huge source of fuel consumption and air pollution. Through previous researches, it can be concluded that by changing speed and acceleration of vehicles according to surrounding traffic information, fuel usage and emissions can be reduced. However, these researches only took control on either arterial, which is greatly influenced by traffic signals, or freeway, which is not interrupted by traffic signals. While their combined effect has not been tested. In this thesis, both arterial and freeway controls are applied separately and simultaneously to a complex road network with different configurations, such as speed limit, traffic demand, and proportion of drivers who can receive the guidance. By comparing simulation results from the combination of traffic controls and network characteristics, the thesis proves that these two controls can cooperate with each other, instead of creating conflicts in the network. And their performance will be largely influenced by network settings. The thesis provides a new effective speed and acceleration control method for vehicles to minimize the impact from transportation system on environment from network-wide. Moreover, inspired by this thesis, much more benefits can be attained from this type of control by adjusting network settings to a suitable status.

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CHAPTER 1 INTRODUCTION

1.1 Motivation

Environment has been the hit issue in recent decades of years. Increasing petroleum-based energy usage results in various problems that severely affect people's life, including global climate change, worse air quality and decreasing storage of natural resources. According to the data from US Energy Information Administration, in 2012, petroleum consumption in the US is 34.577 quadrillion BTU, which is 80% of the usage in North America. Corresponding CO_2 emission is 2,240 million metric tons in the US, which is also 80% of total CO_2 emission among North America [1]. Transportation, as one of the major part in economy, shares 28% of total energy use [2] and 26.5% of total Greenhouse Gas (GHG) emission [3] in 2012. Among all the transportation modes, personal vehicle is the largest source of fuel consumption due to its large population: they consumes more than 60% of the energy in transportation [4]. Meanwhile, the demand for travel is increasing: from 2010 to 2012, vehicle-mileage went up 1.8% [5]. How to improve fuel economy on personal vehicles is the key to save energy and reduce air pollution. Vehicle power technology and advanced traffic management are two effective ways to achieve the goal.

Numerous efforts have been made on improving machine operation and engine design, such as biofuel application [6], hybrid-electric technologies [7], and hydrogen fuel cells [8]. Compared to vehicle technology, traffic management falls behind on its effect on reducing fuel consumption and emissions. Lack of understanding on drivers' behavior and reactions to various traffic conditions is a major obstacle. Moreover, under-developed communications between vehicles and infrastructures (I2V and V2I) as well as among vehicles (V2V) is also one of the challenges that impedes efficient traffic control and management. From previous researches, Eco-driving, a method that helps or teaches drivers to take eco-friendly driving behavior, is proved to be one effective way to reduce the negative impacts on environment from transportation.

Tremendous papers have studied the Eco-driving methods and their influence on energy usage. However, they focused on either freeway or arterial exclusively. Road network in a real world is composed of various types of roads, and the traffic condition on one part will largely influence the traffic status on another. It is hard to say that Eco-driving control on one specific road will benefit the whole network. Because of this, although previous researches have proposed and tested many effective Eco-driving controls, it has not yet been proved that these controls will coordinate together in optimizing energy saving and minimizing pollutant emissions. The mixed effect to a network from Eco-driving on arterial, freeway or combined facilities of arterial and freeway needs to be investigated.

1.2 Research Uniqueness and Objectives

The uniqueness of this thesis is that we combine all the controls together, and apply them both separately and simultaneously to our testbed. In addition, to test the sensitivity of the effectiveness of the controls to the network parameter settings, freeway speed limit, demand level, and market penetration rate are varied to create 19 different traffic scenarios (see parameter design in 4.3). By applying different combinations of Eco-CACC controls on various scenarios of this network, we can not only obtain the result on interaction effects from these control methods under different conditions, but also conclude how network characteristics will influence the performance of controls.

1.3 Thesis Layout

The thesis is organized as follows: Chapter 2 is the literature review introducing the current status of researches on fuel usage, emission models, as well as Eco-driving strategies. Simulation software, emission models, as well as Eco-CACCs used in this thesis are introduced in Chapter 3. Chapter 4 describes the testbed and data used for this thesis. Parameter settings and experiment design are also discussed in Chapter 4. T-tests and pairwise mean comparison (Tukey's HSD) between Eco-CACC and the base case and comparison of simulation results are presented in Chapter 5. In Chapter 6, the conclusions of this study and future research is presented.

CHAPTER 2 LITERATURE REVIEW

2.1 Fuel Consumption and Emissions Estimation Model

Many researchers have developed models and simulation tools for estimating fuel consumption and emission.

MOBILE, NONROAD, ALPHA, GEM, and MOVES are developed by EPA [9]. MOBILE5 produces activity-specific emission rates considering vehicle type and age, average speed, temperature, altitude, vehicle load, air conditioning usage, and vehicle operating mode. It estimates HC, CO and NO_x pollutants by multiplying corresponding emission rates to movement activities, including travel hours, miles and number of trips [10]. MOBILE6 is a revision of the MOBILE5 model [11]. One of the most significant difference of MOBILE6 from MOBILE5 is that it added the "off-cycle emission", which includes aggressive driving with air conditioning operating [12]. Because the driving cycle used in MOBILE6 is significantly different to that of MOBILE5, MOBILE6 generates a higher pollution emission rate than MOBILE5. MOBILE5 and MOBILE6 use average speed profile so they are more suitable to a macroscopic emission estimation. NONROAD is another emission model from EPA that is focused on nonroad transportation equipment (which is "an internal combustion engine or a gas turbine engine used for other purposes than being an engine of a vehicle operated on public roadways" [13]). And it calculates the amount of hydrocarbons, carbon monoxide, oxides of nitrogen, particulate matter, sulfur dioxide and carbon dioxide during trips of nonroad equipment [14]. Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool is an off-cycle evaluation simulator that can estimate the GHG emission from various types and powertrain technologies of light-duty vehicles [15]. It is defined to be capable to simulate five driving cycles. FTP (Federal Test Procedure) cycle is for in-city driving. The highway driving cycle is for highway driving conditions under 60mph and US06 cycle represents more aggressive driving conditions over 60mph. LA92 has a higher top speed, a higher average speed, less idle time, fewer stops per mile and a higher maximum acceleration rate than FTP. SC03 cycle is used to test vehicle A/C system. The inputs of ALPHA include surrounding environment conditions, electrical system which is related to starter, alternator and other electrical accessories, engine and transmission, driveline and vehicle. Greenhouse Gas Emission Model (GEM) estimates GHG emissions and fuel efficiency of specific aspects of heavy-duty vehicles. Similar to ALPHA, inputs for GEM includes Ambient, which is environment characteristics, Electric, Engine, Transmission and Vehicle [16]. Motor Vehicle Emission Simulator (MOVES) is an emission modelling system that can be utilized to generate estimation from on- and off-road automobile sources. Emission models by EPA, such as MOBILE and NONROAD, are integrated and finally replaced "with a single comprehensive modelling system" [17]. Improved from individual models, MOVES enables estimate a wider range of emission from mesoscale to macroscale. California Air Resources Board built another macroscopic on-road emission model called EMFAC and it is widely used in California [12]. Same as MOVES, it can be only used on regional-level spatial scale and cannot produce accurate estimations for individual vehicles (at microscale level) [18]. One thing should be noted is that EMFAC is currently used in the State of California, while MOVES can be used throughout North America [12]. Besides that, EMFAC differs from MOVES from many aspects such as estimated fuel type, emission sources, estimated pollutant, modelled emission processes, and operating modes, etc. [18] .

The major drawback of macroscopic models is that they use average speed instead of instantaneous speed and acceleration of a specific trip, the estimation thus is not accurate enough to reflect differences between levels of congestion and facility. Compared to macroscopic model, microscopic models, which consider individual movement, can provide results that are more detailed and individual vehicle oriented. In microscopic models, instantaneous energy usage and emission are based on second-by-second vehicle activities, including vehicle power, tractive effort, acceleration and speed. Network, traffic and environment conditions are also taken into consideration. One of the most representative microscopic emission model is the Comprehensive Modal Emissions Model (CMEM) by University of California, Riverside. CMEM predicts light-duty vehicle (LDV) emissions based on the operating model of vehicle with vehicle operation variables and model parameters [19]. As "comprehensive" indicates, it can be used for a wide range of vehicle and technology categories. Inputs required for CMEM include second-by-second vehicle activity and fleet composition of traffic. During estimation, emission process is broken down into different components corresponding to different phenomena related to vehicle operation and emissions [20]. These divided components are modeled with parameters that are varied from vehicle categories like type, age and operation technology, emission control technologies, etc. [21]. The Virginia Tech microscopic energy and emission model (VT-MICRO) by Rakha is another microscopic model that is built and calibrated using speed and acceleration data collected from Oak Ridge National Laboratory (ORNL). It is a combination of linear, quadratic, and cubic regression model to provide a relatively good fit to all measures of effectiveness (MOE including fuel consumption and emissions) [22]. The Virginia Tech comprehensive power-based fuel consumption model (VT-CPFM) by Rakha eliminated a bang-bang control system, which could cause incorrect result. This model is based on publicly available data such as EPA city and highway fuel economy ratings [23]. This improvement makes the model much easier to calibrate since compared to experimental data, the data used in VT-CPFM is much more convenient to collect. In this thesis, VT-MICRO, which is integrated into simulation software INTEGRATION, is used to model the fuel consumption.

2.2 Eco-driving Algorithm

As the name of Eco-driving suggested, this control methodology aims at providing eco-friendly driving advice by controlling acceleration, speed and deceleration during trips to minimize the environmental impact. The realization of Eco-driving largely benefits from the development of advanced traffic information system, which enables real-time communication among individual vehicles, and between vehicles and infrastructures. This capability of communication in the network will be extremely helpful under the circumstances when vehicles need to be guided through signalized intersections, when vehicles need to accelerate and decelerate in accordance with the status of the traffic lights, and under congested conditions. In addition, the communication among vehicles and infrastructures significantly influences the efficiency of traffic flow by exchanging driving information along the road.

In this thesis, the applied eco-driving methodology is named Eco-Cooperative Adaptive Cruise Control (Eco-CACC). Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) are developed to improve the traffic-flow performance and they largely rely on V2X communication technology. Adaptive Cruise Control (ACC) is a radar-based system that aims to relieve drivers from continuously changing speed in response to leading vehicles. CACC is an enhancement of ACC, which adds V2V communications and thus enables the coordination among a platoon of vehicles. There are many researches about the benefits of CACC. Bart compared CACC and ACC under different levels of traffic demand and penetration rate, and showed CACC has higher highway capacity than ACC, especially under high-demand and high-penetration, while low-penetration of CACC may cause negative influence to traffic-flow performance [24]. Shladover et al simulated four types of vehicles (manual vehicle, ACC vehicle, CACC vehicle, and HIA vehicle that is driven manually but equipped with a communication radio broadcasting “here I am” massage as well as its location and speed). By changing composition fraction of each two of these vehicles, the paper proved that lane capacity increases with the decreasing of manual vehicle fraction and it can reach up to 4000 vph if the percentage of CACC vehicle is 100%. Moreover, compared to the combination of ACC and CACC, HIA has much more help on improving the performance of CACC-equipped vehicles in the network [25].

In the following section this chapter, to provide a wider overview of the research on related areas, not only Eco-CACC, but also other types of Eco-driving methods and supporting tools will be discussed.

2.2.1 Eco-driving Algorithm on Arterial

Based on the development of V2X communication, researchers have done numerous work about Eco-driving on signalized arterials.

Malakron et al compared the traditional pre-time signal plan scenario and cooperative scenario with vehicles equipped with CACC and communication between infrastructures and vehicles. By adjusting signal timing plan and helping determine the trajectory of vehicles approaching signalized intersections without any stops, cooperative scenario reduced 85% CO_2 emission and 76% fuel consumption on average vehicle than the vehicle that is without CACC and approaching the intersection under traditional pre-time signal plan [26].

Themann et al developed a discrete dynamic optimization on fuel consumption that integrated V2X information into the work. The utility function which defined the usefulness of an optimized speed profile was used in the optimization. The optimization was applied both in the simulation of cooperative intersection and the test drive in the real world of cooperative intersection. For simulated scenario, the optimization system reduced fuel consumption by 6% and in real world test, they proved that fuel consumption would be reduced by 15% without significant increase of travel time [27].

Chen et al developed an advanced control algorithm, model predictive control (MPC), which can calculate optimal result for minimizing cost function in a limited time range. This algorithm took infrastructure, preceding vehicles and following vehicles into consideration, without sacrificing car-following capacity. The paper showed that by applying MPC, absolute value of acceleration decreased, resulting in a higher fuel efficiency. Also, a driver driving style index was introduced in the study. By incorporating this index, MPC became more flexible and adaptive to different types of preceding vehicle drivers [28].

Munoz-Organero and Magnana developed a driving guidance device to reduce fuel consumption by optimizing deceleration when approaching static signals, such as pedestrian crossing signs and stop signs where a stop is needed. They developed and applied an Android mobile app in the experiment, which can detect static signals along the road and provide drivers with a required deceleration intensity. The result showed that by applying it, less fuel consumption can be achieved by smoothing the deceleration rate [29].

Kamal et al developed a novel control method called Ecological Driver Assistant System (EDAS). EDAS can be set in the vehicle, collecting data from current vehicle, preceding vehicle and signal information on the road to optimize and provide suggestions on the speed control. In their research, drivers were assumed to fully follow the EDAS guidance. Using AIMSUN NG simulator, application of the system proved to be much more fuel efficient, especially under transient period such as following a decelerating vehicle or encountering a red light ahead [30].

Nouveliere et al developed a Human-Machine Interface (HMI) module based on the speed optimization from EDAS. HMI shows the information of current speed, desired speed, current gear ratio, and safety warning on the odometer of the vehicle. Eight drivers and two vehicles were utilized for the implementation. From the experiment, HMI with EDAS guidance obtained benefits from both fuel economy and safety [31].

Barth et al described a dynamic eco-driving algorithm which utilized real-time signal and road information to adjust velocity of vehicles for minimizing fuel consumption and emissions. The simulation results showed a 10% to 15% improvement on fuel efficiency was achieved with the control [32].

Mandava et al evaluated the effect from Eco-driving strategy under light traffic conditions. The objective function of the algorithm is to minimize absolute acceleration value, to smooth the speed and acceleration profile when vehicle is approaching a signalized intersection. Current signal information and defined status including distance to the next intersection to provide speed advice, signal states, vehicle initial velocity and time to change signal states can be obtained as the input of the optimization algorithm. Applying the control to a stochastic simulation, 12%-14% energy/emission saving can be achieved [33].

Asadi and Vahidi described a predictive cruise control with I2V communication and concluded that signal-to-vehicle contact will not only benefit traffic safety but also help improve fuel economy by reducing idling at signalized intersection [34].

Niu and Sun tested two types of dynamic speed guiding strategies: Green Wave Speed Guidance Strategy (GWSGS) and Eco-Driving Speed Guidance Strategy (EDSGS) in a signalized highway in a driving simulator. GWSGS aims to let vehicle cross the intersection without stop, and EDSGS generates the most fuel-saving-optimal speed profile for the vehicle when approaching an intersection. The results were compared to non-control scenario and it showed that EDSGS had a 25% decrease on fuel usage. Both strategies did not have significant increase of travel time [35].

Kamalanathsharma and Rakha developed a multi-stage dynamic programming algorithm for eco-cruise control at signalized intersections to maximize fuel benefits with explicit microscopic model as well as vehicle and road characteristics. The algorithm led to about 19% saving in energy use [36].

Chen considered environment impact and delay at the same time and established an optimized algorithm to minimize the linear combination of CO emission and travel time. It took approaching distance to intersections, queue discharging time, weight for emission and travel time into consideration, and tested the performance of the optimization model under different scenarios. By applying genetic algorithm, the model can solve the targeted optimization problem more efficiently and practicably [37]. His research also proved that emission is more sensitive to these traffic scenarios than travel time, and reduction of CO emission is easier to be achieved than shortening delay with the application of eco-cruise strategies [37].

Yang et al developed an Eco-CACC algorithm based on queues at signalized intersection. Minimizing fuel consumption rate, this algorithm provided advice on individual vehicle speed when it was approaching a signalized intersection with information from both infrastructures and traffic queues. It showed 40% reduction on fuel consumption by a synthetic analysis [38].

2.2.2 Eco-driving Algorithm on Freeway

Besides Eco-Cruise models on signalized intersections, there are many researches on development of methodology for controlling vehicle velocity along freeway, which does not involve stops, acceleration and deceleration resulting from stops for traffic signals.

Schwarzkopf and Leipnik developed a mathematical model for vehicle fuel consumption and a non-linear optimal control method for this model. The algorithm was applied in a single vehicle simulation along level road, 0.1 radian upslope road, and -0.1 radian downslope road thus different optimal speed profiles were generated on these conditions. The study suggested that keeping speed in the range of +/- 15% of level road speed is appropriate and fuel-saving on the road with 10% grade [39].

Chang et al studied the optimal vehicle speed profiles for minimizing fuel consumption on freeway with different curve and gradient characteristics. It started with a level tangent (straight path) and then combined it with level curved section, upgrade tangent section and downgrade tangent section. The study proved that constant speed profile is optimal under different guideway characteristics [40].

Saboohi and Farzaneh described an optimal driving strategy based on coordination of speed and gear ratio through engine load, and they showed that this strategy can save fuel in an intense traffic flow [41].

Hellstrom et al designed an efficient fuel-optimal control for heavy diesel truck with road topography information. Dynamic programming with objective of minimizing fuel usage was utilized in the model. Considering characters of heavy truck, mass was introduced and considered in gear shifting in the driving. The model was proved to have a fast and accurate calculation that can be applied in on-board truck driving control [42].

Barth and Boriboonsomsin established a dynamic Eco-driving system with real-time traffic condition data from different level of service (LOS). The study showed that 10-20% fuel saving and CO_2 emission reduction can be achieved without producing much longer delay and it also proved that when congestion is more severe, fuel efficiency becomes more considerable [43].

Mensing et al developed a trajectory optimization method with dynamic programming, which took into account of traffic constrains, such as car-following distance, vehicle speed, acceleration, time-to-collision (TTC), etc. The results showed resistance forces are a major influence to fuel consumption, and taking constrain on TTC in Eco-CACC drive cycle will decrease the improvement on fuel saving compared to non-TTC constrain [44].

Ahn et al developed a predictive eco-cruise control system, which combined eco-cruise control and state-of-art car following model to compute optimal vehicle speed and acceleration based on graded road. The results suggested a 27% energy saving by applying the system [45].

2.2.3 Supporting Tools for Implementation Eco-driving Controls

Section 2.2.1 and 2.2.2 introduced the current researches on the algorithm to improve fuel efficiency by Eco-driving on either arterials and freeways. In addition to providing specific speed/acceleration profiles to drivers, researchers also studied supporting and incentive methods for drivers to adopt eco-friendly driving style, and the results from these studies indicate a reduction on energy using and emissions. Though this thesis did not study the enforcement of Eco-driving controls, related literatures are listed here since it can be one of the directions for future research on Eco-driving.

Ando and Nishihori implemented a social experiment for three weeks on the influential factors on drivers' willing to take eco-driving method. It provided three different frequencies on sending out eco-driving information, and defined category factors related to drivers such as motivation of participating in social experiment, average running distance. The result showed that middle frequency information is more acceptable for drivers to follow compared to high frequency, and the information provision related to Eco-driving and its evaluation should be provided according to individual characteristics [46].

Nozaki et al evaluated two Eco-Driving Support System (EDSS) from the viewpoint of FUBEN-EKI (Further Benefit of a Kind of Inconvenience), which is a system design methodology that appreciates benefit from the process that does not "save labor to attain a specific task". These two EDSS are: direct EDSS, which interferences drivers' operation directly by providing speed profile or a warning beep if drivers' behavior disobeys the objective; and indirect EDSS, which presents the possible result from the current driving behavior. The experiment applied two EDSSs to two groups of drivers. The result showed that, although both EDSSs improve fuel economy, indirect EDSS has a longer and more significant effect on keeping drivers active on taking eco-driving behavior [47].

Tulusan et al did an experiment on the effect of eco-driving feedback in 50 corporate car drivers. Twenty-five drivers were in the control group, which did not use eco-driving feedback application and the other drivers were in a treatment group that used eco-driving feedback application. The experiment utilized an existing mobile app DriveGain that can provide the score for the driving behavior over a period and give advice on recommended gear based on fuel consumption. The result showed that treatment group improves their overall fuel efficiency significantly, indicating feedback of driving behavior has an incentive effect to drivers to take eco-driving strategy even without financial consideration [48].

Pampel et al applied eco-drive, safely drive and normal drive on two types of roads: urban roads which have lower speed and traffic load; and motorway roads with higher speed and traffic load. The study was proposed to identify the mental models of eco-driving from regular drivers, and it proved that people have eco-driving mental model when they are required to drive eco-friendly. The indicators of taking eco-drive behavior included acceleration/deceleration, braking, coasting and car-following. The result showed that when drivers are required to "eco-driving", fuel consumption decreases 7.7% comparing to the base case [49].

Satou et al described the function and result of on-board eco-driving support system. This system is designed for drivers who have no access to Internet, not familiar with off-board function, or does not have high attention on eco-driving. From before and after experiment, result showed that fuel consumption decreases after using on-board eco-driving support system, and CO_2 reduction is also realized with more drivers beginning to use eco-driving [50].

2.3 Literature Review Conclusion

2.1 and 2.2 give a broad overview on current researches about fuel consumption emissions estimation model, Eco-driving algorithm on different types of roads, and supporting tools for Eco-driving control. To give an accurate individual-vehicle-oriented estimation on fuel consumption and emissions during the trip, microscopic model, which uses second-by-second speed and acceleration profiles, is preferred. In the researches on Eco-driving algorithms, some of them were focused on the benefit from a single vehicle, using information from V2I communications, while the other studies utilized information from both infrastructures and surrounding vehicles, to obtain benefits for the traffic flow. Both of these controls have been proved to have significant improvement on energy saving and pollution emitting. However, these researches only tested the influence from Eco-driving algorithm on a specific type of road (signalized intersection or freeway), a combined effect from applying Eco-driving to both of the facilities have not been discussed. It is hard to decide whether Eco-controls on different parts of one network will work together well, or have contradictions with each other. This missing area is what this thesis wants to explore. In the following parts, selected control strategies will be applied separately and simultaneously to a complex, highly congested network, and the effect from three types of Eco-driving controls (only arterial, only freeway and their combination) on mixed facilities will be concluded.

CHAPTER 3 METHODOLOGIES

In this chapter, the simulation tool, fuel consumption and emissions models, as well as the Eco-CACC algorithms applied in the thesis are introduced.

3.1 Simulation Software

INTEGRATION is a trip-based microscopic traffic assignment, simulation, and optimization model [51]. Current X-large version of INTEGRATION is capable of modeling networks of 600,000 OD pairs. The basic input files include node file, link file, signal file, OD file and incident characteristics file. Node file defines number of network nodes, their spatial coordinates, and whether they function as origins or destinations. In link file, nodes are connected by road links, which have lengths, number of lanes, free flow speed, capacities, and other characteristics. Signal file defines traffic signal control strategies (signal timing plan) in the network. OD file includes the information about the demand at a certain simulation time period between origin and destination (defined by node file). In this thesis, traffic assignment is pre-decided, in other word, there is no re-routing process during each run of simulation. Detailed description on format of input and output files can be found in INTEGRATION user manual [52]. The following models discussed in this chapter have been integrated into INTEGRATION.

3.2 Virginia Tech Microscopic Energy and Emission Model (VT-MICRO)

VT-MICRO is a microscopic fuel consumption and pollutant emission model developed by Rakha et al of Virginia Tech. It is a regression model that is composed of multiple polynomial combinations of speed and acceleration, instead of a power-demand model like CMEM. Experiment data from Oak Ridge National Laboratory (ORNL) is used in calibration and establishment of VT-Micro model. ORNL data contains vehicle operation and emission information from six light-duty automobiles and three light-duty trucks, which helps to produce an average vehicle for a consistent vehicle engine displacement, vehicle curb weight and vehicle type. 1300 to 1600 measurements and corresponding MOEs (measurement of effectiveness, which is a set of fuel consumption and emissions) are collected to eliminate the impact of randomness. ORNL data is also much better than other emission data sets that are collected only from a few driving cycles. Since it is almost impossible to cover all types of vehicle engines and operations by small amount of driving cycles, the large set of driving cycles in ORNL data ensures the accuracy and comprehensiveness of VT-MICRO model [12].

The final VT-MICRO regression model contains exponential function, which prevents negative value of MOEs. Since acceleration requires vehicle to exert power while deceleration does not, this difference causes inaccuracy of estimation on MOEs especially for HC and CO emission. Hence the final version of VT-MICRO model separates positive and negative acceleration occasions [22]:

$$MOE_e = \begin{cases} e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}^{e}\times u^{i}\times a^{j})} & For\ a \geq 0 \\ e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(M_{i,j}^{e}\times u^{i}\times a^{j})} & For\ a < 0 \end{cases} \tag{1}$$

Where:

MOE_e = instantaneous fuel consumption or emission rate (l/s or mg/s);

$L_{i,j}^{e}$ = model regression coefficient for MOE “e” at speed power “i” and acceleration power “j”;

$M_{i,j}^{e}$ = model regression coefficient for MOE “e” at speed power “i” and acceleration power “j”;

u = instantaneous vehicle speed (km/h);

a = instantaneous vehicle acceleration (km/h/s).

3.3 Eco-Cooperative Adaptive Cruise Control on Arterial (Eco-CACC-A)

Eco-CACC-A is an eco-cruise algorithm utilized on signalized arterials developed by Yang. Aiming at minimizing fuel consumption rate, Eco-CACC-A estimates an optimal deceleration and acceleration rate when the vehicle approaches and leaves the intersection [38]. The objective function of Eco-CACC-A is (2):

$$\min_{a-,a+} \int_{t_0}^{t_0+T} F\big(v(t)\big)dt \tag{2}$$

s.t.,

$0 \leq a_- \leq a_-^s$

$0 \leq a_+ \leq a_+^s$

In which,

a_- is deceleration rate when the vehicle is approaching intersection;

a_+ is acceleration rate of vehicle when signal turns to green;

a_-^s is the saturate deceleration rate when vehicle is forced to stop at the queue tail;

a_+^s is the saturate acceleration rate.

For the algorithm with queue, the advisory speed limit of individual vehicle, v(t) can be defined as equation (3):

$$v(t) = \begin{cases} v_0 - a_-(t - t_0), & t_0 \leq t < t_0 + \delta t_{q,1} \\ v_{q,t} , & t_0 + \delta t_{q,1} \leq t < t_c \\ v_{q,t} + a_+(t - t_c), & t_c \leq t < t_c + \delta t_{q,2} \\ v_f & t_c + \delta t_{q,2} \leq t \leq t_0 + T_q \end{cases} \tag{3}$$

In which:

v_0 is initial speed;

a_- is decelerate rate when vehicle is approaching intersection;

a_+ is accelerate rate after signal turns to green;

$v_{q,t}$ is speed after vehicle decelerates in avoid of queue and stop delay;

$\delta t_{q,1}$ is decelerate time;

$\delta t_{q,2}$ is accelerate time;

t_c is time point when dissipating shockwave meets the vehicle;

And v_f is speed after accelerating to cross the intersection.

When the vehicle approaches the intersection which is without queue, the advisory speed limit v(t) displays in equation (4):

$$v(t) = \begin{cases} v_0 - a_-(t - t_0), & t_0 \le t < t_0 + \delta t_{n,1} \\ v_{n,t}, & t_0 + \delta t_{n,1} \le t < t_0 + \delta t_{n,1} + \delta t_{n,2} \\ v_{n,t} - a_-^s\left(t - t_0 - \delta t_{n,1}\right), & t_0 + \delta t_{n,1} + \delta t_{n,2} \le t < t_0 + \delta t_{n,1} + \delta t_{n,2} + \delta t_{n,3} \\ 0, & t_0 + \delta t_{n,1} + \delta t_{n,2} + \delta t_{n,3} \le t < t_c \\ v_{n,t} + a_+(t - t_c), & t_c \le t < t_c + \delta t_{n,4} \\ v_f, & t_c + \delta t_2 \le t \le t_0 + T_n \end{cases} \tag{4}$$

The variable set $\{T_n, v_{n,t}, \delta t_{n,1}, \delta t_{n,2}, \delta t_{n,3}, \delta t_{n,4}\}$ can be estimated as follows:

$$\delta t_{n,1} = \frac{v_0 - v_{n,t}}{a_-} \tag{4a}$$

$$v_0 \delta t_{n,1} - \frac{1}{2} a_- \delta t_{n,1}^2 + v_{n,t} \delta t_{n,2} + v_{n,t} \delta t_{n,3} + \frac{1}{2} a_-^s \delta t_{n,3}^2 = d - d_0 \tag{4b}$$

$$v_0 \delta t_{n,1} - \frac{1}{2} a_- \delta t_{n,1}^2 + v_{n,t} \delta t_{n,2} + v_{n,t}(t_g - t_0 - \delta t_{n,1}) = d \tag{4c}$$

$$\delta t_{n,3} = \frac{v_{n,t}}{a_-^s} \tag{4d}$$

$$\delta t_{n,4} = \frac{v_f - v_{n,t}}{a_+}$$
(4e)

$$\frac{1}{2} a_+ \delta t_{n,4}^2 + v_f\left(t_0 + T_n - t_c - t_{n,4}\right) = l + d_0$$
(4f)

3.4 Eco-Cooperative Adaptive Cruise Control on Freeway (Eco-CACC-F)

Ahn et al developed an integrated Eco-CACC system that combines eco-cruise control with car-following model. This car-following model describes the motion under steady state conditions plus a number of constraints that control the acceleration and deceleration of vehicles [45]. Steady state car following model assumes the leading vehicle has a constant speed and both the leading and following vehicles have identical car-following behaviors [12]. At the same time, collision avoidance model (which controls deceleration of the following car to keep a safety distance with the leading car) and vehicle acceleration model (which uses vehicle power train model with engine speed and torque [53]) are applied together with steady state car following model.

The eco-cruise control system uses dynamic programming (DP) implementation of Dijkstra's shortest path algorithm to control vehicle motion for optimal fuel consumption. Stage length (d_s, the distance that estimated vehicle optimal speed remains constant), the look-ahead distance (d_0, the distance that optimization procedure is performed) and optimization implementation distance (d_j, the distance that the optimized speed profile is implemented for the vehicle) are used for DP in the system. Three parameters are set as inputs for the algorithm: target speed, speed range and car-following spacing threshold. Target speed usually is based on speed limit of corresponding link. Speed range defines minimum and maximum of speed accepted by driver and spacing threshold depends on drivers' comfort. The logic can be summarized as the following steps:

1) The model starts with driver input of a target speed, speed range, and car-following spacing threshold ($x_{u\_}T$). By comparing space between the subject and leading car with car

following threshold, eco-cruise control on freeway regulates the speed of the following vehicle in two ways.

2) When the spacing between the subject and lead vehicle ($x_u(t)$) is smaller than $x_{u\_}T$, maximum acceleration is estimated based on the steady state car following model and collision avoidance constrains;

3) When the spacing ($x_u(t)$) is greater than$x_{u_}T$, optimal speed over the look-ahead distance is estimated by DP with consideration of a spatial discretization of stage.

CHAPTER 4 TESTBED NETWORK AND SIMULATION EXPERIMENT DESIGNT

4.1 Network Description

The testbed in the simulation is the Arlington area in Virginia. Two freeways (I66 and I495) and two arterials (US29 and US50) serve as the major traffic corridors. The network is a highly contested connection between resident areas in northern Virginia and Washington DC as well as its surrounding business area. Moreover, it is adjacent to the IAD airport. Traffic load through west and east is very large, especially during peak hour along I66. The network covers an area about 16 miles’ length and 2 miles’ width. **Figure 1** shows the network in the simulation.

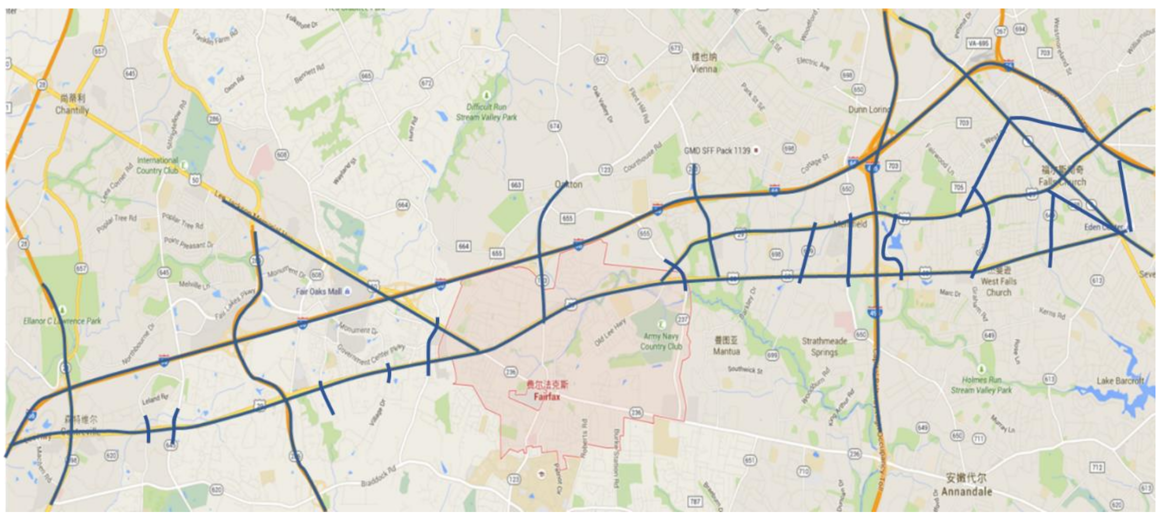


Figure 1 Simulation network

4.2 Data Generation and Calibration

OD data in the simulation is estimated from traffic count data collected from the loop detectors in the area. Blue circles in **Figure 2** show the location of loop detectors along I66 that collected the data for the simulation. Count data during morning peak hour (7:00am to 8:00am) along I66, US29 and US50 on May 12, 2014 are selected for OD estimation in the network.

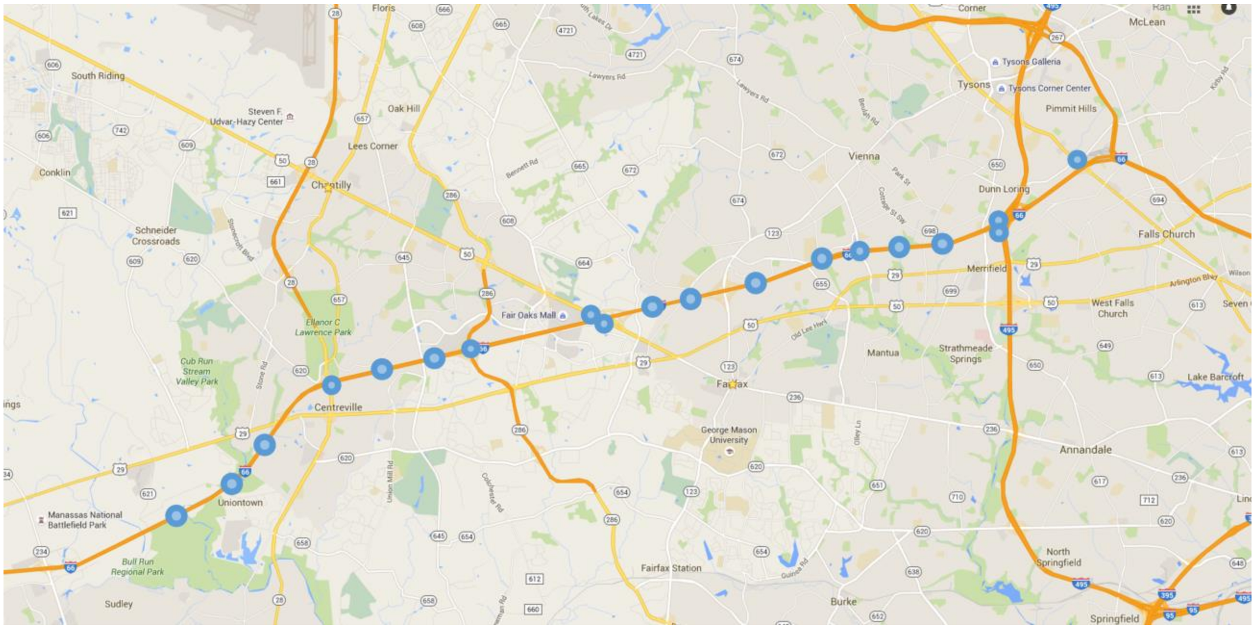


Figure 2 Location of data collection

QueesOD are utilized to calculate origin-destination demand in the network. QueensOD is a tool for estimating traffic demands from observed link traffic flows, observed link turning movement counts, link travel time and information on drivers' route choices. QueensOD implemented Stirling's Approximation for the solution to maximum-likelihood synthetic OD problem, which is a more generalized model compared to OD gravity model [54]. QueensOD can estimate ODs for a large network with over 1000 zones and 5000 links with a personal computer within 1 hour [55]. In this thesis, by applying QueensOD on the testbed with traffic count data, in a total 8,254 pairs of OD are generated and the total number of trips is 34,182.

Figure 3 shows the comparison between estimated link flow from QueensOD and observed flow from original data. R^2 is 0.9921, indicating a high accuracy of the OD estimation.

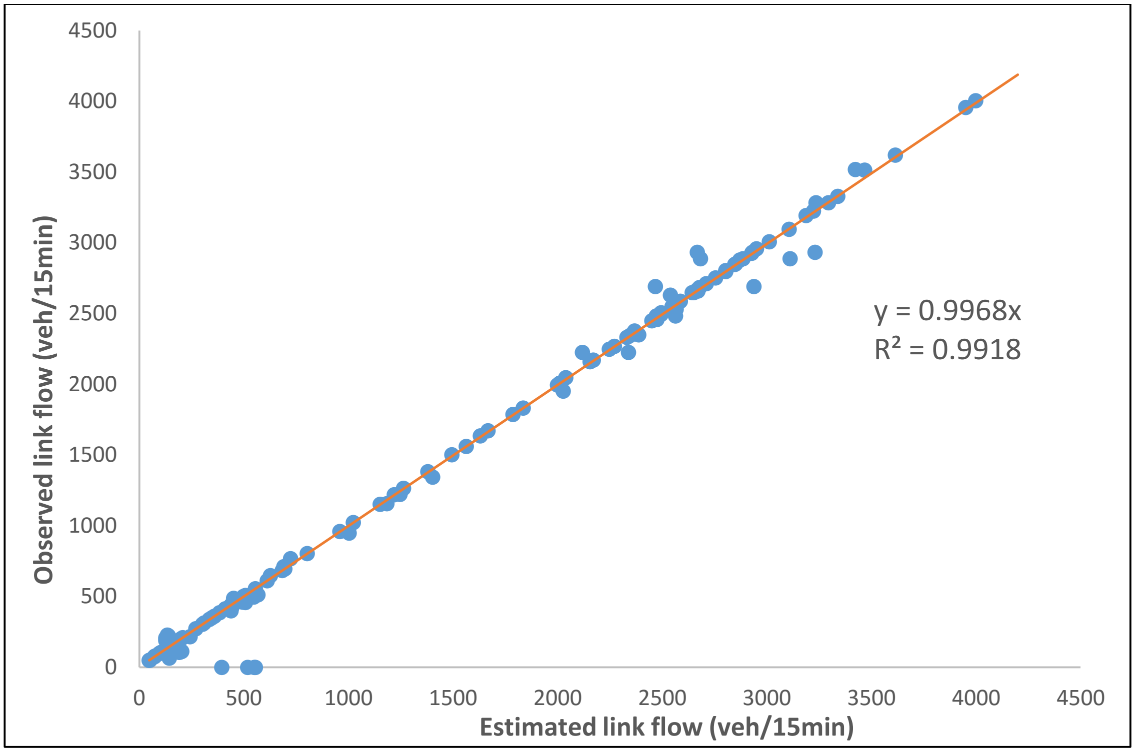


Figure 3 Estimated VS Observed 15 minutes link flow from 7am to 8am

Using OD file generated from QueensOD, we apply a sample simulation in INTEGRATION. **Figure 4** and **Figure 5** show the comparison between observed and simulated speeds on eastbound and westbound of I66 at peak hour. The simulated speed matches with the observed well.

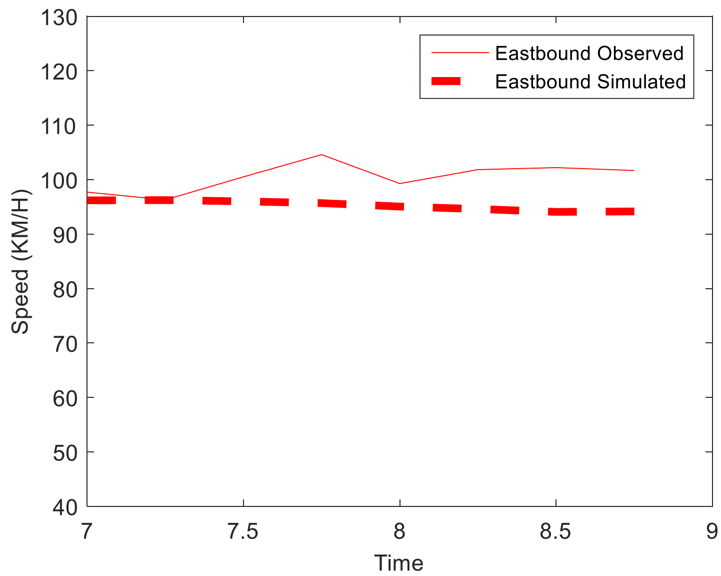


Figure 4 Observed VS Simulated speed on eastbound I66

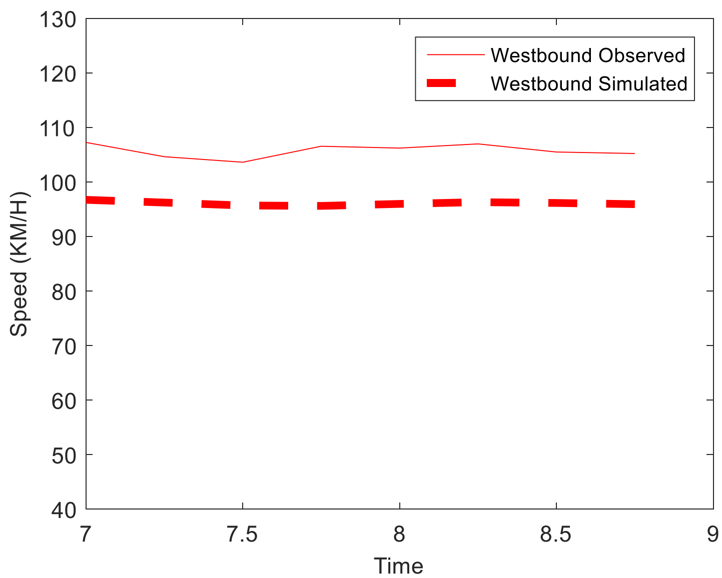


Figure 5 Observed VS Simulated speed on westbound I66

4.3 Experiment Design and Parameter Settings

Figure 6 shows the steps of this research. First network is coded from GIS file. Freeway speed limit, demand level and penetration rate are varied in the network to create different traffic scenarios. Using network-coding files, OD is calibrated with count data on major links. Both network settings and OD files are coded in simulation input files. By adding Eco-CACC in the simulation, three different controls are applied to the network, along with the base case without any control. T-test and comparison are implemented based on the simulation results from these four cases.

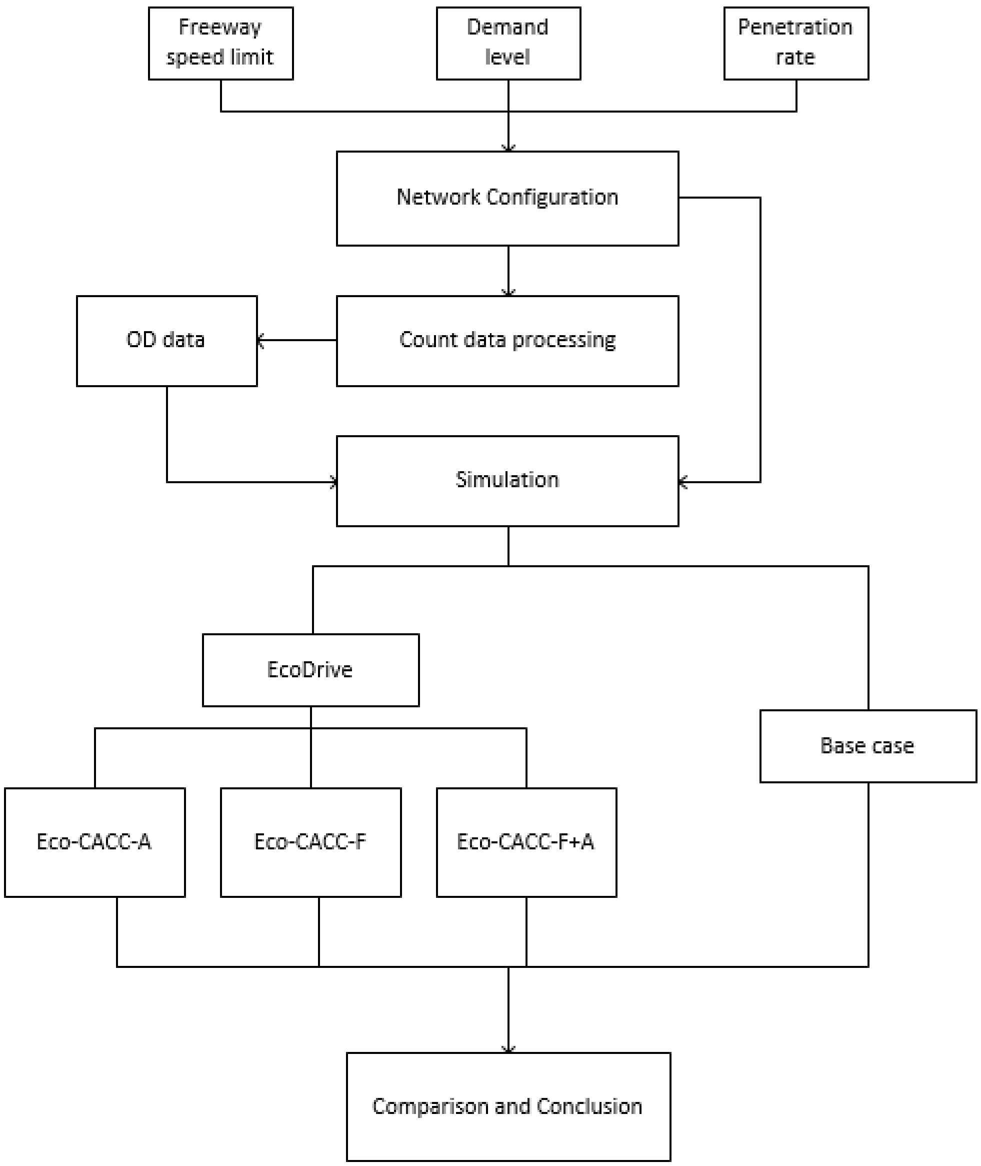


Figure 6 Research Logic

There are many researches proving that speed limit, demand level and penetration rate have great influence on fuel consumption and emission. Rilett and Benedek indicated that fuel consumption is "typically modeled as a function of speed", and the range of optimal speed is between 45 and 55 mph. Target speed, which is the objective set by the Eco-CACC system, is related to the speed limit of the link. In terms of OD, change of demand is directly related to fuel consumption [56]. It showed that higher demand ratio increases the CO emission from user CO emission equilibrium method, compared to system CO emission optimization [57]. Penetration rate also affects the performance of control strategies. Kamalanathsharma displayed in his paper that fuel consumption decreases sharply when penetration rate goes from 0.75 to 1 at 100% demand level [56]. Fuel consumption also keeps dropping with higher penetration rate when the demand level is 25%.

In the following chapter, to make sure that Eco-CACC-F control file will only take control on freeway, the lowest level of freeway speed limit in this thesis is defined as 57 mph (93 km/h), and five levels of freeway speed limit (57 mph, and 60 to 75 mph with increment of 5 mph) are varied. In addition, eight levels of OD scale (from 0.125 to 1 with increment 0.125), and six levels of penetration rate (from 0 to 1 with increment 0.2) will also be tested in the simulation. Overall, 19 different scenarios will be tested first in a base case scenario, where no Eco-CACC control strategies are used. The same set of the traffic scenarios will then be applied with the three Eco-CACC methods: Eco-CACC-A, Eco-CACC-F and combined eco-cruise control (Eco-CACC-F+A). To eliminate the stochastic influence from a single run of simulation, 10 random seeds are applied in each run, and average results will be compared. In total, 76 different simulations with different parameter settings and control methods times under 10 random seeds will be run.

APPENDIX shows the format and content of Eco-CACC control files. In the simulation, we define vehicle class 1 as controlled vehicle. For Eco-CACC-F control file, target speed is equal to speed limit along the freeway. Since the largest arterial freeway speed limit in this network is 90 km/h (56 mph), to ensure that Eco-CACC-F only works for freeway, speed threshold is set as 9 km/h for OD and penetration variation scenarios, and 2 km/h, 6 km/h, 10 km/h, 10 km/h, 10 km/h for five levels of freeway speed limit (details can be found in **Eco-CACC-F Control File for The Network (OD scale and Penetration Rate Scenarios)** and **Eco-CACC-F Control File for The Network (Freeway Speed Limit Scenarios)**).

Table 1 shows parameter design in this research. In the analysis on impact from freeway speed limit (section 5.1), freeway speed limit is set at 5 levels ranging from 57mph to 75 mph, while OD scale and penetration rate keep as 100%. In section 5.2 and 5.3, freeway speed limit is the same as the records along real-world road of this network, while OD scale and penetration rate are varied.

Table 1 Simulation parameter setting

Control	Freeway speed limit	Demand level	Penetration rate
4 cases: Eco-CACC-A Eco-CACC-F Eco-CACC-F+A Base	57 mph	1	1
	60 mph	1	1
	55 mph	1	1
	60 mph	1	1
	75 mph	1	1
	as recorded	0.125	1
	as recorded	0.25	1
	as recorded	0.375	1
	as recorded	0.5	1
	as recorded	0.625	1
	as recorded	0.75	1
	as recorded	0.875	1
	as recorded	1	1
	as recorded	1	0
	as recorded	1	0.2
	as recorded	1	0.4
	as recorded	1	0.6
	as recorded	1	0.8
	as recorded	1	1

CHAPTER 5 SIMULATION RESULTS

In this chapter, simulation results are illustrated. It should be noted that the y-axis value in the figures (**Figure 8**, **Figure 10, Figure 12**, **Figure 14**, **Figure 16**, **Figure 18**, **Figure 20**, **Figure 22** and **Figure 24**) in this chapter comes from percentage decrease/increase on MOEs from the base case to Eco-CACC cases.

5.1 Impact from Freeway Speed Limit

To analyze the difference between the base case and three Eco-CACC controls from statistical level, t-test is conducted and displayed in the **Table 2:**

Table 2 T-test for the influence of Eco-CACC controls under different freeway speed limits

Control	Freeway Speed limit (mph)	delay	fuel consumption	HC emission	CO emission	NO_x emission	CO_2 emission
		P value	P value	P value	P value	P value	P value
Eco-CACC-A	57	0.0000	0.0000	0.0001	0.0000	0.1718	0.0000
	60	0.0000	0.0000	0.2163	0.0000	0.9870	0.0000
	65	0.0000	0.0000	0.1333	0.0000	0.0023	0.0000
	70	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	75	0.0000	0.0000	0.0000	0.0000	0.0503	0.0000
Eco-CACC-F	57	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	60	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	70	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	75	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Eco-CACC-F+A	57	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	60	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	70	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	75	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

From **Table 2**, in most cases, all the three controls have significant difference to the base case on MOEs with change of freeway speed limit. Except for HC emission under Eco-CACC-A when freeway speed limit is 60 mph and 65 mph, and NO_x emission under Eco-CACC-A when freeway speed limit is 57 mph, 60 mph and 75 mph. Results from Tukey's HSD also support the output from t-test. It can also be noticed in the following analysis.

Table 3 and **Figure 7** illustrate the delays with change of freeway speed limit. With the increasing freeway speed limit, delay also increases. The slope of four lines in **Figure 7**, which indicates the increasing rate of delay when increasing one level of freeway speed limit, becomes especially greater when freeway speed limit is between 60mph and 70mph. The increasing rate then becomes smaller for the base case, Eco-CACC-A and Eco-CACC-F+A when freeway speed limit goes from 70mph to 75mph.

Table 3 Average total delay with change of freeway speed limit

Freeway speed limit	OD scale	Penetration rate	Delay (sec/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
57 mph	1	1	614.74	531.35	654.23	539.60
60 mph	1	1	598.42	529.48	628.89	559.91
65 mph	1	1	711.10	656.61	793.11	749.10
70 mph	1	1	833.16	898.79	948.58	976.23
75 mph	1	1	877.92	957.65	1091.04	1106.30

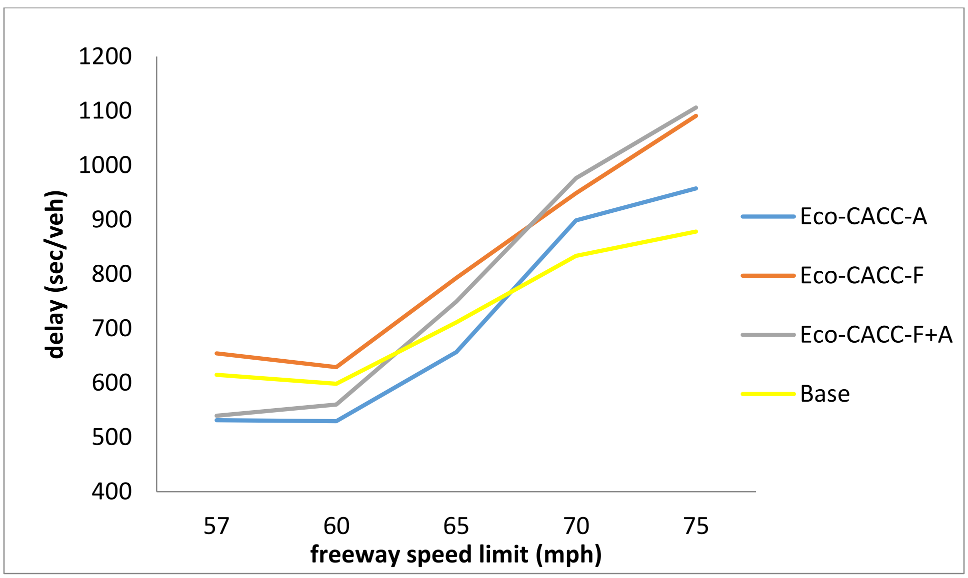


Figure 7 Average total delay with change of freeway speed limit

Figure 8 shows the percentage differences between three Eco-CACC controls and the base case. With the increase of freeway speed limit, delay under Eco-CACC methods becomes longer and worse than the base case. Eco-CACC-F always has longer delay than the base case across the board and the negative impact from Eco-CACC-F increases with the increase of freeway speed limit. Eco-CACC-F+A has shorter delay than the base case when freeway speed limit is smaller than 60 mph. It has a greater delay than the base case with freeway speed limit higher than 60 mph. The average delay under Eco-CACC-F+A becomes longer to the case of Eco-CACC-F in the range of higher speed limit (greater than 65 mph). Eco-CACC-A produces 10% to 15% shorter delay than the base case when freeway speed limit is lower than 65 mph, while it has negative influence (5% to 10% higher than the base case) on delay after freeway speed limit higher than 65 mph. The increasing trend of the negative influence from Eco-CACC-A slows down when freeway speed limit changes from 70 mph to 75 mph.

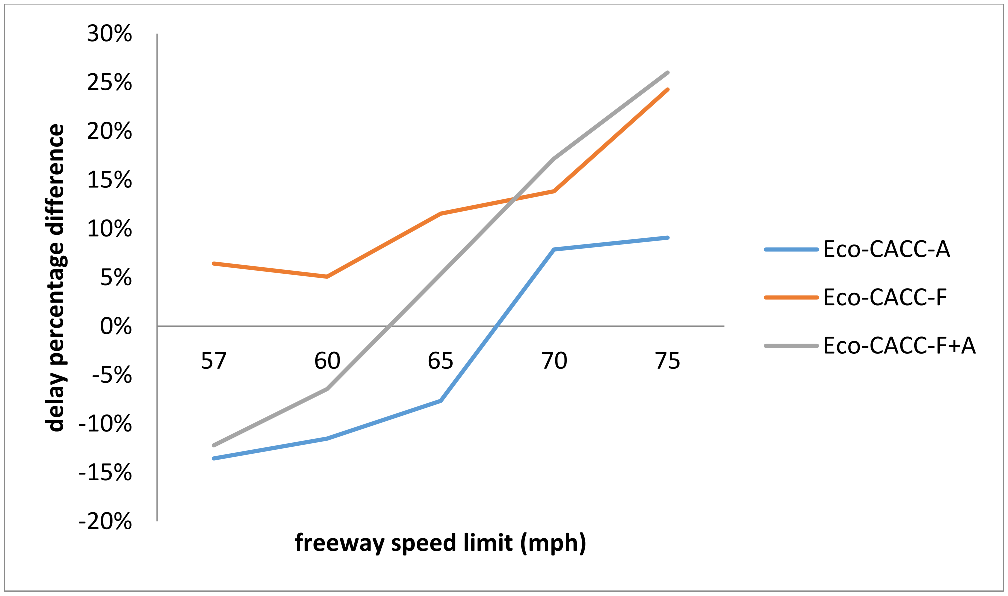


Figure 8 Influence from Eco-CACC to average total delay with change of freeway speed limit

Table 4 and **Figure 9** present the fuel consumption resulting from different cases. Though the increasing trend for four cases is similar, Eco-CACC-A and the base case obviously have larger slope, which means the fuel consumption from these two cases increases much faster than the other two when freeway speed limit increases. The fuel usage from Eco-CACC-A is slightly higher than the base case at higher speed limits when it is greater than 65 mph. Eco-CACC-F and Eco-CACC-F+A have similar result and both of them consume less amount of fuel than the base case.

Table 4 Fuel consumption with change of freeway speed limit

Freeway speed limit	OD scale	Penetration rate	Fuel consumption (l/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
57 mph	1	1	1.6722	1.6440	1.6502	1.6195
60 mph	1	1	1.7053	1.6780	1.6703	1.6414
65 mph	1	1	1.8069	1.7852	1.7551	1.7335
70 mph	1	1	1.9536	1.9939	1.8346	1.8490
75 mph	1	1	2.0945	2.1269	1.9135	1.9141

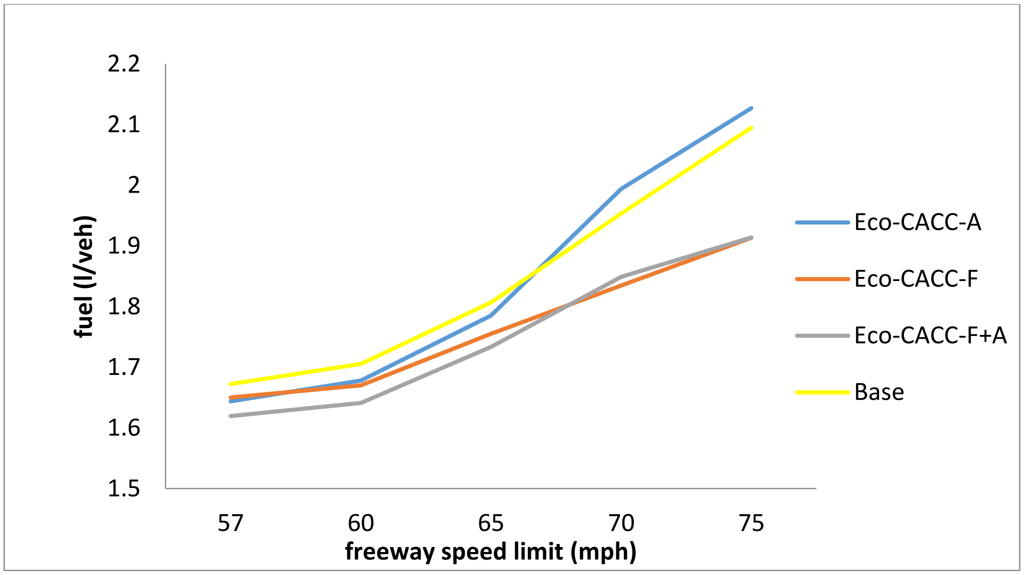


Figure 9 Fuel consumption with change of freeway speed limit

It can be seen from **Figure 10** that, with the increase of freeway speed limit, the difference between Eco-CACC-F/Eco-CACC-F+A and the base case becomes greater, which indicates that the positive effect from Eco-CACC-F and Eco-CACC-F+A is more significant when the speed limit is higher. However, for Eco-CACC-A, the difference between it and the base case is much smaller. When freeway speed limit is lower than 65 mph, Eco-CACC-A has around 2% less fuel consumption. However, it consumes more amount of fuel than the base case when freeway speed limit is greater than 65 mph.

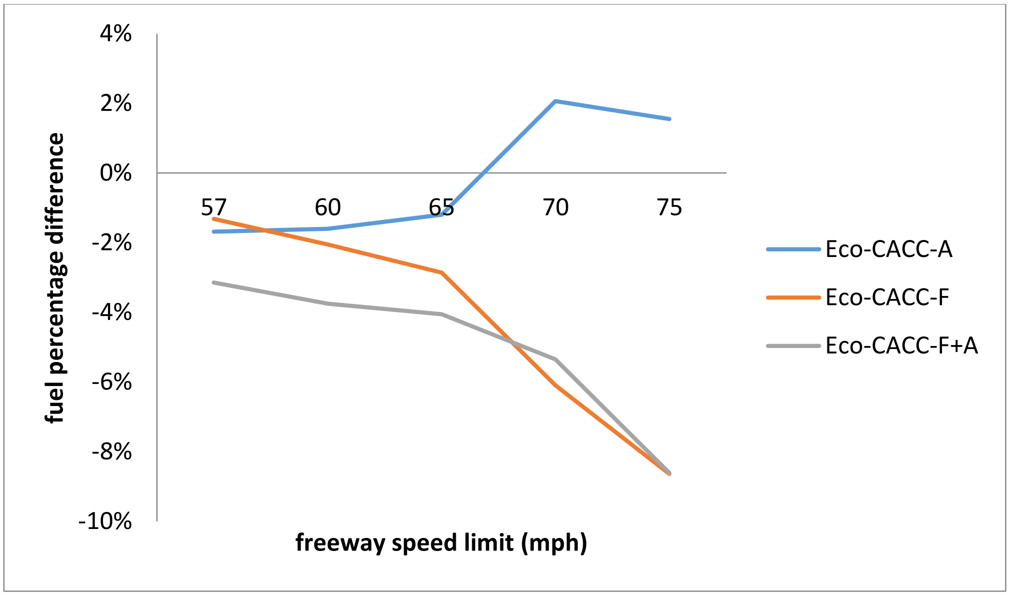


Figure 10 Influence from Eco-CACC to fuel consumption with change of freeway speed limit

Table 5 and **Figure 11** are the emissions that result from these four cases. For HC, CO and NO_x, increasing freeway speed limit causes higher emissions for all the four cases. Comparing among four cases, Eco-CACC-F and Eco-CACC-F+A have much smaller increasing rate than the base case and Eco-CACC-A, especially for HC and CO when freeway speed limit is higher than 65mph, and NO_x across the whole board. When freeway speed limit is greater than 65mph, the slope of the base case and Eco-CACC-A that indicates the increasing rate of emissions from one level change of freeway speed limit, increases on HC and CO emissions, while the increasing rate of Eco-CACC-F and Eco-CACC-F+A is constant with the growth of freeway speed limit. When freeway speed limit is 75mph, HC, CO and NO_x emissions from the base case and Eco-CACC-A is about 2 times of that from the other two controls. CO_2 has a similar increasing trend to fuel consumption due to linear relationship between them.

Table 5 HC, CO, NO_x and CO_2 emissions with change of freeway speed limit

(a) HC

Freeway speed limit	OD scale	Penetration rate	HC emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
57 mph	1	1	3.9669	3.9548	3.9159	3.8665
60 mph	1	1	4.5093	4.5051	4.3445	4.3418
65 mph	1	1	5.0959	5.1024	4.8695	4.8359
70 mph	1	1	6.0017	6.1367	5.2339	5.2965
75 mph	1	1	7.3354	7.4696	5.6445	5.5840

(b) CO

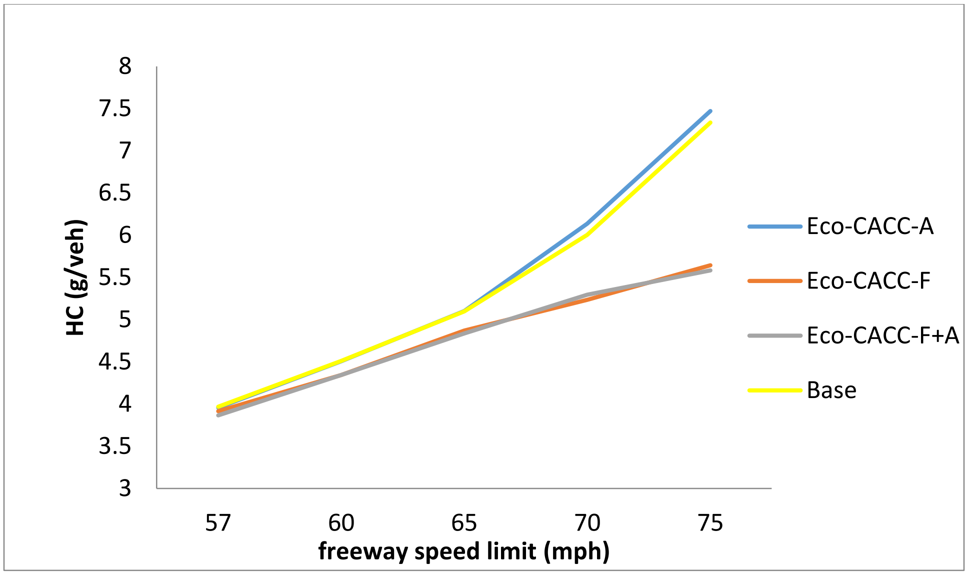
Freeway speed limit	OD scale	Penetration rate	CO emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
57 mph	1	1	90.38	90.78	89.30	89.30
60 mph	1	1	104.11	104.61	101.87	102.32
65 mph	1	1	118.73	119.32	115.13	114.25
70 mph	1	1	143.78	146.30	123.70	125.03
75 mph	1	1	183.33	186.15	133.82	131.97

(c) NO_x

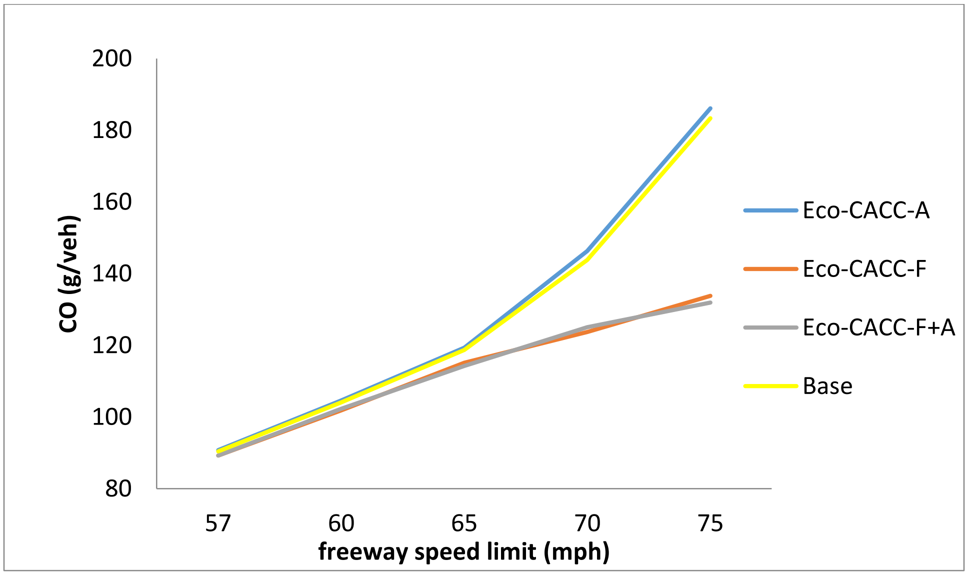
Freeway speed limit	OD scale	Penetration rate	NO_x emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
57 mph	1	1	3.8745	3.8715	3.7130	3.7028
60 mph	1	1	4.3385	4.3364	3.8301	3.8246
65 mph	1	1	4.8816	4.8854	3.9601	3.9396
70 mph	1	1	5.6353	5.6771	4.0590	4.0838
75 mph	1	1	6.4658	6.4722	4.1929	4.1833

(d) CO_2

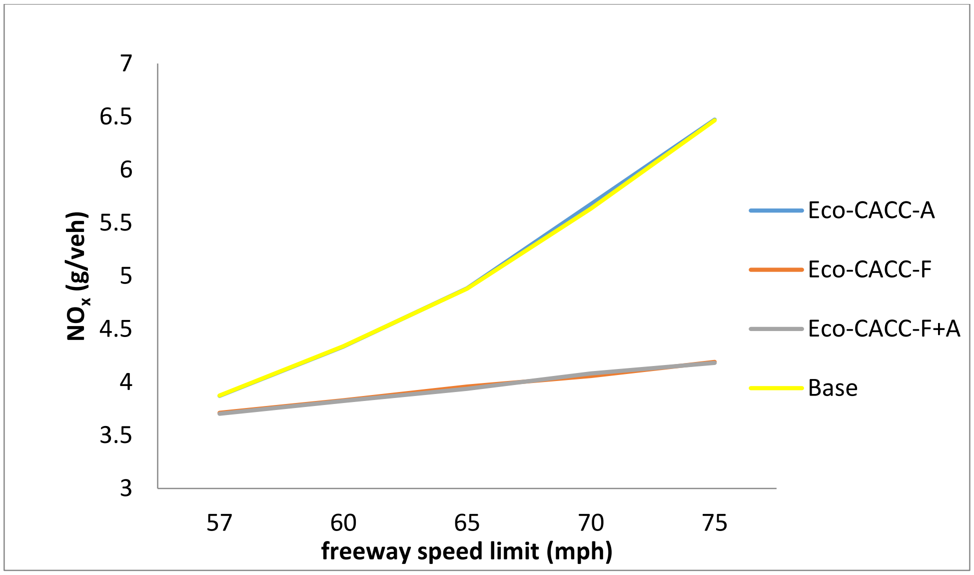
Freeway speed limit	OD scale	Penetration rate	CO_2 emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
57 mph	1	1	3766.56	3702.44	3716.40	3649.01
60 mph	1	1	3822.47	3760.88	3747.37	3681.16
65 mph	1	1	4031.22	3979.63	3924.75	3875.54
70 mph	1	1	4330.90	4419.83	4095.91	4127.17
75 mph	1	1	4601.90	4672.44	4261.11	4267.21


8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
HC (g/veh)
57
60
65
70
75
freeway speed limit (mph)
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A
Base

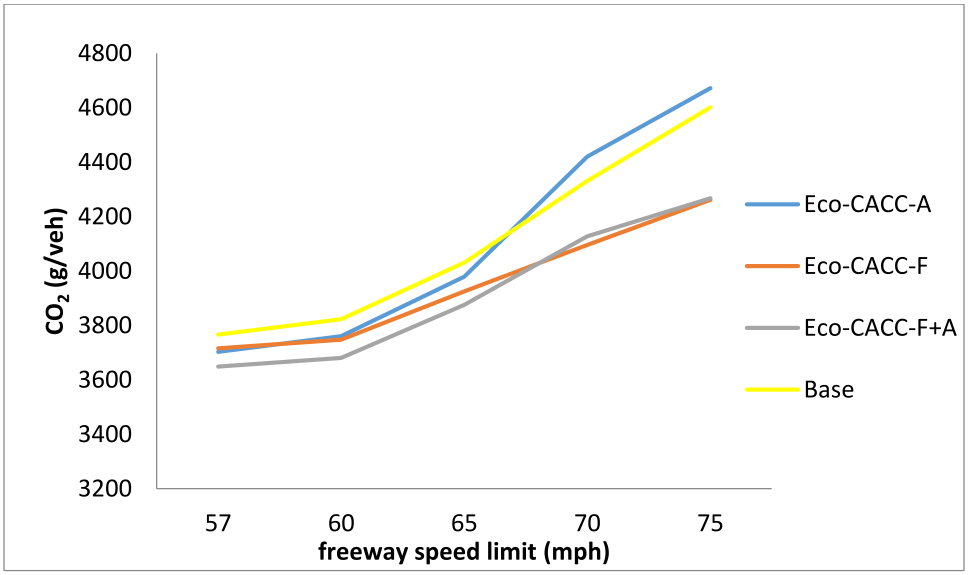
(a) HC


200
180
160
140
120
100
80
CO (g/veh)
57
60
65
70
75
freeway speed limit (mph)
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A
Base

(b) CO



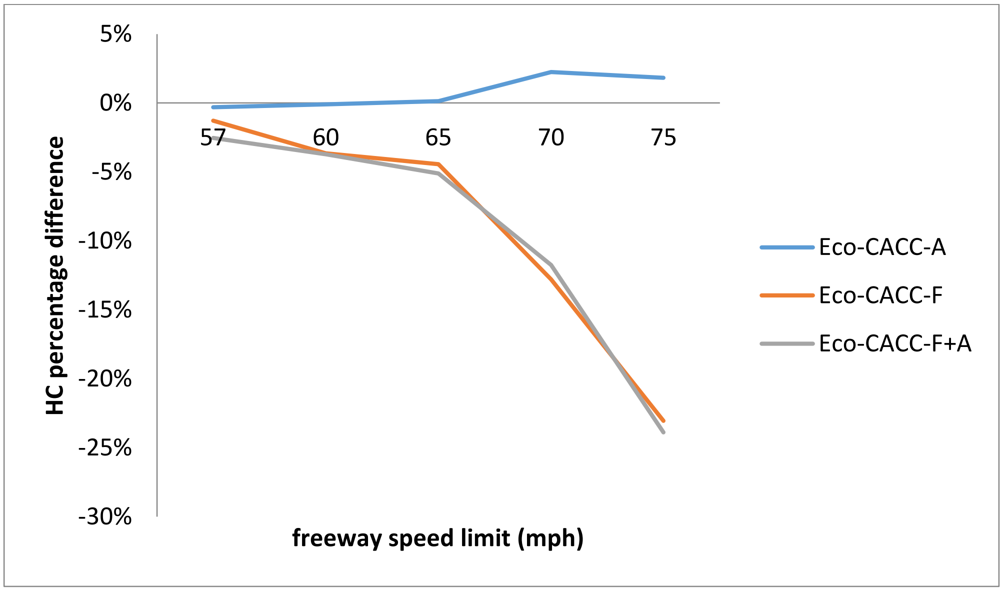
(c) NO_x



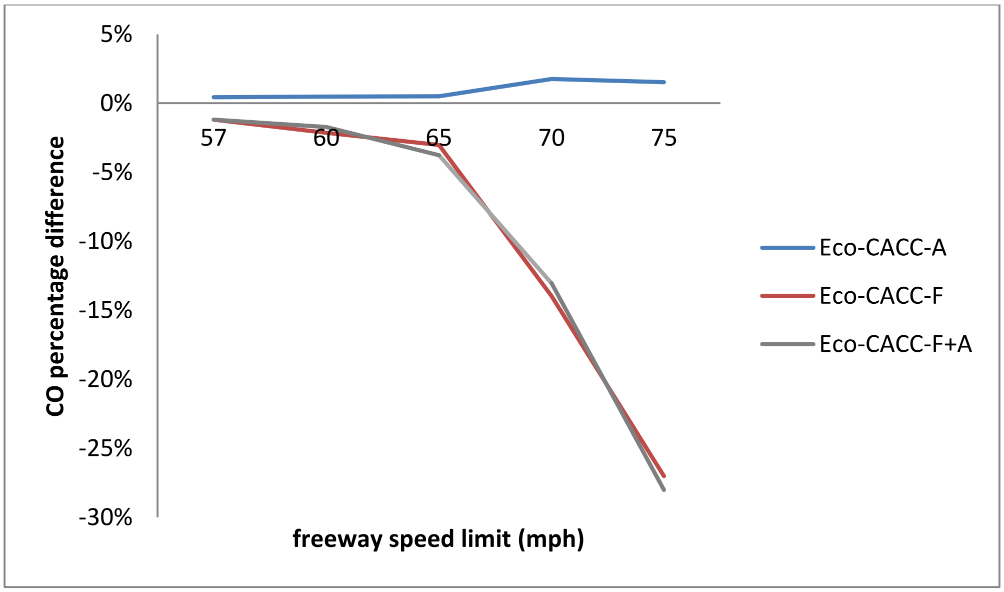
(d) CO_2

Figure 11 HC, CO, NO_x and CO_2 emissions with change of freeway speed limit

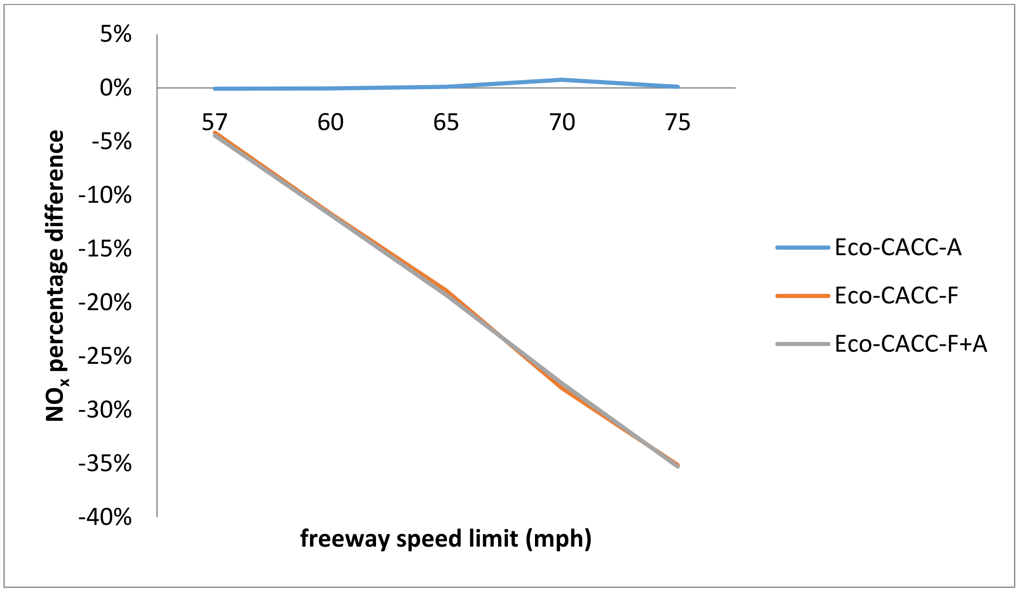
Figure 12 illustrates the percentage difference between the three controls versus the base case. It can be seen that Eco-CACC-F and Eco-CACC-F+A always produce less HC, CO and NO_x emissions than the base case. The improvements from these two controls are more significant at higher speed limits. When freeway speed limit is 75 mph, Eco-CACC-F and Eco-CACC-F+A lead to 23.5% less of HC, 27.5% less of CO and 35.2% less of NO_x than the base case. The influence from Eco-CACC-A is much smaller compared to the other two controls. And the performance of Eco-CACC-A on three emissions becomes worse with higher freeway speed limit.



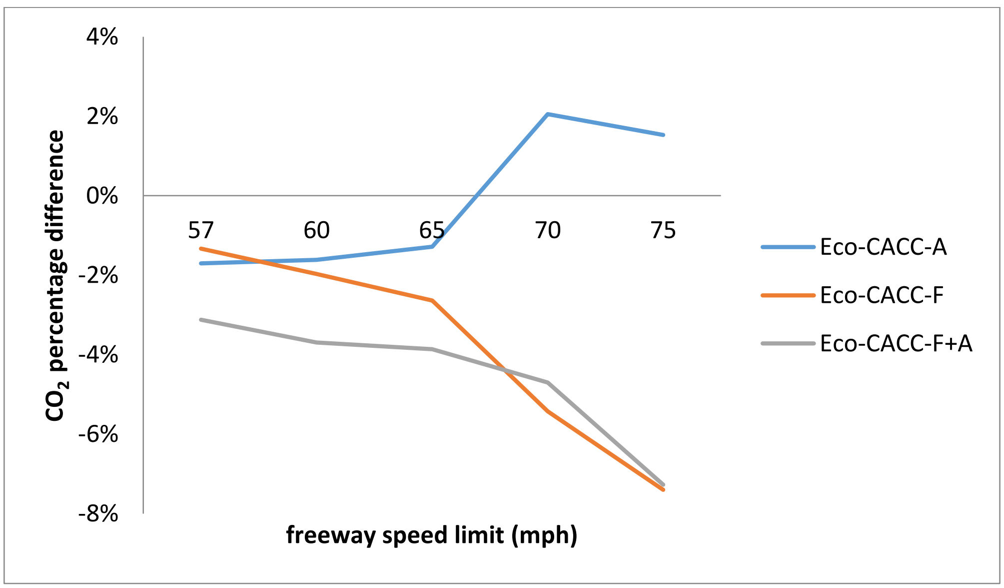
(a) HC



(b) CO



(c) NO_x



(d) CO_2

Figure 12 Influence from Eco-CACC to emissions with change of freeway speed limit

5.2 Impact from OD Scale

From **Table 6**, controls have significant difference to the base case under each level of OD scale, for almost all the MOEs. While when OD scale is 1, HC emission under Eco-CACC-A is not significantly different to that of base case, and it is same to NO_x under Eco-CACC-A with OD scale of 0.625 and 1. From Tukey's HSD, Eco-CACC-A also has similar mean to the base case under the scenarios described above.

Table 6 T-test for the influence of Eco-CACC controls under different OD scales

Control	OD scale	delay	fuel consumption	HC emission	CO emission	NO_x emission	CO_2 emission
		P value	P value	P value	P value	P value	P value
Eco-CACC-A	0.125	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.25	0.0000	0.0001	0.0000	0.0000	0.0160	0.0000
	0.375	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0000	0.0000	0.0000	0.0000	0.0204	0.0000
	0.625	0.0000	0.0000	0.0000	0.0000	0.2295	0.0000
	0.75	0.0000	0.0000	0.0000	0.0000	0.0016	0.0000
	0.875	0.0000	0.0000	0.0000	0.0000	0.0025	0.0000
	1	0.0000	0.0000	0.3466	0.0000	0.2605	0.0000
Eco-CACC-F	0.125	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.25	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.375	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.625	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.75	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.875	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Eco-CACC-F+A	0.125	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.25	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.375	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.625	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.75	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.875	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 7 and **Figure 13** illustrate the delays under the four cases with different demand level. As the demand level increases in the network, delay is growing up. In addition, the slope of the lines for each case is greater with higher demand level, indicating that the increasing rate for

delay from all the four cases becomes larger under heavier traffic load. It also indicates that the traffic changes from free-flow to a more congested condition when OD scale is higher than 0.625.

Table 7 Average total delay with change of OD scale

Freeway speed limit	OD scale	Penetration rate	Delay (sec/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	0.125	1	34.40	31.77	69.19	66.43
as recorded	0.25	1	38.87	36.83	73.25	70.98
as recorded	0.375	1	44.04	41.35	77.70	75.25
as recorded	0.5	1	60.76	58.17	93.44	90.91
as recorded	0.625	1	116.01	108.45	147.29	141.65
as recorded	0.75	1	233.36	198.65	259.32	233.77
as recorded	0.875	1	380.11	334.87	421.37	367.34
as recorded	1	1	589.25	546.50	624.73	579.11

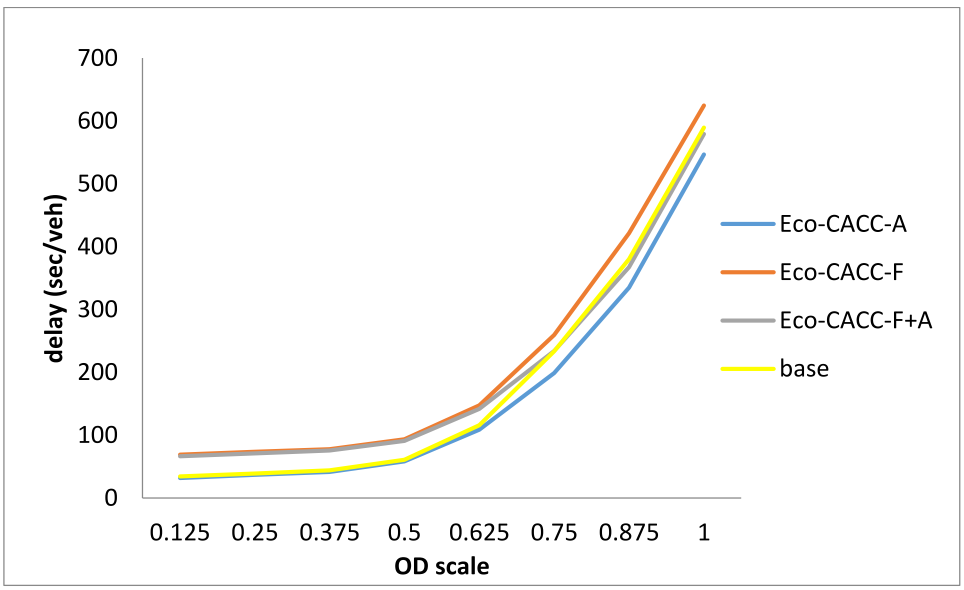


Figure 13 Average total delay with change of OD scale

Figure 14 shows how delay is influenced by Eco-CACC controls under different demand levels. The change of OD scale does not have influence on the percentage difference between Eco-CACC-A and the base case: Eco-CACC-A has a consistently smaller delay than the base case. Different demand levels have a great influence on the other two Eco-CACC controls. The percentage difference between them and the base case keeps decreasing dramatically with the growth of demand level. For Eco-CACC-F, when the network is less congested, it generates much longer delay than the base case. However, with the traffic becoming more congested, the negative effect from Eco-CACC-F on delay becomes smaller. The trend for Eco-CACC-F+A is similar to that of Eco-CACC-F, only that Eco-CACC-F+A produces less delay than the base case when OD scale is beyond 0.75.

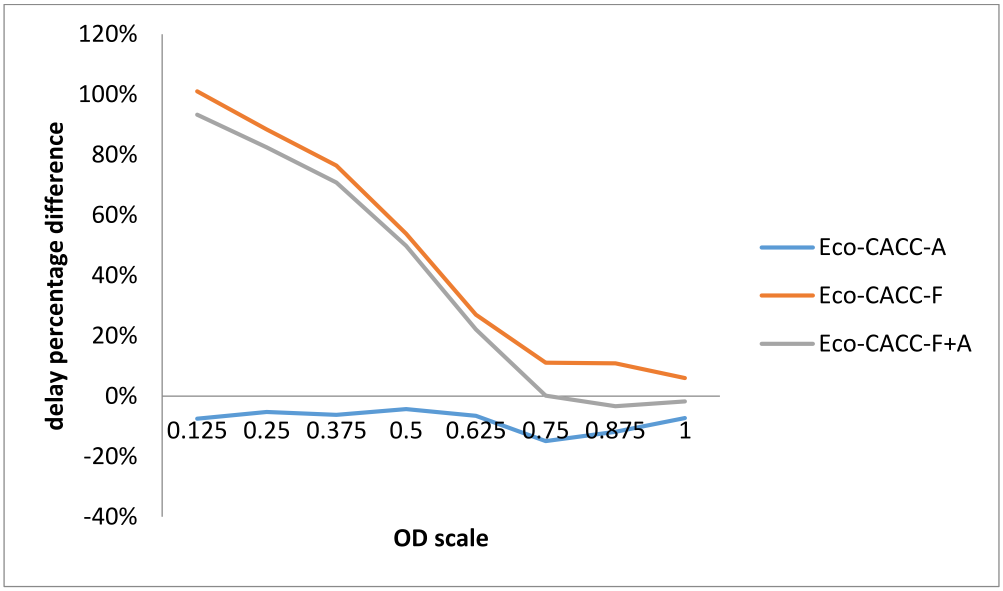


Figure 14 Influence from Eco-CACC on average total delay with change of OD scale

Table 8 and **Figure 15** show that fuel consumption increases with larger demand. Similar to delay, the increasing rate for all the four cases becomes higher with a more congested traffic condition (when OD scale is above 0.625). When comparing between the scenarios when OD scale is 0.125 and 1, Eco-CACC-F has the greatest increase on fuel consumption, which is 27.8%. Eco-CACC-A has the least increase on fuel usage, which is 25.4%.

Table 8 Fuel consumption with change of OD scale

Freeway speed limit	OD scale	Penetration rate	Fuel consumption (l/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	0.125	1	1.3937	1.3877	1.3421	1.3335
as recorded	0.25	1	1.4218	1.4183	1.3738	1.3687
as recorded	0.375	1	1.4349	1.4311	1.3878	1.3829
as recorded	0.5	1	1.4526	1.4491	1.4087	1.4050
as recorded	0.625	1	1.4929	1.4887	1.4510	1.4459
as recorded	0.75	1	1.5605	1.5418	1.5142	1.5052
as recorded	0.875	1	1.6432	1.6268	1.6009	1.5926
as recorded	1	1	1.7581	1.7403	1.7162	1.7044

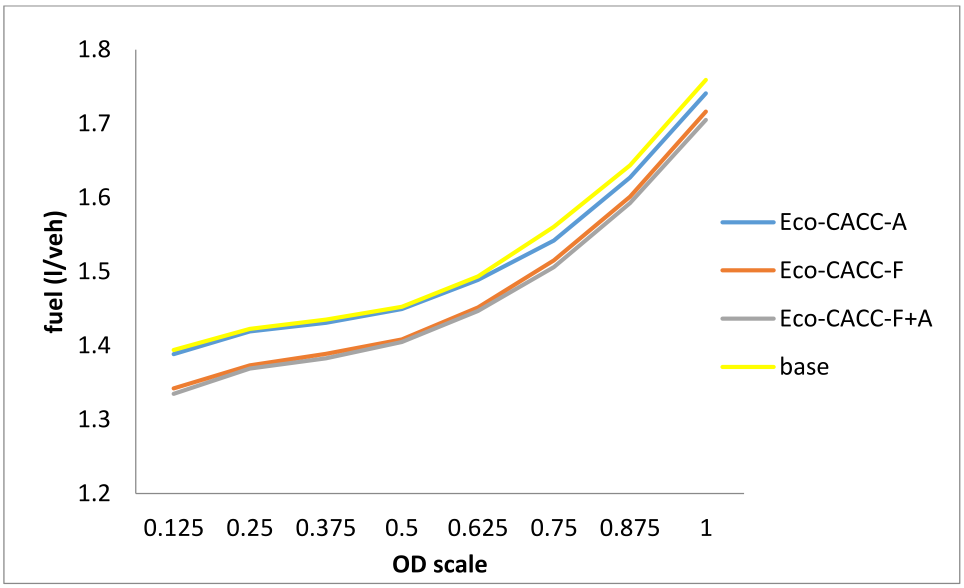


Figure 15 Fuel consumption with change of OD scale

Figure 16 shows the influence to fuel consumption by taking Eco-CACC controls. All of the three Eco-CACC controls improve fuel consumption, especially Eco-CACC-F+A. Applying Eco-CACC-F+A in the network can get the greatest benefit on fuel consumption, followed by Eco-CACC-F, which also generates a large positive effect to the fuel consumption. Meanwhile, the positive effect from Eco-CACC-F and Eco-CACC-F+A decreases with the growth of OD scale and Eco-CACC-F+A keeps relatively stable benefit when the network is congested (OD scale larger than 0.625). When the OD scale is 1, Eco-CACC-F leads to 2.3% less fuel consumption and

Eco-CACC-F+A saves 3.0% fuel consumption compared to the base case. Eco-CACC-A has a big jump for the improvement of fuel consumption when OD scale is beyond 0.625. When OD scale is 1, Eco-CACC-A produces 1% less of fuel consumption than the base case.

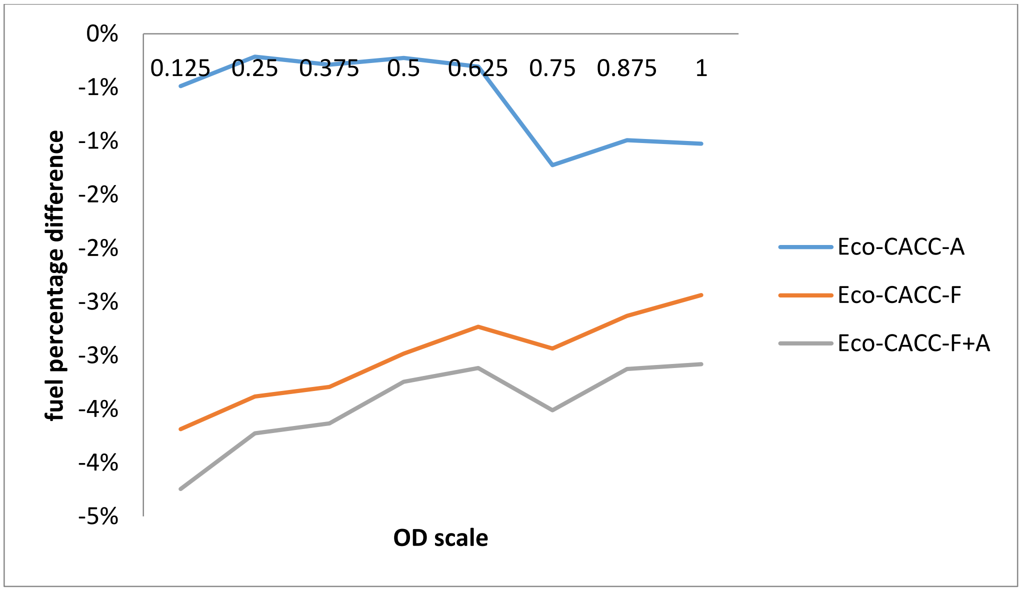


Figure 16 Influence from Eco-CACC to fuel consumption with change of OD scale

HC, CO, NO_x and CO_2 emissions are shown in **Table 9** and **Figure 17**. The increasing rate for HC, CO and NO_x is relatively constant with the increasing OD scale, compared to the other three MOEs. Moreover, the amount of emissions under Eco-CACC-A and the base case is obviously higher than the other two controls for every demand level.

Table 9 Emissions with change of OD scale

(a) HC

Freeway speed limit	OD scale	Penetration rate	HC emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	0.125	1	3.7929	3.7202	3.4075	3.3180
as recorded	0.25	1	3.9584	3.9377	3.6261	3.5865
as recorded	0.375	1	4.1041	4.0534	3.7984	3.7406
as recorded	0.5	1	4.2699	4.2366	4.0038	3.9662
as recorded	0.625	1	4.4584	4.4340	4.2295	4.1804
as recorded	0.75	1	4.7245	4.6600	4.4759	4.4421
as recorded	0.875	1	5.0025	5.0243	4.8068	4.8405
as recorded	1	1	5.3980	5.3990	5.1461	5.1780

(b) CO

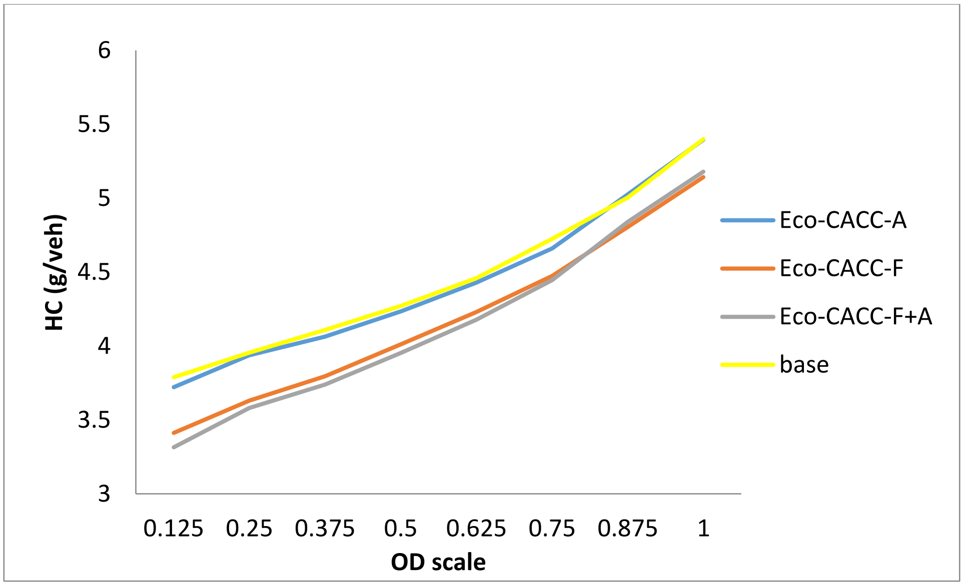
Freeway speed limit	OD scale	Penetration rate	CO emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	0.125	1	88.74	86.93	79.41	77.18
as recorded	0.25	1	93.00	92.45	85.27	84.10
as recorded	0.375	1	96.84	95.65	89.72	88.09
as recorded	0.5	1	101.31	100.39	95.24	94.03
as recorded	0.625	1	105.82	105.10	100.66	99.44
as recorded	0.75	1	111.55	110.42	106.19	105.56
as recorded	0.875	1	117.58	118.34	113.22	114.20
as recorded	1	1	125.60	126.10	119.82	121.40

(c) NO_x

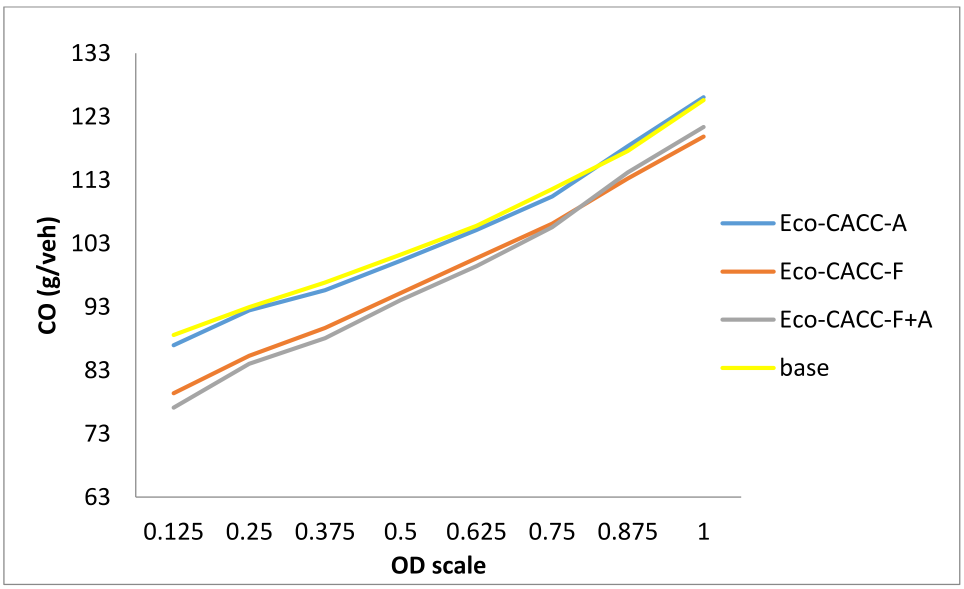
Freeway speed limit	OD scale	Penetration rate	NO_x emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	0.125	1	4.2388	4.2100	3.6477	3.6174
as recorded	0.25	1	4.3189	4.3070	3.7551	3.7422
as recorded	0.375	1	4.3638	4.3523	3.8172	3.7991
as recorded	0.5	1	4.4185	4.4061	3.8885	3.8805
as recorded	0.625	1	4.4979	4.4835	3.9851	3.9760
as recorded	0.75	1	4.5860	4.5631	4.0897	4.0782
as recorded	0.875	1	4.6923	4.7034	4.2267	4.2500
as recorded	1	1	4.7939	4.7917	4.3439	4.3538

(d) CO_2

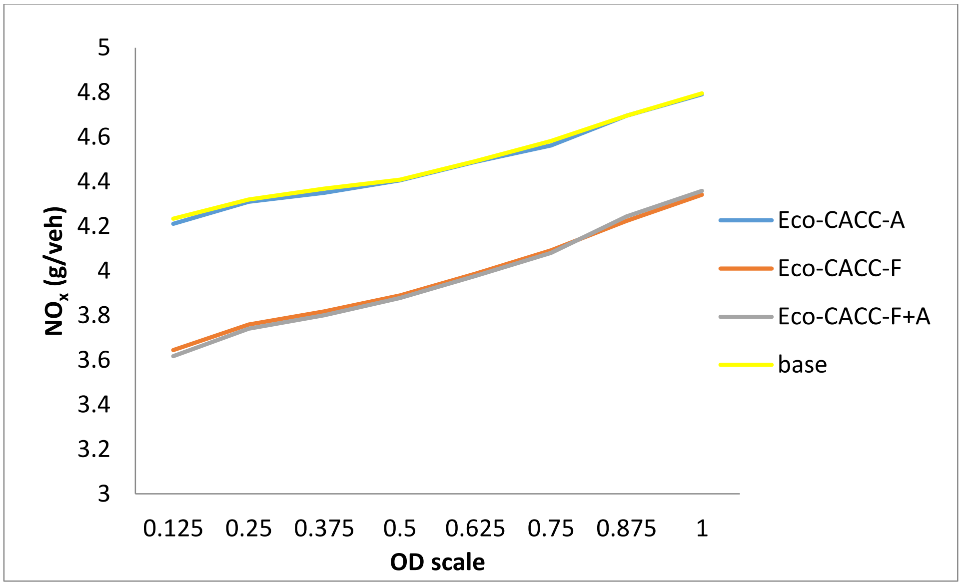
Freeway speed limit	OD scale	Penetration rate	CO_2 emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	0.125	1	3121.00	3109.56	3020.47	3007.18
as recorded	0.25	1	3180.47	3173.28	3085.09	3076.52
as recorded	0.375	1	3204.65	3197.50	3112.40	3103.56
as recorded	0.5	1	3238.59	3233.18	3151.43	3143.97
as recorded	0.625	1	3326.08	3316.75	3241.81	3231.70
as recorded	0.75	1	3474.00	3432.44	3382.07	3360.73
as recorded	0.875	1	3656.45	3617.44	3564.39	3547.11
as recorded	1	1	3910.32	3868.11	3815.44	3797.45


6
5.5
5
4.5
4
3.5
3
HC (g/veh)
0.125
0.25
0.375
0.5
0.625
0.75
0.875
1
OD scale
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A
base

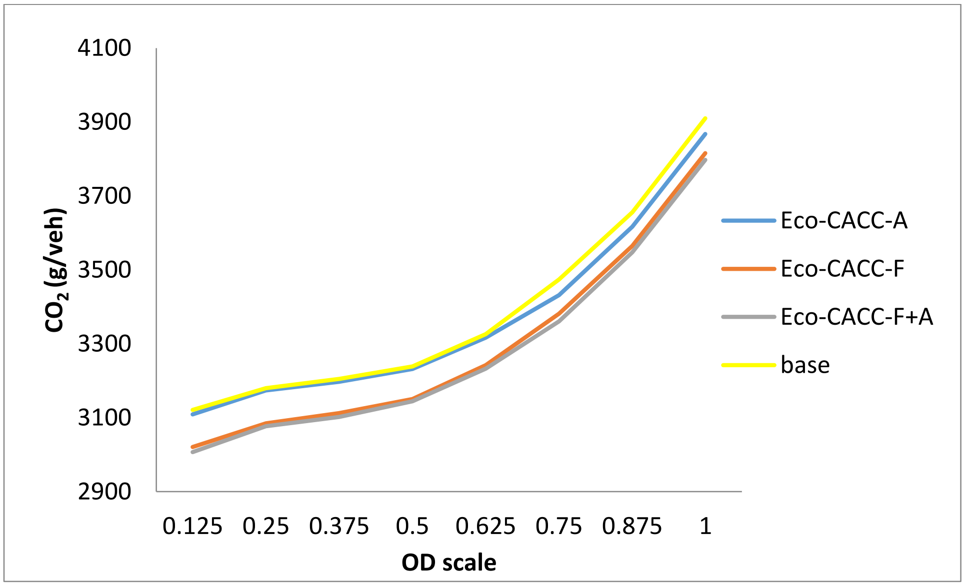
(a) HC


133
123
113
103
93
83
73
63
CO (g/veh)
0.125
0.25
0.375
0.5
0.625
0.75
0.875
1
OD scale
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A
base

(b) CO



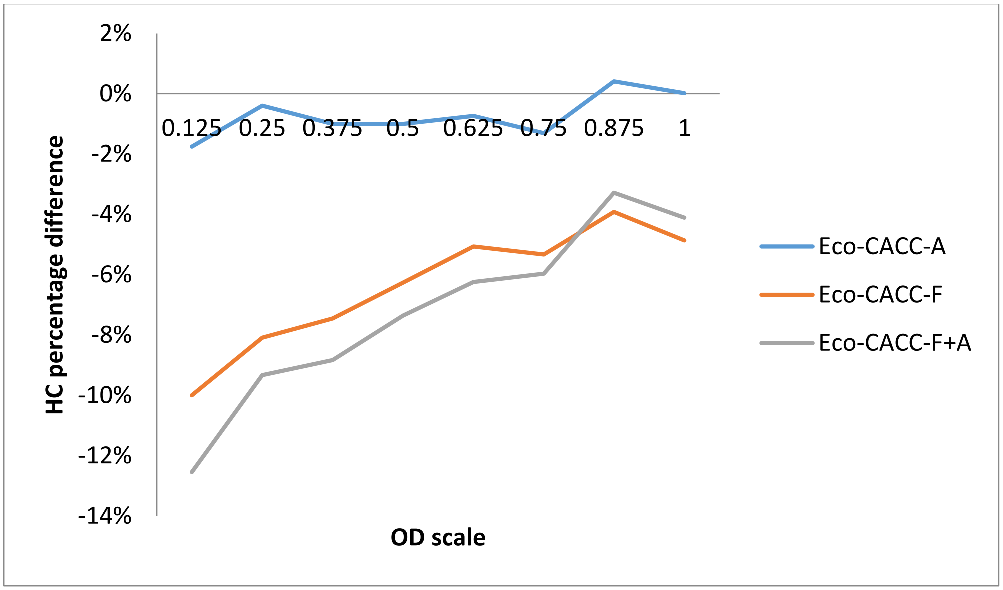
(c) NO_x



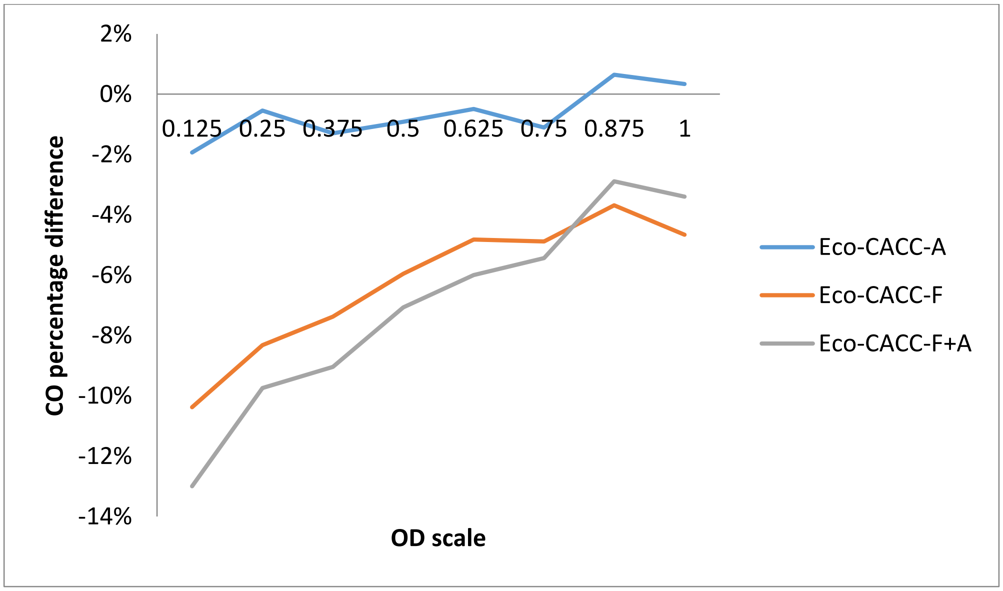
(d) CO_2

Figure 17 Emissions with change of OD scale

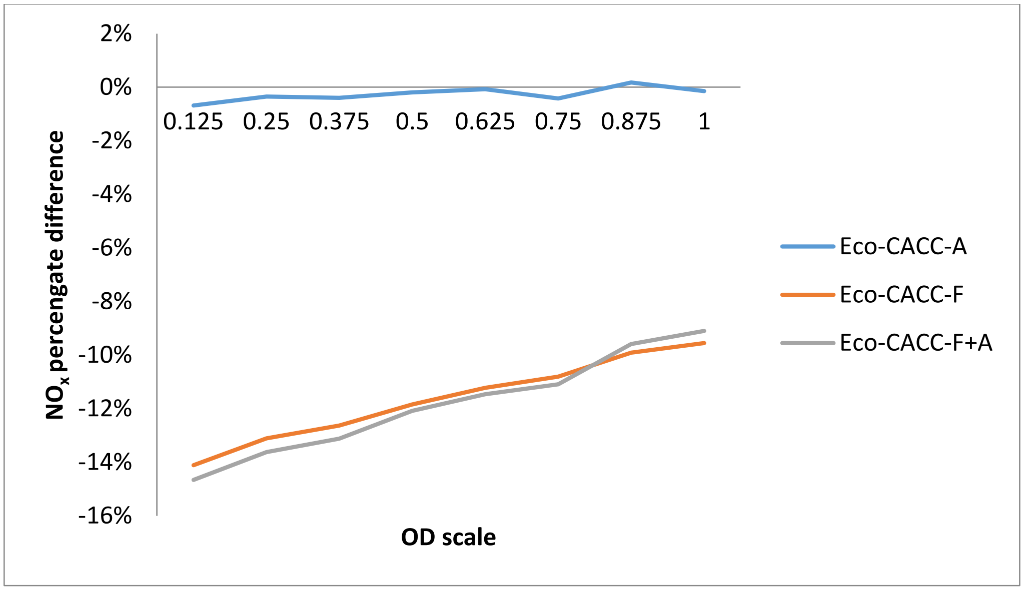
From **Figure 18**, it can be seen that when network is less congested, Eco-CACC-F and Eco-CACC-F+A have great benefits to emissions reduction. This advantage becomes less significant when the network becomes more congested, especially for the HC and CO emissions. When the scale goes beyond 0.875 to 1, benefit from these two controls slightly improves. When the OD scale increasing from 0.125 to 1, the percentage of HC emission reduction from Eco-CACC-F changes from 10.1% to 4.7%, and from 10.5% to 4.6% for CO. Similar change occurs on Eco-CACC-F+A as well. On average, the percentage of reduction on HC and CO emissions from these two controls change from 11.3% to 4.4% and 11.8% to 4.0% respectively when the scaling factor grows from 0.125 to 1. For NO_x, the percentage reduction from Eco-CACC-F and Eco-CACC-F+A also decrease from 14.3% to 9.3%. However, Eco-CACC-A has relatively much smaller positive effect to the three emissions than the other two control cases.


2%
0%
-2%
-4%
-6%
-8%
-10%
-12%
-14%
HC percentage difference
0.125
0.25
0.375
0.5
0.625
0.75
0.875
1
OD scale
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A

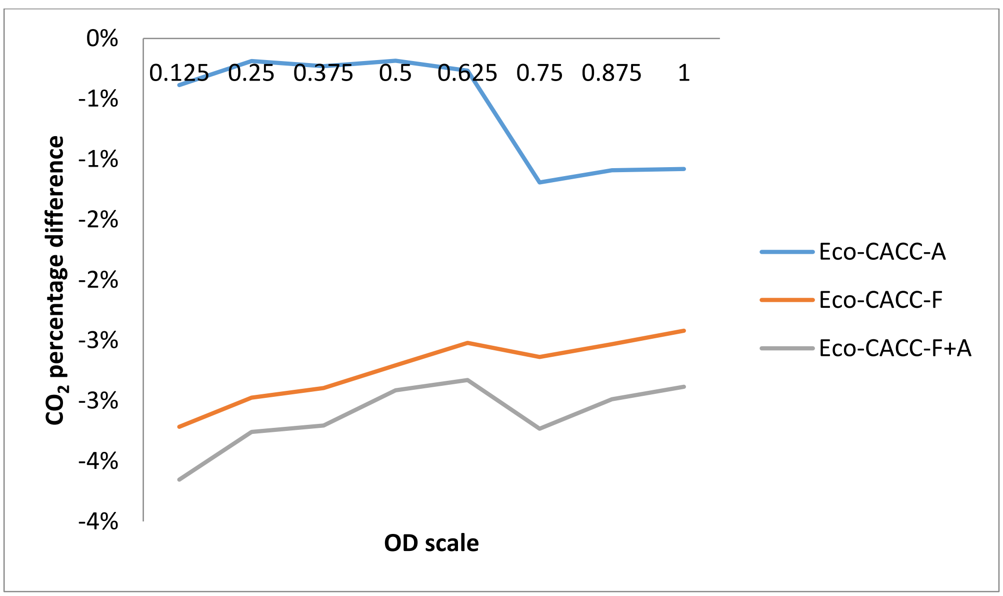
(a) HC


2%
0%
-2%
-4%
-6%
-8%
-10%
-12%
-14%
CO percentage difference
0.125
0.25
0.375
0.5
0.625
0.75
0.875
1
OD scale
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A

(b) CO



(c) NO_x



(d) CO_2

Figure 18 Influence from Eco-CACC to emissions with change of OD scale

5.3 Impact from Market Penetration Rate

In this section, influences from different penetration rate are displayed. In the simulation, penetration rate is controlled by assigning different proportions to the class of vehicles being controlled, and the randomness for each class of vehicle is different in INTEGRATION. Because of it, MOE value of the base case in this section also changes with different penetration rate though no control is applied in this case.

Table 10 shows the result from t-test. Three Eco-CACC controls start to have significantly different results to the base case once the guidance information has been assigned to the network., except for fuel consumption under Eco-CACC-F with penetration rate of 0.2, and HC emission under this control when the rate is 0.6. The result from Tukey's HSD is the same to t-test.

Table 10 T-test for the influence of Eco-CACC controls under different penetration rates

Control	Penetration Rate	delay	fuel consumption	HC emission	CO emission	NO_x emission	CO_2 emission
		P value	P value	P value	P value	P value	P value
Eco-CACC-A	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	0.2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.8	0.0000	0.0067	0.0000	0.0000	0.0000	0.0000
	1	0.0000	0.0000	0.0000	0.0000	0.0262	0.0000
Eco-CACC-F	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	0.2	0.0000	0.1178	0.0000	0.0000	0.0000	0.0014
	0.4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.6	0.0000	0.0000	0.7206	0.0006	0.0000	0.0000
	0.8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Eco-CACC-F+A	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	0.2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Average total delay from the four cases under different Eco-CACC penetration rate is displayed in **Table 11** and **Figure 19**. Penetration rate does not bring much influence on delays from Eco-CACC-F. For Eco-CACC-F+A, it shows a decreasing of delay when the penetrate rate goes up from 0.2 to 1. And for Eco-CACC-A, delay has an obvious drop when penetration rate increases from 0.8 to 1.

Table 11 Average total delay with change of penetration rate

Freeway speed limit	OD scale	Penetration rate	Delay (sec/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	1	0	589.25	589.26	589.25	589.25
as recorded	1	0.2	589.07	593.29	611.42	627.97
as recorded	1	0.4	610.63	616.34	600.98	620.03
as recorded	1	0.6	612.79	610.57	628.48	597.31
as recorded	1	0.8	604.51	604.97	619.57	598.29
as recorded	1	1	626.61	546.40	620.97	579.12

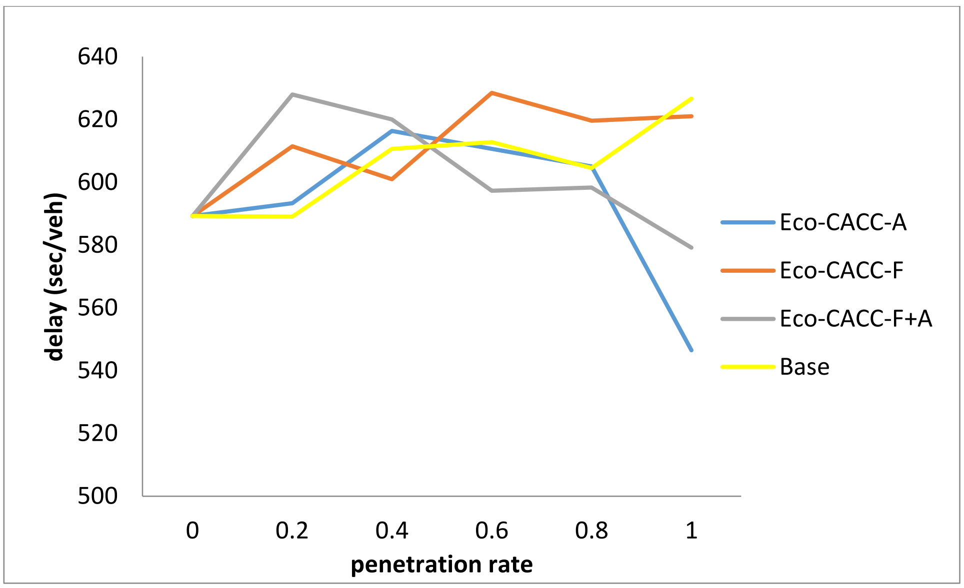


Figure 19 Average total delay with change of penetration rate

From **Figure 20**, it is clear that applying Eco-CACC-F to network does not have much impact on delay. The difference between Eco-CACC-F and the base case on delay fluctuates with change of penetration rate, and does not show an obvious increasing/decreasing trend like the other two controls. Eco-CACC-A starts to have a dramatic decrease on delay when penetration rate grows from 0.8 to 1, while before that, this control does not have significant benefit on delay. Eco-CACC-F+A does not have improvement on delay when the market penetration rate is low.

However, when penetration rate goes higher than 0.4, positive effect from Eco-CACC-F+A can be noticed and the benefit becomes greater with the increase of penetration rate.

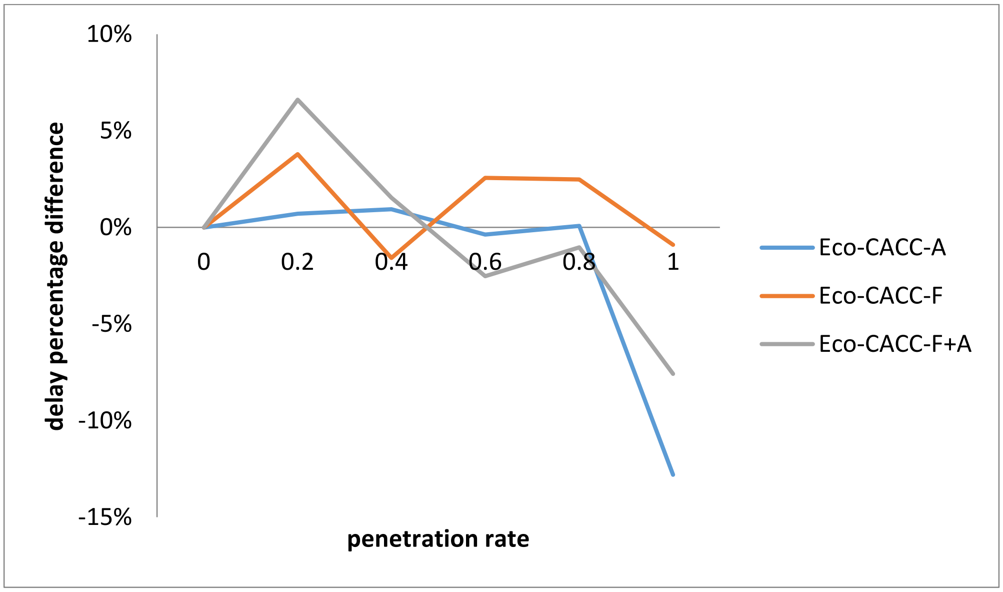


Figure 20 Influence from Eco-CACC to average total delay with change of penetration rate

As can be seen from **Table 12** and **Figure 21**, Eco-CACC has a continuously decreasing amount of fuel usage with higher penetration rate. Eco-CACC-A starts to decrease fuel consumption when penetration rate is greater than 0.4. For Eco-CACC-F+A, fuel consumption keeps dropping with the increase of the penetration rate starting from 0.2. Fuel consumption decreases for 2.3% from Eco-CACC-F when penetration rate goes from 0 to 1 and 3.0% for Eco-CACC-F+A. When penetration rate is greater than 0.6, Eco-CACC-F+A has a better performance on energy saving than Eco-CACC-F.

Table 12 Fuel consumption with change of penetration rate

Freeway speed limit	OD scale	Penetration rate	Fuel consumption (l/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	1	0	1.7576	1.7582	1.7584	1.7577
as recorded	1	0.2	1.7546	1.7646	1.7563	1.7791
as recorded	1	0.4	1.7689	1.7779	1.7471	1.7584
as recorded	1	0.6	1.7671	1.7637	1.7415	1.7369
as recorded	1	0.8	1.7613	1.7597	1.7318	1.7234
as recorded	1	1	1.7731	1.7403	1.7176	1.7051

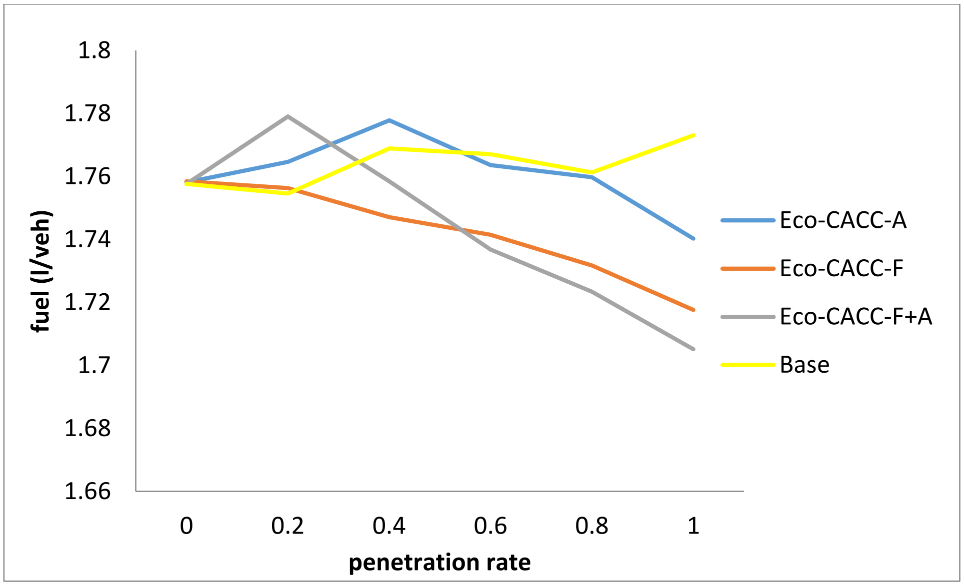


Figure 21 Fuel consumption with change of penetration rate

Figure 22 shows the difference of fuel consumption between Eco-CACC controls and the base case. With the increase of percentage of vehicles that follow Eco-CACC guidance, the amount of fuel saving becomes greater with all three ECO-CACC controls. For Eco-CACC-F+A, increasing penetration rate results in a significantly better performance than base case when the rate is greater than 0.4. In addition, Eco-CACC-F starts to have obvious positive effect on fuel consumption when penetration rate is greater than 0.2. When penetration rate is 1, Eco-CACC-F saves 3.1% and Eco-CACC-F+A saves 3.8% of fuel usage compared to the base case. When only taking control on arterial, fuel consumption does not have a significant benefit compared to the base case until the penetration rate goes beyond 0.6.

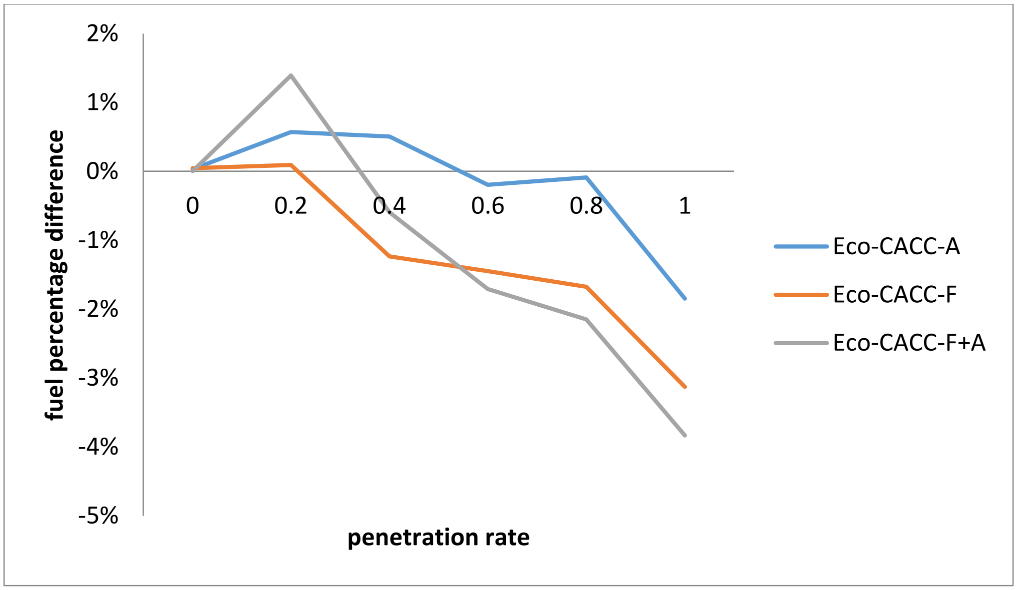


Figure 22 Influence from Eco-CACC to fuel consumption with change of penetration rate

Table 13 and **Figure 23** show how the amount of emissions changes with the growth of penetration rate. CO_2 has the same trend as fuel consumption based on their linear relationships. HC and CO emissions increase when the market penetration rate is low under Eco-CACC-F and Eco-CACC-F+A control. However, HC and CO emissions from Eco-CACC-F start to decrease when penetration rate is above 0.2, and this changing point for Eco-CACC-F+A is 0.4. Comparing the emission between the scenario when penetration rate is 0 and 1, HC and CO emissions for Eco-CACC-F drop down for 5.3% and 5.2% separately, and for Eco-CACC-F+A, HC decreases by 4.1% and CO decreases by 3.4%. For NO_x, Eco-CACC-F and Eco-CACC-F+A lead to an obvious continuous drop with the growing of the penetration rate. Compared to the condition when penetration rate is 0 and 1, Eco-CACC-F and Eco-CACC-F+A lead to around 9% decrease on NO_x emission. For Eco-CACC-A, the amount of HC, CO and NO_x emissions first increases with the growth of penetration rate. When the rate is greater than 0.6, this control decreases HC and CO emission, and this turning point for NO_x is 0.4. However, increasing penetration rate does not have benefit to these emissions under Eco-CACC-A, compared to the scenario when no vehicle receives control message.

Table 13 Emissions with change of penetration rate

(a) HC

Freeway speed limit	OD scale	Penetration rate	HC emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	1	0	5.3963	5.3968	5.3975	5.4013
as recorded	1	0.2	5.3605	5.4743	5.4798	5.5733
as recorded	1	0.4	5.4206	5.5321	5.4590	5.5960
as recorded	1	0.6	5.3874	5.5265	5.3889	5.4774
as recorded	1	0.8	5.3518	5.4617	5.2970	5.3183
as recorded	1	1	5.3582	5.3993	5.1114	5.1801

(b) CO

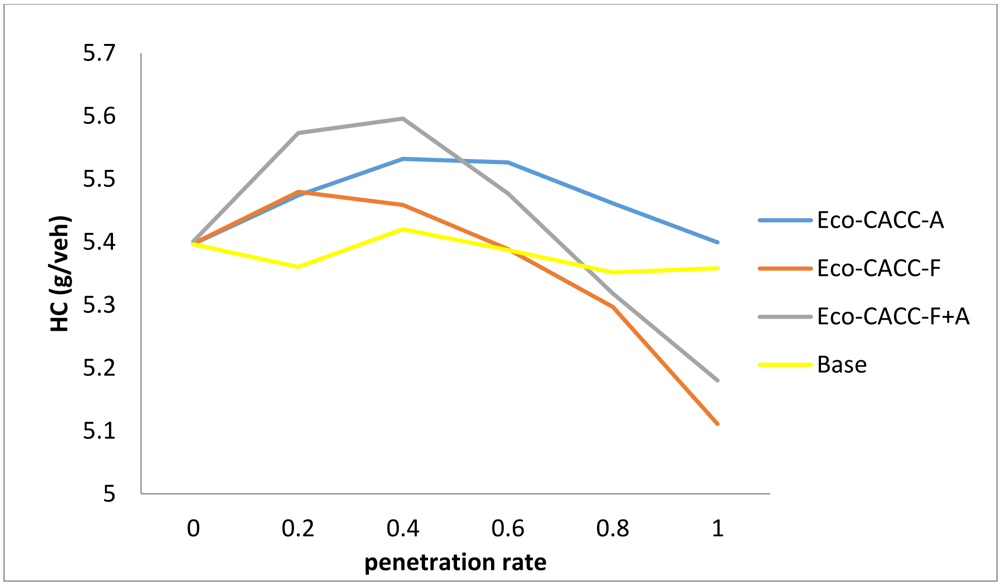
Freeway speed limit	OD scale	Penetration rate	CO emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	1	0	125.59	125.63	125.62	125.60
as recorded	1	0.2	124.57	127.66	128.60	130.93
as recorded	1	0.4	126.00	129.05	128.28	131.81
as recorded	1	0.6	125.24	129.04	125.43	129.13
as recorded	1	0.8	124.42	127.26	123.31	124.81
as recorded	1	1	123.98	126.07	119.12	121.37

(c) NO_x

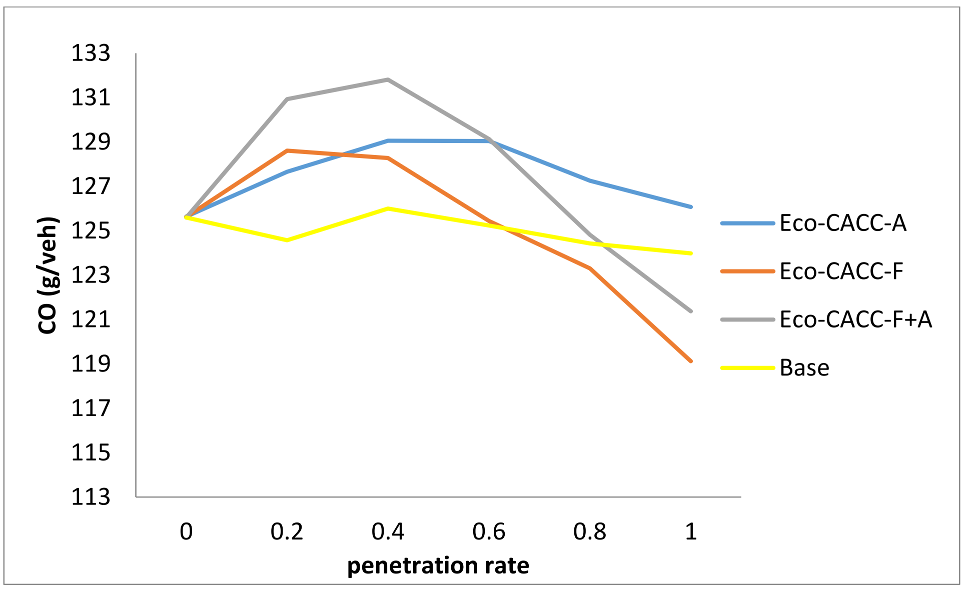
Freeway speed limit	OD scale	Penetration rate	NO_x emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	1	0	4.7943	4.7946	4.7974	4.7978
as recorded	1	0.2	4.7818	4.8215	4.6491	4.6927
as recorded	1	0.4	4.8057	4.8468	4.5536	4.6085
as recorded	1	0.6	4.7987	4.8367	4.4637	4.5082
as recorded	1	0.8	4.7818	4.8234	4.4190	4.4365
as recorded	1	1	4.7931	4.7947	4.3392	4.3605

(d) CO_2

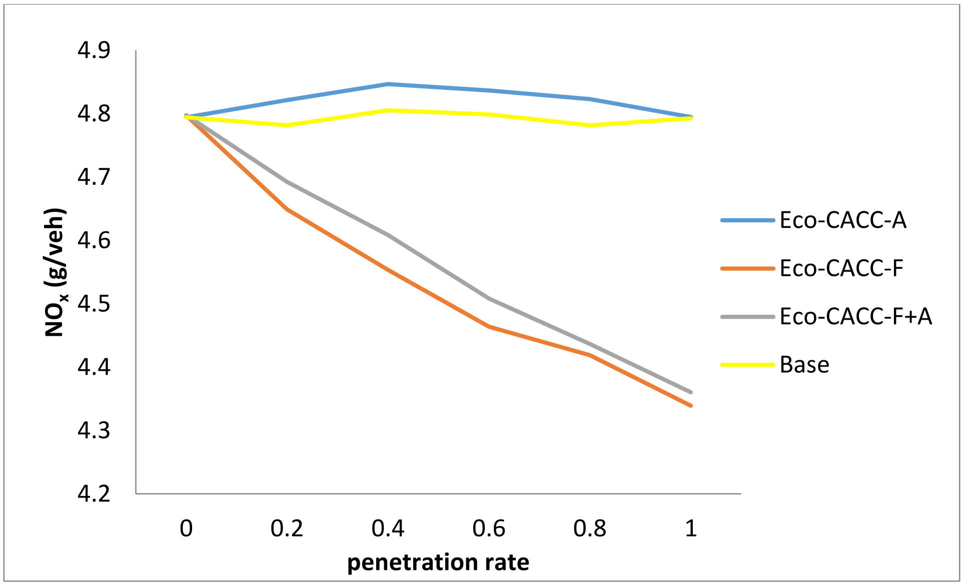
Freeway speed limit	OD scale	Penetration rate	CO_2 emission (g/veh)			
			Base	Eco-CACC-A	Eco-CACC-F	Eco-CACC-F+A
as recorded	1	0	3910.51	3909.75	3909.76	3910.45
as recorded	1	0.2	3904.04	3922.18	3901.90	3952.17
as recorded	1	0.4	3933.93	3950.54	3888.66	3904.03
as recorded	1	0.6	3931.62	3921.50	3874.91	3858.43
as recorded	1	0.8	3919.20	3912.51	3855.05	3834.83
as recorded	1	1	3946.28	3868.22	3829.78	3797.32


5.7
5.6
5.5
5.4
5.3
5.2
5.1
5
HC (g/veh)
0
0.2
0.4
0.6
0.8
1
penetration rate
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A
Base

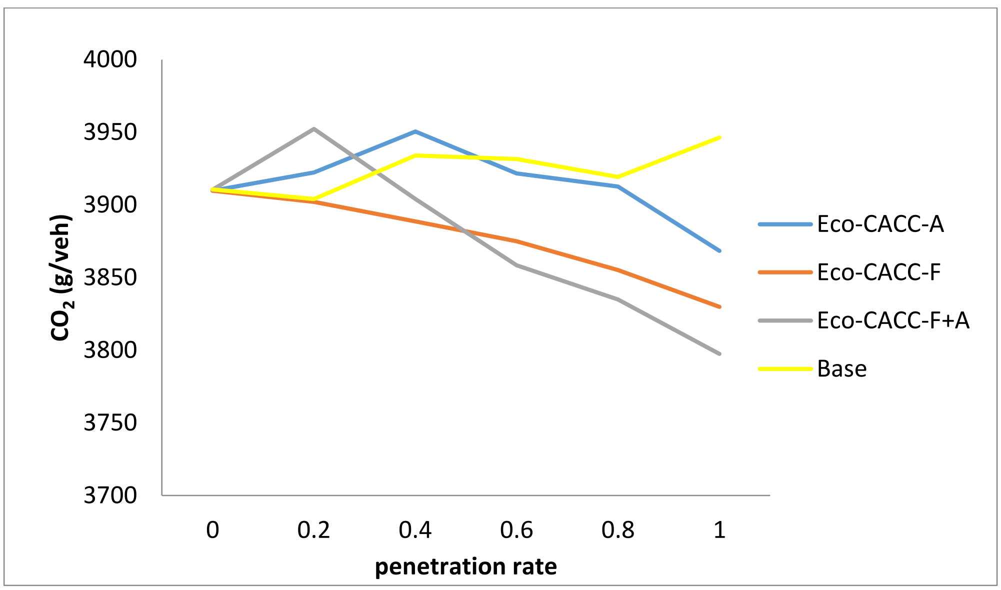
(a) HC


133
131
129
127
125
123
121
119
117
115
113
CO (g/veh)
0
0.2
0.4
0.6
0.8
1
penetration rate
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A
Base

(b) CO



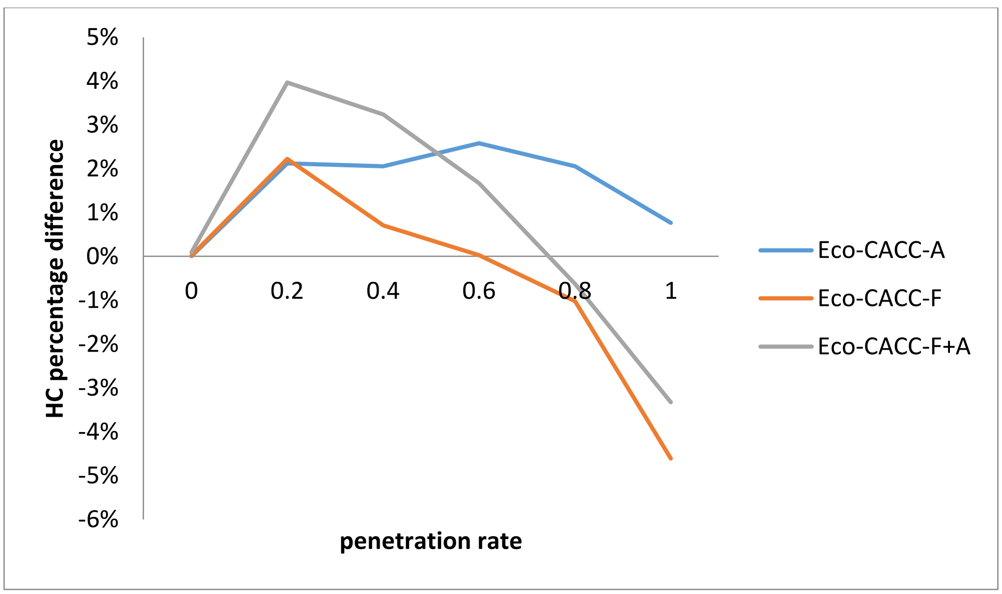
(c) NO_x



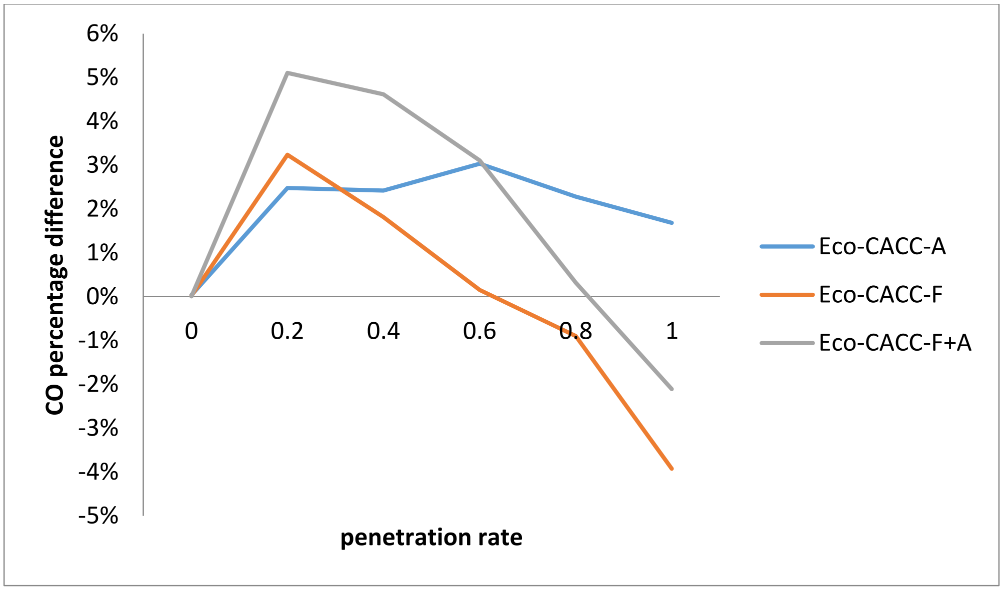
(d) CO_2

Figure 23 Emissions with change of penetration rate

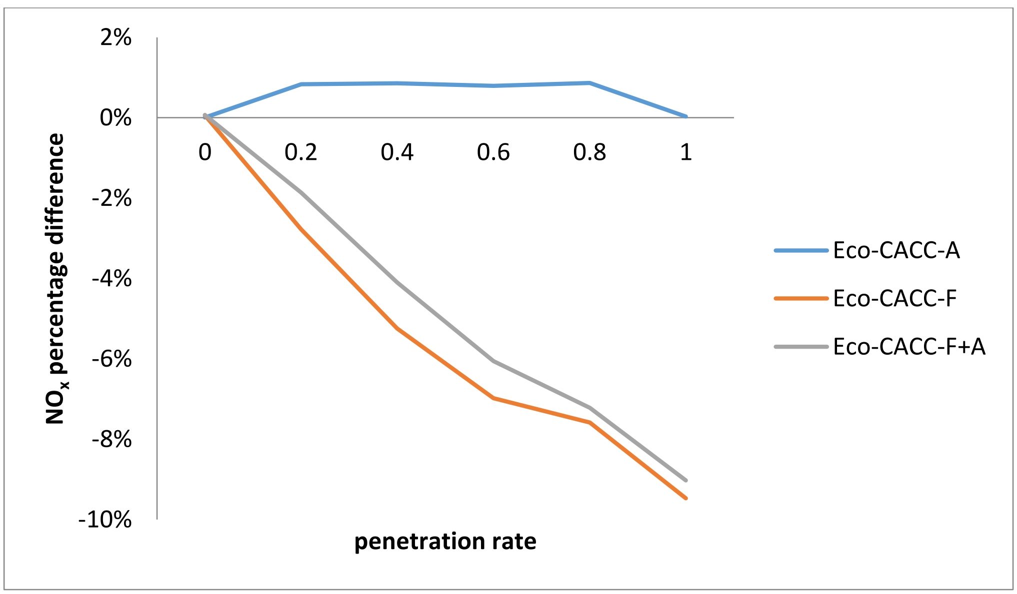
Figure 24 shows the effect on emissions by applying Eco-CACC methods to the network. In general, Eco-CACC-A does not have positive effect on HC, CO and NO_x emissions. For the other two Eco-CACC controls, they have negative influence on HC and CO emissions when the penetration rate is low. Eco-CACC-F starts to have a smaller amount of HC/CO compared to the base case when penetration rate reaches around 0.6 and Eco-CACC-F+A also produces less HC/CO when penetration rate is higher than around 0.8. When penetration rate is 1, compared to the base case, Eco-CACC-F leads to 4.6% less of HC and 3.9% less of CO, and Eco-CACC-F+A has 3.3% less of HC, 2.1% less of CO. In terms of NO_x emission, the positive effect from Eco-CACC-F and Eco-CACC-F+A keeps improving and when the penetration rate increases to 1, they have a 9.5% and 9.0% drop of NO_x compared to the base case, respectively.



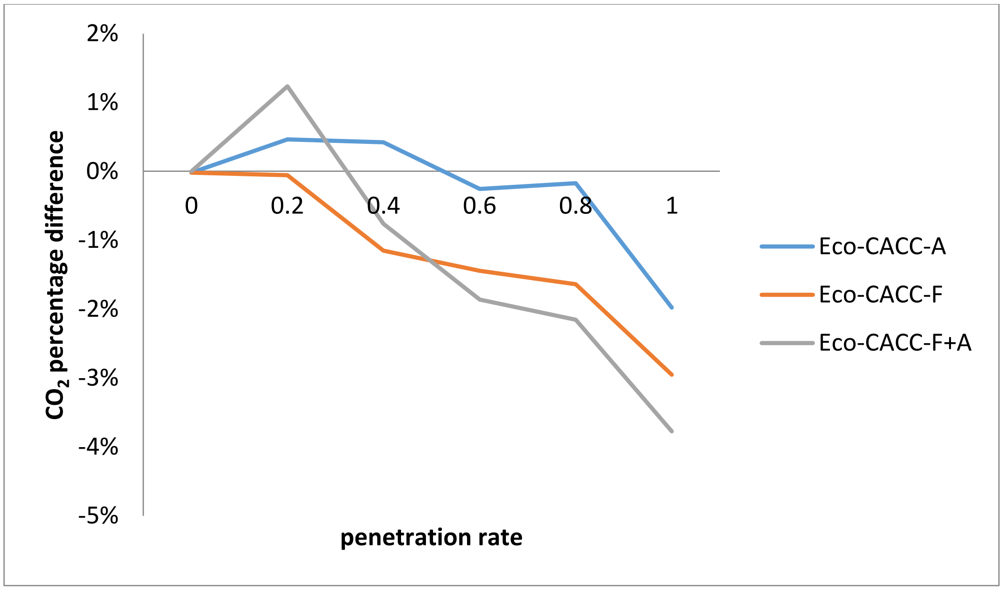
(a) HC


6%
5%
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
-5%
CO percentage difference
0
0.2
0.4
0.6
0.8
1
penetration rate
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A

(b) CO


2%
0%
-2%
-4%
-6%
-8%
-10%
NO_x percentage difference
0
0.2
0.4
0.6
0.8
1
penetration rate
Eco-CACC-A
Eco-CACC-F
Eco-CACC-F+A

(c) NO_x



(d) CO_2

Figure 24 Influence from Eco-CACC to emissions with change of penetration rate

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 Discussion and Conclusion

There are many existing researches studying Eco-driving strategies. It is proved that by applying Eco-driving strategies, even to just a limited proportion of the vehicles in the network, benefit to fuel efficiency and emissions could be achieved. However, these researches only focused on one specific control on either freeway or signalized arterial, instead of applying them together into a highly congested network. The uniqueness and breakthrough of this thesis is that it combines Eco-CACC on arterial and freeway and applies them both separately and simultaneously to a highly congested network to explore the different impacts that ECO-CACCs have on different scenarios. In total, the average results from 10 random seeds for 76 different traffic simulation runs, including both the three Eco-CACC control strategies and a base case, which has no eco-controls, were studied in this thesis. T-tests and pairwise mean comparison between control cases and the base case were conducted and the results for different cases and scenarios were compared. The following conclusions are reached:

a) The performance of Eco-CACC is negatively impacted by higher freeway speed limits in terms of delay controls. When freeway speed limit is 75 mph, Eco-CACC-A, Eco-CACC-F and Eco-CACC-F+A produce 9.1%, 24.3% and 26.0% higher delay than the base case respectively. Meanwhile, Eco-CACC on freeway and combined facilities has increasingly significant advantage on fuel economy when the speed limit is higher. In terms of fuel consumption and CO_2 emission, the positive effects from Eco-CACC-F and Eco-CACC-F+A improve significantly with freeway speed limit going up. They lead to an average of 8.6% less of fuel usage and 7.3% reduction of CO_2 than the base case when freeway speed limit reaches 75 mph. At the same time, these two controls produce 23.5%, 27.5% and 35.2% less of HC, CO and NO_x on average, respectively. For Eco-CACC-A, though it has positive effect on fuel usage and CO_2 emission when freeway speed limit is lower than 65 mph, in general, it does not have a significant benefit to fuel efficiency with increasing freeway speed limits.

b) The increasing rate for delay, fuel consumption and CO_2 emission is remarkably higher for all the four cases when traffic condition transfers from free flow to congestion (when OD scale is greater than 0.625), while the increasing rate for HC, CO and NO_x emissions keeps stable under different demand levels. Eco-CACC-A generates the shortest delay across the board, and the percentage of benefit from it is constant with different OD scales. The negative impacts on delays by Eco-CACC-F and Eco-CACC-F+A decrease with the increase of demand level, and Eco-CACC-F+A starts to have a shorter delay than the base case when OD scale is higher than 0.75. When OD scale is greater than 0.625, Eco-CACC-A brings a large improvement on fuel saving and CO_2 reduction and then keeps a stable benefit under higher traffic load. Eco-CACC-F+A has the least amount of fuel usage and CO_2 emission of all the four cases with all the demand levels, followed by Eco-CACC-F. With the increasing demand level, the benefit from these two Eco-CACC controls becomes smaller in general with some small fluctuations, but still greater than the benefit from Eco-CACC-A. For HC, CO and NO_x, the influence from Eco-CACC-A is statistically significant, while compared to the other two controls, it is neglectable. Eco-CACC-F+A generates a similar HC, CO and NO_x emission to Eco-CACC-F. Though the benefit from Eco-CACC-F and Eco-CACC-F+A has a small improvement from scaling factor of 0.875 to 1, in general, the benefit decreases with higher demand levels. When the OD scale goes from 0.125 to 1, the average percentage of reduction in HC, CO and NO_x emissions in the case of Eco-CACC-F and Eco-CACC-F+A comparing to the base case decrease from 11.3% to 4.4%, 11.8% to 4.0% and 14.3% to 9.3% respectively. However, positive effect on these three MOEs from Eco-CACC-F and Eco-CACC-F+A is always greater than that from Eco-CACC-A across the board.

c) Eco-CACC-F+A starts to generate shorter delay than the base case when the penetration rate is higher than 0.4, and for Eco-CACC-A, this reversing point is 0.8. The difference on delay from Eco-CACC-F to the base case fluctuates, without showing an obvious increasing/decreasing trend. For fuel consumption and CO_2 emission, Eco-CACC-F starts to show positive effect when the rate is greater than 0.2, and for Eco-CACC-F+A, the turning point occurs at the market penetration rate of 0.4. This is consistent with previous research, which proved that fuel efficiency will improve obviously when penetration rate is larger than 0.3 [38]. For Eco-CACC-A, dramatic drop on delay, fuel consumption and CO_2 emission happens when market penetration rate goes from 0.8 to 1. For HC and CO, Eco-CACC-F and Eco-CACC-F+A have positive effect after penetration rate higher than

0.6 and 0.8, respectively. These two controls have a growing positive effect on NO_x with the growth of penetration rate. When penetration rate is 1, on average, Eco-CACC-F and Eco-CACC-F+A produce 4.0% less of HC, 3.0% less of CO and 9.2% less of NO_x, respectively. However, Eco-CACC-A does not have positive effect on these three MOEs under different penetration rate.

To summarize, Eco-CACC-A leads to more improvement on delay but little positive effect on fuel economy. Eco-CACC-F, compared to Eco-CACC-A, performs much better on fuel saving and pollutant emitting. Due to high demand on freeway in the testbed, Eco-CACC-F+A has a similar result to Eco-CACC-F for all the evaluations. Meanwhile, it can also be noticed that the trend for Eco-CACC-F+A is influenced by Eco-CACC-A.

6.2 Future Work

The major focus of this thesis is on the integrated effects of different Eco-CACC controls over the network. Future research can be extended in the following fields:

a) In this simulation, no re-routing strategy was applied. INTEGRATION has several different routing strategies including eco-routing that aims at minimizing fuel consumption. We will continue to work on the combination influences from both Eco-CACC and eco-routing controls.

b) Signal timing plan in the simulation of this thesis is pre-defined, which may have contradicting effects on the efficiency of Eco-CACC. Coordinated signal timing on minimizing fuel consumption and emissions can be developed and utilized in the network The integrated results from both the Eco-CACC controls and coordinated signal timing plans can be studied for maximizing the fuel efficiency.

c) In this thesis, it was assumed that drivers will follow the Eco-CACC instructions once the information is conveyed to them. However, in real-life, drivers may not follow the guidance. According to the results from a previous study, only about 56% drivers will take eco-friendly driving behavior when informing of such information [58]. Strategies on improving the acceptance for Eco-CACC need to be studied to ensure a more efficient enforcement of Eco-CACC controls.

d) This thesis only focuses on vehicles using petroleum energy. With the development of vehicle engine and operation technology, vehicles can now adopt new energy sources (introduced in Chapter 2). Future work can be extended to the new types of vehicles to model the energy and emission of a mixture of vehicles using different energy.

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APPENDIX

Eco-CACC-A Control File Format

Line	Field	Description
1	1	File description
2	1	Number of links where the vehicles will apply the Eco-CACC-A control algorithm [integer]
	2	Format of the input file [integer] 1: Eco-CACC-A control without the consideration of Queues; 2: Eco-CACC-A control with the consideration of Queues
3+	1	Line number
	2	Link number nl (0<x<max link number)
	3	Probe vehicle class: abcde 1 indicates the class of vehicles is controlled; 0, otherwise. a: vehicle class 1 b: vehicle class 2 c: vehicle class 3 d: vehicle class 4 e: vehicle class 5
	4	Link location indicator [integer] 1: upstream of the signal -1: downstream of the signal
	5	Signal number [integer] (0<x<max signal number)
	6	Phase number that vehicle on link nl can go through the signal [integer]
	7	Distance to the signal where the Eco-CACC-A control algorithm is activated (meter) (in current version, this distance is equal to link length)
	8	Updating frequency for the vehicle class 1 (second)
	9	Updating frequency for the vehicle class 2 (second)
	10	Updating frequency for the vehicle class 3 (second)
	11	Updating frequency for the vehicle class 4 (second)
	12	Updating frequency for the vehicle class 5 (second)
	13	Detector number at the start point of the controlled link (only applied for upstream link)

Eco-CACC-F Control File Format

Line	Field	Description
1	1	File description
2	1	Number of vehicle classes controlled [integer]
	2	Format of the Eco-CACC-F control system [integer] 0: constant threshold; 1: dynamic threshold
3+	1	Line Number
	2	Vehicle class
	3	Look-ahead distance for vehicle class vt (meter)
	4	Updating interval for vehicle class vt (second)
	5	Target speed for vehicle class vt (km/hr)
	6	Speed threshold for vehicle class vt (km/hr)
	7	Car-following threshold for vehicle class vt (meter)

Eco-CACC-A Control File for The Network

Eco-CACC-A

181	2												
1	17	10000	1	15	1	20	1	1	1	1	1	17	200
2	22	10000	1	1	2	202	1	1	1	1	1	22	200
3	30	10000	1	42	2	412	1	1	1	1	1	30	200
4	37	10000	1	31	1	95	1	1	1	1	1	37	200
5	43	10000	1	32	1	97	1	1	1	1	1	43	200
6	50	10000	1	5	1	178	1	1	1	1	1	50	200
7	53	10000	1	3	1	78	1	1	1	1	1	53	200
8	56	10000	1	4	1	65	1	1	1	1	1	56	200
9	73	10000	1	6	2	200	1	1	1	1	1	73	200
10	83	10000	1	43	2	132	1	1	1	1	1	83	200
11	106	10000	1	41	2	103	1	1	1	1	1	106	200
12	136	10000	1	8	1	318	1	1	1	1	1	136	200
13	150	10000	1	39	2	260	1	1	1	1	1	150	200
14	156	10000	1	9	1	360	1	1	1	1	1	156	200
15	159	10000	1	40	2	344	1	1	1	1	1	159	200
16	203	10000	1	38	2	280	1	1	1	1	1	203	200
17	258	10000	1	13	1	240	1	1	1	1	1	258	200
18	259	10000	1	13	2	636	1	1	1	1	1	259	200
19	263	10000	1	14	2	617	1	1	1	1	1	263	200
20	302	10000	1	51	1	95	1	1	1	1	1	302	200
21	304	10000	1	51	2	163	1	1	1	1	1	304	200
22	354	10000	1	52	4	53	1	1	1	1	1	354	200
23	364	10000	1	17	1	45	1	1	1	1	1	364	200
24	401	10000	1	61	2	211	1	1	1	1	1	401	200
25	409	10000	1	60	2	135	1	1	1	1	1	409	200
26	420	10000	1	4	2	45	1	1	1	1	1	420	200
27	438	10000	1	7	1	20	1	1	1	1	1	438	200
28	440	10000	1	7	2	20	1	1	1	1	1	440	200
29	459	10000	1	6	3	728	1	1	1	1	1	459	200
30	460	10000	1	6	1	174	1	1	1	1	1	460	200
31	487	10000	1	45	2	220	1	1	1	1	1	487	200
32	506	10000	1	15	2	291	1	1	1	1	1	506	200
33	513	10000	1	1	1	1801	1	1	1	1	1	513	200
34	523	10000	1	55	2	92	1	1	1	1	1	523	200
35	566	10000	1	40	2	163	1	1	1	1	1	566	200
36	571	10000	1	9	1	371	1	1	1	1	1	571	200
37	590	10000	1	59	1	264	1	1	1	1	1	590	200
38	612	10000	1	33	2	1394	1	1	1	1	1	612	200
39	616	10000	1	45	2	503	1	1	1	1	1	616	200
40	619	10000	1	45	1	2000	1	1	1	1	1	619	200
41	625	10000	1	16	2	21	1	1	1	1	1	625	200

42	628	10000	1	35	2	200	1	1	1	1	1	628	200
43	629	10000	1	35	3	630	1	1	1	1	1	629	200
44	632	10000	1	16	1	334	1	1	1	1	1	632	200
45	643	10000	1	8	4	727	1	1	1	1	1	643	200
46	660	10000	1	38	2	400	1	1	1	1	1	660	200
47	718	10000	1	43	2	164	1	1	1	1	1	718	200
48	764	10000	1	36	2	400	1	1	1	1	1	764	200
49	827	10000	1	34	2	1970	1	1	1	1	1	827	200
50	833	10000	1	34	2	748	1	1	1	1	1	833	200
51	855	10000	1	49	2	133	1	1	1	1	1	855	200
52	872	10000	1	48	2	96	1	1	1	1	1	872	200
53	874	10000	1	14	2	193	1	1	1	1	1	874	200
54	896	10000	1	48	2	130	1	1	1	1	1	896	200
55	903	10000	1	49	2	63	1	1	1	1	1	903	200
56	921	10000	1	17	2	270	1	1	1	1	1	921	200
57	933	10000	1	33	2	747	1	1	1	1	1	933	200
58	948	10000	1	3	2	36	1	1	1	1	1	948	200
59	971	10000	1	51	2	55	1	1	1	1	1	971	200
60	1004	10000	1	5	2	96	1	1	1	1	1	1004	200
61	1059	10000	1	57	2	108	1	1	1	1	1	1059	200
62	1071	10000	1	59	2	106	1	1	1	1	1	1071	200
63	1089	10000	1	44	2	171	1	1	1	1	1	1089	200
64	1104	10000	1	41	2	475	1	1	1	1	1	1104	200
65	1106	10000	1	49	1	78	1	1	1	1	1	1106	200
66	1108	10000	1	18	1	71	1	1	1	1	1	1108	200
67	1110	10000	1	18	2	75	1	1	1	1	1	1110	200
68	1114	10000	1	18	1	1906	1	1	1	1	1	1114	200
69	1121	10000	1	37	2	298	1	1	1	1	1	1121	200
70	1147	10000	1	46	1	86	1	1	1	1	1	1147	200
71	1156	10000	1	8	3	199	1	1	1	1	1	1156	200
72	1175	10000	1	16	1	195	1	1	1	1	1	1175	200
73	1189	10000	1	45	1	1600	1	1	1	1	1	1189	200
74	1257	10000	1	13	1	296	1	1	1	1	1	1257	200
75	1278	10000	1	57	1	142	1	1	1	1	1	1278	200
76	1313	10000	1	36	2	634	1	1	1	1	1	1313	200
77	1361	10000	1	37	3	860	1	1	1	1	1	1361	200
78	1365	10000	1	53	1	22	1	1	1	1	1	1365	200
79	1367	10000	1	46	2	140	1	1	1	1	1	1367	200
80	1397	10000	1	54	2	54	1	1	1	1	1	1397	200
81	1398	10000	1	50	2	117	1	1	1	1	1	1398	200
82	1408	10000	1	50	1	90	1	1	1	1	1	1408	200
83	1412	10000	1	19	2	74	1	1	1	1	1	1412	200
84	1414	10000	1	19	1	44	1	1	1	1	1	1414	200
85	1427	10000	1	53	2	76	1	1	1	1	1	1427	200
86	1439	10000	1	52	1	114	1	1	1	1	1	1439	200

87	1442	10000	1	20	1	162	1	1	1	1	1	1442	200
88	1446	10000	1	20	2	173	1	1	1	1	1	1446	200
89	1457	10000	1	30	2	1667	1	1	1	1	1	1457	200
90	1502	10000	1	42	2	26	1	1	1	1	1	1502	200
91	1509	10000	1	32	2	203	1	1	1	1	1	1509	200
92	1512	10000	1	32	2	97	1	1	1	1	1	1512	200
93	1518	10000	1	3	2	84	1	1	1	1	1	1518	200
94	1519	10000	1	5	2	72	1	1	1	1	1	1519	200
95	1522	10000	1	6	3	21	1	1	1	1	1	1522	200
96	1533	10000	1	9	2	20	1	1	1	1	1	1533	200
97	1543	10000	1	14	1	46	1	1	1	1	1	1543	200
98	1594	10000	1	61	2	249	1	1	1	1	1	1594	200
99	1609	10000	1	60	2	101	1	1	1	1	1	1609	200
100	1624	10000	1	7	1	20	1	1	1	1	1	1624	200
101	1626	10000	1	7	2	20	1	1	1	1	1	1626	200
102	1636	10000	1	1	1	20	1	1	1	1	1	1636	200
103	1648	10000	1	55	2	229	1	1	1	1	1	1648	200
104	1653	10000	1	17	2	48	1	1	1	1	1	1653	200
105	1657	10000	1	30	2	270	1	1	1	1	1	1657	200
106	1668	10000	1	16	2	175	1	1	1	1	1	1668	200
107	1683	10000	1	44	2	196	1	1	1	1	1	1683	200
108	1686	10000	1	15	1	254	1	1	1	1	1	1686	200
109	1716	10000	1	8	2	119	1	1	1	1	1	1716	200
110	1726	10000	1	39	2	1035	1	1	1	1	1	1726	200
111	1736	10000	1	53	3	20	1	1	1	1	1	1736	200
112	1740	10000	1	54	2	73	1	1	1	1	1	1740	200
113	1747	10000	1	50	1	1262	1	1	1	1	1	1747	200
114	1749	10000	1	50	2	115	1	1	1	1	1	1749	200
115	1761	10000	1	19	2	84	1	1	1	1	1	1761	200
116	1765	10000	1	19	1	84	1	1	1	1	1	1765	200
117	1787	10000	1	20	1	474	1	1	1	1	1	1787	200
118	1800	10000	1	52	3	161	1	1	1	1	1	1800	200
119	1902	10000	1	30	1	118	1	1	1	1	1	1902	200
120	1906	10000	1	31	2	24	1	1	1	1	1	1906	200
121	2002	10000	1	33	1	303	1	1	1	1	1	2002	200
122	2003	10000	1	33	1	420	1	1	1	1	1	2003	200
123	2004	10000	1	34	1	448	1	1	1	1	1	2004	200
124	2006	10000	1	34	1	583	1	1	1	1	1	2006	200
125	2007	10000	1	35	1	270	1	1	1	1	1	2007	200
126	2009	10000	1	35	1	1074	1	1	1	1	1	2009	200
127	2011	10000	1	36	1	290	1	1	1	1	1	2011	200
128	2013	10000	1	36	1	326	1	1	1	1	1	2013	200
129	2015	10000	1	37	1	927	1	1	1	1	1	2015	200
130	2016	10000	1	37	1	310	1	1	1	1	1	2016	200
131	2017	10000	1	38	1	927	1	1	1	1	1	2017	200

132	2019	10000	1	38	1	417	1	1	1	1	1	2019	200
133	2021	10000	1	39	1	218	1	1	1	1	1	2021	200
134	2023	10000	1	40	1	471	1	1	1	1	1	2023	200
135	2024	10000	1	39	1	471	1	1	1	1	1	2024	200
136	2025	10000	1	40	1	422	1	1	1	1	1	2025	200
137	2027	10000	1	41	1	1279	1	1	1	1	1	2027	200
138	2028	10000	1	42	1	1279	1	1	1	1	1	2028	200
139	2029	10000	1	41	1	403	1	1	1	1	1	2029	200
140	2031	10000	1	42	1	198	1	1	1	1	1	2031	200
141	2033	10000	1	15	2	350	1	1	1	1	1	2033	200
142	2035	10000	1	1	2	72	1	1	1	1	1	2035	200
143	2037	10000	1	44	1	341	1	1	1	1	1	2037	200
144	2039	10000	1	43	1	1627	1	1	1	1	1	2039	200
145	2040	10000	1	44	1	1627	1	1	1	1	1	2040	200
146	2041	10000	1	43	1	277	1	1	1	1	1	2041	200
147	2043	10000	1	48	1	130	1	1	1	1	1	2043	200
148	2045	10000	1	54	1	1660	1	1	1	1	1	2045	200
149	2051	10000	1	55	1	2270	1	1	1	1	1	2051	200
150	2052	10000	1	54	1	2270	1	1	1	1	1	2052	200
151	2053	10000	1	60	1	300	1	1	1	1	1	2053	200
152	2054	10000	1	61	1	300	1	1	1	1	1	2054	200
153	2055	10000	1	60	1	150	1	1	1	1	1	2055	200
154	2058	10000	1	61	1	400	1	1	1	1	1	2058	200
155	43	10000	-1	4	1	97	1	1	1	1	1	43	200
156	56	10000	-1	5	1	65	1	1	1	1	1	56	200
157	513	10000	-1	55	1	1801	1	1	1	1	1	513	200
158	2052	10000	-1	55	1	2270	1	1	1	1	1	2052	200
159	619	10000	-1	16	1	2000	1	1	1	1	1	619	200
160	833	10000	-1	33	1	748	1	1	1	1	1	833	200
161	1114	10000	-1	33	1	1906	1	1	1	1	1	1114	200
162	921	10000	-1	30	1	270	1	1	1	1	1	921	200
163	933	10000	-1	34	1	747	1	1	1	1	1	933	200
164	1189	10000	-1	37	1	1600	1	1	1	1	1	1189	200
165	2017	10000	-1	37	1	927	1	1	1	1	1	2017	200
166	1442	10000	-1	52	1	162	1	1	1	1	1	1442	200
167	1747	10000	-1	52	1	1262	1	1	1	1	1	1747	200
168	1457	10000	-1	53	1	1667	1	1	1	1	1	1457	200
169	1512	10000	-1	31	1	97	1	1	1	1	1	1512	200
170	1657	10000	-1	17	1	270	1	1	1	1	1	1657	200
171	1800	10000	-1	20	1	161	1	1	1	1	1	1800	200
172	2015	10000	-1	38	1	927	1	1	1	1	1	2015	200
173	2023	10000	-1	39	1	471	1	1	1	1	1	2023	200
174	2024	10000	-1	40	1	471	1	1	1	1	1	2024	200
175	2027	10000	-1	42	1	1279	1	1	1	1	1	2027	200
176	2028	10000	-1	41	1	1279	1	1	1	1	1	2028	200

177	2039	10000	-1	44	1	1627	1	1	1	1	1	2039	200
178	2040	10000	-1	43	1	1627	1	1	1	1	1	2040	200
179	2051	10000	-1	54	1	2270	1	1	1	1	1	2051	200
180	2053	10000	-1	61	1	300	1	1	1	1	1	2053	200
181	2054	10000	-1	60	1	300	1	1	1	1	1	2054	200

Eco-CACC-F Control File for The Network (OD scale and Penetration Rate Scenarios)

Eco-CACC-F Control system file:

```
1    1
1    1    1000    10    100    9    50
```

Eco-CACC-F Control File for The Network (Freeway Speed Limit Scenarios)

Freeway Speed Limit = 57 mph

```
Eco-CACC-F Control system file:
1   1
1   1   1000   10   93   2   50
```

Freeway Speed Limit = 60 mph

```
Eco-CACC-F Control system file:
1   1
1   1   1000   10   97   6   50
```

Freeway Speed Limit = 65 mph

```
Eco-CACC-F Control system file:
1   1
1   1   1000   10   105   10   50
```

Freeway Speed Limit = 70 mph

```
Eco-CACC-F Control system file:
1   1
1   1   1000   10   113   10   50
```

Freeway Speed Limit = 75 mph

```
Eco-CACC-F Control system file:
1   1
1   1   1000   10   121   10   50
```