ECO-COOPERATIVE ADAPTIVE CRUISE CONTROL AT SIGNALIZED INTERSECTIONS CONSIDERING VEHICLE QUEUES

By

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Abstract

Traffic signals typically produce vehicle stops and thus increase vehicle fuel consumption levels. Vehicle stops produced by traffic signals, decrease vehicle fuel economy on arterial roads making it significantly lower than that on freeways. Eco-Cooperative Adaptive Cruise Control (Eco-CACC) systems can improve vehicle fuel efficiency by receiving Signal Phasing and Timing (SPaT) data form downstream signalized intersections via vehicle-to-infrastructure communication. The algorithm that was developed in an earlier study provides advisory speed recommendations to drivers to reduce vehicle fuel consumption levels in the vicinity of traffic signalized intersections. The research presented in this thesis enhances the algorithm by adding a queue length estimation component and incorporates the algorithm in the INTEGRATION microscopic traffic simulation software to test the system under varying conditions. The enhanced Eco-CACC algorithm is then tested in a simulation environment considering different levels of connected vehicle (CV) market penetration levels. The simulation analysis demonstrates that the algorithm is able to reduce the vehicle fuel consumption level by as high as 40%. Moreover, the overall benefits of the proposed algorithm is evaluated for different intersection configurations and CV market penetration rates (MPRs). The results demonstrate that for single lane approaches, the algorithm can reduce the overall fuel consumption levels and that higher MPRs result in larger savings. While for multilane approaches, lower MPRs produce negative impacts on fuel efficiency; only when MPRs are greater than 30%, can the algorithm work effectively in reducing fuel consumption levels. Subsequently a sensitivity analysis is conducted. The sensitivity analysis demonstrates that higher market penetration rates of Eco-CACC enabled vehicles can improve the environmental benefits of the algorithm, and the overall savings in fuel consumption are as high as 19% when all vehicles are equipped with the system. While, on multi-lane approaches, the algorithm has negative impacts on fuel consumption levels when the market penetration rate is lower than 30 percent. The analysis also indicates that the length of control segments, the SPaT plan, and the traffic demand levels affect the algorithm performance significantly. The study further demonstrates that the algorithm has negative impacts on fuel consumption levels when the network is over-saturated.

ECO-COOPERATIVE ADAPTIVE CRUISE CONTROL AT SIGNALIZED INTERSECTIONS CONSIDERING VEHICLE QUEUES

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General Audience Abstract

Vehicles have to stop and wait for light to turn green when they approach the intersection during a red light. This stop and go motion results in wastage of fuel. The momentum generated by the engine is wasted as the vehicle breaks to slow down. The fuel is also wasted as the vehicle idles at the intersection. Without the traffic light the vehicle would continue at its desired speed covering longer distance in same amount of time. Thus vehicle consumes more fuel to travel the same distance in presence of traffic lights. Eco-Cooperative Signal Phasing Control (Eco-CACC) systems can potentially avoid stop and go motion by informing the driver about the upcoming traffic light status. The vehicle which can communicate to the signals are called connected vehicle (CV). They are also capable of communicating with other vehicles on the road. This CV idea was developed by researchers to provide the driver with advisory speed recommendations to avoid stopping at intersection. The vehicle is advised to drive at a certain speed as soon as it enter the communication range to reach the intersection exactly when it turns green. The system works for a single vehicle approaching the traffic light. The results show that having this communication system in vehicles can reduce fuel consumption up to 40 % when compared to standard car. In case of real traffic, there are cars standing at intersection waiting for green. The research provided in this paper improves the earlier idea by including the effect of queue length of the vehicles at the traffic signal. The idea is simulated on a software to replicate the traffic movement at an intersection to compare the results with real traffic. The simulation is repeated for various intersection configurations and various percentages of vehicles in traffic that are capable to communicate. On a single lane intersection, the system can reduce the fuel consumption of all the cars on the road and this benefit increases with increase in the percent of CV. In case of multiple lane intersections the system increases fuel consumption at lower percent of CV's and only when the percent of CV's increases beyond 30% the system starts to achieve fuel benefit. Subsequently all the factors that influence the fuel benefit achieved by the system are analyzed. Analysis proved that with a higher percent of CV's the environmental benefit achieved by the Eco-CACC system and average savings in fuel of all cars can reach up to 19% when all vehicles are capable of communicating. The research also indicates that the distance at which the traffic light information is provided to the vehicle and the amount of traffic affect the benefit achieved by the idea. Finally the research shows how the system fails when roadway gets saturated.

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Table of Contents

List of Figures

Chapter 1: Introduction

1.0 Introduction

Climate change is the greatest environmental threat of our time and global warming is the most discussed term in this century. It is responsible for rising sea levels, storms, searing heat, severe drought and punishing floods. Worldwide many nations are taking steps to combat this growing threat. Increased concentrations of greenhouse gases (GHGs) is the biggest contributor for this climatic change. Industrial revolution has increased the amount of GHGs in the atmosphere. Fossil fuel burning alone is responsible for three quarters of the increase in the GHGs. Although there are other factors which affect the production of these GHGs, burning of fossil fuel in power plants and vehicles is undoubtedly the biggest factor. The development in the last two decades alone is more than the development in the previous three decades combined. This explosive development lead to an increase in road connectivity and a significant spike in vehicle ownership. More than 45 million people in the US are living, working within 300 feet of major roads, airports or railroads [1]. The pollution emitted by the vehicles have a direct impact on the health of the people. In the US alone, the transportation sector consumed over 137 billion gallons of fuel in 2014 [2]. Each gallon of this fossil fuel burnt is responsible for 20 pounds of CO_2 emissions released into our environment [3]. In the other direction deforestation reduces the nature's capacity of being a CO_2 sink. Consequently, there is an urgent need to reduce the consumption hydrocarbons and GHG emissions. The possible solutions are fuel efficient vehicles, cleaner fuels, electric cars etc.

Under the FHWA's Intelligent Transportation Systems (ITSs) program in 2003 the vehicle infrastructure integration initiative was started. Its main aim was to bring the benefits of connected vehicles and infrastructure to enhance roadway safety, reduce traffic congestion and mitigate the environmental impacts of the transportation system. Under this initiative, research efforts attempting to reduce the carbon footprint and fuel consumption associated with driving have advanced significantly. On the mechanical side, non-propulsion system improvements such as improved aerodynamics, rolling friction, weight reduction have enhanced the average passenger vehicle gas mileage. On the systems side, enhancements focused on reducing vehicular stops, travel time, and smoothing vehicle trajectories etc. Thus on the one hand researchers are working to increase the efficiency of the vehicle and on the other hand to optimize traffic signal timings based on traffic volumes to reduce the transportation system delay. Maintaining a vehicle helps in maintaining the efficiency of the vehicle. Similarly, ensuring that the tire pressure and engine oil are adequate help in achieving fuel and emission savings. However, the vehicle efficiency is also affected by idling time at signalized intersections. To counter this, researchers have been working on improving the efficiency of the traffic signal system to reduce average vehicle delays. The final approach to reduce fuel consumption and increase fuel efficiency is to drive eco-friendly by breaking less and avoiding hard accelerations. Research has proven that cruising at 60 mph is more fuel efficient. Many countries have adopted this speed limit to harness efficiency in fossil fuel. Although training drivers to drive efficiently works for a while they tend to go back to their original driving methods unless there is constant motivation to do so. One such effort is the eco-driving framework that utilizes vehicle-to-infrastructure (V2I) communications to receive signal phasing and timing (SPaT) information to compute the optimum course of action of the vehicle. The idea behind eco-driving is providing real-time driving advice to the individual vehicle so that the driver can adjust their driving behavior to take certain driving actions to reduce fuel consumption and emission levels. Generally, most eco-driving strategies modify driving behavior through advisory speed recommendations, recommended acceleration or deceleration levels and speed alerts. Studies have indicated that eco-driving can reduce fuel consumption and greenhouse gas emissions by approximately 10% on average.

1.1 Emerging Cooperative Adaptive Cruise Control Systems

Cruise Control (CC) systems automatically control the speed of a motor vehicle to maintain a user-specified desired speed. The system controls the vehicle throttle to maintain the desired speed. Most modern cars are equipped with CC systems. CC is mainly used to reduce driving load and to avoid subconscious speeding over speed limits. However, cruise control has been a reason for many accidents because drivers failed to reduce the vehicle speed on curves and when the terrain is variable, rough or wet, causing the vehicle to lose traction and control. Modern day vehicles have an advanced version of cruise control called Adaptive Cruise Control (ACC), which can perform automatic downshifting, braking and throttle control functions. The system uses radar or laser technology to measure the distance between the subject and lead vehicles to maintain a safe following speed and headway. Whenever the lead vehicle slows down, the system decelerates the subject vehicle to maintain a preset headway and accelerates again to the preset speed when the lead vehicle accelerates. This system also features forward collision warning, which alerts the driver whenever the vehicle gets too close to its lead vehicle and may also perform emergency braking if the driver fails to do so. Thus ACC helps in controlling the vehicle speed dynamically based on surrounding traffic. However as the system tries to mirror the actions of the leading vehicle, it fails to exhibit string stability and induces oscillations in traffic which travel upstream with increasing amplitude. This problem is addressed by Cooperative Adaptive Cruise Control (CACC) systems, which extend the capability of ACC by using information gathered from infrastructure and other cars to calculate and produce a safe and smooth trajectory.

Present day CACC systems can communicate with infrastructure (V2I) and other vehicles (V2V) using Dynamic Short Range Communication (DSRC) or other wireless communication mediums. DSRC is based on IEEE802.11p standard, which defines wireless access in vehicular environments (WAVE). The sensor range varies between 10-1000m. However the actual communication range depends on the traffic density. Delay and loss of information increases as the distance of communication increases [4]. The optimal range of communication is approximately 500m when the traffic density is 0.2 vehicles per meter (200 veh/km) with acceptable level of delay and awareness [5]. DSRC technology is particularly useful in making driving safe and in avoiding potential collisions. It can also be used to warn the traffic of a downstream accident and provide detour information which could eventually save time and gas. Some of the important features of DSRC are (1) automatic emergency braking, (2) forward collision warning (3), safe passing warning (4), blind spot warning, (5) pedestrian and bike warning, (6) intersection movement warning, and (7) blind curve warning. DSRC uses a built in radio that operates in the 5.9 GHz range and transmits the GPS positon, direction, transmission state, speed, acceleration, break status, steering wheel angle, path history and predicted behavior of the equipped vehicle. The technology will be effective only when the percent of vehicles equipped are above a certain critical value. ABI research predict 20% of all cars in the US will be equipped with this technology by 2020 [6]. The technology is of two types, namely: active and passive. In active V2I and V2V technology the vehicle automatically avoids collisions by controlling steering, acceleration and braking. In passive V2I and V2V, the car merely provides information about a potential dangerous event. Although passive communication does not guarantee safety, it is easy to retrofit approximately half a billion of old cars that exist without this technology. This paper discusses how DSRC is also used to communicate the upcoming signal phase and timing (SPaT) data to the vehicle to control the vehicle trajectory in an attempt to optimize its fuel consumption level in the proximity of traffic signalized intersections.

1.2 Research Need and Justification

The U.S. Department of Transportation (USDOT) proposed V2I and V2V initiatives that allow vehicles to receive SPaT data from intersection controllers. This information when paired with CACC systems, can be used to reduce vehicle idling at signalized intersections. Consequently, recently research efforts have been dedicated to the development of algorithms that would utilize SPaT information to reduce vehicle fuel consumption levels and thereby reduce vehicle emissions. The system can either notify the driver of an upcoming signal status, provide advisory speed recommendations to the driver, or provide automated vehicle control of longitudinal motion to avoid hard braking or hard acceleration maneuvers [7]. This system is known as Eco-Cooperative Adaptive Cruise Control (Eco-CACC), which refers to driving in an eco-friendly and economical fashion while conserving momentum and improving vehicle fuel efficiency. In the Eco-CACC algorithm an explicit fuel consumption model to compute the total fuel consumed is used as the objective function. Depending on the upcoming signal change information there are three different scenarios that an Eco-CACC equipped vehicle may encounter while approaching an intersection. These are:

1. The vehicle is able to procced through the intersection at its current speed.
2. The vehicle may accelerate to the roadway speed limit to traverse the intersection without coming to a stop.

3. The vehicle will not be able to traverse the intersection and thus must adjust its speed to reach the approach stop-line when the traffic light turns green.

In scenario 3 the vehicle may reach the approach stop line in an infinite number of ways. For example, the vehicle can cruise to the intersection at its current speed, or continuously decelerate to reach the intersection just as the traffic light turns green, or any other possibilities between these two extreme cases. One possible case is to decelerate to a cruising speed and then cruise to reach the approach stop line as the light turns green. The deceleration-cruising speed profile just adds delay to the vehicle trajectory to ensure that it arrives at the approach stop line just as the traffic light turns green. Subsequently, the vehicle accelerates to reach the speed limit downstream after passing the intersection. Thus the vehicle movement is divided into three states, namely: decelerating, cruising and accelerating. The speed profile of a vehicle approaching an intersection can be divided into two portions, namely: (a) deceleration-cruising upstream of the approach stop line and (b) accelerating downstream of the intersection. The deceleration ($3m/s^2$) and acceleration ($2m/s^2$) levels are chosen within the comfort limits of a driver. The amount of fuel consumed for constant deceleration is less than the fuel required for cruising. However the fuel required for acceleration is many times greater when compared to cruising or decelerating maneuvers. Thus the impact of acceleration on the objective function is very high when compared to the upstream speed profile. The fuel consumed to reach the speed limit downstream can be greatly conserved by driving through the intersection at a higher speed. Thus the algorithm computes the optimal speed profile for the Eco-CACC equipped vehicle to decelerate/cruise to reach stop line at its highest possible speed while incurring a desired delay. The following examples illustrates how different speed profiles in Figure 1.1 incur exact same delay as they reach stop line with different speeds and fuel consumption rates. Figure 1.2 illustrates corresponding trajectories.

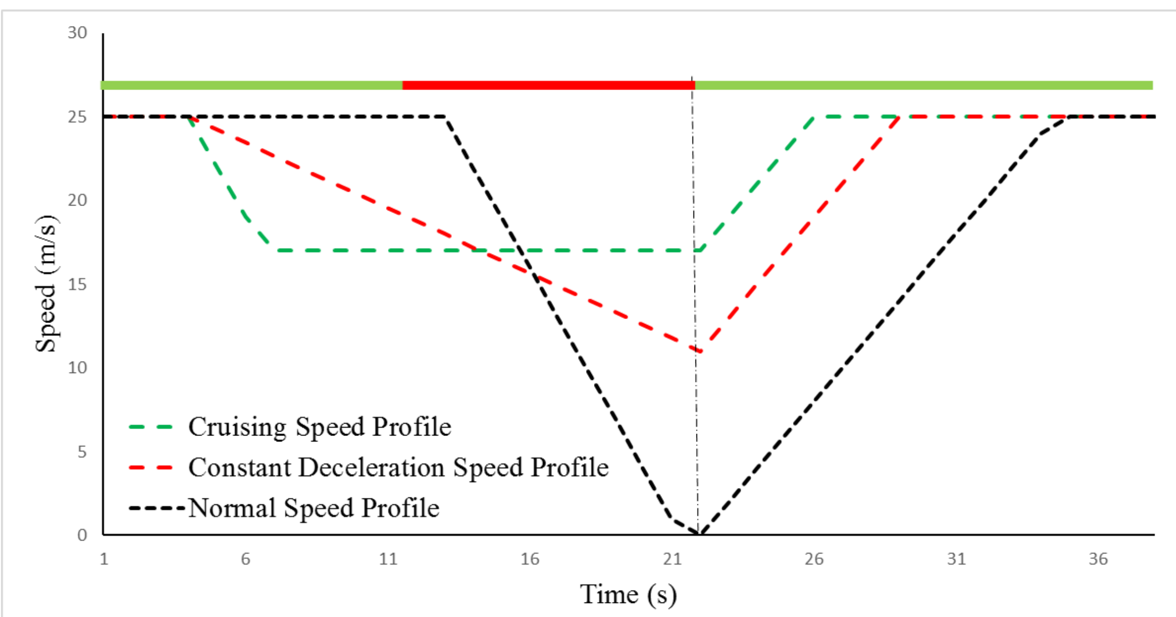


Figure 1.1: Speed profiles of Eco-CACC equipped vehicle

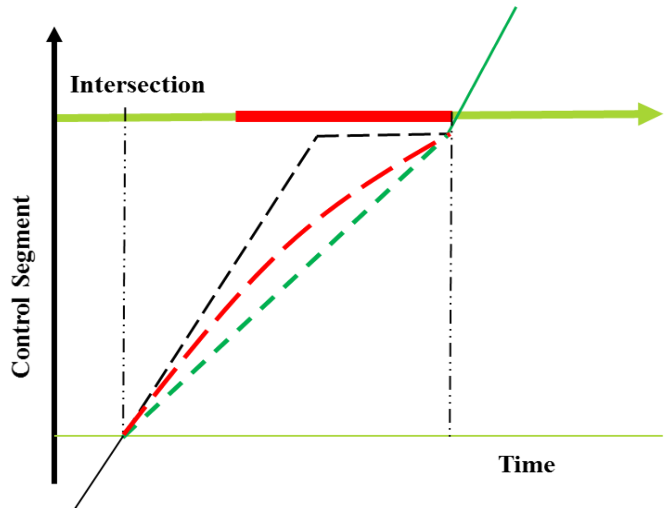


Figure 1.2: Trajectories of Eco-CACC equipped vehicle

The vehicle approaching the intersection without the SPaT data from the controller, comes to a complete stop as soon as it encounters red light. The speed profile of such vehicle is shown by the black line in Figure 1.1. The vehicle continued its current speed of 25m/s until 13th second at which it realizes that it cannot clear the intersection and decelerates at 3m/s^2 to stop at the stop line. After the light turns green it takes about 14 seconds to reach its desired speed of 25m/s and consumed fuel at a rate of 0.412 L/km. The Eco-CACC equipped vehicle can calculate the status of the traffic light if it continues at the current speed and determine its speed profile to avoid any stopped delay at the intersection. To reach the same stop line with some added delay, in this example the vehicle continuously decelerates from 5th second at a rate of $0.77\ \text{m/s}^2$ such that it arrives at the stop line when light turns green as shown by a red dotted line in Figure 1.1. In this example the vehicle arrived at a speed of $11.7\ \text{m/s}^2$ and after the light turned green, it takes about 9 seconds to accelerate to its desired speed at a rate of 2m/s^2 while maintaining an average fuel consumption rate of 0.3408 L/km. The last profile is where a vehicle decelerates at a comfortable rate i.e. 3m/s^2 to attain cruise speed and then cruise to stop line such that it incurs the same amount of delay as shown by a green dotted line in Figure 1.1. In this example the vehicle arrived at the intersection at a speed of 17m/s and after the light turned green, it took about 4 seconds to reach desired speed of 25m/s, with an average fuel consumption rate of 0.2701 L/km. All three vehicle profiles reached the stop line after 22 seconds after entering the control segment but with different speeds and fuel consumption rates and there are infinite other possibilities of such deceleration-cruise profiles which add same amount of delay to avoid stopping at intersection. The later deceleration-cruise speed profile has the highest speed while passing through the intersection and also consumed much less fuel when compared to continuous deceleration and normal speed profiles. The Eco-CACC algorithm calculates one such fuel optimal deceleration-cruise speed profile for equipped vehicles to save fuel.

When sensitivity analysis is conducted using this algorithm, it has been observed that the fuel benefit achieved by the algorithm decreased with an increase in the cycle length of the traffic signal while keeping the g/C ratio constant at 0.5. Moreover the benefit achieved became negative at higher demand at longer cycle length. Figure 1.3 illustrates the sensitivity of the algorithm to cycle length and traffic volume. At 700 veh/hr the fuel benefit reached zero when the cycle length is 92 seconds with amber of 4 seconds. Increase in cycle length results in increased fuel consumption. Increasing cycle length with fixed g/C ratio is similar to increasing red light time at a signal. With a longer red light, stopping at the intersection becomes inevitable and there should be no benefit imparted by the algorithm as the situation becomes similar to the base case where vehicles are not aware of SPaT infromation. Contrary to the expectation, the algorithm caused further increase in fuel consumption as the cycle length is increased. This leads us to look at the trajectories of individual vehicles to determine the problem.

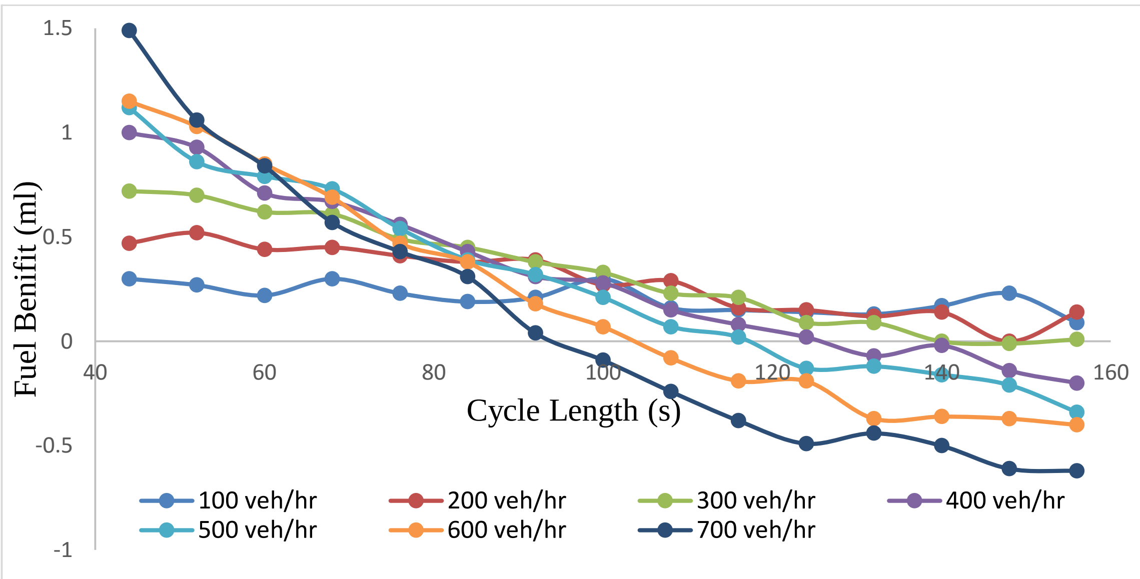


Figure 1.3: Sensitivity of algorithm to cycle length and demand

Figure 1.4 shows the trajectories of vehicles when all the vehicles are equipped with Eco-CACC. Vehicle trajectories indicate that few Eco-CACC equipped vehicles miscalculated their arrival at signal and had to stop at the intersection. This even lead to a chain of events which affected the trajectory of other vehicles, since a vehicle stop was unexpected and unaccounted for in the algorithm. The trajectories also show strong evidence of shockwaves travelling upstream at the intersection and summary results of simulation indicates increase in acceleration deceleration noise. Investigation of shockwaves during simulation indicates that vehicle queue not serviced by an earlier cycle at the intersection is the reason for increase in acceleration/deceleration noise.

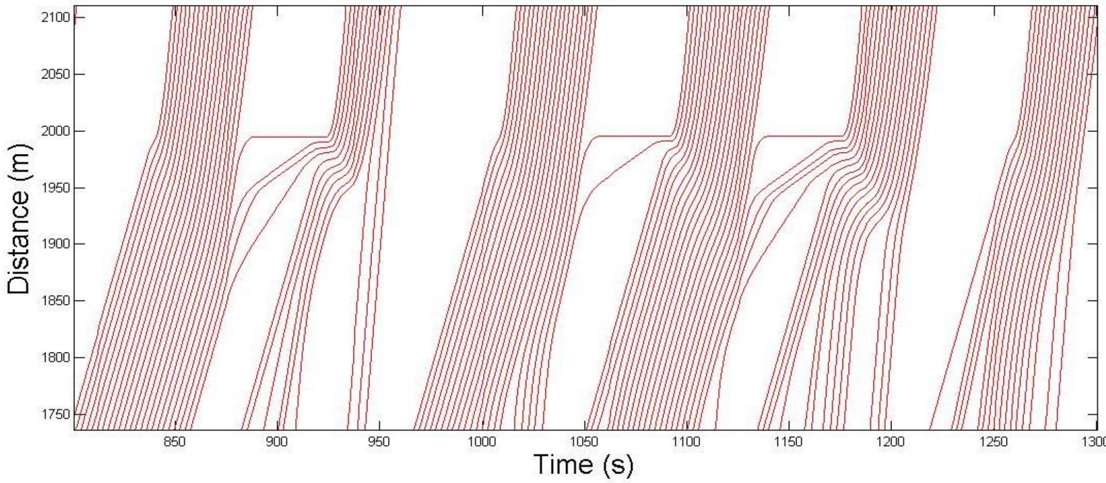


Figure 1.4: Trajectories of Eco-CACC vehicles

Earlier research developed an Eco-CACC algorithm that only considered SPaT information in computing the optimum vehicle trajectory. However, because vehicle queues often exist at the signalized approaches, the Eco-CACC vehicle would fluctuate between car-following and Eco-CACC modes of operation producing fluctuations in their speeds. Figure 1.5 shows how the vehicles which encountered a standing queue at the intersection exhibit acceleration and deceleration noise. According to the Eco-CACC algorithm, the aim of the equipped vehicle is to reach the stop line at the intersection when the traffic signal turns green. Vehicles are supposed to attain fuel-optimal cruise speed and cruise until the stop line as illustrated in Figure 1.1. The algorithm does not include the effect of possible vehicle queues and when the vehicles encounters a standing queue, the car-following model takes over and vehicle decelerates to stop at the end of the queue. When the queue starts dissipating, the Eco-CACC equipped vehicles fluctuate between the speed posted by the Eco-CACC algorithm and safe following speed obtained from the car-following model. This unnecessary acceleration deceleration results in loss of efficiency and causes the vehicle to pass the intersection at much lower speed. Consequently, the research presented in this thesis extends the model to consider the effect of queues in computing the fuel-optimum vehicle trajectory.

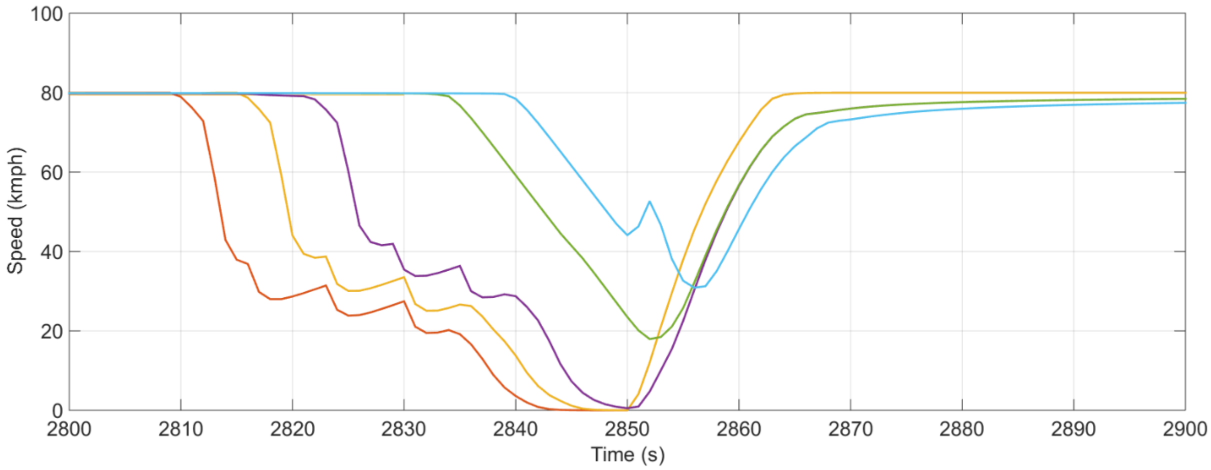


Figure 1.5: Speed profiles of Eco-CACC equipped vehicles in presence of vehicle queues

1.3 Thesis Objectives and Approach

Vehicles traveling on arterial roads encounter many signalized intersections. Signalized intersections are used traditionally to control conflicting flows of traffic. Although signalized intersections improve road safety and avoid conflicting movements, they induce delay, acceleration noise and increased vehicle fuel consumption levels. Hence researchers have been working to optimize the signal timing and estimating green waves by coordinating traffic signals in order to reduce vehicle stops. Presently, increasing pollutant emissions in the transportation sector is driving researchers to work on algorithms for assisting and modifying driver behavior to avoid unnecessary acceleration/deceleration maneuvers so as to drive economically, smoothly and improve fuel efficiency. In this regard, one of the research efforts is to develop an algorithm that provides advisory speed recommendations to the driver to help him/her make decisions regarding their accelerating/decelerating/cruising behavior. An Eco-CACC system developed by Rakha and Kamalanathsharma [7] is one such algorithm that addresses this need. However, the algorithm is developed for a single vehicle without consideration of queues on traffic signalized approaches. The research presented in this thesis extends the algorithm to consider queues on signalized approaches and then evaluates the algorithm for different demand levels.

The following are the objectives of the thesis

1. Enhance the Eco-CACC algorithm to incorporate the effect of surrounding traffic i.e. the presence of queues at the intersections and lane sharing behavior into the algorithm.
2. Conduct a comprehensive sensitivity analysis of the algorithm to evaluate its performance for different traffic conditions.
3. Determine the limitations of the algorithm and identify additional areas for the algorithm improvement.

This study uses the VT-CPFM fuel consumption model to compute the fuel consumption levels due to its simplicity, accuracy, and ease of calibration [8]. The fuel consumption model utilizes instantaneous power as an input variable and can be calibrated using publicly available fuel economy data (e.g., Environmental Protection Agency [EPA]-published city and highway fuel ratings). Thus, the calibration of the model parameters does not require gathering any empirical vehicle-specific data.

1.4 Thesis Organization

This thesis uses a manuscript format that include two peer-reviewed papers that were published as part of this research effort. The thesis is divided into four chapters. A brief description of each of these chapters along with their attributions are given below:

Chapter 1 provides an introduction to the research work, the research objectives and the thesis organization.

Chapter 2 is based on a paper co-authored by Dr. Hesham Rakha and Dr. Hao Yang that was presented at the 2016 TRB Annual Meeting. This chapter integrates the effect of surrounding traffic by introducing queue length prediction into the Eco-CACC algorithm. The benefit of this addition is quantified for some limited scenarios by comparing to the base Eco-CACC system without queue length prediction. This paper was mainly written by Dr. Yang and Dr. Rakha. The candidate ran all the simulations that were included in the paper.

Chapter 3 was co-authored by Dr. Hesham Rakha and Dr. Hao Yang and was presented at the 2016 TRB Annual Meeting and is accepted for publication in the Transportation Research Record. This chapter conducts a sensitivity analysis of the Eco-CACC algorithm for varying traffic, algorithm, and signal settings in order to identify the potential limitations of the proposed algorithm. All simulations and the first draft of the paper was done by the candidate and then edited by Drs. Yang and Rakha.

Chapter 4 summarizes the conclusions of the research and discusses some future research directions.

1.5 References

[1] United States Environmental protection Agency, “Near Roadway Air Pollution and Health” 2015 [online] Available: http://www3.epa.gov/otaq/nearroadway.htm

[2] United States Energy Information Administration, “Energy Use for Transportation in United states explained” 2015 [online] Available: http://www.eia.gov/Energyexplained/?page=us_energy_transportation

[3] Carbon Dioxide Information Analysis Center, “Environmental Protection Agency frequent questions” 2015[online] Available: http://cdiac.ornl.gov/faq.html

[4] Yunxin li. An overview of the DSRC/WAVE technology. Quality, Reliability, Security and Robustness in Heterogeneous Networks, Volume 74 of the series Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering pp 544-558

[5] Vaishali and ketan. Performance of vehicle to vehicle communication using IEEE 802.11p in vehicular ad-hoc network environment. International journal of network security and its applications (IJNSA), vol.5, No.2, March 2013.

[6] ABI research, “Global advanced driver assistance systems market” 2015 [online]. https://www.abiresearch.com/press/global-advanced-driver-assistance-systems-adas-mar/

[7] Raj Kishore and Hesham Rakha. Leveraging connected vehicle technology and telematics to enhance vehicle fuel efficiency in the vicinity of signalized intersections. , journal of intelligent transportation systems. Volume 20, issue 1, 2016

[8] Hesham A Rakha, Kyoungho Ahn, Kevin Moran, Bart Saerens, and Eric Van den Bulck. Virginia tech comprehensive power-based fuel consumption model: model development and testing. *Transportation Research Part D: Transport and Environment*, 16(7):492–503, 2011.

[9] Vehicle Infrastructure Integration, ITS Standards Acquire A New Mission: Transitioning the ITS Standards Program to align with the USDOT’s New ITS Research Initiatives

Chapter 2: Eco Cooperative Adaptive Cruise Control at Signalized Intersections Considering Queue Effects

This chapter is based on: Yang H., Ala M.V., and Rakha H. (2016), "Eco-Cooperative Adaptive Cruise Control at Signalized Intersections Considering Queue Effects," 95th Transportation Research Board Annual Meeting, Washington DC, January 10-14. [Paper # 16-1593]

Abstract

Traffic signals typically produce vehicle stops and thus increase vehicle fuel consumption levels. Eco-cooperative adaptive cruise control (Eco-CACC) systems can improve vehicle fuel efficiency by receiving Signal Phasing and Timing (SPaT) data from downstream signalized intersections via vehicle-to-infrastructure communication. The research presented in this paper develops an algorithm that provides advisory speed recommendations to drivers using received SPaT data to reduce vehicle fuel consumption levels. To construct an efficient algorithm, we first analyze the impact of different advisory speed limits and queue lengths on vehicle dynamics and their corresponding fuel consumption levels. The proposed Eco-CACC algorithm with the consideration of vehicle queues is then proposed to provide the most fuel-efficient recommendation to connected vehicles (CVs). A simulation analysis demonstrates that the algorithm is able to reduce the vehicle fuel consumption level by as high as 40%. Moreover, the overall benefits of the proposed algorithm is evaluated for different intersection configurations and CV market penetration rates (MPRs). The results demonstrate that for single-lane approaches, the algorithm can reduce the overall fuel consumption levels and that higher MPRs result in larger savings. While for multi-lane approaches, lower MPRs produce negative impacts on fuel efficiency; only when the MPRs are greater than 30%, can the algorithm work effectively in reducing fuel consumption levels.

2.0 Introduction

The recent rapid growth in passenger car and freight truck volumes has resulted in increased energy usage and air pollutant emissions. In U.S. alone, the transportation sector consumed over 135 billion gallons of fuel in 2013, and more than 70% was consumed by passenger cars and trucks [1]. Globally, 60% of the oil consumption is related to transportation sector [2]. The urgent need to reduce the transportation sector fuel consumption levels requires researchers and policy makers to develop various advanced fuel-reduction strategies. Eco-Driving is one efficient and cost effective strategy to improve fuel efficiency of the transportation sector [3]. The major idea behind eco-driving is providing real time driving advice to individual vehicles so that the drivers can adjust their driving behavior or take certain driving actions to reduce fuel consumption and emission levels.

There are various causes of high fuel consumption levels and air pollutant emissions generated by vehicles. Research in [4, 5] showed that frequent accelerations associated with stop-and-go waves are one major cause of greenhouse gas emissions in transportation systems. Move over, if a vehicle travels at an excessive speed over 60 mph, or moves slowly on a congested road, air pollutant emissions and fuel consumption levels will increase dramatically [6, 5]. And obviously, a complete stop or vehicle idling on roads result in inefficient fuel consumption. Consequently, it is clear that reducing traffic oscillations and avoiding idling are two critical operations to reduce fuel consumption levels. In general, eco-driving research can be categorized as freeway-based and city-based strategies.

On freeways, traffic stream is continuous, and there rarely include signals to slow down or stop vehicles. A vehicle can travel to a particular destination without any extra constraints. Developing eco-driving strategies on freeways is relatively straightforward. Providing advisory speed or speed limits to drivers based on road traffic conditions can alter driving behavior as well to minimize fuel consumption and emission levels.

2.1 Background

To date, numerous eco-driving strategies have been proposed to smooth traffic along freeways. Barth and Boriboonsomsin utilized vehicle-to-infrastructure communications to provide the average and variance of the speed along a roadway segment, and provide advisory speeds to drivers to reduce their fuel consumption and emission levels [7]. Yang and Jin estimated advisory speed limits for drivers based on the movements of surrounding vehicles with the assistance of vehicle-to-vehicle communications [8]. Ahn and Rakha developed a novel dynamic programming predictive eco-driving system that finds the optimum vehicle speed within a user-specified range using topographic and surrounding traffic information [9, 10].

Unlike freeways, traffic streams on arterial roads are interrupted by traffic signals. Vehicles are forced to stop at signals on red, which increases their travel time, fuel consumption and emission levels due to acceleration/deceleration maneuvers and idling required at the traffic signals. In the past several decades, most research efforts have focused on controlling traffic signal timings based on traffic volumes and vehicular queue lengths to optimize the performance of intersections [11, 3, 12]. Recently, with the development of connected vehicles (CVs), controlling individual vehicles to minimize fuel consumption and emissions is possible. Generally, eco-driving on arterial roads requires traffic signal phasing and timing (SPaT) and vehicle queue information to control Eco-CACC equipped vehicle movements to achieve environmental benefits. The primary assumption is that SPaT information for the upcoming traffic signal is available to the vehicle approaching it using V2I communications. Another assumption is that the vehicle is in full control and their driver follow precise instructions. This avoids the effects due to human interaction and the vehicles behaves just as completely automated. Connected vehicle technologies establish communications between vehicles and signals, and among vehicles to collect such information [13]. In the literature, researchers have spent significant time and efforts to develop connected vehicle environmental applications. Mandava et al. and Xia et al. proposed a velocity planning algorithm based on traffic signal information to maximize the probability of approaching a green indication when approaching multiple intersections [14, 15]. The algorithm reduced fuel consumption rates by minimizing acceleration/deceleration levels while avoiding complete stops. Asadi and Vahidi applied traffic signal information to design optimal cruise speeds for Eco-CACC equipped vehicles to minimize the probability of stopping at signals during red indications [16]. Malakorn and Park utilized SPaT information and developed a cooperative adaptive cruise control system to minimize absolute acceleration levels of Eco-CACC equipped vehicles as well as reducing fuel consumption levels [17]. Barth et al. developed a dynamic eco-driving system for arterial roads, which provided optimal acceleration/deceleration profiles for Eco-CACC equipped vehicles to minimize the total tractive power demand and the idling time so that the fuel consumption levels were reduced [18]. Rakha and Kamalanathsharma constructed a dynamic programming based fuel-optimization strategy using recursive path-finding principles, and evaluated it with an agent-based model [19, 20, 21]. De Nunzio et al. combined a pruning algorithm and an optimal control to find the best possible green wave if the vehicles were to receive SPaT information from multiple upcoming intersections [25]. Munoz and Magana developed an Android mobile application to evaluate the impact of an eco-driving assistant with moderate deceleration/acceleration on fuel consumption [26]. Most existing studies related to eco-driving on arterial corridors attempt to minimize idling time and smooth acceleration/deceleration maneuvers without considering the impact of surrounding traffic.

However, in reality, the idling time is determined not only by the SPaT plan, but also by vehicle queues at signals. So far, this problem is rarely mentioned in the literature. Moreover, most research efforts focus on optimizing speed profiles of Eco-CACC equipped vehicles upstream of the intersection, which ignores the accelerating behaviors after the signal turns to green. In this paper, we conduct a comprehensive analysis of eco-driving on arterial roads to fill this gap. We first investigate the impact of the SPaT and the vehicle queue information on fuel consumption levels at signalized intersections. Then, an analytical study on the impact of vehicle queues on the eco-driving algorithm proposed in [21] is introduced. Finally, an advanced eco-driving algorithm, Eco-CACC algorithm, is developed to minimize fuel consumption levels while considering the impact of vehicle queues. We also evaluate the benefits of the algorithm within a microscopic simulation environment, and evaluate the impact of market penetration rates of Eco-CACC equipped vehicles and intersection configurations on the performance of the system.

In terms of the layout, this chapter introduces a kinematic wave model to describe traffic dynamics at intersections and the generation and release of vehicle queues. Section 2.3 develops a synthetic eco-driving algorithm and evaluates the impact of advisory speed limits and queue length on environmental benefits. Section 2.4 describes the proposed Eco-CACC algorithm with the consideration of queue length. Section 2.5 evaluates the environmental benefits of the algorithm using microscopic simulation. Finally, Section 2.6 summarizes the study conclusions.

2.2 Traffic Dynamics at intersections

Lighthill, Whitham (1955) and Richards (1956) used kinematic waves from fluid dynamics in studying traffic dynamics. This modeling approach was later referred as LWR model [22, 23, 24]. This was the first major step in development of macroscopic models. It all started by identification of road traffic flow is analogous to flood movement in long rivers. According to this theory it was assumed that, on a coarse scale of measurement (macroscopic) traffic could be viewed as a fluid with a well-defined density everywhere. Richard (1956) complimented this idea with the introduction of shock waves on roadway traffic in a similar approach. Thus the LWR model came into existence after which there have been numerous developments in this field all beginning with the basic simple LWR model.

A relationship was proposed between density and flow for traffic on crowed arterial road with experimental backing. The equation of conservation was considered as first relation. If no net flow enter highway, vehicle conservation can be written as a sum of rate of change of density (ρ) with respect to time (t) and rate of change of flow (q) with respect to space (x).

$$\frac{\partial \rho}{\partial t} + \frac{\partial q}{\partial x} = 0 \qquad (2.1)$$

Into this, the proposed idea of flow as a function of density is introduced. The density is in turn a function of space and time.

LWR model in its original form has certain deficiencies like infinite deceleration for vehicle across shock waves, assumption of equilibrium relation for non-equilibrium traffic, non-representation of stop and go behavior and platoon dispersion. They also neglected heterogeneity of traffic as is the traffic observed in many cases.

In this section, we introduce a kinematic wave model to simulate traffic dynamics on a signalized road to analyze the impact of traffic signals on the movement of individual vehicles. The LWR model is one traditional kinematic wave model that describes the dynamics at any point on a road. The model assumed that both flow and speed are functions of the traffic stream density and traffic stream density is in turn a function of space and time, i.e.

$$\frac{\partial \mathrm{\rho}(x,\ t)}{\partial t} + \frac{\partial \mathrm{q}(x,\ t)}{\partial x} = 0 \qquad (2.2)$$

$$q(x,t)=Q(\rho(x,t)); \tag{2.2a}$$

$$v(x,t)=V(\rho(x,t)). \tag{2.2b}$$

Moreover, we know

$$q(x,t)=v(x,t)\rho(x,t). \tag{2.2c}$$

These relationships are called fundamental diagrams. Fig. 2.1 illustrates a general fundamental diagram. Generally flow is a function of the density. This diagram is used in calculating shockwave speeds in the system when there is a change in density and flow. The slope of the line joining the initial and final states gives the speed of shockwave.

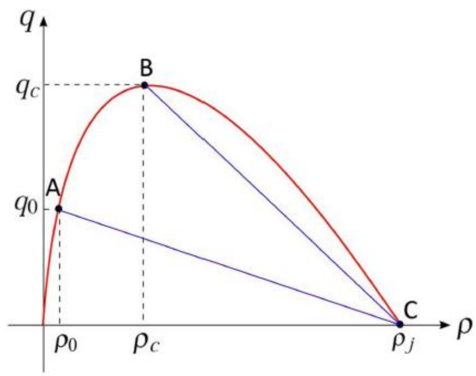


Figure 2.1: Fundamental Diagram

In the transportation system, shock waves or rarefaction waves are defined as the motion of an abrupt change or discontinuity in traffic stream density. Traffic signals generate various shockwaves and rarefaction waves, which lead to high variations in vehicular movements. Fig.2.2 illustrates the movements of vehicles approaching and passing an intersection. In general, there are two signal states: red and green. If one vehicle arrives at the intersection when the traffic signal indication is green, it proceeds through the intersection without any delay; while it has to wait at the stop bar for a green indication when the traffic signal is red. Clearly, the red signal generates a shock wave upstream of the intersection.

Assume that the flow entering the intersection is q_0, and during the green indication, the state at the upstream of the intersection is *A*, as shown in Fig.2.1. Once the signal turns red, no vehicle can proceed through the intersection, i.e., its upstream operates at the maximum road density, ρ_j, and the discharge volume is reduced to 0. The upstream state becomes *C*. Hence, a shock wave is generated and propagates backward. The speed of the shock wave is determined by the states *A* and *C*, i.e.

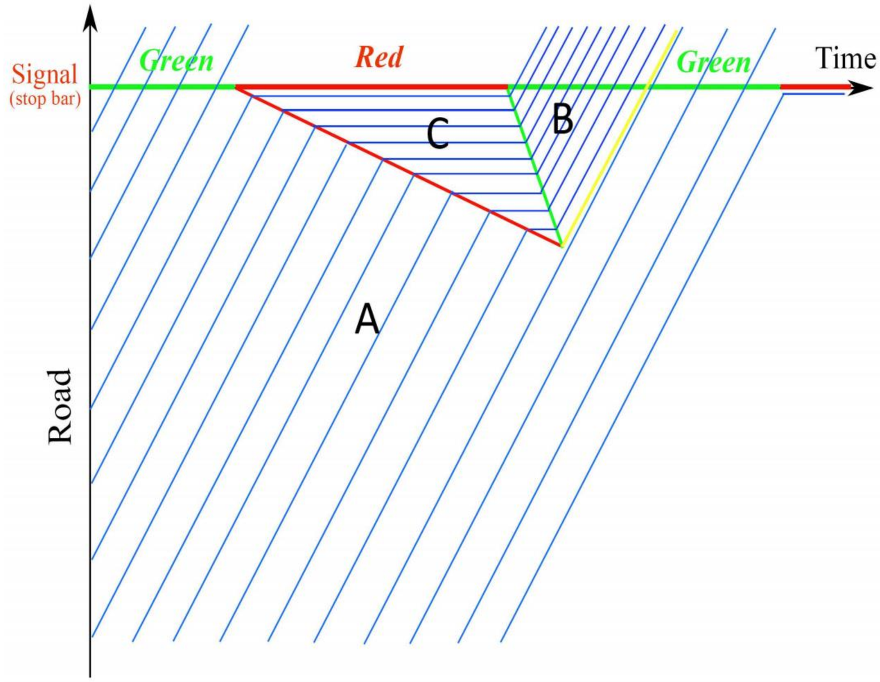


Figure 2.2: Traffic dynamics at signalized intersection

$$v_{AC} = \frac{q_0}{\rho_0 - \rho_j} \tag{2.3}$$

Once the traffic signal turns green, the intersection starts to discharge vehicles at the saturation flow rate, i.e. q_c in Fig 2.1, then a rarefaction wave is formed to mitigate the congestion upstream of the intersection, and the downstream state becomes B. The speed of the rarefaction wave is defined as

$$v_{AC} = \frac{q_0}{\rho_c - \rho_j} \tag{2.4}$$

In general the speed of the rarefaction wave is greater than that of the shockwave as show in Fig.2.1. As time progresses, the rarefaction wave will catch the shockwave and dissipate the queue/congestion upstream of the intersection. Obviously, the traffic signal generates stop-and-go driving for individual vehicles, which increases their fuel consumption rates significantly. In order to minimize fuel consumption rates on arterial roads, controlling vehicles to ensure that they proceed through intersections smoothly without stopping is a critical factor in reducing vehicle fuel consumption levels.

2.3 Synthetic Eco-CACC algorithm

In this section, we develop a synthetic Eco-Driving Algorithm based on the study in [21] to minimize the fuel consumption of vehicles proceeding through the intersections. The algorithm is described as follows.

Once a Eco-CACC equipped vehicle enters the segment between Eco-Speed control link and the signal, as shown in Fig 2.2 the following two actions will be applied.

1. If the Eco-CACC equipped vehicle can pass through the intersection at its original speed, v_0, we do not control the vehicle, and set the advisory speed limit as the road speed limit, v_f.

2. If the vehicle cannot proceed through the intersection, we provide a lower speed limit, $v_c \leq v_0$, for the vehicle to approach he signal.

The basic criteria for estimating the advisory speed limit, v_c, is to reduce the stop duration while maintain the average speed of the controlled vehicles.

2.3.1 Impact of speed limits on Vehicle Fuel Consumption Levels

Assume that when the distance between the Eco-CACC equipped vehicle and the signal is less than d, an advisory speed limit, v_c, is estimated for the Eco-CACC equipped vehicle. The limit is chosen from 0 to v_0. There are three different types of settings for the advisory speed limit (see Fig.2.3).

1. $v_c = v_2$, which allows the Eco-CACC equipped vehicle to arrive the stop bar just when the traffic signal turns green. In this case, the vehicle does not need to stop at the intersection to wait for the green indication, and the stopped delay is avoided. At the same time, the setting maintains the average speed of the Eco-CACC equipped vehicle to pass the intersection.
2. $v_c = v_1$, and $v_2 < v_1 < v_0$. This setting indicates the Eco-CACC equipped vehicle moves to the stop bar with a smaller speed, but it will still stop completely to wait for the green indication. The vehicle applying this setting can maintain its average speed, but cannot avoid incurring the stopped delay caused by the signal.
3. $v_c = v_3$, and $0 < v_3 < v_2$. This setting allows the Eco-CACC equipped vehicle to travel with an even smaller speed so that it does not have to stop at the intersection. However, as the limit is too small, the Eco-CACC equipped vehicle cannot arrive at the stop bar when the traffic signal turns green. In that sense, the vehicle has to accelerate to the free-flow speed to proceed through the intersection. The vehicle applying this setting can avoid incurring stopped delay, but it has to accelerate from a very low value, and its travel time increases as well as its fuel consumption level.

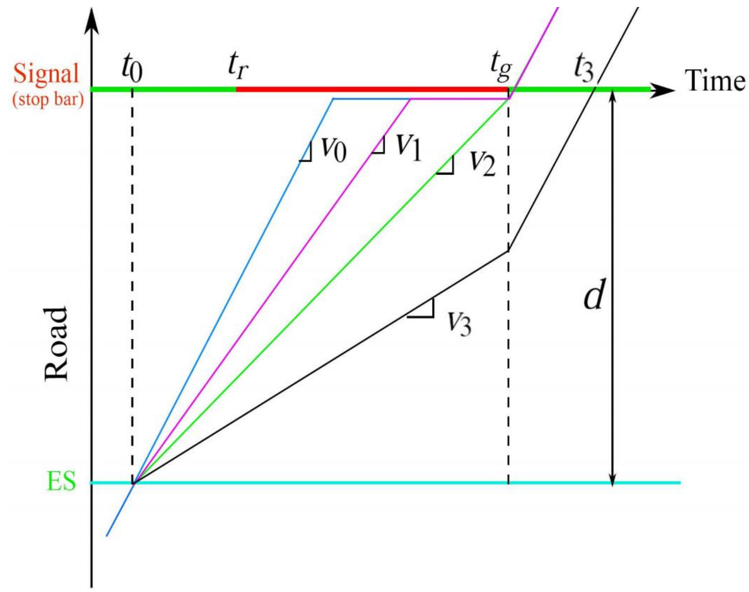


Figure 2.3: Eco-Speed with different advisory speed limits

Here, we introduce a simple example to analyze the impact of different advisory speed limits on the system performance. Assume that the distance from the activation point of the Eco-CACC algorithm to the stop bar is d = 500 meters, and the segment is flat. Initially at $t_0 = 0$, the vehicle is traveling at the free-flow speed, i.e., v_0 = 72 km/h. The next green indication starts at $t_g = 60$ seconds. Fig.2.4 shows the impact of the advisory speed limits on the fuel consumption levels and the travel time. Clearly, when $v_c > v_2$, the algorithm does not increase the travel time. However, a higher v_c value results in larger fuel consumption rates. When $v_c < v_2$, with lower v_c, the fuel consumption rate is higher, and at the same time the travel time increases. In that sense, we see that the best setting of v_c is v_2, which can maintain the travel time and minimize the fuel consumption level simultaneously.

2.3.2 Impact of Queue Length

In reality, a traffic signal delays vehicles not only by the duration of the red indication, but also by the time taken to release the queue. As described in Section 2.2, a red indication generates a shock wave and forms a vehicular queue upstream of the intersection. It takes a certain amount of time for the traffic signal to dissipate the queue. In that sense, applying the optimal speed limit, $v_c = v_2$, proposed in the aforementioned subsection is not sufficient to prevent a complete stop at the intersection. Fig.2.5 illustrates the impact of the vehicle queue on the Eco-CACC control algorithm. Assume that the queue length ahead of one Eco-CACC equipped vehicle is N, and the jam spacing is s_j. Without control, the Eco-CACC equipped vehicle will stop once its distance to the stop bar is $d_0 = N.s_j$. As there is a queue ahead, the vehicle cannot move even when the traffic signal turns green. Only when the rarefaction wave generated by the green indication reaches the Eco-CACC equipped vehicle, can it

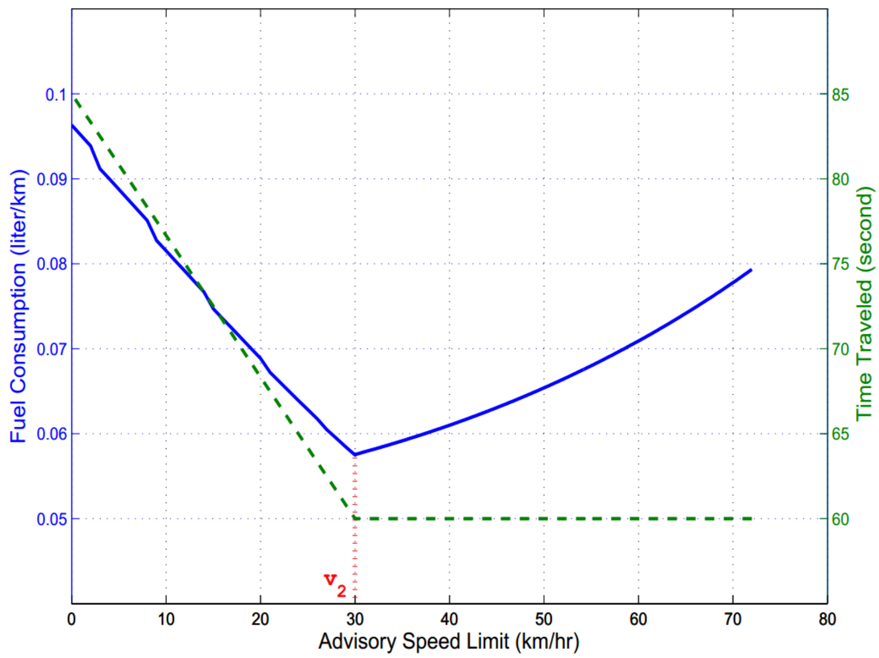


Figure 2.4: Eco-Speed with different advisory speed limits

accelerate to proceed through the intersection. Without the consideration of the vehicular queue, the Eco-CACC algorithm, which we proposed in the aforementioned subsection, estimates an advisory speed limit for the Eco-CACC equipped vehicle so that it can move to the stop bar just when the light turns to green, i.e., $v_c = v_2$. However, with accumulated vehicles ahead of the signal, the Eco-CACC equipped one has to stop at the end of the queue, wait until the queue is released, and then pass the intersection. Hence, the advisory speed limit and the cruise time of the vehicle are

$$v_{c,1} = \frac{d}{\Delta t_c} \tag{2.5a}$$

$$\Delta t_{c,1} = \Delta t'_c = \frac{d - d_0}{v_1} \tag{2.5b}$$

Here, $\Delta t_c^{'}$ is the duration after which the queue starts to be dissipated after the traffic signal turns green. Furthermore, the duration of time that the vehicle is stopped at the signal is

$$\Delta t'_{s,1} = \Delta t_c - \Delta t'_c + \Delta t''_c \tag{2.5c}$$

where Δt is the duration of time for the queue to be released from the start of the green indication

$$\Delta t''_c = \frac{d_0}{v_w} \tag{2.5d}$$

Where,

$$v_w = \frac{q_0}{\rho_c - \rho_j} \tag{2.5e}$$

With the recent introduction of advanced data collection technologies, the queue length at a signalized intersection can be estimated accurately [28, 29]. The Eco-CACC equipped vehicle is able to obtain the length of queues ahead through vehicle-to-signal communication. Considering the impact of queues, the Eco-CACC algorithm has to provide different advisory speed limits. Generally, the limit should allow the Eco-CACC equipped vehicle to pass the intersection without any stop. Hence, as shown in Fig.2.5, the advisory speed limit and the cruise time of the Eco-CACC equipped vehicles are

$$v_{c,2} = \frac{d - d_0}{\Delta t_c + \Delta t''_c} \tag{2.6a}$$

$$\Delta t_{c,2} = \Delta t_c + \Delta t''_c \tag{2.6b}$$

Obviously, the duration of the stop is

$$\Delta t_{s,2} = 0 \tag{2.6c}$$

Moreover, for the base case without control, the speed the vehicle cruises to the stop bar. The cruise time and the stop duration are computed as

$$v_{c,0} = v_0 \tag{2.7a}$$

$$\Delta t_{c,0} = \frac{d - d_0}{v_0} \tag{2.7b}$$

$$\Delta t_{s,0} = \Delta t_c + \Delta t''_c \tag{2.7c}$$

Clearly, there exist $v_{c,0} > v_{c,1} > v_{c,2}$, $t_{c,0} < t_{c,1} < t_{c,2}$, and $t_{s,0} > t_{s,1} > t_{s,2}$.

In the rest of this subsection, we use the example in Section 2.4 to illustrate the impact of the queue length on the estimation of advisory speed limits, stop durations, and fuel consumption rates. Fig.2.6 shows that without considering the queue at the intersection, the advisory speed limit estimated by the Eco-CACC algorithm will be constant for different queue lengths. While with the vehicle queues, the advisory speed limits change with changes in the queue lengths. A longer queue length results in a smaller advisory speed limit. Moreover, from Fig.2.7, we see with the consideration of the vehicular queue, the Eco-CACC equipped vehicle travels at the advisory speed limit to avoid any stops at the intersection, and the duration of the complete stop is 0. But, for the base case and the control without queue, longer queues result in larger durations of stops. Obviously, with the Eco-CACC algorithm, the durations are smaller. Furthermore, we can compare the fuel consumption rates of the three scenarios with different queue lengths (see Fig.2.8).

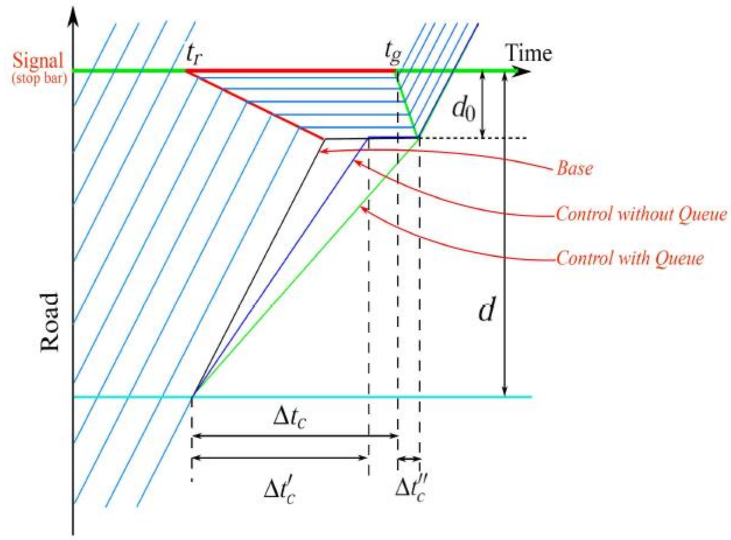


Figure 2.5: Eco-Speed with different advisory speed limits

Obviously, with longer queues, the fuel consumption rates are higher in all three scenarios. However, with the Eco-CACC algorithms, the fuel consumption levels can be reduced. The control with queue results in the least fuel consumption compared to the other scenarios.

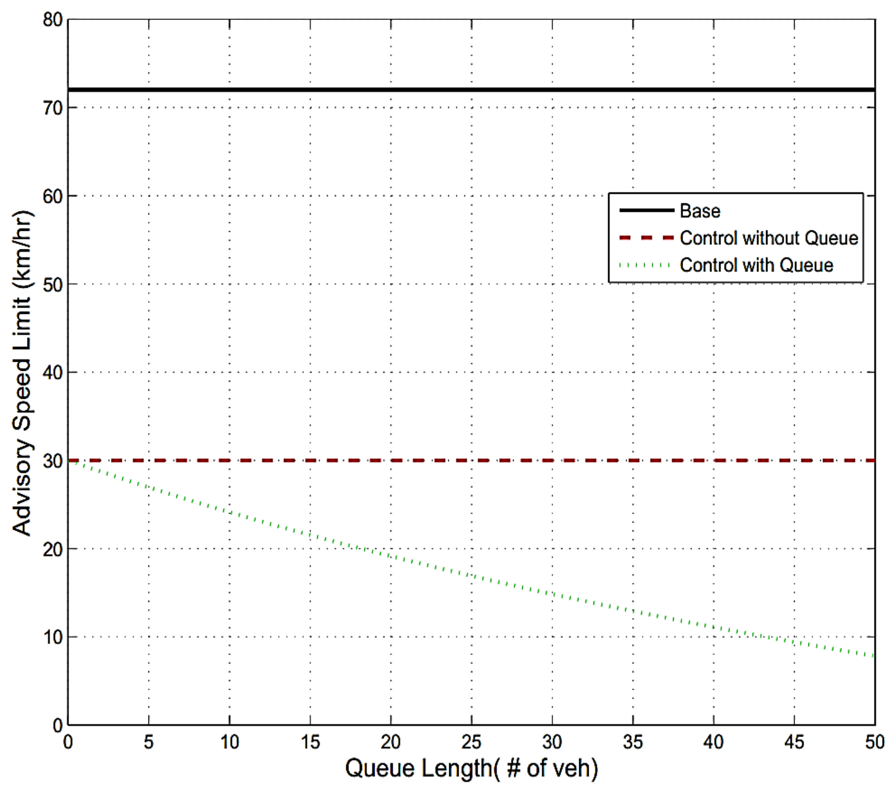


Figure 2.6: Impact of queue length on advisory speed limit

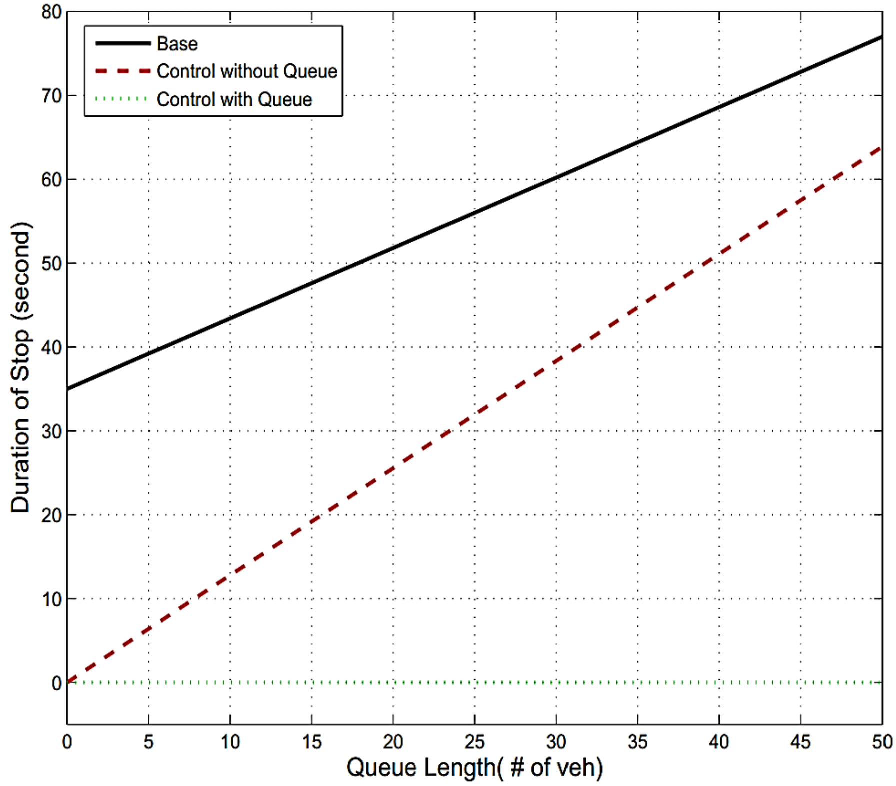


Figure 2.7: Impact of queue length on stop delay

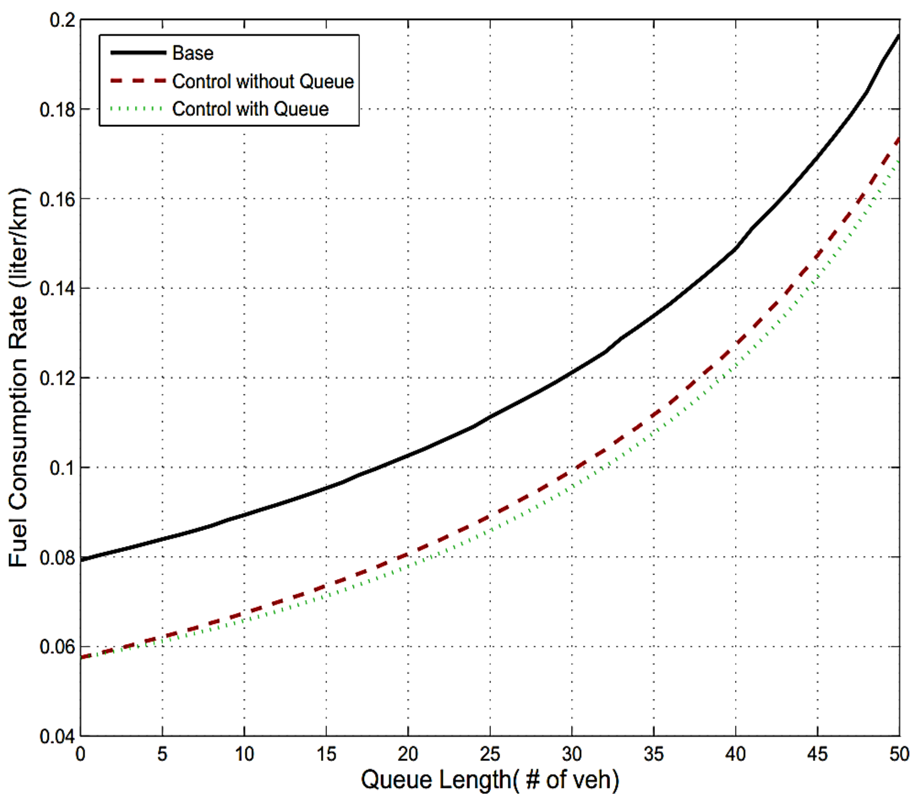


Figure 2.8: Impact of queue length on fuel consumption rate

From the analysis above, we see that the most critical strategy to reduce fuel consumption rates at intersections is minimizing the duration of the complete stop. Furthermore, an ideal case is when the Eco-CACC equipped vehicle is provided with the largest advisory speed limit so as to avoid a complete stop.

2.4 Eco-CACC Algorithm Considering Queue Effects

Section 2.3 demonstrated that the most critical strategy to reduce fuel consumption levels is to prevent vehicles from coming to a complete stop at the stop bar. The section analyzed the impact of the advisory speed limit and the length of the vehicle queue on the fuel consumption rate. However, the analysis assumes that both deceleration and acceleration rates can be infinite, which is not realistic. Hence, to design an applicable Eco-CACC algorithm, we have to consider the impact of deceleration levels upstream of the intersection and acceleration levels downstream. In this section, we first develop an Eco-CACC algorithm to minimize vehicle fuel consumption levels while proceeding through an intersection with the consideration of deceleration and acceleration levels, followed by an investigation about the impact of queue length on the algorithm.

2.4.1 Development of the Eco-CACC Algorithm

In this subsection, we propose an Eco-CACC algorithm that uses realistic deceleration and acceleration levels. Instead of providing a constant advisory speed limit, the algorithm estimates a time-dependent advisory speed limit for the Eco-CACC equipped vehicle to decelerate to a speed and cruise to the stop bar or the tail of the queue. Subsequently, once the queue is released, the vehicle accelerates to the free-flow speed at a constant throttle level. In that sense, the Eco-CACC algorithm estimates an optimal deceleration and acceleration level to minimize the total fuel consumed. As shown in Fig.2.9(a), upstream of the intersection, when the distance between the Eco-CACC equipped vehicle and the signal is less than d, the Eco-CACC algorithm is activated. Without control, the Eco-CACC equipped vehicle maintains its original speed v_0 until it has to stop at the end of the queue at deceleration level, a_s to stop. For the Eco-CACC algorithm without a queue, the Eco-CACC equipped vehicle decelerates to a cruising speed, with which the vehicle cruises to the stop bar just when the signal turns green.

While the queue forces the vehicle to stop at the queue tail at a deceleration level, a_s. Finally, with the consideration of the vehicle queue, the algorithm reduces the speed of the Eco-CACC equipped vehicle at a constant deceleration level to arrive at the tail of the queue just when the queue is released, i.e., at $t = t_c$. Downstream of the intersection, the algorithm should also allow the vehicle to accelerate back to the free-flow speed v_f at location x_d. Without control, the vehicle utilizes a constant acceleration level, a_+^s, to approach v_f. While, with the Eco-CACC algorithm, an optimal acceleration level is used to accelerate from the speed at x_d. The acceleration level is determined by the cruise speed and the distance x_d. Hence, the Eco-CACC algorithm minimizes the vehicle fuel consumption level by searching the optimal combination of the upstream deceleration level, a_-, and the downstream acceleration level, a_+.

In order to develop the Eco-CACC algorithm, we first define the objective function. Obviously, the algorithm is designed to minimize the fuel consumption level of Eco-CACC equipped vehicles traversing the intersection. The objective function is

$$\min_{a_-,a_+} \int_{t_0}^{t_0+T} F\left(v(t)\right)dt \tag{2.8a}$$

s.t.

$$0 \le a_- \le a_-^s \tag{2.8b}$$

$$0 \le a_+ \le a_+^s \tag{2.8c}$$

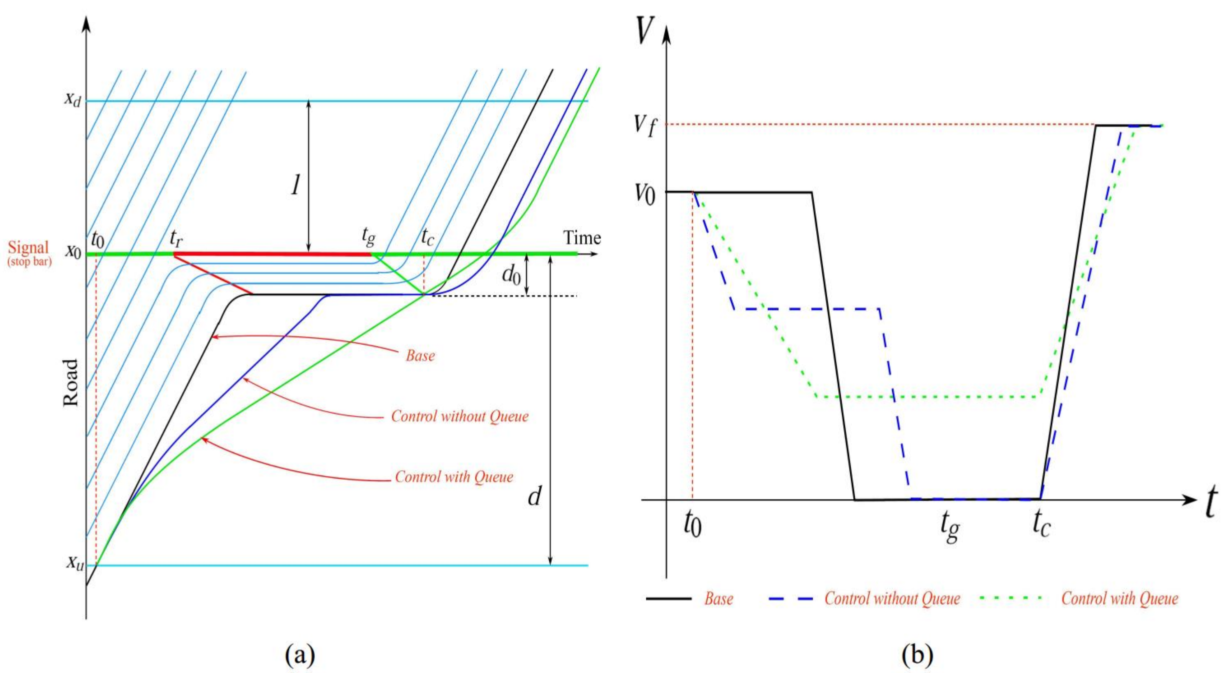


Figure 2.9: Eco-CACC (a) Traffic dynamics at an intersection, (b) speed of Eco-CACC equipped vehicle

Here, $F(.)$ is the function to estimate the fuel consumption rate. In this study, we introduce the Virginia Tech Comprehensive Power-based Fuel consumption Model (VT-CPFM) [30] to estimate the fuel consumption rate. For the *algorithm without queue*, the advisory speed limit of the Eco-CACC equipped vehicle, $v(t)$, can be computed as

$$v(t) = \begin{cases} v_0 - a_-\left(t - t_0\right) & t_0 \le t < t_0 + \delta t_{n,1} \\ v_{n,t} & t_0 + \delta t_{n,1} \le t < t_0 + \delta t_{n,1} + \delta t_{n,2} \\ v_{n,t} - a_-^s\left(t - t_0 - \delta t_{n,1}\right) & t_0 + \delta t_{n,1} + \delta t_{n,2} \le t < t_0 + \delta t_{n,1} + \delta t_{n,2} + \delta t_{n,3} \\ 0 & t_0 + \delta t_{n,1} + \delta t_{n,2} + \delta t_{n,3} \le t < t_c \\ v_f & t_0 + \delta t_2 \le t \le t_0 + T_n \end{cases} \tag{2.9a}$$

Here, $v_{n,t}$ is defined as the algorithm cruise speed without considering the queue effects. The speed profile is shown as the blue dashed line in Fig.2.9(b). Furthermore, the variables, $\{T_n, v_{n,t}, \delta t_{n,1}, \delta t_{n,2}, \delta t_{n,3}, \delta t_{n,4}\}$ can be estimated using Eq 2.9(b)-2.9(g) using the given values of a_- and a_+.

$$\delta t_{n,1} = \frac{v_0 - v_{n,t}}{a_-} \tag{2.9b}$$

$$v_0.\delta t_{n,1} - \frac{1}{2} a_- \delta t_{n,1}^2 + v_{n,t} \delta t_{n,2} + v_{n,t} \delta t_{n,3} + \frac{1}{2} a_-^s \delta t_{n,2}^2 = d - d_0 \tag{2.9c}$$

$$v_0.\delta t_{n,1} - \frac{1}{2} a_- \delta t_{n,1}^2 + v_{n,t} \delta t_{n,2} + v_{n,t}(t_g - t_0 - \delta t_{n,1}) = d \tag{2.9d}$$

$$\delta t_{n,3} = \frac{v_{n,t}}{a_-^s} \tag{2.9e}$$

$$\delta t_{n,4} = \frac{v_f - v_{n,t}}{a_+} \tag{2.9f}$$

$$\frac{1}{2} a_+ \delta t_{n,4}^2 + v_f.(t_0 + T_n - t_c - t_{n,4}) = l + d_0 \tag{2.9g}$$

For the *algorithm with queue*, the advisory speed limit of the Eco-CACC equipped vehicle, $v(t)$, is

$$v(t) = \begin{cases} v_0 - a_-(t - t_0) & t_0 \le t < t_0 + \delta t_{q,1} \\ v_{q,t} & t_0 + \delta t_{q,1} \le t < t_c \\ v_{q,t} + a_+(t - t_c) & t_c \le t < t_c + \delta t_{q,2} \\ v_f & t_c + \delta t_{q,2} \le t < t_0 + T_q \end{cases} \tag{2.10a}$$

Here, $v_{q,t}$ is the cruise speed of the algorithm with queue. The speed profile is illustrated as the green dotted line in Fig.2.9(b). And, the variables, $\{T_q, v_{q,t}, \delta t_{q,1}, \delta t_{q,2}\}$ can be estimated by Eq (2.10)(b)-(e) under the given values of a_- and a_+.

$$\delta t_{q,1} = \frac{v_0 - v_t}{a_-} \tag{2.10b}$$

$$v_0.\delta t_{q,1} - \frac{1}{2} a_- \delta t_1^2 + v_{q,t}(t_c - t_0 - \delta t_{q,1}) = d - d_0 \tag{2.10c}$$

$$\delta t_{q,2} = \frac{v_f - v_{q,t}}{a_+} \tag{2.10d}$$

$$v_t.\delta t_{q,1} + \frac{1}{2} a_+ \delta t_{q,2}^2 + v_f.(t_0 + T_q - t_c - \delta t_{q,2}) = l + d_0 \tag{2.10e}$$

Here, given the road traffic condition, including the queue length, start and end times of each phase, and the approaching speed of the Eco-CACC equipped vehicles, the speed profile is a function of a_- and a_+. Since the fuel consumption rate is determined by the speed profile, it is constant given the constant values of a_- and a_+. In that sense, there exist the optimal deceleration and acceleration rates to minimize the fuel consumption rate. The Eco-CACC algorithm searches the optimal values within appropriate ranges (Eq (2.8)(b) and (c)).

The details of the Eco-CACC algorithm with queue consideration is described below.

1. For a Eco-CACC equipped vehicle k, once it enters the segment $[x_u, x_0]$, the Eco-CACC algorithm is activated.
2. Upstream of the intersection.
    a. The algorithm provides an advisory speed limit to the Eco-CACC equipped vehicles for the following two scenarios; otherwise, the road speed limit is used as the advisory limit.
        i. The current signal indication is green, but the traffic signal will turn red when the vehicle arrives at the stop bar if it travels at its current speed.
        ii. The current signal indication is red and will continue to be red when the vehicle arrives at the stop bar while traveling at its current speed.
    b. Once either of the above scenarios occurs, we predict the queue length ahead of the Eco-CACC equipped vehicle, and estimate the release time of the queue, tc, based on the speed of the rarefaction wave (see Eq (2.4)).
    c. The algorithm estimates the optimal upstream deceleration level and the downstream acceleration level using Eq (2.8) and Eq (2.10) to minimize the vehicle fuel consumption, and provides an advisory speed limit to the Eco-CACC equipped vehicle at the next time step t + Δt, where Δt is the updating interval of the speed advices.

3. Downstream of the intersection, the algorithm searches for the optimal acceleration level based on its current speed to minimize the fuel consumption to reach the free-flow speed v fat location x_d .
4. Once the Eco-CACC equipped vehicle arrives at x_d, the Eco-CACC algorithm is deactivated.

2.4.2 Impact of Queue Length

In this subsection, we will investigate the impact of the queue length on the Eco-CACC algorithm with queue proposed in the aforementioned subsection. From Eq (2.9) and Eq (2.10), we see given the values of the upstream deceleration level, a_-, and the downstream acceleration level, a_+, the speed profile of the Eco-CACC equipped vehicle is determined, and the fuel consumption rate can be estimated using the VT-CPFM model. In that sense, it is able to find an optimal combination of $\{a_-,a_+\}$to minimize the total fuel consumed. Another variable that affects the Eco-CACC algorithm is the queue length. With longer queue length, the Eco-CACC equipped vehicle should stop at the intersection with longer time, and the cruise speed estimated by the Eco-CACC algorithm is smaller. Hence, the fuel consumption rate is larger. In the rest of this subsection, we apply a synthetic example to analyze the impact of queue length. Assume that the lengths of the controlled segments upstream and downstream of the intersection are d = 500 m, and l = 200 m, respectively. The Eco-CACC equipped vehicle arrives at location x_u at t_0 = 0s with an initial speed v_0 = 72 km/h, and the signal turns green at t_g = 60s. Moreover, the free-flow speed, the roadway saturation flow rate, the jam density, and the density at the capacity are v_f = 72 km/h, q_c = 1600 veh/h, ρ_j = 160 veh/km, and ρ_c = 20 veh/km, respectively.

Fig.2.10 and Fig.2.11 illustrates the impact of queue length on the total fuel consumed rate and the cruise speed. Clearly, the Eco-CACC algorithm can significantly reduce the fuel consumption of the Eco-CACC equipped vehicles. The algorithm without queue reduces the fuel consumption by as high as 36%, and 38% when the queue is considered. Moreover, when we compare the two Eco-CACC algorithms with and without the queue, the first produces fuel consumption levels that are 10% lower. Furthermore, with longer queues, the cruise speed is smaller, which can be derived from Eq (2.10). At the same time, the fuel consumption is larger. Obviously, introducing the Eco-CACC algorithm considering the queue effects can improve the fuel efficiency of the Eco-CACC equipped vehicles.

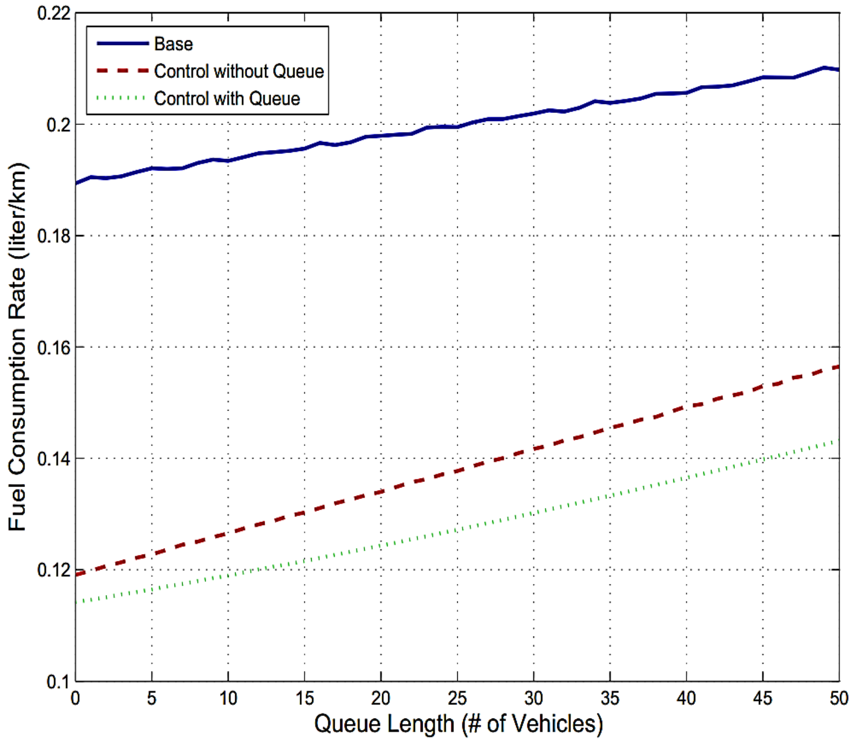


Figure 2.10: Impact of queue length on fuel consumption rate

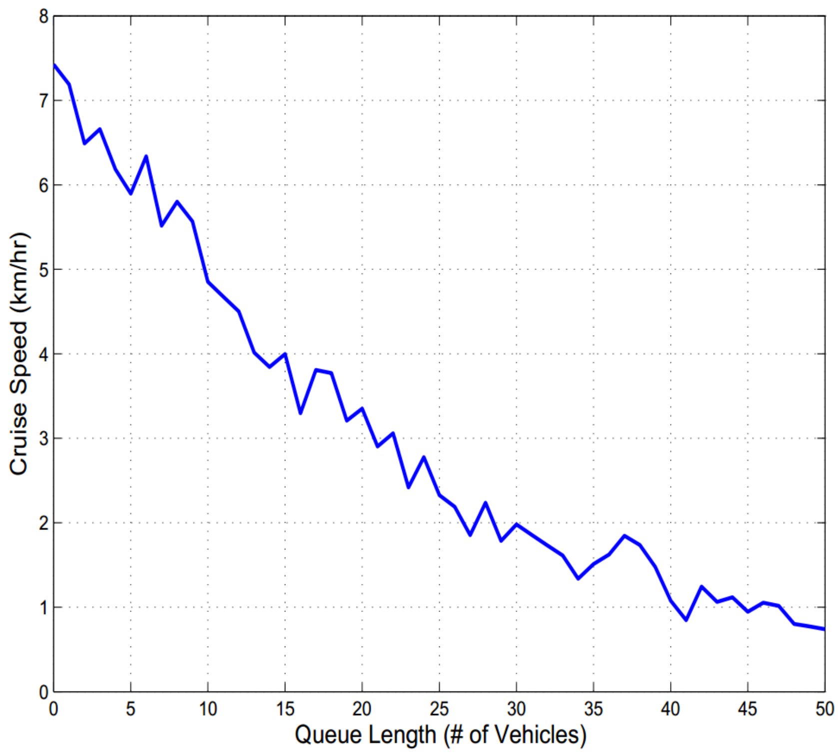


Figure 2.11: Impact of queue length on cruise speed from the eco-speed algorithm

2.5 Case Studies

In this section, we evaluate the Eco-CACC algorithm proposed above with different configurations of intersections. Fig.2.12 illustrates the configuration of the intersection applied for the evaluation. In the case studies, we start with an intersection with a single movement. The upstream segment of the signal with the length *d*, and the downstream segment with the length *l* are the control segment. With the Eco-CACC algorithm, the Eco-CACC equipped vehicle at the upstream will decelerate to an optimal cruise speed to avoid complete stop, and at the downstream, it will accelerate to the free-flow speed with an optimal rate. The two operations are integrated to minimize the fuel consumption rate from the Eco-CACC equipped vehicle on the control segment. In this section, the intersection with a one- and two-lane roads is simulated with a microscopic traffic simulator, INTEGRATION [29], to verify the benefits of the Eco-CACC algorithm.

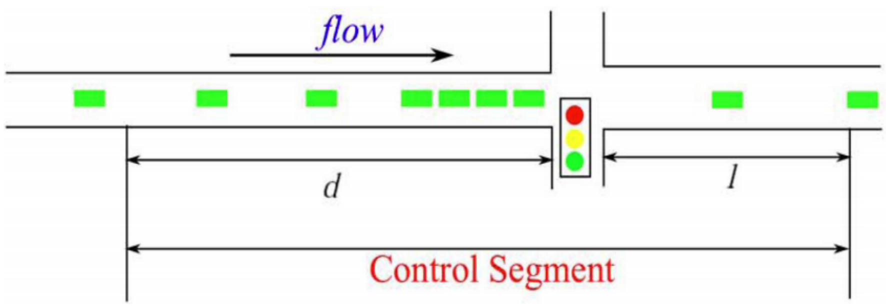
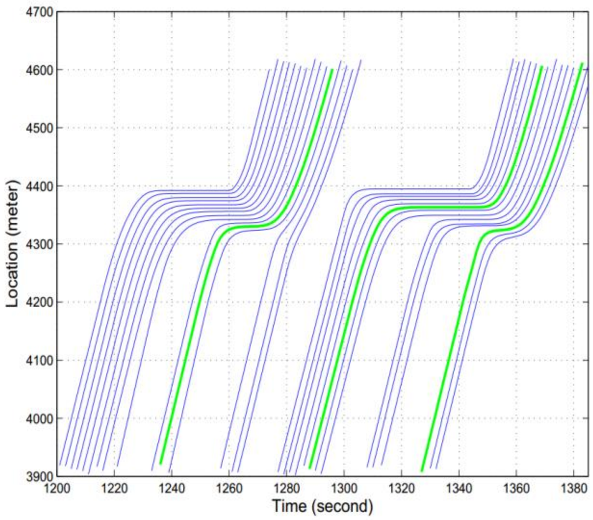


Figure 2.12: Intersection configuration

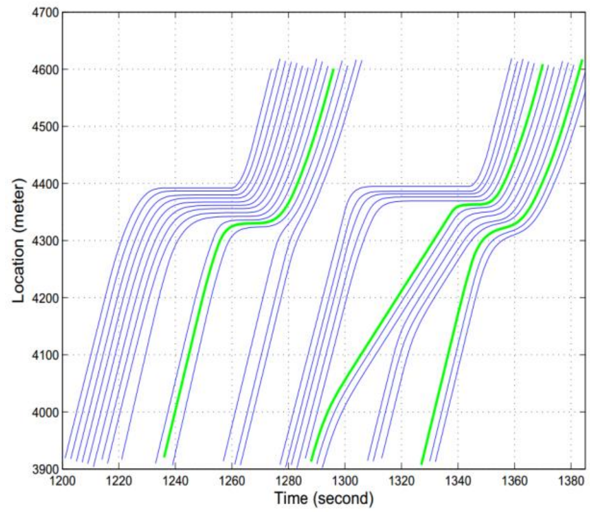
2.5.1 Single-lane Intersection

In this subsection, we simulate a single-lane intersection, where both upstream and downstream roads have only one lane. The free-flow speed, the jam density, the saturation flow rate, and the speed-at-capacity are set as v_f = 80 km/h, ρ_j = 160 veh/km, q_c = 1600 veh/h, and v_c = 60 km/h, respectively. For the signal phasing and timing plan of the intersection, we set the green, amber, and red durations to be 40 seconds, 4 seconds, and 40 seconds, respectively. Assume that we load a constant demand of q = 500 veh/h to the intersection for one hour, and 20% of the vehicles act as CVs with wireless communication devices to receive the SPaT and vehicle queue information, i.e., approximately 100 CVs are loaded on the network. The Eco-CACC algorithms with and without queue consideration are implemented in the CVs to minimize their fuel consumption levels. The length of the control segments upstream and downstream of the intersection are assumed to be d = 500 meters and l = 200 meters, respectively. Fig.2.13 illustrates the trajectories of all vehicles before and after applying the Eco-CACC algorithms at the intersection over two cycles, where the signal is located at x = 4400 meters. In Fig.2.13(a), without the Eco-CACC algorithm, the Eco-CACC equipped vehicles just follow their leaders, and they come to a complete stop ahead of the signal waiting for the green indication to release the queue.

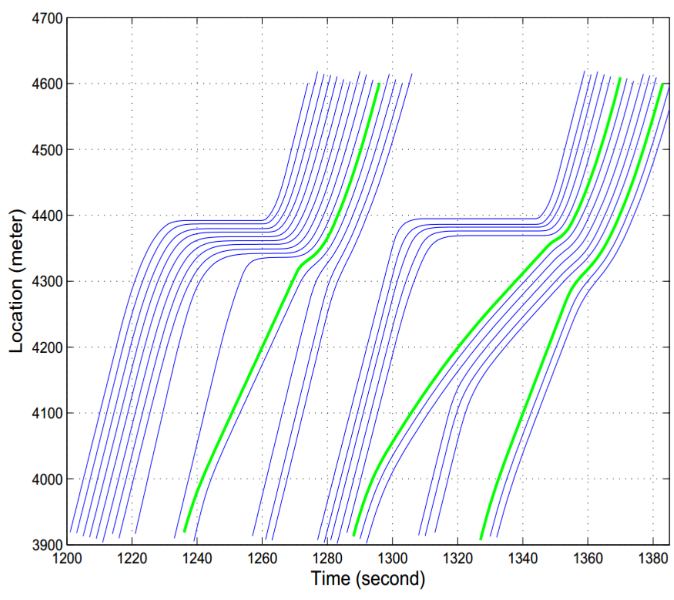
Fig.2.13(b) shows the trajectories after applying the algorithm without the consideration of the queue. As can be seen from the second Eco-CACC equipped vehicle in the figure, the vehicle slows down to approach the signal and catches the green light. Because of the vehicle queue, the vehicle has to stop ahead of the intersection to wait for the release of the queue. While in Fig.2.13(c), the algorithm with queue can assist the Eco-CACC equipped vehicle to cruise to the intersection and catch the tail of the queue



(a)



(b)



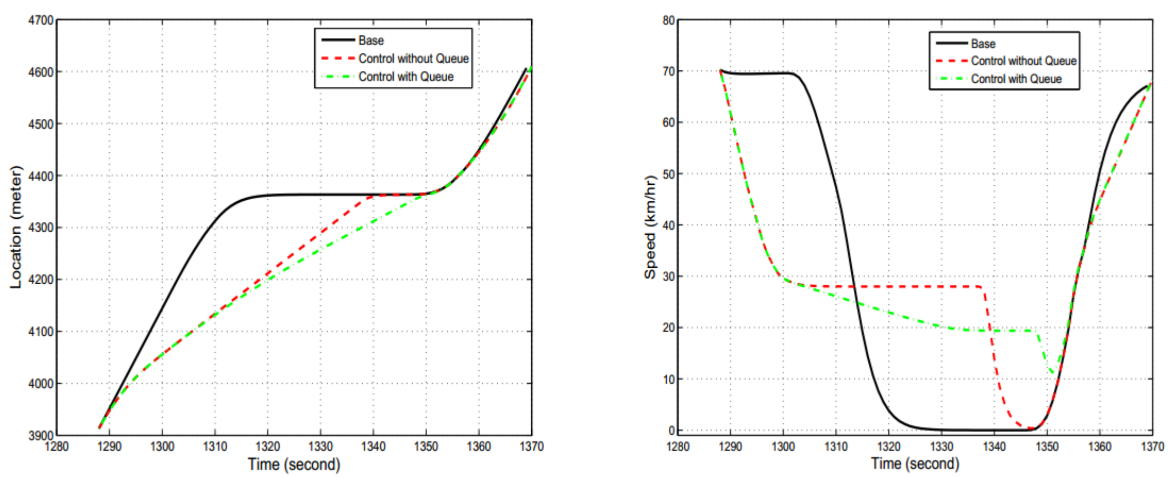
(c)

Figure 2.13: Vehicle trajectories around a single lane intersection (a) base case, (b)eco-speed without queue, (c) eco speed with queue.

just when it is released, so that the vehicle can avoid coming to a complete stop upstream of the intersection.

Note that in Fig.2.13(b), the first and the third Eco-CACC equipped vehicles are not controlled by the Eco-CACC algorithm. The reason is that the algorithm without queue consideration estimates that the Eco-CACC equipped vehicles will proceed through the intersection at their current speed. However, due to the impact of the vehicle queues, the Eco-CACC equipped vehicles have to wait for the release of the queue. Hence, they still experience a complete stop. The algorithm with queue consideration solves this problem. Consequently, we observe these two vehicles that are controlled in Fig.2.13(c) do not stop at the signal.

Fig.2.14 (a) and (b) compare the trajectories and the speed profiles of the second Eco-CACC equipped vehicle for the three different scenarios, respectively. The results are quite similar to Fig.2.9. The trajectories controlled by the Eco-CACC algorithms is much smoother than the base case, and the algorithm with queue consideration generates the smoothest trajectory. Moreover, for the algorithm without queue, the Eco-CACC equipped vehicle cruises at a speed of 28 km/h, and stops for approximately 8 seconds (for the base case, it stops for approximately 30 seconds.)3. While being controlled by the algorithm with queue consideration, the vehicle cruises at 20 km/h, and does not stop upstream of the signal. Furthermore, the fuel consumption rates generated by the Eco-CACC equipped vehicles are 0.125 l/km for the base case, 0.116 l/km for the algorithm without queue consideration, and 0.111 l/km for the algorithm with queue consideration, respectively. In summary, the algorithm that considers the queue is the most efficient control strategy, with reductions in fuel consumption levels as high as 11.4%.



(a) (b)

Figure 2.14: Comparison of second Eco-CACC equipped vehicles dynamics on a single lane intersection by (a) trajectories and (b) speed profiles

Besides the Eco-CACC equipped CVs, the Eco-CACC algorithm also smooths the behavior of non-CVs given that they are governed by car-following rules and thus would have to follow the behavior of their lead vehicle (it should be noted that the approaches are single lanes). This means the algorithm is able to reduce the overall fuel consumption at the signalized intersection. The example above indicates that the algorithm without queue consideration and with queue consideration reduces the fuel consumption level by approximately 8.4% and 10.4%, respectively. In addition, we investigate the impact of market penetration rates (MPRs) on the Eco-CACC algorithm. The settings of the simulation are the same as the example above, except that the MPR varies from 0 to 100%. Fig.12 shows the savings in the average fuel consumption derived from

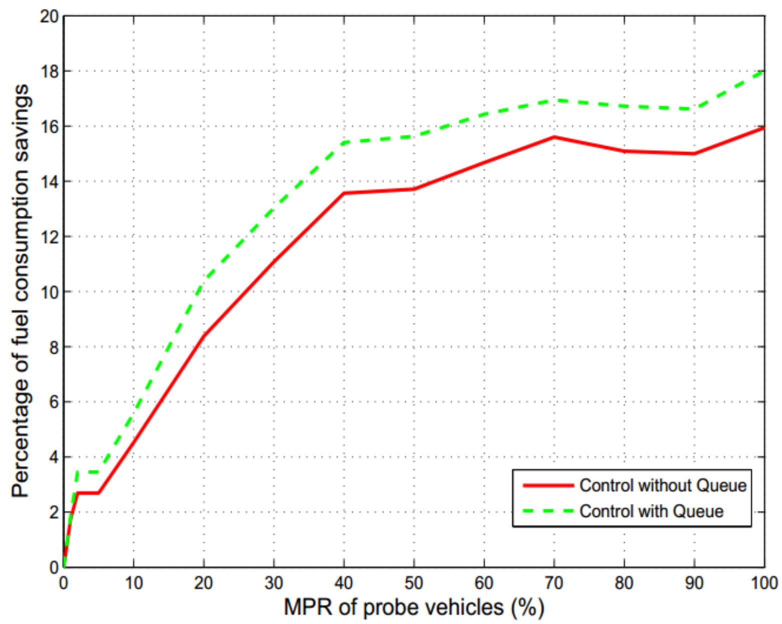


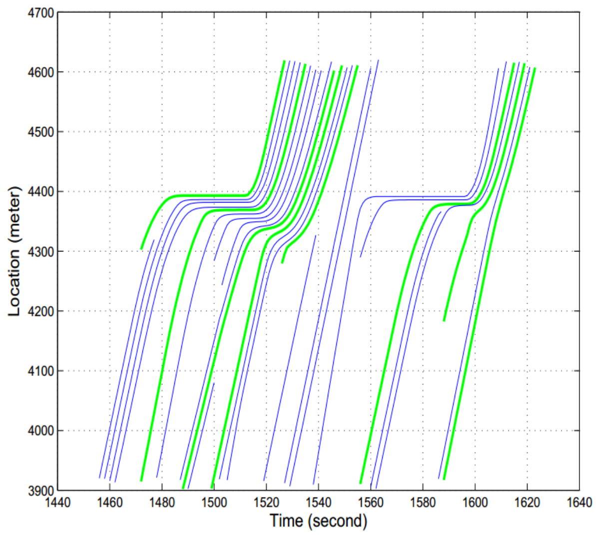
Figure 2.15: Saving of fuel consumption rate under different MPRs on a single lane intersection

the algorithm with and without queue consideration. Clearly, with higher MPRs, the fuel savings are higher. If all vehicles are controlled with the algorithm, the fuel consumption is reduced by approximately 15.9% without queue consideration, and 18.0% with queue consideration. Thus, the algorithm considering the queue produces additional fuel savings.

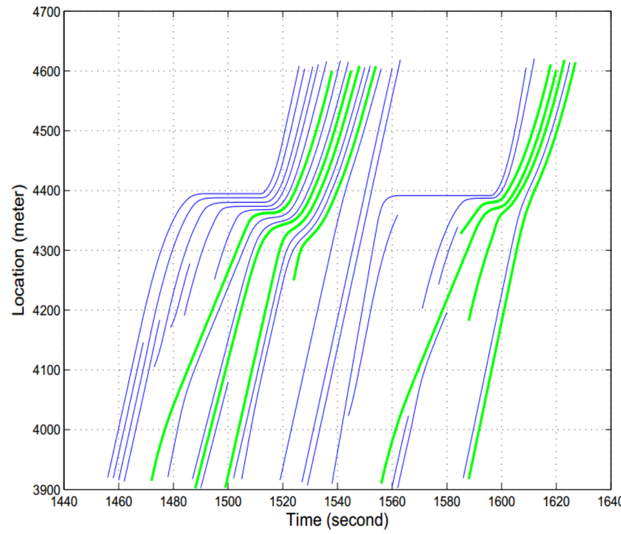
2.5.2 Multi-lane Intersection

In this subsection, we consider a simulation with a more realistic intersection layout, namely a multi-lane intersection where the roads upstream and downstream of the intersection have more than one lane. To simplify the simulation, we simulate a two-lane intersection. The scenario is designed to verify the benefits of the algorithm under different MPRs with realistic network topologies. The settings of the roads, the signal phasing and timing plan, and the Eco-CACC algorithm are the same as the simulation configuration that was described in Section 2.5.1. The demand entering the intersection is set as q = 500 veh/h/lane, i.e., 1000 veh/h. Vehicles are loaded to the network for approximately one hour. We assume 20% of vehicles are CVs that receive SPaT and vehicle queue information.

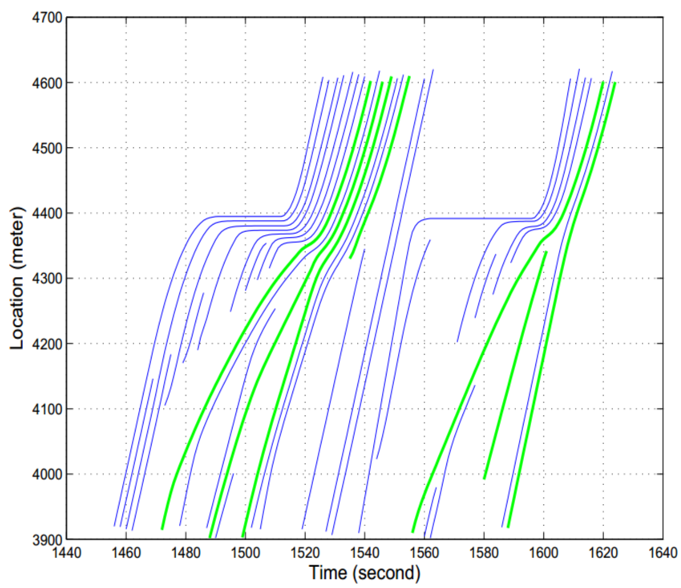
Fig.2.16 illustrates the vehicle trajectories for vehicles on the left lane before and after applying the Eco-CACC algorithm over two cycle lengths, where the signal is located at x = 4400 meters. Similar to the example in Section 2.5.1, the Eco-CACC equipped vehicles in Fig.2.16(a) only follow their leaders. In Fig.2.16(b), the Eco-CACC equipped vehicles are controlled by the algorithm without queue consideration, and thus cannot avoid incurring a complete stop..



(a)



(b)

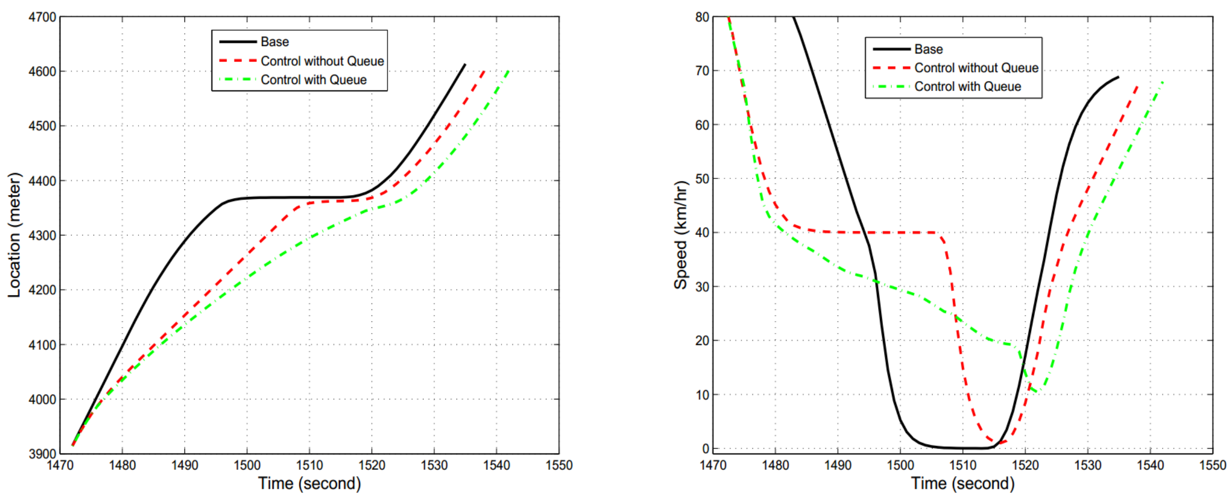


(c)

Figure 2.16: Vehicle trajectories around the intersection: (a) base case, (b) Eco-CACC without queue, (c) Eco-CACC with queue

In Fig.2.16(c), the Eco-CACC equipped vehicles are controlled by the algorithm using the queue information to allow the vehicles to proceed through the intersection without having to stop

Fig.2.17 (a) and (b) compare the trajectories and speed profiles of the first CV (the second one in Fig.2.17(a)) for the three scenarios, respectively. The trajectories controlled by the Eco-CACC algorithms is much smoother when compared to the base case, and the algorithm with queue consideration generates the smoothest trajectory. Moreover, for the algorithm without queue consideration, the CV cruises at a speed of 40 km/h, and experiences a stop of approximately 6 seconds in duration (for the base case, it stops for approximately 17 seconds). While when controlled with the algorithm that considers the queue effects, the vehicle cruises at 20 km/h, and does not stop



(a) (b)

Figure 2.17: Comparison of the second Eco-CACC equipped vehicle's dynamics: (a) trajectories, (b) speed profiles

upstream of the traffic signal. The fuel consumption rates generated by the Eco-CACC equipped vehicles are 0.125 l/km for the base case, 0.107 l/km for the algorithm without queue consideration, and 0.101 l/km for the algorithm with queue consideration, respectively. In summary, the algorithm with queue consideration provides the most efficient control, with reductions in fuel consumption levels for CVs as high as 19.2%. Unlike the example in Section 2.5.1, both roads have two lanes. Consequently, as the CVs are controlled and travel at a lower speed compared to the surrounding traffic, non-CVs make lane changes to cut into the gaps ahead of the CVs (see Fig.2.16). The overall average speed of the CVs is further reduced, i.e., they take longer time to reach the same position downstream of the intersection (see Fig.2.17(a)). Moreover, another drawback of the algorithm is that the intense lane changes, which cause frequent accelerations and traffic oscillations, result in high fuel consumption levels. In that sense, the overall fuel consumption may increase. Below 20% MPR, both the algorithm with and without queue consideration result in an increase in the fuel consumption level by approximately 5%.

Moreover, we investigate the impact of market penetration rates (MPRs) on the eco-CACC algorithm. The settings of the simulation are the same as the example above, except that the MPR varies from 0 to 100%. Fig.2.18 shows the savings of the average fuel consumption rate of all vehicles from the algorithm with and without queue. Under lower MPRs, the Eco-CACC algorithms have a negative impact on the overall fuel consumption rate. This is caused by the intense lane changes generated by the controlled vehicles. Once the MPR is greater than 30%, the number of Eco-CACC equipped vehicles is large enough to block the road and prevent lane changes. Hence,

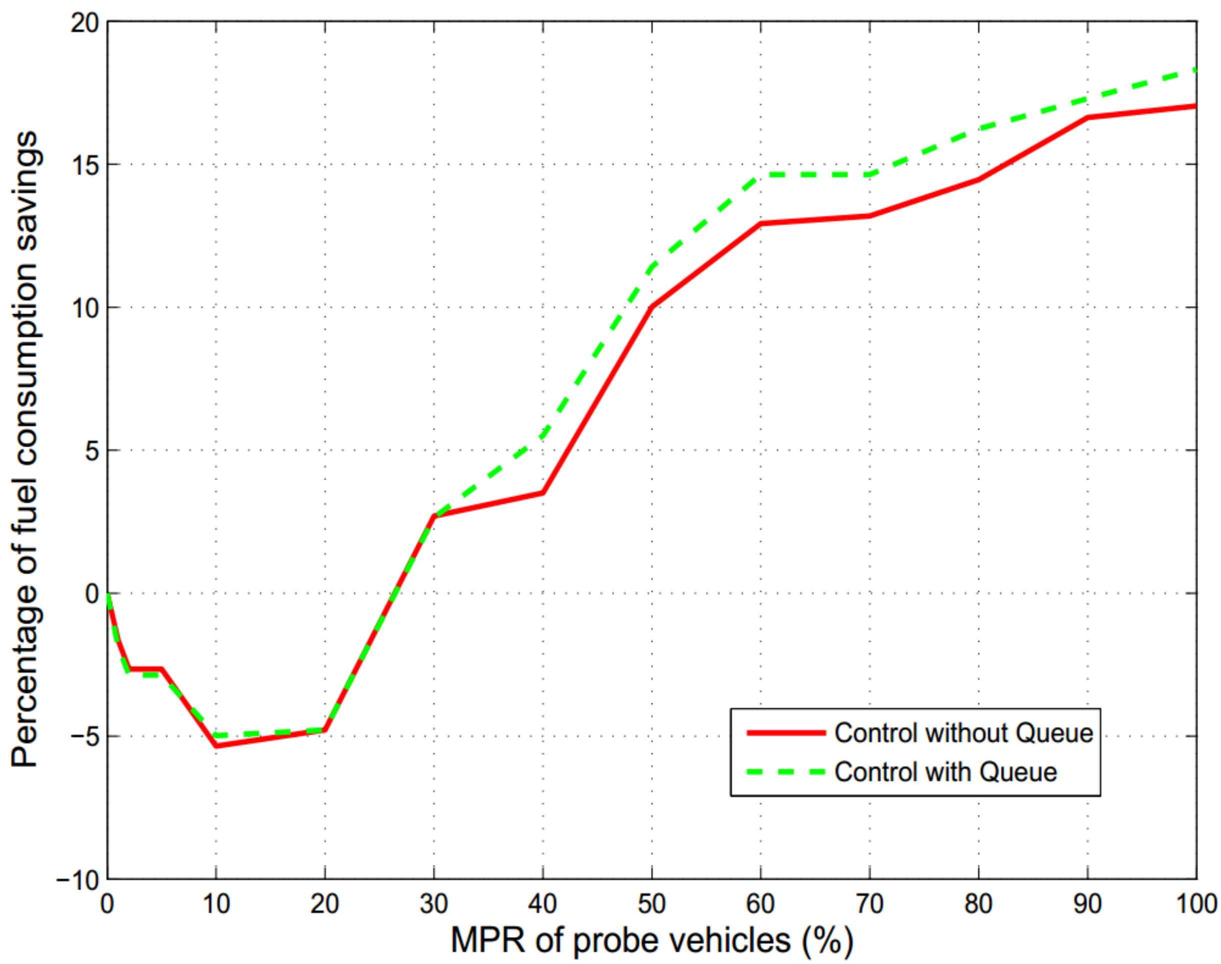


Figure 2.18: Savings of fuel consumption rate under different MPRs on a multi-lane intersection.

the Eco-CACC algorithms can obtain positive benefits on the fuel consumption rates. With higher MPRs, the savings of the fuel consumption rate are higher. If all vehicles are equipped with the algorithm, the rate is reduced about 17.0% without queue, and 18.3% with queue. The algorithm with queue is more efficient on reducing the fuel consumption rate.

2.6 Conclusions

In this paper, we developed an eco-cooperative adaptive cruise control (Eco-CACC) algorithm to minimize fuel consumption levels of vehicles proceeding through signalized intersections. The algorithm utilizes SPaT information accessed through V2I communication and predicted vehicle queues derived from road-side loop detectors to compute optimum instantaneous vehicle speeds. In the study, we first analytically investigated the impact of different advisory speed limits and queue lengths on fuel consumption levels of vehicles traversing a signalized intersection. The analysis demonstrated that the most fuel-efficient advice for vehicles is to travel at the highest possible speed while traversing the intersection. The algorithm predicts the length of the queue ahead of the Eco-CACC equipped vehicles using the LWR model to estimate the release time of the queue using the SPaT information. A second-by-second advisory speed limit is provided to the CVs to reduce the stops and an optimal upstream deceleration and downstream acceleration level are estimated to minimize the fuel consumption level. The analysis of the proposed Eco-CACC algorithm indicates that longer vehicle queue lengths result in higher fuel consumption levels, but Eco-CACC with and without queue prediction produce reductions in fuel consumption levels. However, the consideration of the queue length produces larger reductions in fuel consumption levels. Besides the analytical work, we also evaluated the algorithm using microscopic simulations. The simulation of a single-lane intersection indicated that Eco-CACC algorithm with and without queue prediction produce smoother vehicle trajectories. The queue prediction enhanced Eco-CACC algorithm produced the smoothest vehicle trajectories and resulted in the highest fuel savings, approximately 11.4%. Moreover, with higher MPRs, the savings increase. At an MPR of 100% fuel savings of approximately 18.0% are achievable. For a multi-lane intersections, the algorithm is still able to reduce the fuel consumption level of Eco-CACC equipped vehicles by approximately 19.2%. However, for MPRs less than 30%, the slower CVs can produce intense lane changes in the gaps they leave ahead of them and thus produce increased fuel consumption levels. Only when the MPRs were greater than 30% did the Eco-CACC system produce fuel savings. For MPRs of 100% fuel savings of 17.0% and 18.3% were achieved when queue prediction was not considered and when it was considered, respectively. The analysis presented in the paper only investigated the impact of MPRs on the algorithm performance. Other factors that should be considered include the length of the controlled segments, the traffic demand levels, and the signal timing plan. Consequently, a comprehensive sensitivity analysis of these factors on the algorithm performance is needed. Moreover, further improvements to the proposed Eco-CACC algorithm may be made by considering multiple signalized intersection in the optimization. Furthermore, one drawback of the algorithm is that it fails once the road is over-saturated. Hence, we propose that we combine the speed harmonization algorithm [30] on arterial roads and combine it with the Eco-CACC algorithm to solve this problem.

2.7 References

[1] C2ES. Transporation overview, 2013. URL http://www.c2es.org/.

[2] Nigel Jollands, Paul Waide, Mark Ellis, Takao Onoda, Jens Laustsen, Kanako Tanaka, Philip-pine de TSerclaes, Ingrid Barnsley, Rick Bradley, and Alan Meier. The 25 iea energy efficiency policy recommendations to the g8 gleneagles plan of action. *Energy policy*, 38(11): 6409–6418, 2010.

[3] Jack N Barkenbus. Eco-driving: An overlooked climate change initiative. *Energy Policy*, 38 (2):762–769, 2010.

[4] Hesham Rakha, Kyoungho Ahn, and Antonio Trani. Comparison of mobile5a, mobile6, vt-micro, and cmem models for estimating hot-stabilized light-duty gasoline vehicle emissions. *Canadian Journal of Civil Engineering*, 30(6):1010–1021, 2003.

[5] Matthew Barth and Kanok Boriboonsomsin. Real-world carbon dioxide impacts of traffic congestion. *Transportation Research Record*, 2058(1):163–171, 2008.

[6] Yonglian Ding and Hesham Rakha. Trip-based explanatory variables for estimating vehicle fuel consumption and emission rates. *Water, Air and Soil Pollution: Focus*, 2(5-6):61–77, 2002. ISSN 1567-7230. doi: 10.1023/A:1021350310219. URL http://dx.doi.org/10.1023/A%3A1021350310219.

[7] Matthew Barth and Kanok Boriboonsomsin. Energy and emissions impacts of a freeway-based dynamic eco-driving system. *Transportation Research Part D: Transport and Environ ment*, 14(6):400–410, 2009.

[8] Hao Yang and Wen-Long Jin. A control theoretic formulation ofgreen driving strategies based on inter-vehicle communications. *Transportation Research Part C: Emerging Technologies*, 41:48–60, 2014.

[9] Sangjun Park, Hesham Rakha, Kyoungho Ahn, Kevin Moran, Bart Saerens, and Eric Van den Bulck. Predictive ecocruise control system: model logic and preliminary testing. *Transportation Research Record: Journal of the Transportation Research Board*, (2270):113–123, 2012.

[10] Kyoungho Ahn, Hesham Rakha, and Sangjun Park. Ecodrive application: Algorithmic development and preliminary testing. *Transportation Research Record: Journal of the Transportation Research Board*, (2341):1–11, 2013.

[11] Xiugang Li, Guoqiang Li, Su-Seng Pang, Xiaoguang Yang, and Jialin Tian. Signal timing of intersections using integrated optimization of traffic quality, emissions and fuel consumption: a note. *Transportation Research Part D*, 9(5):401–407, 2004.

[12] Aleksandar Stevanovic, Jelka Stevanovic, Kai Zhang, and Stuart Batterman. Optimizing traffic control to reduce fuel consumption and vehicular emissions. *Transportation Research Record: Journal of the transportation research board,* 2128(1):105–113, 2009.

[13] USDOT. Connected vehicle reserach in the united states, 2015. URL http://www.its.dot.gov/connected_vehicle/.

[14] Sindhura Mandava, Kanok Boriboonsomsin, and Matthew Barth. Arterial velocity planning based on traffic signal information under light traffic conditions. In *Intelligent Transportation Systems, 2009. ITSC'09. 12th International IEEE Conference on*, pages 1–6. IEEE, 2009.

[15] Haitao Xia, Kanok Boriboonsomsin, and Matthew Barth. Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits. *Journal of Intelligent Transportation Systems*, 17(1):31–41, 2013.

[16] Behrang Asadi and Ardalan Vahidi. Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time. *Control Systems Technology, IEEE Transactions on*, 19(3):707–714, 2011.

[17] Kristin J Malakorn and Byungkyu Park. Assessment of mobility, energy, and environment impacts of intellidrive-based cooperative adaptive cruise control and intelligent traffic signal control. In *Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on*, pages 1–6. IEEE, 2010.

[18] Matthew Barth, Sindhura Mandava, Kanok Boriboonsomsin, and Haitao Xia. Dynamic eco-driving for arterial corridors. In *Integrated and Sustainable Transportation System (FISTS),2011 IEEE Forum on*, pages 182–188. IEEE, 2011.

[19] Hesham Rakha and Raj Kishore Kamalanathsharma. Eco-driving at signalized intersections using v2i communication. In *Intelligent Transportation Systems (ITSC), 2011 14th International IEEE Conference on*, pages 341–346. IEEE, 2011.

[20] Raj K Kamalanathsharma, Hesham Rakha, et al. Multi-stage dynamic programming algorithm for eco-speed control at traffic signalized intersections. In *Intelligent Transportation Systems-(ITSC), 2013 16th International IEEE Conference on*, pages 2094–2099. IEEE, 2013.

[21] Raj Kishore Kamalanathsharma, Hesham A Rakha, and Hao Yang. Network-wide impacts of vehicle eco-speed control in the vicinity of traffic signalized intersections. In *Transportation Research Board 94th Annual Meeting*, number 15-4290, 2015.

[22] Giovanni De Nunzio, Carlos Canudas de Wit, Philippe Moulin, and Domenico Di Domenico. Eco-driving in urban traffic networks using traffic signal information. In *Decision and Control (CDC), 2013 IEEE 52nd Annual Conference on*, pages 892–898. IEEE, 2013.

[23] Mario Munoz-Organero and Vıctor Corcoba Magana. Validating the impact on reducing fuel consumption by using an ecodriving assistant based on traffic sign detection and optimal deceleration patterns. *Intelligent Transportation Systems, IEEE Transactions on*, 14(2):1023–1028, 2013.

[24] Michael J Lighthill and Gerald Beresford Whitham. On kinematic waves. ii. a theory of traffic flow on long crowded roads. *The Royal Society of London. Series A. Mathematical and Physical Sciences*, 229(1178):317–345, 1955.

[25] Paul I Richards. Shock waves on the highway. *Operations research*, 4(1):42–51, 1956.

[26] Henry X Liu, Xinkai Wu, Wenteng Ma, and Heng Hu. Real-time queue length estimation for congested signalized intersections. *Transportation research part C*, 17(4):412–427, 2009.

[27] Xuegang Jeff Ban, Peng Hao, and Zhanbo Sun. Real time queue length estimation for signalized intersections using travel times from mobile sensors. *Transportation Research Part C*, 9(6):1133–1156, 2011.

[28] Hesham A Rakha, Kyoungho Ahn, Kevin Moran, Bart Saerens, and Eric Van den Bulck. Virginia tech comprehensive power-based fuel consumption model: model development and testing. *Transportation Research Part D: Transport and Environment*, 16(7):492–503, 2011.

[29] H Rakha. Integration c release 2.40 for windows: User's guide. *M. Van Aerde & Assoc., Ltd., Blacksburg, VA*, 2013.

[30] Hao Yang and Hesham Rakha. Developemnt of a speed harmonization algorithm: Methodology and preliminary testing. Submitted to Transportation Research Part B, 2015.

[31] B. E. Badillo, H. Rakha, and et al., "Queue Length Estimation using Conventional Vehicle Detector and Eco-CACC equipped Vehicle Data," 15th International IEEE Conference on Intelligent Transportation Systems, 2012, pp.1674-1681.

Chapter 3: Sensitivity Analysis of Eco-Cooperative Adaptive Cruise Control at Signalized Intersections

This chapter is based on: Ala M.V., Yang H., and Rakha H. (2016), "Sensitivity Analysis of Eco-Cooperative Adaptive Cruise Control at Signalized Intersections," Accepted for publication in the Transportation Research Record: Journal of the Transportation Research Board.

Abstract

In transportation systems, due to vehicle stops produced by traffic signals, fuel economy on arterial roads is generally much lower than that on freeways. Recently, eco-driving on arterial roads, which aims at improve fuel efficiency of passenger cars and trucks, attracts increasing interests. The Eco-Cooperative adaptive cruise control (ECACC) algorithm can utilize traffic signal phasing and timing (SPaT) information and vehicle queue information of upcoming signalized intersections collected by vehicle-to-signal communications to minimize fuel consumption of vehicles passing intersections. The algorithm computes advisory speed limits for Eco-CACC equipped vehicles to pass intersections smoothly without experiencing complete stops either by red lights or vehicle queues. In this paper, we incorporate the INTEGRATION microscopic traffic simulation model with the ECACC algorithm to assess its environmental benefits. The sensitivity analysis verifies that higher market penetrate rate of Eco-CACC equipped vehicles can improve the environmental benefits of the algorithm, and the overall savings in fuel consumption are as high as 19% when all vehicles are equipped. While, on multi-lane roads, the algorithm has negative impact on fuel consumption when the market penetrate rate is very low. The analysis also indicates that the length of control segments, the SPaT plan, and the demands affect the algorithm significantly. We further reveal that the algorithm has negative impact on fuel consumption when the network is over-saturated.

3.0 Introduction

The high pressure of reducing fuel consumption from the transportation sector requires researchers and policy makers to investigate various advanced strategies. Eco-driving, which aims at improving fuel efficiency of the transportation sector, is one efficient and cost-effective strategy [1]. Most eco-driving algorithms are operated by providing real-time driving advices, such as advisory speed or speed limits, recommended acceleration or deceleration profiles, speed alerts, etc, for individual vehicles. So that, the drivers can adjust driving behaviors or take certain driving actions to reduce fuel consumption and emissions. Obviously, complete stops on roads result in wastage of fuel usage. So, it is clear that smoothing traffic oscillations and avoiding idling time are two critical operations to perform eco-driving. In [5], Yang et al. proposed an advanced eco-cooperative adaptive cruise control (ECACC) algorithm based on vehicle-to-signal communications to minimize fuel consumption from vehicles passing intersection.

Different from the other studies in the literature, the algorithm investigated the impact of surrounding traffic on driving behaviors of Eco-CACC equipped vehicles. Moreover, the advisory speed limits computed by the algorithm were provided for the vehicles to travel at both upstream and downstream of intersections, so that the impact of the downstream acceleration to the desired speed after the signal turned to green was also considered. In this paper, we introduce a microscopic simulation model, INTEGRATION [6, 7], and develop a simulation environment to assess the benefits of the ECACC algorithm. The model is open-source, and it is easy to incorporate vehicle or traffic control strategies in transportation system. We first combine the INTEGRATION model with the ECACC algorithm to realize vehicle-to-signal communications and estimate advisory speed limits. Then, we make a comprehensive sensitivity analysis about market penetrate rates of Eco-CACC equipped vehicles, phase splits, length of control segments, and demands in the algorithm. The effectiveness of the algorithm under different configurations of intersections is also investigated. Finally, we examine the limitation of the algorithm under some extreme road conditions.

In terms of the paper layout, Section 3.1 reviews the ECACC algorithm with queue effects developed in [5], and incorporates the algorithm with INTEGRATION to minimize fuel consumption rates of vehicles passing intersections. Section 3.3 makes sensitivity analysis of the market penetrate rate of Eco-CACC equipped vehicles, the configuration of intersections, the SPaT plan, and the demand levels, and investigates the limitation of the algorithm. Section 3.4 examines the benefits of the algorithm with a four-legged intersection. Finally, section 3.5 summarizes the study in this paper.

3.1 Methodology

This study aims at assessing the environmental benefits of an ECACC algorithm proposed in [5] with a microscopic traffic simulation model, INTEGRATION [6, 7]. In this section, we first make a brief description about the mechanism of the ECACC algorithm with queue effects (ECACC-Q). Then, we introduce an INTEGRATION based-simulation environment to incorporate and evaluate the algorithm.

3.1.1 Eco-cooperative adaptive cruise control with queue effects

In this subsection, we review the eco-cooperative adaptive cruise control algorithm proposed in [5] to minimize fuel consumption rates from vehicles passing signalized intersections. The algorithm utilizes vehicle-to-signal communications to collected signal phasing and timing information to control driving behaviors. The driving behaviors of Eco-CACC equipped vehicles are optimized through applying advisory speed limits estimated by the ECACC-Q algorithm.

Different from the algorithm in [4], ECACC-O, which ignores the impact of surrounding traffic, the algorithm here also consider the vehicle queue effects on improving the network performance.

As shown in Fig.3.1, a series of vehicles attempts to approach and pass an intersection. The signal is located at x_s in the figure. Once a Eco-CACC equipped vehicle enters the section [x_u, x_d], the ECACCQ algorithm is activated. At the upstream of the intersection, [x_u, x_s], when the Eco-CACC equipped vehicle is delayed by the red light or the vehicle queue ahead, the algorithm estimates an advisory speed limit, $v_e(t)$, for the vehicle to pass the intersection smoothly without complete stop. The advisory speed limit allows the vehicle to decelerate with an constant rate, a_-, to a cruise speed, v_c, so that it arrives the tail of the queue just when the queue is dissipated, $t = t_c$, or the stop bar when the signal turns to green, $t = t_g$, if there is no queue ahead of the signal. At the downstream of the intersection, [x_s, x_d], the algorithm controls the Eco-CACC equipped vehicle to accelerate to the road speed limit, v_f with a constant rate a_+ to reach the location, x_d. Fig.3.2 illustrates the speed profile of the Eco-CACC equipped vehicle with the ECACC-Q algorithm. Compared with the based case (black line), the speed profile with the algorithm is much smoother, and the stop delay is avoided completely. As the objective of the ECACC-Q algorithm is minimizing fuel consumption rate from the Eco-CACC equipped vehicle. Then, in addition to the shape of the speed profile shown in Fig.3.2, the algorithm have to find the optimal upstream deceleration rate, a_-, and the optimal downstream acceleration rate, a_+. That is, the objective function of the algorithm is

$$\min_{a_-, a_+} \int_{t_0}^{t_0+T} F\left(v\left(t\right)\right) dt \tag{3.1a}$$

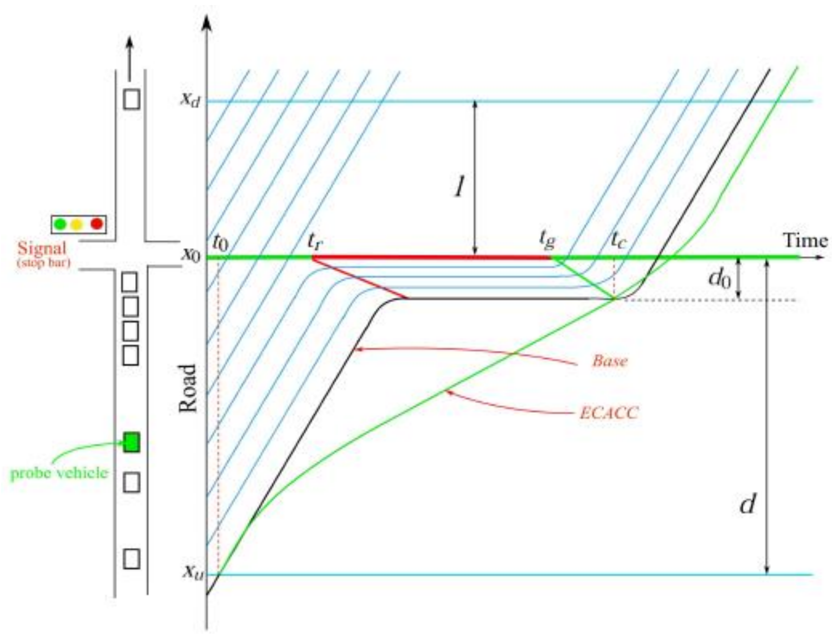


Figure. 3.1: Vehicle with the ECACC-Q algorithm

s.t.

$$v(t)=\begin{cases} v_0-a_-(t-t_0) & \mathrm{t}_0\le t<t_0+\delta t_1 \\ v_c & \mathrm{t}_0+\delta t_1\le t<t_c \\ v_c+a_+(t-t_c) & \mathrm{t}_c\le t<t_c+\delta t_2 \\ v_f & t_c+\delta t_2\le t<t_0+T \end{cases} \tag{3.1b}$$

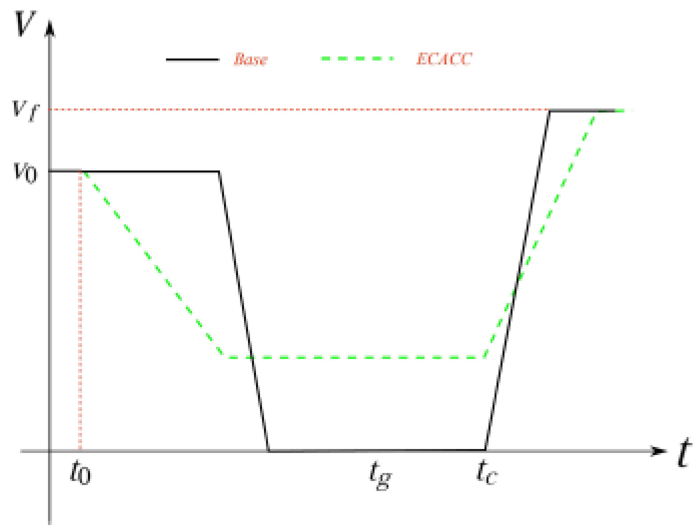


Figure 3.2: Speed profile of the probe vehicle with ECACC-Q

$$\delta t_1=\frac{v_0-v_c}{a_-} \tag{3.1c}$$

$$v_0.\delta t_1-\frac{1}{2}a_-\delta t_1^2+v_c(t_c-t_0-\delta t_1)=d-d_0 \tag{3.1d}$$

$$\delta t_2=\frac{v_f-v_c}{a_+} \tag{3.1e}$$

$$v_0.\delta t_1+\frac{1}{2}a_+\delta t_1^2+v_f(t_0+T-t_c-\delta t_2)=l+d_0 \tag{3.1f}$$

$$0<a_-\le a_-^s \tag{3.1g}$$

$$0<a_+\le a_+^s \tag{3.1h}$$

Here, we define that

- $F(v)$: the fuel consumption rate that a vehicle travels with speed v. The function is defined by the VT-CPFM model [8];
- v_0: the speed of the Eco-CACC equipped vehicle when it arrives at x_d;

- d: the length of the upstream control segment, [x_u, x_s];
- l: the length of the downstream control segment, [x_s, x_d];
- T: the time duration for which the Eco-CACC equipped vehicle travels on the segment, [x_u, x_d];
- t_0: the time that the 1 vehicle arrives at x_u;
- t_g: the time that the light turns to green;
- t_c: the time that the queue ahead of the Eco-CACC equipped vehicle is dissipated;
- δt_1: the time duration of the upstream deceleration;
- δt_2: the time duration of the downstream acceleration;
- d_0: the length of the queue ahead of the Eco-CACC equipped vehicle
- $a_{=}^{s}$: the saturate deceleration rate
- a_{+}^{s} : the saturate acceleration rate.

Eq (3.2(b)) indicates that given the road traffic condition, including queue length, start and end times of each phase, and the approaching speed of the Eco-CACC equipped vehicles, the speed profile is a function of a_- and a_+. The ECACC-Q algorithm searches the values of the two rates during the ranges defined in Eq (3.1(g)) and Eq (3.1(h)) to minimize the fuel consumption of the Eco-CACC equipped vehicle passing the intersection. The details of the ECACC-Q algorithm is described below.

1. For a Eco-CACC equipped vehicle k, once it enters the segment [x_u, x_0], the ECACC-Q algorithm is activated.
2. At the upstream of the intersection
    a. The algorithm provides the advisory speed limit to the Eco-CACC equipped vehicles under the following two scenarios; otherwise, the road speed limit/free-flow speed, v_f, is applied as the advisory limit.
        i. Currently, the permitted phase for the Eco-CACC equipped vehicle to pass the intersection is green, but the light will turn to red when the vehicle arrives the stop bar with its current speed.
        ii. Currently, the permitted phase is red, and the light is still red when the vehicle arrives the stop bar with its current speed.
    b. Once either one of the scenarios described above occurs, we calculate the queue length based on the number of vehicle ahead of the Eco-CACC equipped vehicle , and estimate the dissipation time of the queue, t_c, based on the speed of the rarefaction wave.
    c. The algorithm estimates the optimal upstream deceleration rate and the downstream acceleration rate with Eq (3.1) to minimize the fuel consumption rate, and provides the advisory speed limit to the Eco-CACC equipped vehicle at the next time step $t + \Delta t$, where Δt is the updating interval of the advices.
3. At the downstream 1 of the intersection

The algorithm searches the optimal acceleration rate based on its current speed to minimize the fuel consumption rate to approach the location x_d at v_f .

4. Once the Eco-CACC equipped vehicle arrives at x_d, the ECACC-Q algorithm is deactivated.

3.2 INTEGRATION

This research will incorporate the ECACC-Q algorithm with INTEGRATION to evaluate its environmental benefits at signalized intersections. In this subsection, we first make a brief introduction about INTEGRATION, followed by a description about the incorporation of the ECACC-Q algorithm into INTEGRATION. The INTEGRATION model was first developed in the mid 1980's [9, 10, 11, 12] and is being continuously developed [2, 13, 14, 6, 7]. It was conceived as an integrated simulation and traffic assignment model and performs traffic simulations by tracking the movement of individual vehicles every 1/10th second. This allows detailed analysis of lane-changing movements and shock wave propagations. It also permits considerable flexibility in representing spatial and temporal variations in traffic conditions. In addition to estimating stops and delays, the model can also estimate the fuel consumed by individual vehicles, as well as the emissions [15]. Finally, the model also estimates the expected number of vehicle crashes using a time-based crash prediction model. The model tracks each vehicle from its origin until it exits the network at its destination. The INTEGRATION model applies the Van Aerde's fundamental diagram [16] to describe the macroscopic traffic dynamics along roads. The fundamental diagram describes the steady-state traffic with the density-speed relationship below (see Fig.3.3.)

$$\rho(x,t) = \frac{1}{c_1 + c_3.v(x,t) + \frac{c_2}{v_f - v(x,t)}} \tag{3.2a}$$

where $v(x, t)$ signifies the speed at location x and time t. The coefficients can be computed as

$$c_1 = \frac{v_f}{\rho_j v_c^2}(2v_c - v_f)^2 \tag{3.2b}$$

$$c_2 = \frac{v_f}{\rho_j v_c^2}(v_f - v_c)^2 \tag{3.2c}$$

$$c_3 = \frac{1}{q_c} - \frac{v_f}{\rho_j v_c^2} \tag{3.2d}$$

where v_f, ρ_j, q_c, v_c signify the free flow speed, jam density, road capacity, and speed at capacity, respectively. Fig.3.1 illustrates the fundamental diagram. Here, we also have the speed-density $v(x, t) = V(\rho(x, t))$ and flow-speed $q(x, t) = Q_v(v(x, t)) = \rho(x, t). v(x, t)$ relationships (Fig.3.1(b) and (c)). Then, given $\{q_c, v_f, \rho_j, v_c\}$, the speed of the rarefaction wave generated by the green light can be estimated, and the time of the queue dissipation is also predictable.

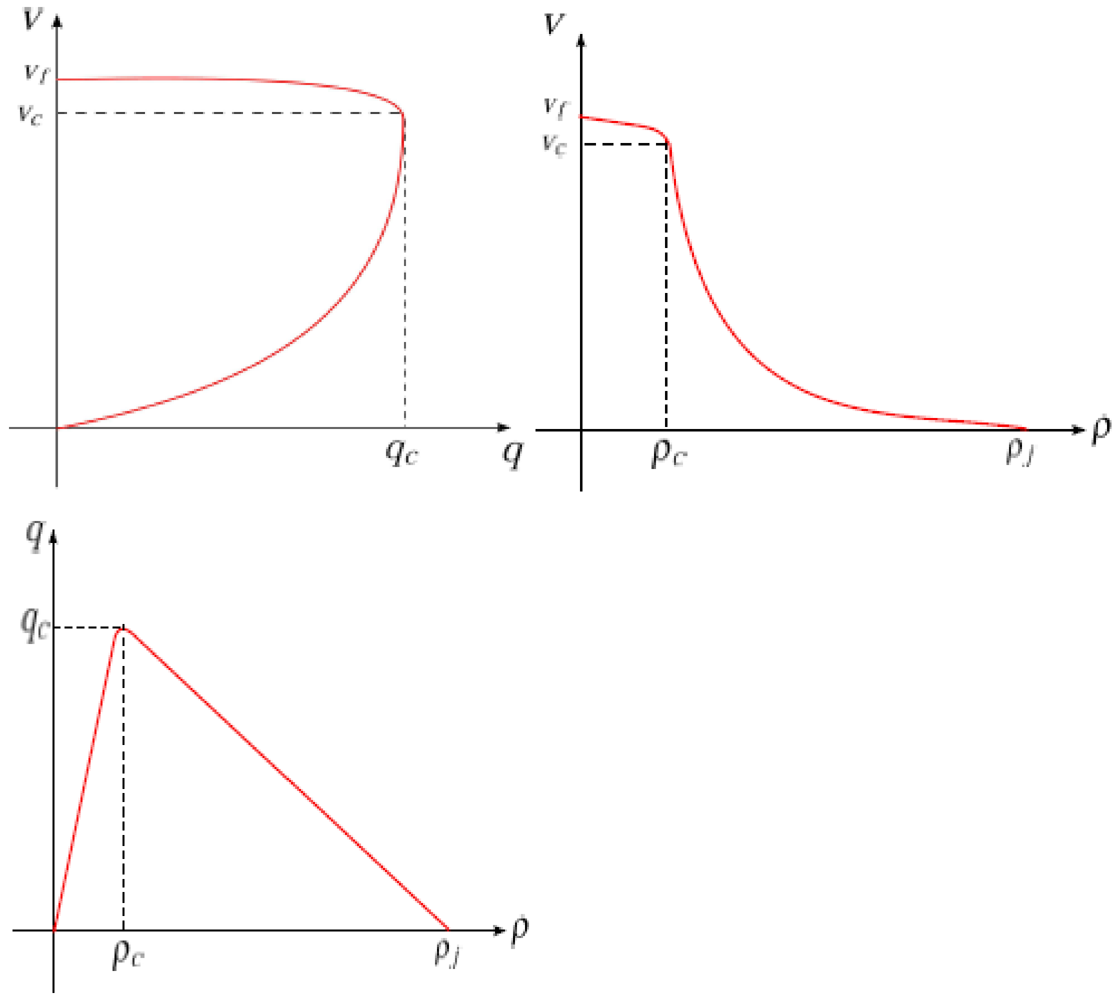


Figure 3.3: Van Aerde's fundamental diagram: (a) speed flow (b) speed density, (c) flow density

Moreover, the model computes the vehicle speed as the minimum of three speeds, namely: the maximum vehicle speed based on vehicle dynamics considering the driver throttle level input, the desired speed based on the Van Aerde steady-state car-following model formulation [16, 17], and the maximum vehicle speed that the vehicle can travel at ensuring that it does not collide with the vehicle ahead of it. In addition, the model is open-source, and it is very friendly for users to add functions to realize various traffic and vehicle control strategies. In this study, we incorporate vehicle-to-signal communications to transmit two types of information to Eco-CACC equipped vehicles: (1) the SPaT information from the intersection, and (2) the queue information, including its length and the time of dissipation, estimated by the loop detectors installed at the beginning and the ending of the control segment, $[x_u, x_s]$. As described in section 3.1.1, the ECACC algorithm utilizes this information to estimate the advisory speed limit. Then, at every Deci second, the Eco-CACC equipped vehicle receives an advisory speed limit, which forces it to pass the intersection smoothly. The actual speed of the vehicle at time t, $v(t)$, is determined by two values: (1) the advisory speed limit, $v_e(t)$ and (2) the speed computed by INTEGRATION, $v_I(t)$; i.e., $v(t) = \min\{v_e(t), v_I(t)\}$. Hence, the influence of the ECACC-Q algorithm on driving behaviors of individual vehicles and its environmental benefits on the network performance can be well assessed by INTEGRATION.

3.3 Sensitivity Analysis

In this section, we focus on investigating the impact of market penetration rates (MPRs) of probe vehicles with the ECACC-Q algorithm, the number of lanes of the controlled segments, the phase splits, the length of the control segments, and the demand levels. Then, we analyze the limitation of the algorithm under extreme traffic conditions.

As the starting point of the study, we simulate a simple intersection defined in Fig.2.12. Assume that vehicles are only loaded from one origin and exit to one destination, i.e., we only simulate one direction through traffic. Then, for the SPaT plan, we set the cycle length as C = 84 seconds, and the green and amber durations of the through traffic are 40 and 2 seconds, respectively. For all case studies below, we assume that the speed limits of all roads are v_f = 50 mph, and their capacities are all q_c = 1600 vph. The INTEGRATION simulation software is introduced to describe the movements of individual vehicles, and control the dynamics of Eco-CACC equipped vehicles.

3.3.1 Sensitivity to market penetration rates

In this subsection, we examine the impact of MPRs of Eco-CACC equipped vehicles on the ECACC-Q algorithm. Table 3.1 shows the settings of the ECACC-Q algorithm. Under these settings, once a Eco-CACC equipped vehicle travels at the upstream of the signal, and their distance is less than d = 500 meters, the ECACC-Q algorithm is activated, and the Eco-CACC equipped vehicle receives an advisory speed limit. Similarly, if the vehicle is at the downstream of the signal, and the distance is less than l = 200 meters, then an advisory speed limit is estimated to restrict the vehicle's acceleration rate.

Parameters	Values
Length of the upstream control segment, d (meter)	500
Length of the downstream control segment, l (meter)	200
Saturate deceleration rate, a^s_-, (m/s^2)	3
Saturate acceleration rate, a^s_-, (m/s^2)	2

Table 1: Settings of the ECACC-Q algorithm

In this simulation, we set that the control segment has only one lane, i.e., this is a single-lane intersection. So that, vehicles cannot overpass their leaders, and the ECACC-Q algorithm is not interrupted by lane-changing behaviors. Moreover, the demand from the origin to the destination is constant as 300 vph during one-hour simulation period. In order to investigate the sensitivity of MPRs, only a part of vehicles apply the ECACC-Q algorithm, and the others behave reactively. Fig.3.4 illustrates the overall environmental benefits of the network with the ECACC-Q algorithm under different MPRs. The figure indicates that a higher MPR results in greater savings in the overall fuel consumption rate. Once all vehicles are equipped with the algorithm, we can achieve the savings in the fuel consumption as high as 19%. The savings come from two aspects. First, obviously, the Eco-CACC equipped vehicles are controlled by the algorithm to minimize their fuel consumption rates to pass the intersection. Second, for the non-Eco-CACC equipped vehicles, which follow the Eco-CACC equipped ones, due to the car-following rules on the single-lane road, their movements is restricted by the leaders, and their speed profiles are also smoothed. This also results in savings in the fuel consumption.

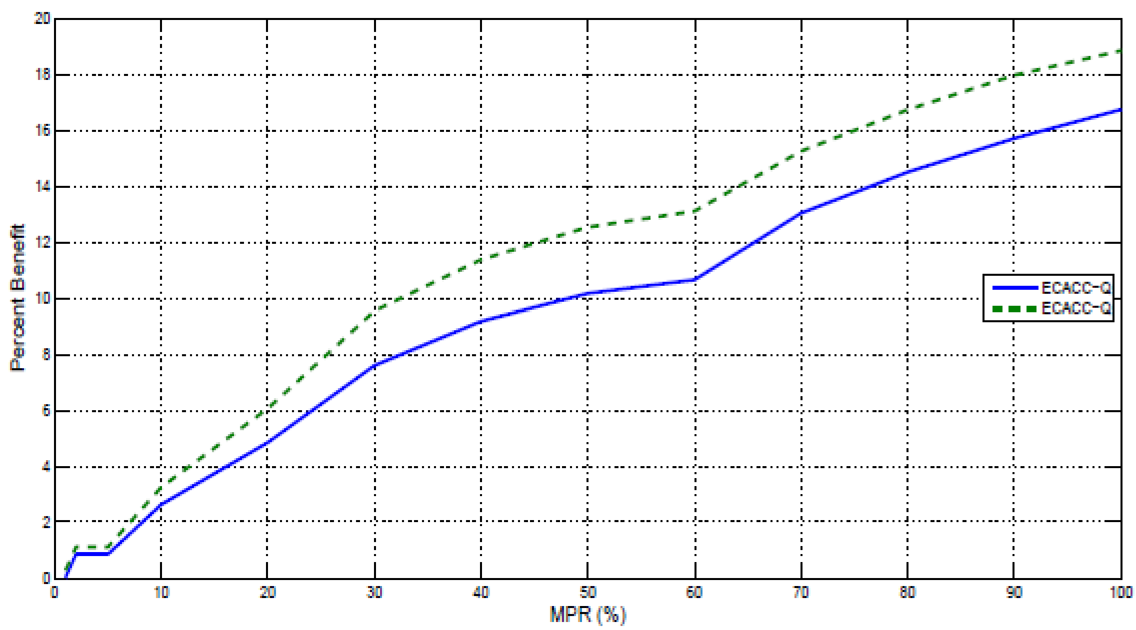


Figure 3.4: Savings in fuel consumption at a single-lane intersection under different MPRs

Besides the examination of ECACC-Q, we also compare the environmental benefits of the algorithm with a similar one, ECACC-O [4], which does not consider the impact of vehicles queues. The settings of ECACC-O is also shown in Table 1. Fig.3.4 illustrates that ECACC-O also obtains larger savings of the fuel consumption rate at higher MPRs. However, the savings are much smaller than those from ECACC-Q. Without considering the queue, the fuel consumption rate is only reduced about 17%.

3.3.2 Impact of multi-lane roads

In the aforementioned subsection, we investigated the impact of MPRs at a single-lane intersection, where lane-changing behaviors is restricted. However, in reality lane changes are normal and much possible. In this subsection, we apply both ECACC-Q and ECACC-O algorithms in a multilane intersection, where the links approaching and leaving the signal have more than one lanes. Assume that both links have two lanes, and the demand is 300 vphpl. The setting of the ECACC-Q algorithm is shown in Table 1.

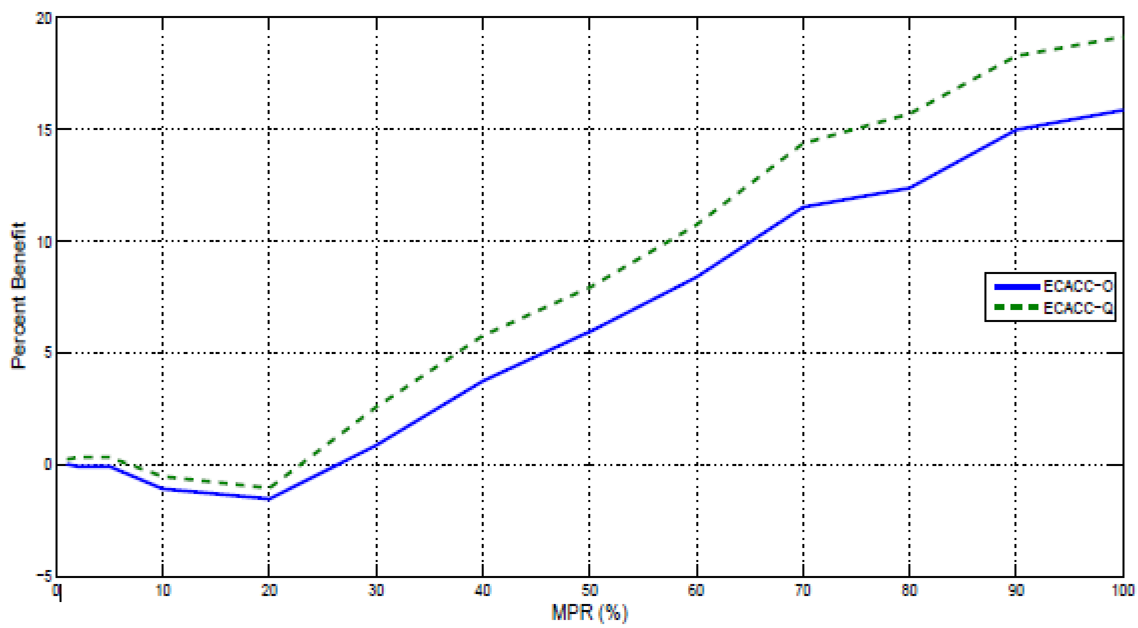


Figure 3.5: Savings in fuel consumption at a two-lane intersection under different MPRs

Fig.3.5 compares the environmental benefits of both ECACC-Q and ECACC-O algorithms under different MPRs. Different from the single-lane intersection, we cannot always observe the savings in the overall fuel consumption under different MPRs in this example. When the MPR is less than 30%, applying both algorithms increases the overall fuel consumption. The negative impact under low MPRs is caused by lane-changing behaviors of non-Eco-CACC equipped vehicles on the two-lane roads. As both algorithm algorithms controls Eco-CACC equipped vehicles to travel smoothly, they move slower than the non-Eco-CACC equipped vehicles around them, and leaves larger gaps ahead. In this case, when the MPR is small, the non-Eco-CACC equipped vehicles are able to accelerate to pass the Eco-CACC equipped ones and cut into the gaps ahead. These behaviors results in traffic oscillations on the roads as well as increasing the fuel consumption. However, when the MPR is greater than 30%, it is very possible that two Eco-CACC equipped vehicles move side-by-side to block both lanes, restricting the non-Eco-CACC equipped ones from over-passing. Thus, the number of lane changes are reduced significantly. Both algorithms (ECACC-O and ECACC-Q) start to impart positive results once the MPR is greater than 30%. If all vehicles are equipped, the ECACC-Q can reduce fuel consumption as high as 19%, and ECACC-O 16%. Similar to the single-lane intersection, ECACC-Q performs better than ECACC-O.

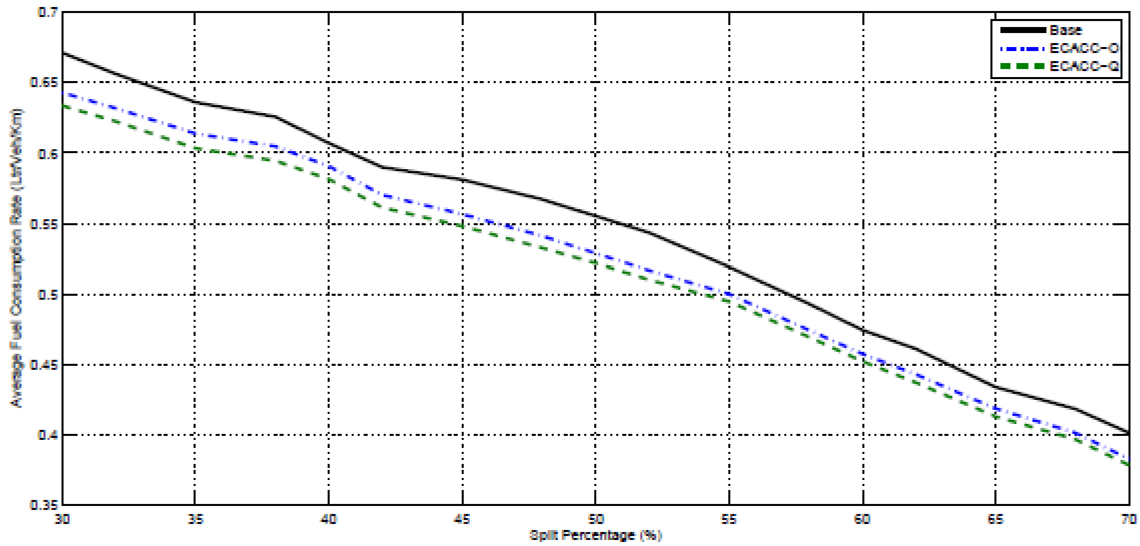
3.3.3 Sensitivity to phase splits

In an intersection, the SPaT plan determines the split of each phase, and the performance of the intersection is highly related to the split. As our ECACC algorithms utilizes the SPaT information to advise the driving behaviors of Eco-CACC equipped vehicles, the impact of the phase splits has to be carefully examined. In this subsection, we make a sensitivity analysis of the split percentage. The single-lane intersection defined in section 3.1 is simulated in this subsection, and the link characters and the settings of the ECACC algorithms are kept the same. We still load vehicles at the rate of 300 vph, but only 20% of them are equipped with the algorithm. The split percentage of the phase, which allows vehicles to pass the intersection, varies from 30% to 70%. Fig.3.6(a) compares the average fuel consumption rates of each vehicle from the base case without control, ECACCO, and ECACC-Q under different split percentages. Obviously, with greater split percentages, vehicles have higher probability to pass the intersection without experiencing the red light, i.e., they are less likely to be stopped by the signal. Hence, they can move smoothly to the destination with less fuel consumption. Regarding the savings in the fuel consumption, Fig.3.6(b) shows that the phase split almost does not affect the benefits of the algorithm. The saving difference from various split percentages is only about 1%. Moreover, the comparison between ECACC-Q and ECACC-O also verifies the advancement of considering vehicle queue. Under all split percentages, ECACC-Q gives the lowest fuel consumption, and the savings is about 1-2% higher than that from ECACC-O.

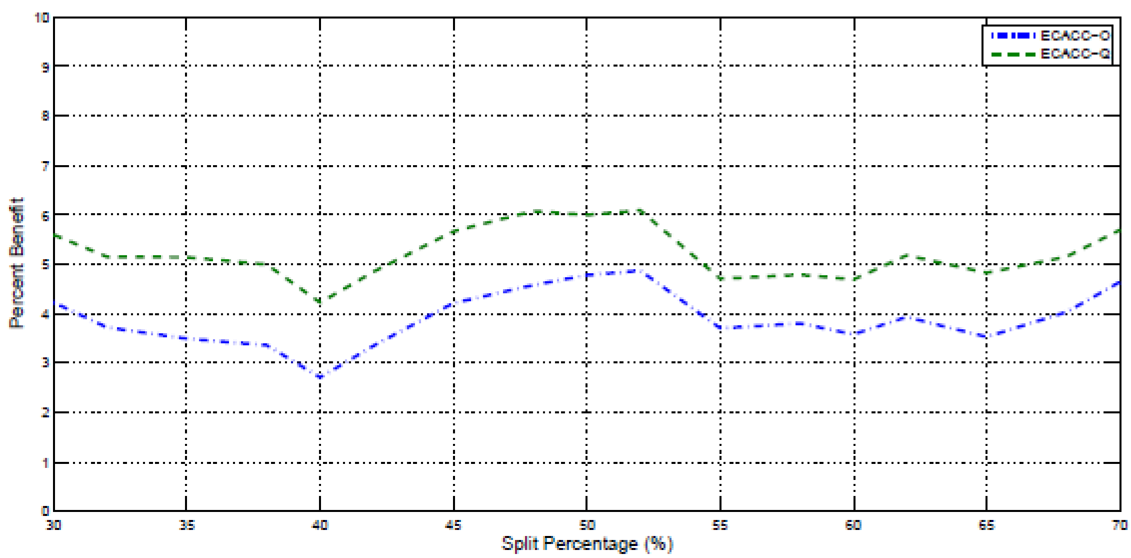
3.3.4 Sensitivity to control length

Besides phase splits, another variable affecting the performance of the ECACC-Q algorithm is the length of the control segment, especially the upstream segment length, *d*. In this subsection, we make a sensitivity analysis about *d* in the algorithm under both single-lane and two-lane intersecions. First, the single-lane intersection in section 3.3.1 is simulated, and the link characters and the SPaT plan are the same. Vehicles are loaded for the OD pair at the rate of

500vph. The settings of the ECACC-Q algorithm in Table 3.1 are kept the same, except the upstream control segment length, *d*, varies from 200 to 700 meters.



(a)



(b)

Figure 3.6: Impact of split percentages: (a) average fuel consumption, (b) savings in fuel consumption

Fig.3.7 compared the savings of fuel consumption from different control length under various MPRs. Similarly to the conclusion in section 3.3.1, with higher MPRs, the savings from different *d*'s are larger. Moreover, comparing different *d*'s, we find that basically a longer control length results in larger savings. At *MPR* = 100%, 700-meter control segment reduces fuel consumption as high as 18%, while 200-meter segment saves 12%.

The observation is reasonable as the longer length indicates that the Eco-CACC equipped vehicles are able to get the SPaT information earlier, and they have longer time to smooth their movements, so that the algorithm can perform better. In addition, Fig.3.7 shows that when the length is longer than 500 meters, the savings are quite similar. This indicates 500-meter segment is long enough for the Eco-CACC equipped vehicles to find the optimal movements to pass the intersection. In the second example, we simulate a two-lane intersection defined in section 3.3.2. Similar to the example above, we keep the link characters and the settings of the ECACC-Q algorithm, and only change the length the upstream control segment. Vehicles are loaded for the OD pair at the rate of 500 vphpl. Fig.3.8 compares the savings of fuel consumption from different control length under various MPRs. Similar to the results in section 3.3.2, under low MPRs (< 30%), the algorithm has negative effect on fuel consumption due to intense lane changes. With a longer control length, non-Eco-CACC equipped vehicles are able to overpass more Eco-CACC equipped ones, and the frequency of lane changes is

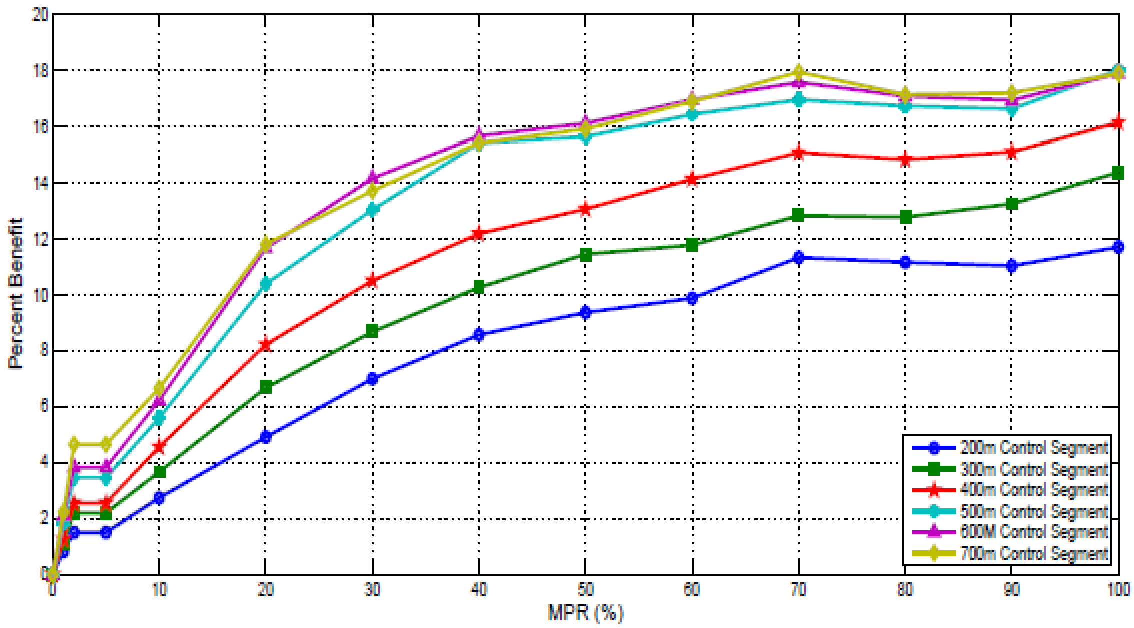


Figure 3.7: Savings in fuel consumption at a single-lane intersection under different control length

higher. In that sense, when the control length increases, the algorithm [1] results in an increased overall fuel consumption of the network. While, under high MPRs (≥ 30%), the Eco-CACC equipped vehicles are able to block the whole link as well as preventing lane-changing and over-passing. Hence, the benefits of the algorithm are similar to those at the single-lane intersection.

And, the savings of fuel consumption are similar when the length is longer than 500 meters. At *MPR*=100%, the 500-meter control segment can reduce fuel consumption as high as 18%, while the 200-meter segment only saves 11%.

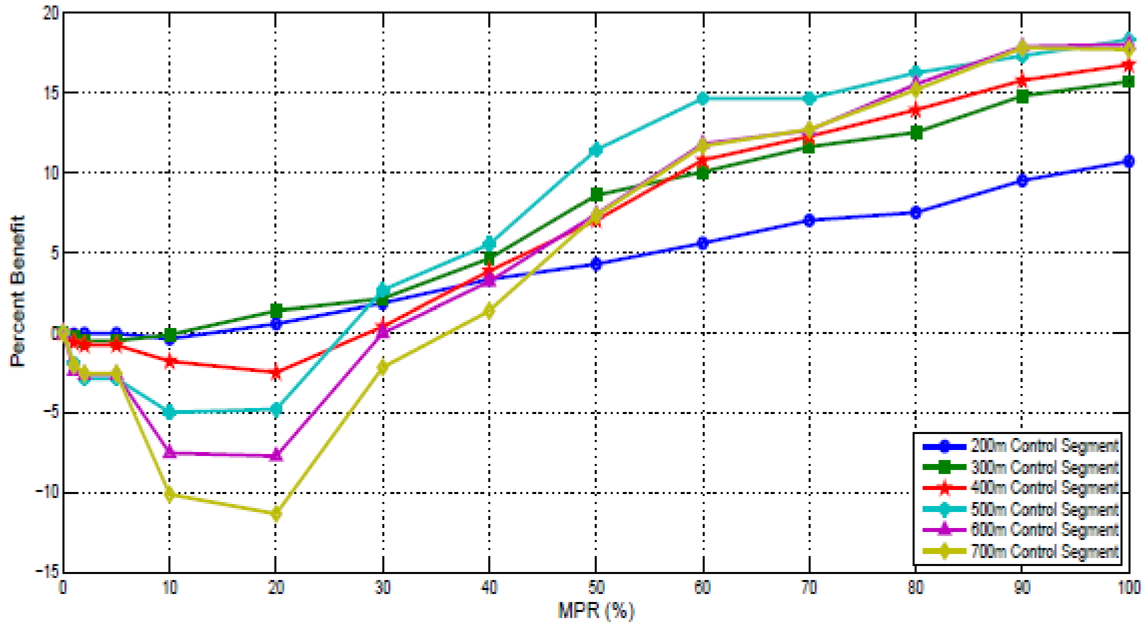


Figure 3.8: Savings in fuel consumption at a two-lane intersection under different control length

3.3.5 Sensitivity to demands

In the evaluation of the ECACC-Q algorithm, the impact of demands should be carefully studied, as they are directly related to the number of Eco-CACC equipped vehicles controlled and the performance of the network. This subsection deals with the sensitivity of demands on the environmental benefits of the algorithm under a single-lane and a multi-lane intersections.

The first example simulates the single-lane intersection defined in section 3.3.1, and all link characters, the SPaT plan, and the settings of the ECACC-Q algorithm are the same. But, the demand varies from 300 to 700 vph. Fig.3.9 illustrates the savings of fuel consumption under different demands. The results indicate that under the given settings of the control length and the split percentage, the algorithm can obtain the highest savings in fuel consumption for a constant demand under different MPRs. In this example, loading vehicles at the rate of 500 vph can achieve the lowest fuel consumption, i.e.,the greatest saving.

The second example simulates the two-lane intersection defined in section 3.3.2. The settings of link characters and the ECACC-Q algorithm are the same. The demand of the OD pair varies from 300 to 700 vphpl. Fig.3.10 illustrates the savings of fuel consumption. Similarly, under lower MPRs, the algorithm has a negative impact on the fuel consumption. With higher demands, the algorithm generates more fuel consumption, and it needs a greater MPR to obtain positive benefit.

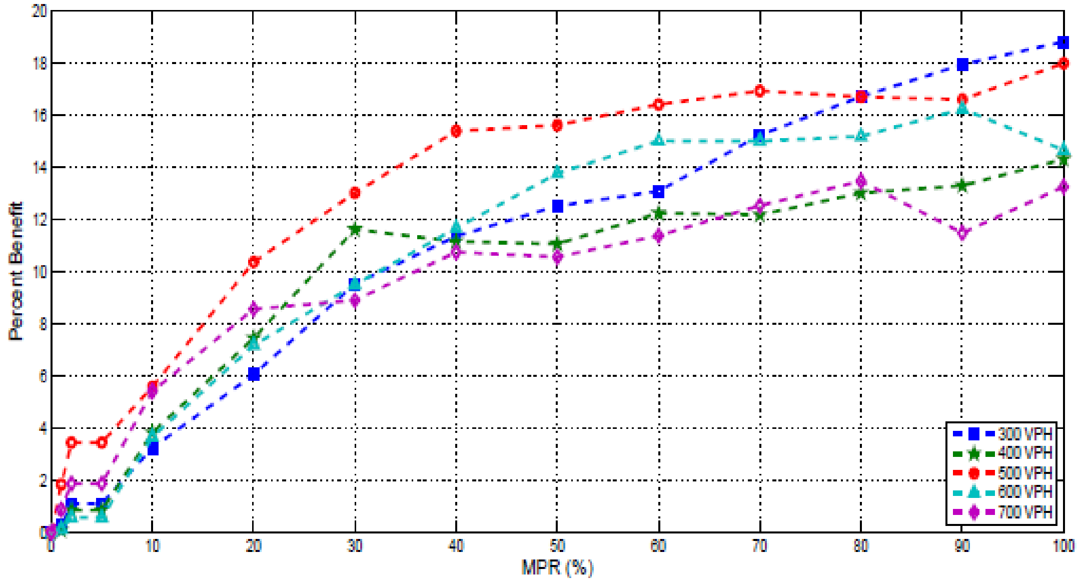


Figure 3.9: Savings in fuel consumption at a single-lane intersection under different demands

This is intuitively correct, as larger demands indicate more vehicles traveling on the control segment simultaneously. Hence, more non-Eco-CACC equipped vehicles are corresponding increasing lane changes, and it is more difficult for the Eco-CACC equipped ones to block the whole link to get positive savings of fuel consumption. Under high MPRs (> 50%), the conclusion is similar to the first example. Loading vehicles at the rate of 600 vph can achieve the lowest fuel consumption.

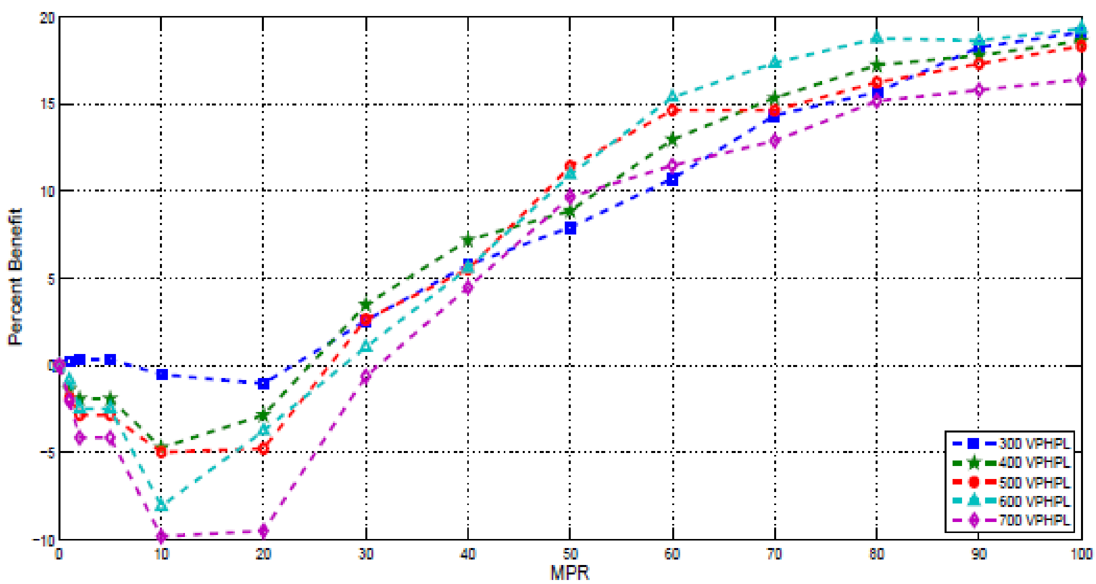
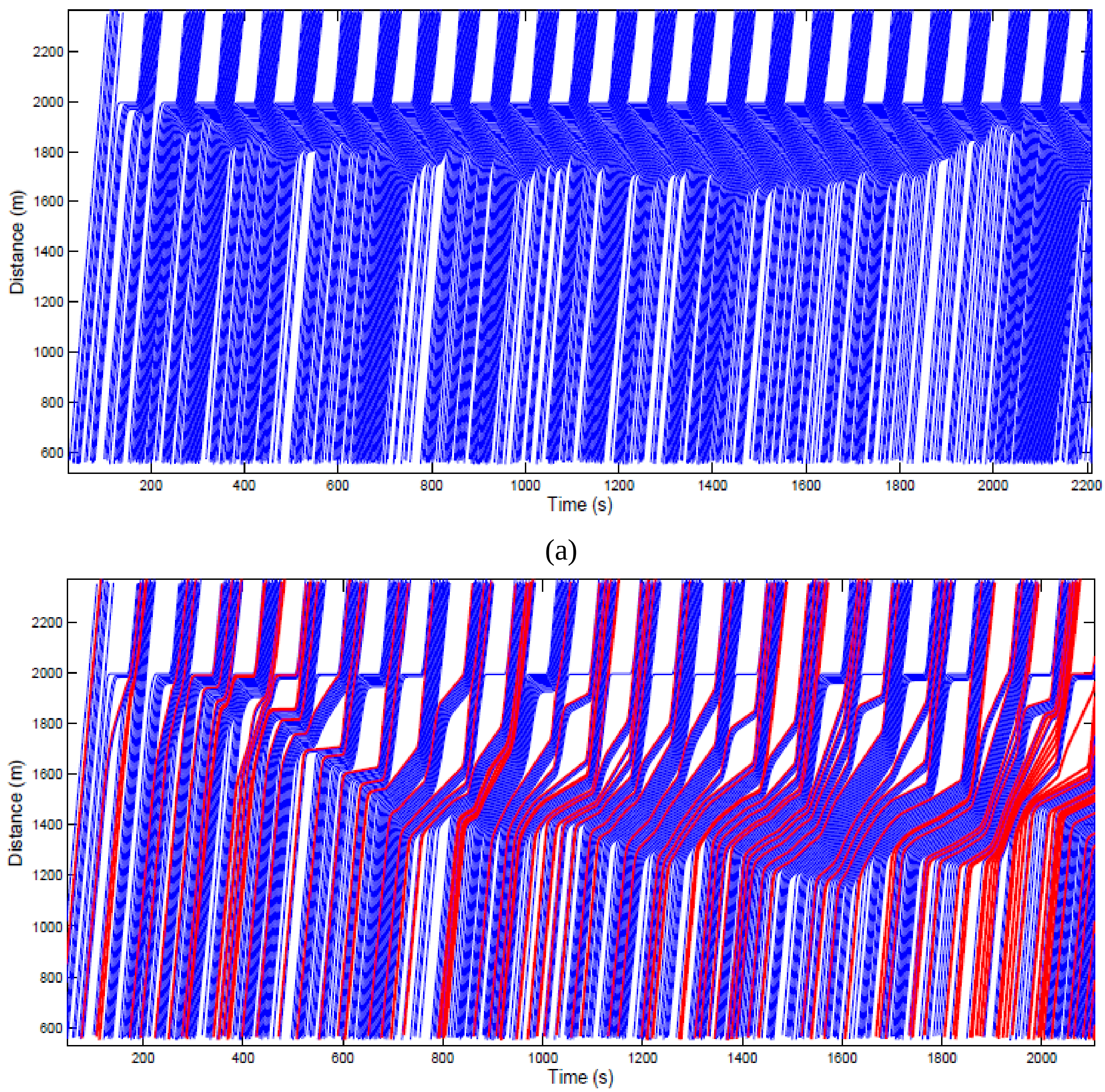


Figure 1.10: Savings in fuel consumption at a two-lane intersection under different demands

3.3.6 Failure of the Algorithm

In the development of the ECACC-Q algorithm with the consideration of queue, one critical assumption is that the studied network should never be over-saturated; otherwise, the estimation of queue length would not be accurate. In that sense, the advisory speed limits cannot control the behaviors of Eco-CACC equipped vehicles appropriately to minimize their fuel consumption rates. In this subsection, we simulate the single-lane intersection defined in section 3.3.1 to explain this limitation.

In the simulation, all link characters, the SPaT plan, and the settings of the ECACC-Q algorithm are kept the same. Vehicles are loaded for the OD pair at the rate of 800 vph, which is greater than the actual capacity of the control segment, and makes the network over-saturated. Fig.3.11 shows the vehicular trajectories around the intersection before and after applying the ECACC-Q algorithm, where the signal is located at x = 2000 meters. From Fig. 3.11 (a), the queues ahead of the signal is very long, and some vehicles in the queues should wait two or three cycles to pass the intersection. This indicates they will experience more than one stop-and-go behaviors during the whole trips. Fig.3.11(b) shows the trajectories of all vehicles when 20% of them are equipped with the algorithm. Clearly, we see once the queue is not dissipated by the next green light, the algorithm fails at providing appropriate advisory speed limits to the Eco-CACC equipped vehicles inappropriately. There are two major causes of the problem. First, when the road is oversaturated, the queue might not be dissipated by the green light during one cycle. Then in the next cycle, the unreleased queue is not formed at the stop bar, x_s, of the intersection; instead, it is rolling in between the intersection and the starting point of the control segment, x_u. Thus, the queue estimation method based on the kinematic wave model proposed in [5] cannot update the queue length correctly based on the instantaneous traffic information collected by loop detectors. Unless historical road conditions are provided, the estimation cannot be accurate. Second, the algorithm assumes that Eco-CACC equipped vehicles only perform deceleration at the upstream control segment, and they enter the segment with a high speed (such as the road speed limit). But, the rolling queue generated several stop-and-go waves[2] on the control segment, which prevent the Eco-CACC equipped vehicles to keep the cruise speed estimated by the algorithm. When they enter the rolling queue ahead, they will slow down and keep the low speed even there is a large gap ahead (see black circles in Fig.3.11(b)). These two causes can be eliminated when vehicle-to-vehicle communications are introduced. With the assistance of the technology, the queue length can be updated in real time accurately, and the stop-and-go behaviors are also able to be detected. Then, a more robust advices can be estimated to address the problem.



(a)

(b)

Figure 3.11: Vehicular Trajectories under an over-saturated intersection: (a) base, (b) ECACC-Q

3.4 Evaluation of ECACC-Q

In the aforementioned sections, only one approach of an intersection is simulated. In reality, vehicles can pass the intersection from upto four directions (see Fig.3.13). In this section, we make a comprehensive simulation about traffic conditions around a four-legged intersection, and examine the environmental benefits of the ECACC-Q algorithm. Fig.3.12 illustrates the configuration of the simulated intersection. In the network, vehicles are loaded from four origins, {1,2,3,4}, and exits to four destinations, {5,6,7,8}. The speed limits of all roads are v_f = 50 mph, and their capacities are all q_c = 1600 vph. The length of the upstream control segment for the major roads (1 and 3 to the signal) is set as 500 meters, and for the minor roads (2 and 4 to the signal) as 300 meters). All downstream control segments are set as 200 meters. The saturated deceleration and acceleration rates are 3 m/s^2 and 2 m/s^2, respectively.

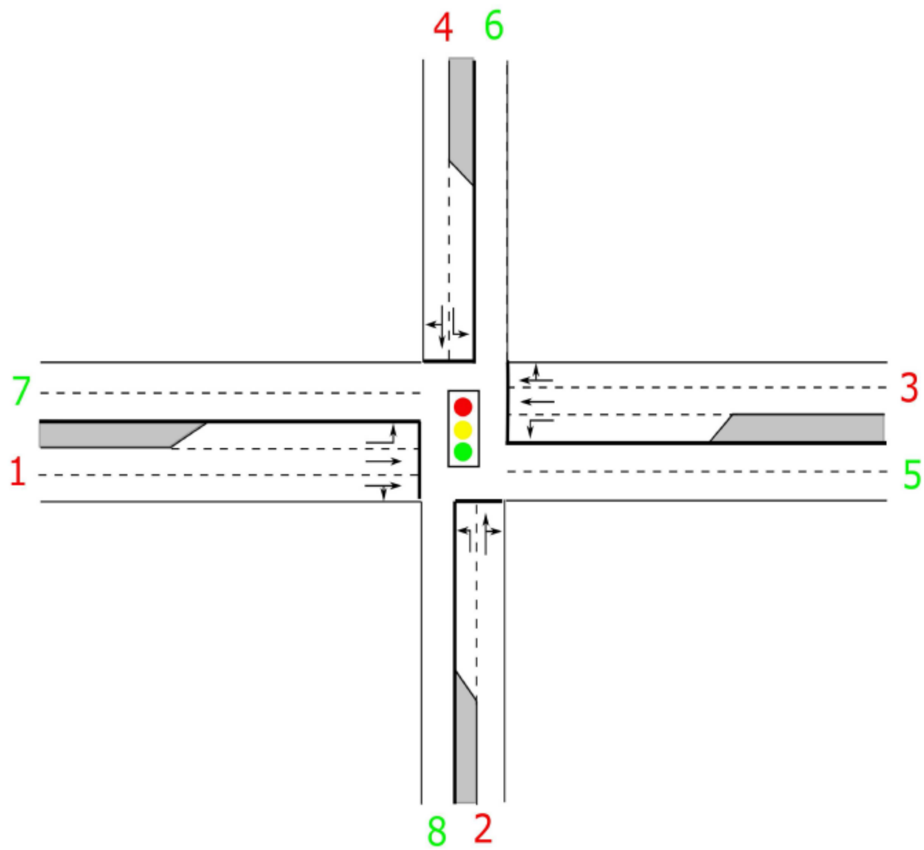


Figure 3.12: Configuration of a four-legged intersection

Table 2 shows the simulation settings with the demand of each OD, and the SPaT plan. The through traffic on the major roads is as high as 1000 vph, and on the minor roads, the left-turn volumes are higher than their through volumes. Fig.3.13 illustrates the savings in fuel consumption of all vehicles traveling across the intersection. As the through traffic on the major roads is very high, the benefits of the algorithm should mainly be determined by the Eco-CACC equipped vehicles there, and the results is similar to the example with a two-lane intersection in section 3.3.2. Under lower MPRs (< 25%), the algorithm has negative impact on reducing the overall fuel consumption. As long as the MPR is greater than 25%, the algorithm imparts positive benefits to the network. Once all vehicles are equipped, the fuel consumption can be reduced to as much as 12.5%.

Table 2: Simulation Setting of the four-legged intersection

Origin	Destination	Movement	Demand (vph)	Green+Amber:Cycle (second)
1	5	Through	1000	72:113
1	6	Left	150	12:113
2	6	Through	50	12:113
2	7	Left	150	17:113
3	7	Through	1000	72:113
3	8	Left	150	12:113
4	8	Through	50	12:113
4	5	Left	150	15:113

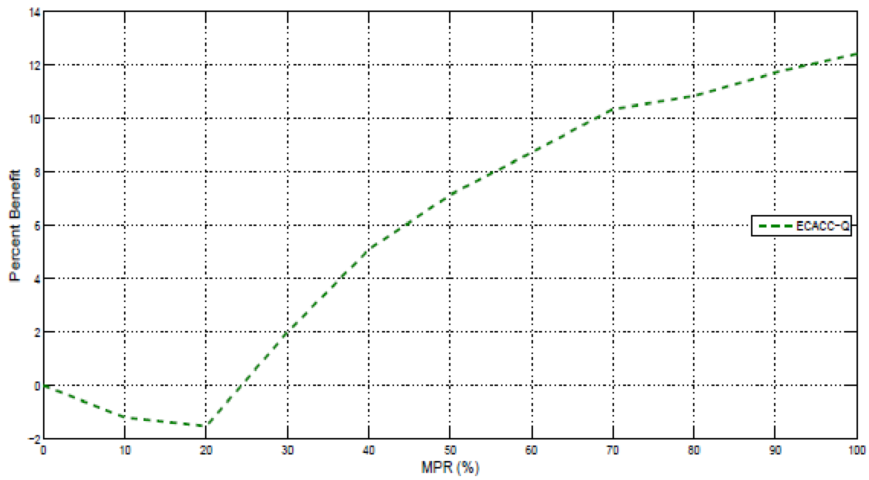


Figure 3.13: Savings in fuel consumption at a four-legged intersection

3.5 Conclusions

In this paper, we evaluate an ECACC-Q algorithm using the INTEGRATION simulation software. The proposed ECACC-Q algorithm utilized both SPaT information and vehicle queue information at signalized intersections to minimize the fuel consumption generated by Eco-CACC equipped vehicles. The algorithm provided advisory speed limits for the Eco-CACC equipped vehicles to move smoothly and to avoid complete stop at signals. This study made a comprehensive sensitivity analysis to examine the environmental benefits of the algorithm on reducing fuel consumption. The simulation of a single-lane intersection indicates that with higher MPRs of Eco-CACC equipped vehicles, the savings in fuel consumption were greater. When all vehicles were equipped with the ECACC-Q algorithm, the overall fuel consumption was reduced as high as 19%. While, the results at multi-lane intersections were different. At a two-lane intersection, due to intense lane-changing and over-passing behaviors, the algorithm increased the overall fuel consumption when the MPR was lower than 30%. Only when the MPR was greater than 30%, positive benefits could be observed; and with higher MPRs, the benefits were larger. Moreover, the comparison of ECACC-Q and ECACC-O indicated that considering the impact of vehicle queues ahead of signals would improve the benefits of the algorithm. Besides MPRs of Eco-CACC equipped vehicles, the sensitivity to phase splits was studied. With larger split percentages, the overall fuel consumption was smaller. But, the split percentages rarely affected the benefits of the algorithm. In addition, the sensitivity to the length of the upstream control segment was investigated. The results indicated that the fuel consumption was reduced more by the algorithm when the control length was longer, and a 500-meter control segment was long enough to obtain the greatest saving in fuel consumption. Furthermore, the sensitivity to the demands demonstrated that under the given control length and the split percentage, the algorithm could obtain the highest savings at a constant demand under different MPRs. Finally, we simulated a four-legged intersection, where the ECACC-Q algorithm was applied for all movements. The results showed that the algorithm could reduce the network-wide fuel consumption as high as 12.5%.

In this paper, we showed that the algorithm had negative impact on fuel consumption when the network was over-saturated. The algorithm only utilized loop detectors to estimate the queue length ahead of the signal. Once the road was over-saturated, the queue could not be dissipated during one cycle, and it was rolling on the upstream controlled segment. In that sense, the queue estimation tended to be inaccurate, and the advices of the speed limit from ECACC-Q was not effective on reducing fuel consumption. Moreover, the rolling queue caused stop-and-go waves ahead of the signal, which affected the upstream decelerating behaviors of Eco-CACC equipped vehicles. There are two potential solutions for this drawback. First, we can introduce connected vehicles to obtain individual vehicles' information, including their location and speed. So that, even the road is oversaturated, the estimation of the queue length can still be accurate. Second, we could introduce the speed harmonization algorithm [18] on arterial roads to restrict traffic entering intersections, or the green driving algorithm [3] to mitigate the impact of stop-and-go waves on the Eco-CACC equipped vehicles along a over-saturated road. Hence, the upstream segments are not over-saturated, and the ECACCQ algorithm can work appropriately. Currently, the algorithm only minimizes fuel consumption of vehicles crossing one intersection. In the future, we will improve the algorithm for Eco-CACC equipped vehicles passing multiple intersections.

3.6 References

[1] Nigel Jollands, PaulWaide,Mark Ellis, Takao Onoda, Jens Laustsen, Kanako Tanaka, Philippine de TSerclaes, Ingrid Barnsley, Rick Bradley, and Alan Meier. The 25 iea energy efficiency policy recommendations to the g8 gleneagles plan of action. Energy policy, 38(11): 6409–6418, 2010.

[2] Hesham Rakha, Kyoungho Ahn, and Antonio Trani. Comparison of mobile5a, mobile6, vt-micro, and cmem models for estimating hot-stabilized light-duty gasoline vehicle emissions. Canadian Journal of Civil Engineering, 30(6):1010–1021, 2003.

[3] Hao Yang andWen-Long Jin. A control theoretic formulation ofgreen driving strategies based on inter-vehicle communications. Transportation Research Part C, 41:48–60, 2014.

[4] Raj Kishore Kamalanathsharma, Hesham A Rakha, and Hao Yang. Network-wide impacts of vehicle eco-speed control in the vicinity of traffic signalized intersections. In Transportation Research Board 94th Annual Meeting, number 15-4290, 2015.

[5] Mani V. Ala Yang, Hao and Hesham Rakha. Eco-speed algorithm based on vehicle queues at traffic signalized intersections. Submitted to Transportation Research Board AnnualMeeting,2016.

[6] H Rakha and M Van Aerde. Integrationc release 2.50 for windows: 1 User's guide–volumei: Fundamental model features. Technical report, M. Van Aerde & Assoc., Ltd., Blacksburg,VA USA, 2013.

[7] H Rakha and M Van Aerde. Integrationc 4 release 2.50 for windows: User's guide–volume ii:Advanced model features. Technical report, M. Van Aerde & Assoc., Ltd., Blacksburg, VA USA, 2013.

[8] Hesham A Rakha, Kyoungho Ahn, Kevin Moran, Bart Saerens, and Eric Van den Bulck. Virginia tech comprehensive power-based fuel consumption model: model development and testing. Transportation Research Part D, 16(7):492–503, 2011.

[9] M Van Aerde. Modelling of traffic flows, assignment and queueing in integrated freeway/traffic signal networks. In Transportation Research Board 64th AnnualMeeting, number784855, 1985.

[10] Michel Van Aerde and Sam Yagar. Dynamic integrated freeway/traffic signal networks: Problems and proposed solutions. Transportation Research Part A, 22(6):435–443, 1988.

[11] Michel Van Aerde and Sam Yagar. Dynamic integrated freeway/traffic signal networks: A routing-based modelling approach. Transportation Research Part A, 22(6):445–453, 1988.

[12] MW Van Aerde and S Yagar. Combining traffic management and driver information in integrated traffic networks. In 3rd International Conference on Road Traffic Control, pages11–15. IET, 1990.

[13] Hesham Rakha and Yihua Zhang. Integration 2.30 framework for modeling lane-changing behavior in weaving sections. Transportation Research Record, 1883(16):140–149, 2004.

[14] Hesham Rakha and Kyoungho Ahn. Integration modeling framework for estimating mobile source emissions. Journal of transportation engineering, 130(2):183–193, 2004.

[15] Hesham Rakha, Kyoungho Ahn, and Antonio Trani. Development of vt-micro model for estimating hot stabilized light duty vehicle and truck emissions. Transportation Research Part D, 9(1):49–74, 2004.

[16] M Van Aerde. Single regime speed-flow-density relationship for congested and uncongested highways. In Transportation Research Board 74th Annual Meeting, volume 6, 1995.

[17] Michel Van Aerde and Hesham Rakha. Multivariate calibration of single 1 regime speed-flow density relationships. In 6th 1995 Vehicle Navigation and Information Systems Conference, pages 334–341, 1995.

[18] Hao Yang and Hesham Rakha. Developemnt of a speed harmonization algorithm: Methodology and preliminary testing. Submitted to Transportation Research Part B, 2015.

Chapter 4: Conclusions and Recommendations for Future Research

4.0 Conclusions

In this thesis, we developed an eco-cooperative adaptive cruise control (Eco-CACC) algorithm to minimize fuel consumption levels of vehicles proceeding through signalized intersections. The algorithm utilizes SPaT information accessed through V2I communication and predicted vehicle queues derived from road-side loop detectors to compute optimum instantaneous vehicle speeds. In the study, we first analytically investigated the impact of different advisory speed limits and queue lengths on fuel consumption levels of vehicles traversing a signalized intersection. The analysis demonstrated that the most fuel-efficient advice for vehicles is to travel at the highest possible speed while traversing the intersection. Advisory speed also depends on queue length at intersection. The algorithm predicts the length of the queue ahead of the Eco-CACC equipped vehicles using the LWR model to estimate the release time of the queue using traffic count and SPaT data. A second-by-second advisory speed limit is provided to the CVs to reduce the stops and an optimal upstream deceleration and downstream acceleration level are computed to minimize the vehicle fuel consumption level. The analysis of the proposed Eco-CACC algorithm indicates that longer vehicle queue lengths result in higher fuel consumption levels, but Eco-CACC with and without queue prediction produce reductions in fuel consumption levels. However, the consideration of the queue length produces larger reductions in fuel consumption levels compared to the base algorithm that does not predict queues. Besides the analytical work, we also evaluated the algorithm using microscopic simulations.

The simulation of a single-lane approach demonstrate that the Eco-CACC algorithm with queue prediction produces smoother vehicle trajectories. However, queue prediction on multilane approaches is not accurate since non-Eco-CACC equipped vehicles tend to change lanes to pass the Eco-CACC equipped vehicles. While assessing the factors that affect the performance of the algorithm, we considered the length of the controlled segments, number of lanes, the traffic demand levels, and the signal timing plan for further study and sensitivity analysis. Results of this comprehensive sensitivity analysis indicate that the savings in fuel consumption are greater with higher MPRs of Eco-CACC equipped vehicles on a single-lane approach. When all vehicles are equipped with the Eco-CACC-Q algorithm, the overall fuel consumption is reduced by as high as 19%. While, the results on a two-lane approach are different due to intense lane-changing and passing behaviors. The algorithm increased the overall fuel consumption level when the MPR was lower than 30%. Only when the MPR was greater than 30%, could positive benefits be observed; and with higher MPRs, the benefits were larger. Moreover, the comparison of Eco-CACC-Q and Eco-CACC-O indicated that considering the impact of vehicle queues ahead of traffic signals improves the algorithm performance, which confirms the analysis in Chapter 2. Besides MPRs of Eco-CACC equipped vehicles, the sensitivity to phase splits was studied. With larger split percentages, the overall fuel consumption is smaller. But, the split percentages rarely affect the benefits of the algorithm. In addition, the sensitivity to the length of the upstream control segment was investigated. The results indicate that there is reduction in fuel consumption when the control length is longer, and a 500-meter control segment is long enough to obtain the greatest savings in fuel consumption levels. Furthermore, the sensitivity to the demand levels demonstrated that under the given control length and the split percentage, the algorithm could obtain the highest savings at a constant demand for different MPRs. We also simulated a four-legged intersection, where the Eco-CACC-Q algorithm was applied for all movements. The results showed that the algorithm could reduce the network-wide fuel consumption level by as high as 12.5%.

Furthermore, the algorithm was tested for over-saturated conditions and we concluded that the algorithm fails once the road is over-saturated. The algorithm only utilized loop detectors to estimate the queue length ahead of the traffic signal. Once the road was over-saturated, the queue could not be dissipated during one cycle, and it was rolling on the upstream controlled segment. In that sense, the queue estimation tended to be inaccurate, and the advices of the speed limit from ECACC-Q was not effective on reducing fuel consumption. Moreover, the rolling queue caused stop-and-go waves ahead of the signal, which affected the upstream decelerating behaviors of Eco-CACC equipped vehicles. There are two potential solutions for this drawback. First, we can introduce connected vehicles to obtain individual vehicles' information, including their location and speed. So that, even the road is oversaturated, the estimation of the queue length can still be accurate. Second, we could introduce the speed harmonization algorithm [1] on arterial roads to restrict traffic entering intersections, or the green driving algorithm [3] to mitigate the impact of stop-and-go waves on the Eco-CACC equipped vehicles along an over-saturated road. Hence, the upstream segments are not over-saturated, and the ECACCQ algorithm can work appropriately.

4.1 Recommendations for Future Research

The algorithm was evaluated at an isolated fixed-time traffic signal controlled intersection and for a maximum of two through lanes in each direction. Consequently, it is recommended that the algorithm be tested and extended to consider actuated traffic signal control, an arterial network considering both coordinated and uncoordinated traffic signal control, and approaches with more than two lanes per approach. At present, the algorithm could be evaluated on an arterial network, however the control lengths of the intersections cannot overlap because each intersection acts independent of all other intersections. In such a case, a vehicle travelling through the first intersection attains the speed limit by the end of the downstream control length and may have to decelerate to a lower cruising speed as soon as it enters the control segment of the second intersection. Although there is a definite reduction in fuel consumption at each intersection, it is not the most efficient approach because it ignores this interaction in computing the vehicle trajectory. The algorithm could be redesigned to compute an advisory speed profile in-between intersections and to avoid unnecessary acceleration/deceleration maneuvers.

It was observed that when the control length is less than 100m, vehicles fail to reach their desired cruising speed in such short distances and in all situations they come to a complete stop at the stop line. In such cases coordinating a group of minor intersections can be investigated such that vehicles may have to stop at one major intersection and the control length for that major intersection passes through minor intersections. The efficiency of the algorithm in case of coordinated and uncoordinated intersections needs to be investigated.

Due to continuous lane changing behavior of non-equipped vehicles there is a corresponding change in the predicted queue length, which leads to erroneous vehicle behavior. The algorithm can be actually tested on a connected vehicle test bed in presence of surrounding traffic to determine the actual benefit harnessed by the algorithm in real life.

4.2 References

[1] Hao Yang and Wen-Long Jin. A control theoretic formulation of green driving strategies based on inter-vehicle communications. Transportation Research Part C, 41:48–60, 2014.

[2] Hao Yang and Hesham Rakha. Developemnt of a speed harmonization algorithm: Methodology and preliminary testing. Submitted to Transportation Research Part B, 2015