A Fuel-Saving Green Light Optimal Speed Advisory for Signalized Intersection Using V2I Communication

By

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Abstract

The research in this thesis introduces a connected vehicle environmental green light speed advisory which helps the vehicle to avoid unnecessary stops before intersections and improves the fuel consumption efficiency. Lots of works for Eco-driving on GLOSA (Green Light Optimal Speed Advisory) have been done by the previous researchers. Most of them focus on the macro level where the process of speed changes is ignored. Hesham Rakha, etc[12] considered the acceleration process, but there is no simulation and field data to support his result and also the fuel consumption objective is the total consumption which did not consider the total distance. As the total fuel consumption will depend on the processing distance. This paper will formulate fuel consumption objective functions based on VT (Virginal Tech) Micro model to analyze the fuel consumption on vehicle's different speed profiles. To avoid the unnecessary stops, different speed strategies will be provided by the system. Over 100,000 rounds of simulations have been conducted in MATLAB and the result shows that the average fuel saving for green light signal is 21% and for red signal scenarios is 56%. Also an android based app has been developed to collect the field data on connected vehicle environment. The result from the field shows 14% of fuel was saved for vehicle with GLOSA application compared to vehicle without GLOSA. However, the research on this paper only considered one vehicle and one intersection for ideal conditions. In the future, queues at intersection need to be considered as well as multi-intersections condition.

Acknowledgement

To finish this thesis, I got lots of help from other people. It would not be possible for me to finish it without the help from them.

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Last but not least, I wish to express my love to my family and friends. Only with their support and love can I enjoy, and finish my graduation study. Thanks for their understanding for all these years.

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List of Abbreviation

ARRB	Australian Road Research Board
CMEM	Comprehensive Modal Emission Model
CST	Center for Smart Transportation
DSRC	Dedicated Short Range Communication
GLOSA	Green Light Optimal Speed Advisory
ITS	Intelligent Transportation System
OBU	Onboard Unit
PHEM	Passenger car and Heavy Duty Emission Model
RSU	Roadside Unit
SPAT	Signal Phase and Timing
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
VT-Micro	Virginia Tech Microscopic
WAVE	wireless access for vehicular environments

CHAPTER 1 INTRODUCTION

This chapter presents the background of Green Light Optimal Speed Advisory (GLOSA) and Eco driving in Connected Vehicle environment. The research motivation, research objectives and research problems are also introduced in this part. At the last of this part, the structure of thesis is presented.

1.1 Background

Transportation fuel consumption is a critical problem for society. The 2012 report of World Wild Fund has indicated that road transportation is the single most significant contributor to carbon emission in Canada, accounting for 19 percent of the country's total greenhouse gas emissions. Meanwhile, light-duty vehicles make up to 65% of the road transportation emission. In addition, the emission of road transportation has increased 35 percent since 1990[1]. How to reduce carbon emission and save fuel is an issue considered not only by government, but also individual drivers.

Both car manufacturers and transportation researchers are trying to use new technologies to reduce fuel consumption. Recently, cylinder deactivation, start-stop system, etc. haven been used in car manufacturers industry[2]. In transportation area, intelligent transportation system (ITS), which applies the wireless communication, information technologies, etc., is one of the effective solutions to critical transportation problems. The GLOSA is one of the important applications to reduce traffic delay and fuel consumption in ITS.

The GLOSA application provides the driver with accurate speed advice about the approaching intersection by taking advantage of traffic light timing and vehicle positions. The aim of this application is to guide the vehicle going through signaled intersections with a more appropriate speed in order to reduce stopped time and save fuel[3]. Typically, this kind of applications is implemented as roadside message signs with a speed advice that placed ahead the intersection[4]. Divers need to adjust their speed in order to pass the intersection without stop as they are approaching to the intersection. However, only a few of this kind of GLOSA applications have been deployed due to its hardware cost, impractical deployment and need lots of maintenance. Another GLOSA application is the countdown timer. The countdown timer is more common for pedestrian signals in North America while it is widely used in China for drivers. The countdown timer is only visible in a short range which made it difficult for the driver to make decision in order to pass the intersection without stop[5].

Recently, the connected vehicle technologies, specifically the Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications have been discussed a lot in transportation area. The GLOSA application also can be achieved by providing each driver with downstream intersection signal information based on dedicated short-range communications (DSRC). In connected vehicle environment, it is easy to get accurate signal timing information and provide the driver with speed advice to avoid unnecessary stop at the intersections.

1.2 Problem Statement

A lot of researches have been done on emission or traffic time reducing based on GLOSA in connected vehicle environment. Some of them do not care about the micro process of vehicle movement and only coordinate the vehicle speeds considering the whole road network performance. This should be effective when the whole road network has been implemented with connected vehicle devices. But it’s hard to do the field test experiment as its high requirement of devices and vehicle deployment. And also the acceleration and deceleration process have been ignored which make fuel consumption model inaccurate. Some other researches are focus on the individual vehicle in one or two intersections and have done the field test. However, they do not have a large scale field test or simulation using an emission model which makes the results less credible. To the best of my knowledge, few researchers set up a micro emission model and real field test for single vehicle in single intersection and consider all scenarios when vehicles are approaching to intersections. Vehicle movement should include the acceleration, constant speed and deceleration stages. The objective function for fuel consumption also should consider the status before and after passing the intersections. All these kinds of problems should be taken into consideration. This thesis will summarize the works of previous researchers and develop a practical GLOSA application in V2I environment.

1.3 Research Motivation

Transportation fuel consumption is a critical problem for society. Both vehicle manufacturers and transportation researchers are trying to use new technologies to reduce fuel consumption. While GLOSA is a useful and important application in ITS, and a lots of researches have been done on this topic. But there are still some issues in the previous researches. How to apply the GLOSA application in connected vehicle environment? Is it possible for GLOSA application to reduce fuel consumption? And how many percentage of fuel can the application save?

This thesis is going to set up a fuel saving GLOSA application based emission model in connected vehicle environment. Large scale of simulation in MATLAB will be done and the simulation results will be analyzed. Also, a smartphone application integrated with the emission model will be used as a terminal in field test.

1.4 Research Objectives

The research introduces a practical fuel saving GLOSA application in connected vehicle environment. The goals of this research are as following:

a) Review the works of previous researchers' on both on Eco-driving and GLOSA applications in connected vehicle environment.
b) Develop a GLOSA application based on SPAT message in CST connected vehicle environment.
c) Evaluation of the fuel saving efficiency based on MATLAB simulation and field test results.
d) Providing suggestion and evaluate the possibility of the future GLOSA application implementation on the first Canadian connected test bed.

1.5 Structure of Thesis

The structure for this thesis is as follows.

Chapter 1 introduces the background for GLOSA applications, Eco-driving and connected vehicle environment.

Chapter 2 will discuss about the works that have been done in past few years on GLOSA applications.

Chapter 3 is the methodology part which introduces the emission model and presents the strategies when facing different scenarios for vehicle approaching to intersections. And also the system framework is introduced.

Chapter 4 will introduce the setting up of simulation in MATLAB and its results together with results analysis. Also the field test result is discussed in this chapter.

Chapter 5 concludes the whole research and provides suggestions for the future research and applications development on the connected vehicle test bed.

CHAPTER 2 LITERATURE REVIEW

This chapter presents and discusses the previous researchers' work on emission models, signal control, Eco-driving, GLOSA and its applications in connected vehicle environment. The first part of this section will introduce the fuel consumption and emission models. And then the researches on Eco-driving for single vehicle in single intersections, multi-vehicles in single intersection, and multi-vehicles in multi-intersections will be discussed. The last part will summarize the literatures and propose the research value points for this thesis.

2.1 Fuel Consumption and Emission Models

Basically, there are two types of emission model, the macroscopic emission models and microscopic energy and emission models[6]. The macroscopic emission models are a function of vehicle type and age, average speed, temperature, altitude, vehicle load, air conditioning usage and vehicle operating model. This is not the focus of this research; the research of this thesis will mainly focus on the microscopic emission and fuel consumption models.

For microscopic models, second by second vehicle characteristics, traffic conditions, and roadway conditions are the input for estimating the expected fuel consumption and emission rate. Vehicle characteristics can be the instantaneous vehicle power, tractive efforts, acceleration, speed, etc[6].

Some fuel consumption models are based on instantaneous power demand and some other are based on the instantaneous vehicle speed and accelerations. In 1984, Post et al. developed a fuel consumption model based upon the instantaneous power demand undergone by a vehicle and they used 177 vehicles to do experiments to get the model parameters[7]. The instantaneous fuel consumption-power relationship was described as the following:

$$\text{FC(ml/min)}\begin{cases} = \left(\alpha + \beta * Z_{tot}(\text{KW})\right) & for\ Z_{tot} \geq 0KW \\ = \alpha(ml/min) & for\ Z_{tot} < 0KW \end{cases}$$

Where α, β is the model coefficients that can be get from experiments, FC is the fuel consumption and Z_{tot} is the instantaneous power demand. The values for α, β for each vehicle can vary as the vehicle's condition varies. It's had been concluded that both α and β did not show any dependence upon vehicle age or mileage. The total power Z_{tot} is the sum of drag power, inertial power, and gradient power. As a result, the power demand Z_{tot} can be described as the following:

$$Z_{tot} = f(u, u^2, u^3, ua)$$

Where u is the instantaneous speed and a is the instantaneous acceleration for vehicle. This model is useful and could be used to calculate the instantaneous vehicle fuel consumption. However, the zero power fuel consumption rate α was highly correlated to vehicle's engine capacity. What's more important, the parameters were found to be unstable and vary with time in range of 10 percent[6]. In 1987, C. S. Fisk et al. improved the Post model by adding two efficiency parameters,$\beta 1, \beta 2$, and allowed for an engine drag component to be part of the total drag power. The improved model is called the Australian Road Research Board (ARRB) model.

In recent years, several microscopic emission models were developed. Among these models, the Comprehensive Modal Emission Model (CMEM) and the Virginia Tech Microscopic (VT-Micro) energy and emission model received most repute and are available for third party use. Passenger car and Heavy Duty Emission Model (PHEM) is an instantaneous vehicle emission model developed by the TU Graz since 1999[8] and also a perfect model for emission computation of single vehicle[9]. PHEM is capable of simulation vehicle hot and cold emission for different cycles gear shift strategies, vehicle loadings, road gradients and vehicle characteristics. It has been validated by emission measurements both from light and heavy duty vehicles in the laboratories and on the road under different test conditions[10]. However, the model is not opened to third party use. Similarly with PHEM, CMEM model is one of the newest power demand-based emission models and was developed by researchers at the University of California, Riverside. The CMEM model estimates the light duty cars and trucks as a function of the vehicle's operation mode and has the ability to predict emissions for a wide variety of vehicles and various operating states[11].

However, in the research of this thesis, the instantaneous speed and acceleration of vehicle will be considered a lot and it's better to use the model which takes the speed and acceleration as input and fuel consumption as output. VT-Micro emission model was developed as a statistical model consisting of linear, quadratic and cubic combination of speed and acceleration levels. All the measurement data was collected by Oak Ridge National Laboratory and the Environmental Protection Agency[12]. The final regression model included a combination of linear, quadratic, and cubic speed and acceleration terms as it provided the least number of terms with a relatively good fit to original data[11]. This research is going to use this fuel consumption model as it's easier to implement and convenient for the smartphone device to get the instantaneous speed and acceleration values.

2.2 Eco-Driving and GLOSA

The goal of Eco-Driving is to reduce fuel consumption while meeting the driver's traffic demand. Besides the new technologies of Eco-driving from vehicle manufacturers, transportation researchers have done lots of work on this. Behrand Adadi et al. proposes an optimization based control algorithm using short range radar and predicted traffic signal information to reduce idle time and fuel consumption[13]. The control objectives are timely arrival at green light with minimal use of braking, maintaining safe distance between vehicles and cruising at or near set speed. In 2013, Giovanni De Nunzio et al. proposed an eco-driving assistance algorithm which provides vehicle velocity trajectory advisories in order to save fuel[14]. The paper optimizes whole urban traffic networks assuming communication between infrastructure and vehicles and a complete knowledge of the upcoming traffic lights timing. And Sanjiban Kundu et al in 2013 present a new approach to eco-speed control where the control of focus is on infrastructure side. This paper used a platoon of vehicles to reduce fuel consumption in a journey covering multiple intersections[15]. Besides, Grant Mahler in 2012 proposed a probabilistic prediction model to predict traffic signal timings in order to reduce idling at red lights[16]. The core part of this paper is the signal phase prediction model which use historically averaged timing data and real time phase data. Aleksandar et al. evaluated GLOSA implementation for predictable fixed-time signal timing and unpredictable actuated-coordinated signal timing. In the experiment of this paper, two-intersection traffic network was modeled in VISSIM. The results indicated that actuated-coordinated signal timings were not dependable for use in GLOSA systems. But for fixed-time signals, higher penetration rate and more frequent GLOSA activations resulted in better traffic performance[17]. Tessa Tiellert et al. applied large scale GLOSA simulations and did the sensitivity analysis in 2010. The results showed that distance from traffic light at which vehicles are is a key influencing factor[18].

For vehicles approaching intersections, the large sources of fuel consumption are the idle waiting at the stop line, strong braking and acceleration. The driver should avoid these in order to saving fuel. In fact smoothing velocity trajectories was found to be an efficient fuel-saving method. Therefore, intelligent speed adaptation (ISA) devices have been developed to provide advised speed for drivers in UK. The ISA devices were mainly designed for traffic safety purpose, but it also helps to reduce fuel consumption due to smoother speed variations[12]. To sum up, avoiding acceleration and deceleration and keep a constant speed are the key strategies behind the eco-driving. However, the traffic condition is complicated. The variation of speed can be affected by external factors, such as nearby vehicles, traffic signals. Thus using new technologies to get the real-time signal information to forecast the vehicle nearby conditions is becoming one of the new strategies for eco-driving research[12].

The V2I communication makes it possible to get the real-time signal information for the vehicle approaching intersection. Once the vehicle gets the signal phase and timing information, together with the real-time vehicle speed and distance to intersection, appropriate speeds can be proposed to driver in order to reduce fuel consumption and avoid unnecessary stops. The idea is called green light optimal speed advisory (GLOSA).

Different researchers have different viewpoints dealing with GLOSA research. B. Bradai, et al. proposed a GLOSA system to reduce CO2 emissions, which indicated an average of 13% CO2 emission reduce. And field test showed an average traffic time saving is 12%[19]. In this research, a smartphone was used as a human machine interface, as well as the device to get instantaneous speed data and GPS locations. The details of advisory strategies were not explored. The paper only presented the signal information to the driver and did not provide specific speed advisory. The driver needed to make the decision based on the signal information. This is the primary stage of the GLOSA application and more directly and readable information should be provided to the driver. If the details of vehicle movement are not consider, then it’s better to take the trip route into consideration.

In 2013, Marcin Serdynski, et al. proposed a multi-segment GLOSA application, which handled multi-segment. Most researches are focused on single segment, which means only the approaching intersection is considered for optimization. However, this research took a route consisted of several signal lights. The speed optimization was performed using a genetic algorithm and an advisory speed is provided for each segment[20]. The experiment in this research indicated that multi-segment GLOSA method was better when compared to single-segment approach both for traffic time and fuel consumption measurements. This paper gave a good viewpoint for GLOSA research and there is no doubt that the results will be better is the whole road network can be considered. In contrast, the ignorant of acceleration and deceleration processes in the paper made the results less credible. And the paper took the difference of speed as fuel consumption indicator is not accurate as far as I am concerned.

Katsaros, et al. studied the performance of a GLOSA application in an integrated cooperative ITS simulation platform. This paper monitor the impacts of GLOSA on fuel and traffic efficiency by introducing metrics for average fuel consumption and average stop time behind a traffic light. The simulation based on a simple two signalized intersections showed that the system can improve the fuel consumption and reduce travel time. The results for different connected vehicle penetration rate indicated that the higher penetration rate, the more benefits the application can get. The best part of this paper is the simulation. The challenge of GLOSA simulation is that it needs to combine and synchronize different simulation aspects, e.g. vehicular traffic, network communication and application handling. To address the problem, the paper used the integrated simulation platform VSimRTI. VSimRTI is lightweight and supports V2X elements[3]. The disadvantage of this paper is that the different scenarios when approaching the signalized intersection were not discussed and no field test to support the simulation results.

Hesham Rakha, et al. presented signalized eco-driving study using V2I communication in 2011. The paper developed a framework to enhance vehicle fuel consumption efficiency while approaching a signalized intersection[21]. In the paper, a simply objective function that indicates the fuel consumption of a vehicle approaching the intersection is optimized. Four different scenarios that the vehicle may encounter when approaching a signalized intersection were discussed. But only one of the scenarios is considered and simulated. It was assumed that the vehicle can adjust the speed to arrive at the stop line when the traffic light is about to change from red to green. Thus for a specific signal condition, the required speed is fixed and only variable for fuel consumption objective function is the acceleration rate. The author considered both upstream and downstream of the intersection as the vehicle needs to recover its speed after passing the intersection. The experiment in paper used the VT-Micro emission model to measure the fuel consumption. This paper proposed a model with an explicit objective function to minimize the fuel consumption, while most models previously developed use constrained optimization algorithms which use simpler objective functions. However, only the red signal scenario was considered and the experiment was limited since it only simulated a specific condition. The experiment should be general and considers all the possible conditions when facing an intersection. What's more important, the optimized result is the acceleration, which is not appropriate to present it as advice to drivers. A more general and practical model should be developed.

The research of this thesis will extend to general condition based on the Hesham Rakha's model. A more practical model will be developed and large scale of value simulation will be done in MATLAB. Also the practical model will be implemented in the smartphone to collect data in real connected vehicle environment.

CHAPTER 3 METHDOLOGY

This chapter will introduce the details of methodology part in this thesis. Firstly, the system hardware and architecture will be introduced. After that, the eco-driving strategies will be discussed and several scenarios that a vehicle may encounter when approaching to intersections will be introduced. Then, the VT-Micro emission model will be introduced and two objective functions will be created in order to get the optimal fuel consumption results. At last, the GLOSA work logic will be presented.

3.1 Connected Vehicles

As U.S. DOT defined, "connected vehicle focus on localized vehicle-to-vehicle, vehicle-to-infrastructure and vehicle to device systems to support safety, mobility and environmental applications using vehicle dedicated short range communications (DSRC) \wireless access for vehicular environments (WAVE)"[22]. WAVE is a set of standards in DSRC suite to support the cooperative and safety critical applications. DSRC is based on Wi-Fi, and is the core part of standards to support cooperative, safety-critical V2X applications. In addition, DSRC is flexible to support mobility and environmental applications. The research purpose here is to improve the mobility and environment.

3.1.1 Dedicated Short Range Communication (DSRC)

DSRC is a two-way short-to-medium-range (1000 meters) wireless communications capability that permits very high data transmission critical in communications-based active safety applications[23]. It supports both public safety and private operations in vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication environments. The United States Federal

Communications Commission allocated 75 MHz of spectrum in the 5.9 GHz band for use by Intelligent Transportation Systems (ITS) vehicle safety and mobility applications[23]. V2I and V2V applications utilizing DSRC have the potential to significantly reduce many of the most deadly types of crashes by real-time advisories alerting the imminent hazards. The benefits of DSRC technologies include the follows.

a) Designated Licensed Bandwidth: For secure, reliable communications to take place.
b) Fast Network Acquisition: Active safety applications require the immediate establishment of communication and frequent updates.
c) Low Latency: Active safety applications must recognize each other and transmit messages to each other in milliseconds without delay.
d) High Reliability When Required: Active safety applications require a high level of link reliability. DSRC works in high vehicle speed mobility conditions and delivers performance immune to extreme weather conditions (e.g., rain, flog, snow, etc.).
e) Priority for Safety Applications: Safety applications on DSRC are given priority over non-safety applications.
f) Security and Privacy: DSRC provides safety message authentication and privacy[23].

3.1.2 Roadside Units (RSUs)

A roadside unit is a DSRC device used to transmit to and receive from, DSRC equipped moving vehicles (OBUs). The RSU transmits from a fixed position on the roadside (which may in fact be a permanent installation or from temporary equipment brought on-site for a period of time associated with an incident, road construction, or other event). RSUs have the ability to transmit signals with greater power than OBUs (Onboard Units) and may have TCP/IP connectivity to other nodes or the internet[24].

In this research, the RSUs used are LocoMate RSU produced by Rrada. It integrated with GPS and high-power 802.11p radios. It is fully compliant with Omni-Air's certification and used worldwide deployments. The following figure is a real RSU device[25].

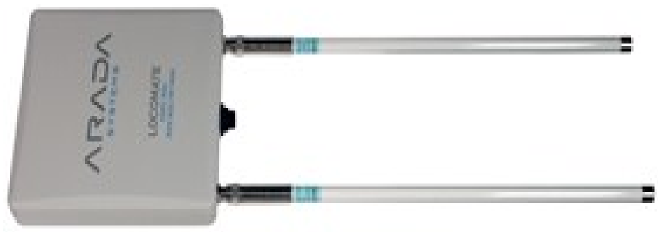

Figure 1 ARADA LocoMate RSU device

3.1.3 On-Board Unit (OBUs)

An on-board unit is a vehicle mounted DSRC device used to transmit and receive a variety of message traffic to and from DSRC devices (other OBUs and SRUs). The research presented in this thesis uses the LocoMate OBU. It is integrated with GPS (better than 1 meter accuracy), Bluetooth and high-power 802.11p radios. The following figure shows a real OBU device[26].

Figure 2 ARADA LocoMate OBU device

3.1.4 Signal Controller

A signal controller is the control device of traffic signals. In this research, we use ASC/3 RackMount offered by Safetran. It's the latest in a series of Advanced System Controllers and builds on the proven software, design flexibility, and unique feature set of the popular ASC/3 family of controllers. The controller is windows-based remote user interface and has Ethernet for 100 base T networks, 16x14 LCD display with adjustable contrast[27]. The following figure is a ASC/3 RackMount controller device.

Figure 3 ASC/3 RackMount Controller

3.1.5 Signal Phase and Timing Message (SPaT)

Signal phase and timing message describes the signal sate of the intersection and how long this state will persist for each approach and lane that is active. The SPaT message sends the current state of each phase, with all-red intervals not transmitted. Movements are given to specific lanes and approaches by use of the lane numbers present in the message[28].

The SPaT message should include the following information:

- DSRCmsgID
- Intersection ID
- Intersection Status
- List of movement states with lanes associated

And the movement of states is described as the follows.

- Movement name
- List of lane numbers in this movement
- Signal/pedestrian state
- Time to change
- Yellow state
- Yellow time to change
- Pedestrian detected

Table 1 Movement names in SPaT Message[29]

	Green	Yellow	Red	Flashing
Ball	0x00000001	0x00000002	0x00000004	0x00000008
Left Arrow	0x00000010	0x00000020	0x00000040	0x00000080
Right Arrow	0x00000100	0x00000200	0x00000400	0x00000800
Straight Arrow	0x00001000	0x00002000	0x00004000	0x00008000
Soft Left Arrow	0x00010000	0x00020000	0x00040000	0x00080000
Soft Right Arrow	0x00100000	0x00200000	0x00400000	0x00800000
U-Turn Arrow	0x01000000	0x02000000	0x04000000	0x08000000

The following is a message fragment illustrating the format of SPaT message[28].

SPaT Message
    Msg id = 0x0c (indicates a SPaT message)
    SPaT id = TBD (indicates a unique value for this intersection)
    States
        State #1
            Lane Set (list of lanes this applies to)
                1, 2
            Movement State (signal state or pedestrian state)
                SignalState = Green light
            TimeToChange = 12.3 seconds
            YellowSignalState =
        State #2

Lane Set u(list of lanes this applies to)
3,4.5.6, etc...
Movement State (signal state or pedestrian state)
SignalState = Red light
TimeToChange = Indeterminate for this state
YellowSignalState =
Preempt = none present

The overall use of SPaT message is to reflect the current state of all lanes in all approaches in a single intersection. Thus, all the preemption and priority should follow in a structure and lanes in the same state are combined. The simplest SPaT message consists of two such states, one for the active lanes, and another for stopped lanes[28].

3.2 Application Framework

The basic work flow for the application is as the following figure shows. RSU gets the signal phase and timing information from the signal controller and then send the message to the OBU via DSRC. After the OBE received the message from RSU, it resends the message to the smartphone by Bluetooth. And the smartphone does the calculation and provides advice based on the message, as well as the real time speed and distance.

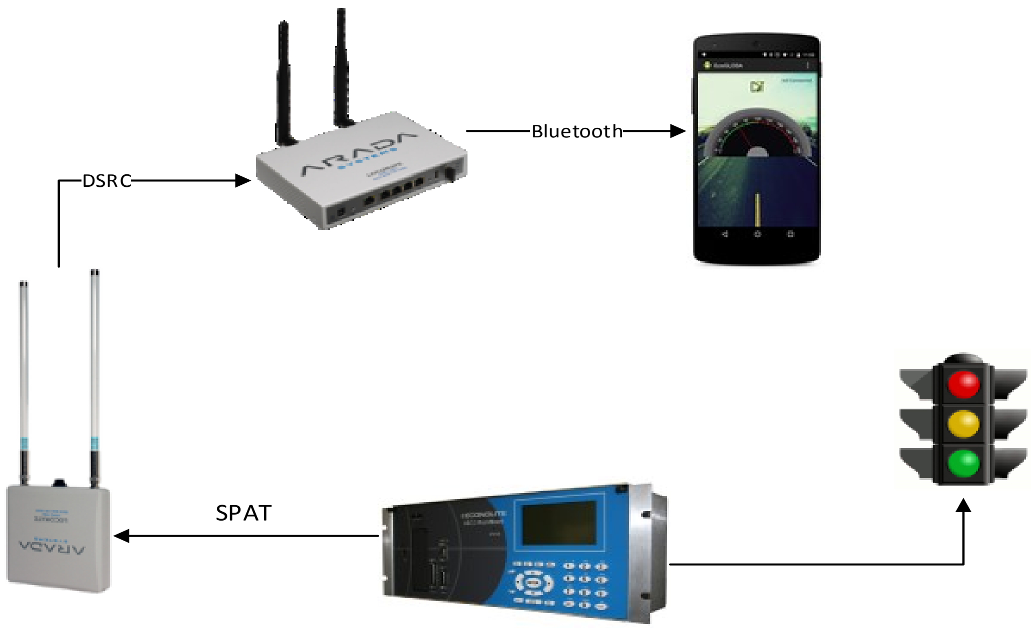

Figure 4 Green Light Optimal Speed Advisory Framework

3.3 Optimal Scenarios at intersections

Basically, there are two types of traffic light control system. One is pre-timed and the other one is the adaptive signal control. For pre-timed control, the cycle length, phase plan, and the phase time are fixed. It's suitable for intersections where traffic volumes and patterns are consistent. As for adaptive signal control, phase time is adjusted based on the traffic volume or other detected data. The data usually comes from the vehicle detection devices or pedestrian push buttons. In the research of this thesis, only the pre-timed signal control is considered[4].

3.3.1 Upstream

When a vehicle is approaching a signal intersection, there are 6 situations that the vehicle may encounter:

I. The signal will still be green when the vehicle arrives at the signal stop line, the system will advise the driver to keep this speed.

II. The signal is green now, and will be red when the vehicle keeps current speed approaching there. But the vehicle could safely pass the intersection if it accelerates a little bit.

III. The signal is green now, and will be red when the vehicle keeps current speed approaching there. If the vehicle speed up to the maximum speed limit and still can't pass intersection without stop, the system will be told stop needed ahead.

IV. The signal is red now, and will be green when the vehicle arrives at the stop line if it decelerates a little bit.

V. The signal is red now, and will change to the green when the vehicle reaches the intersection at the current speed.

VI. The signal is red now, and the will still be red even the vehicle decelerates to the minimum speed.

In the above six scenarios, only the second and fourth scenarios can be optimized. The other scenarios, the GLOSA can provide message to the driver, but can't make the driver to pass the intersection at green signal by adjusting the current vehicle speed.

3.3.2 Downstream

To calculate the fuel consumption, it should not only consider the fuel consumption of the upstream before the vehicle passing the intersection. Also the downstream fuel consumption before the vehicle recover to its original speed needs to be considered. This makes the Eco-driving is more reasonable. As sometime the fuel consumption is reduced because the following of GLOSA advices, but it consumes more fuel when the vehicle speeds up or slows down to its original speed on the downstream.

3.3.3 Green Light Optimization

For the second scenario, using V2I communication, the vehicle receive SPAT message at a distance x meters from the intersection and the current speed is assumed as V_0 m/s. The signal is green now and the remaining time for the green is t_m s. At this speed, the vehicle will encounter red when arrives at the signal stop bar. So, the GLOSA system will advise the driver to speed up a little bit in order to pass the intersection safely. The first bounding solution is to accelerate at the highest possible acceleration. The other bounding solution involves minimizing the level of acceleration exerted by accelerating over the entire distance x. between these two bounding, there are infinite number of possible solutions as illustrated in following figure.

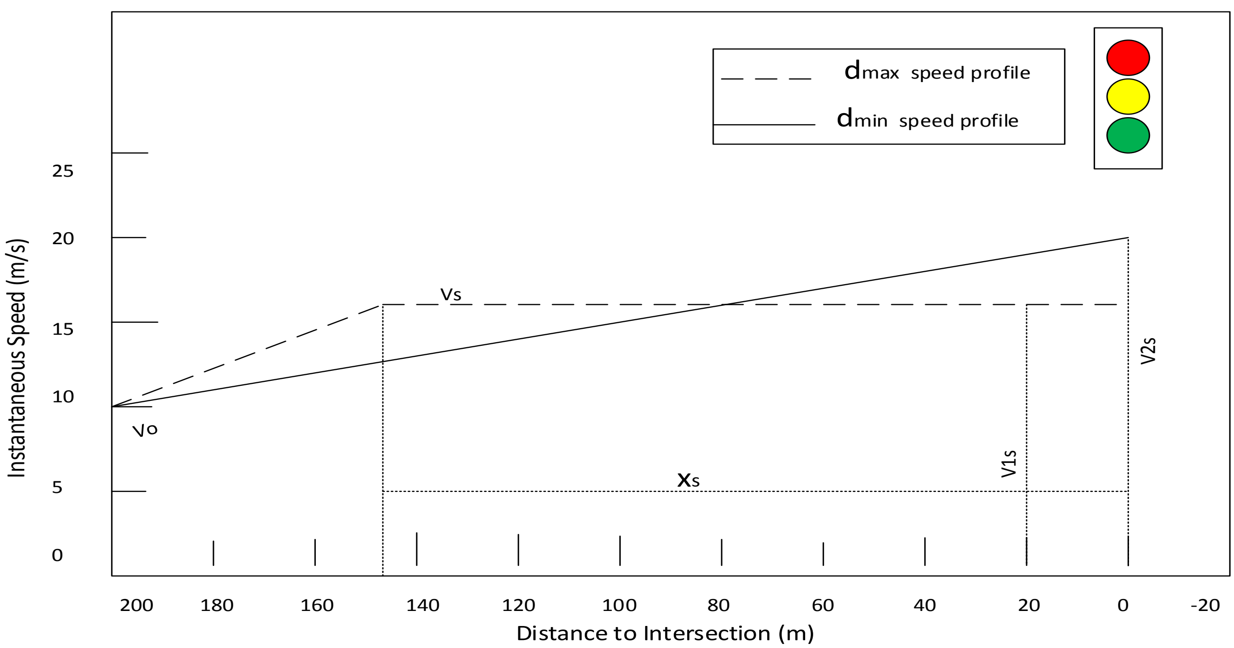

Figure 5 Speed up for Insufficient Green Signal

Assuming the vehicle speeds up to V_s from V_o at the maximum acceleration rate d. Consider basic equations of motion and x is conserved in any case.

$$x = \frac{V_s^2 - V_o^2}{2d} + x_s \quad (1)$$

The remaining time of green light t_m is also conserved for all cases:

$$t_m = \frac{V_s - V_o}{d} + \frac{x_s}{V_s} \quad (2)$$

Combining equations:

$$t_m = \frac{V_s - V_o}{d} + \frac{1}{V_s}\left(x - \frac{V_s^2 - V_o^2}{2d}\right) \quad (3)$$

For each case, the speed V_s is depended on acceleration d:

$$V_s = V_o + d * t_m + \sqrt{d * (d * t_m^2 + 2 * t_m * V_o - 2 * x)} \quad (4)$$

3.4.4 Red Light Optimization

For the fourth scenario, the signal is red now and will be green in seconds. The vehicle will encounter red if approaching at the current speed, but can safely pass the intersection if slow down a little bit. In this scenario, the GLOSA system will recommend the driver to slow down in order to pass the intersection without stop. Similar with the second scenario, the first bounding solution is to decelerate at the largest possible deceleration and then approaching at the low speed. The other bounding is to decelerate with a small deceleration until arriving at the stop line.

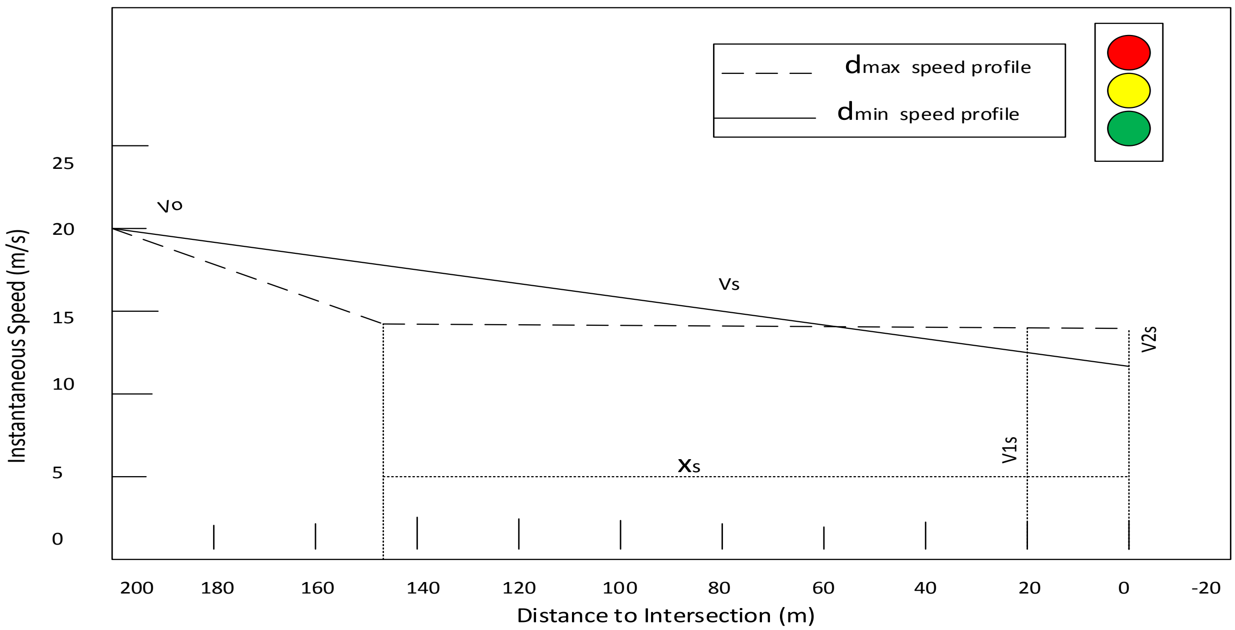

Figure 6 Slow down for Excess Red Signal

Assuming the vehicle speeds up to V_s from V_o at the maximum acceleration rate d. Consider basic equations of motion and x is conserved in any case.

$$x = \frac{V_o^2 - V_s^2}{2d} + x_s \tag{5}$$

The remaining time of green light t_m is also conserved for all cases:

$$t_m = \frac{V_o - V_s}{d} + \frac{x_s}{V_s} \tag{6}$$

Combining equations:

$$t_m = \frac{V_o - V_s}{d} + \frac{1}{V_s}\left(x - \frac{V_o^2 - V_s^2}{2d}\right) \tag{7}$$

For each case, the speed V_s is depended on acceleration d:

$$V_s = V_o - d * t_m + \sqrt{d * (d * t_m^2 - 2 * t_m * V_o + 2 * x)} \tag{8}$$

3.4 Fuel Consumption Model

This section will introduce the VT-Micro emission and fuel consumption model, as well as the needed parameter values in order to calculate the fuel consumption.

3.4.1 VT Micro Model

As discussed in the second chapter, we used VT-Micro Model to estimate the vehicle fuel consumptions. VT-Micro model is a statistical model that was developed based on testing data collected at Oak Ridge National Laboratory (ORNL) and the U.S. Environmental Protection Agency. These data include fuel consumption and emission rate measurements as a function of the vehicle's instantaneous speed and acceleration levels[30]. The final regression models included a combination of linear, quadratic, and cubic speed and acceleration terms because it provided the least number of terms with a relatively od fit to the ORNL data (R^2 in excess of 0.70 for most MOEs). These models fit the ORNL data accurately for high speed and acceleration levels. However, the models are less accurate at low speed and acceleration levels, as shown in the following equations[31]:

$$MOE_e = \begin{cases} e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j} * u^i * a^i\right)} & for\ a \geq 0 \\ e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(M_{i,j} * u^i * a^i\right)} & for\ a < 0 \end{cases} \qquad (9)$$

Where MOE_e is the instantaneous fuel consumption or emission rate (l/s in the case of fuel consumption and mg/s in the case of vehicle emissions), $L_{i,j}^{e}$ and $M_{i,j}^{e}$ represent model regression coefficients for MOE 'e' at speed power 'i' and acceleration power 'j'. The intercept at zero speed and zero acceleration was estimated using the positive acceleration model and fixed in order to ensure a continuous function between the two regression regimes.

3.4.2 Model Coefficients

The model coefficients for estimating fuel consumption rates for a composite vehicle are introduced in Table 2. The composited vehicle was derived as an average across eight light-duty vehicles. The required input parameters of the model are instantaneous speed (km/h), instantaneous acceleration (km/h/s)[32].

Table 2 Coefficients of Composite Vehicle Fuel Consumption

Coefficients	S^0	S^1	S^2	S^3
Positive a				
a^0	-7.73452	0.02799	-0.0002228	1.09E-06
a^1	0.22946	0.0068	-0.00004402	4.80E-08
a^2	-0.00561	-0.00077221	7.9E-07	3.27E-08
a^3	9.77E-05	0.00000838	8.17E-07	-7.79E-09
Negative a				
a^0	-7.73452	0.02804	-0.00021988	1.08E-06
a^1	-0.01799	0.00772	-0.00005219	2.47E-07
a^2	-0.00427	0.00083744	-7.44E-06	4.87E-08
a^3	0.00018829	-0.00003387	2.77E-07	3.79E-10

Most of the previous researches just take the final total fuel consumption as the optimal goal. Indeed, the fuel consumption per kilometer is more accurate to measure the fuel consumption efficiency. To optimize the fuel consumption, the final objective function is

$$f = \text{Min } \frac{F}{L} \tag{10}$$

Where F is the total fuel consumption of the upstream and downstream when go through an intersection. L is the total distance for the upstream and downstream.

3.5 Green Light Scenario Objective Function

For second scenario, the signal is green now and will change to red as the vehicle reaching the intersection at current speed. However, the vehicle is able to pass the intersection at green signal time if it speeds up a little bit. The following figure illustrates the speed profiles for vehicle with GLOSA and without GLOSA at this scenario. The vehicle with GLOSA will speed up to a specific speed under speed limit and keep the speed until it passes the intersection. And then slow down the original speed. The vehicle without GLOSA will keep the current speed until the signal changed to red and slow down quickly. It has to wait at stop bar until the signal change to green.

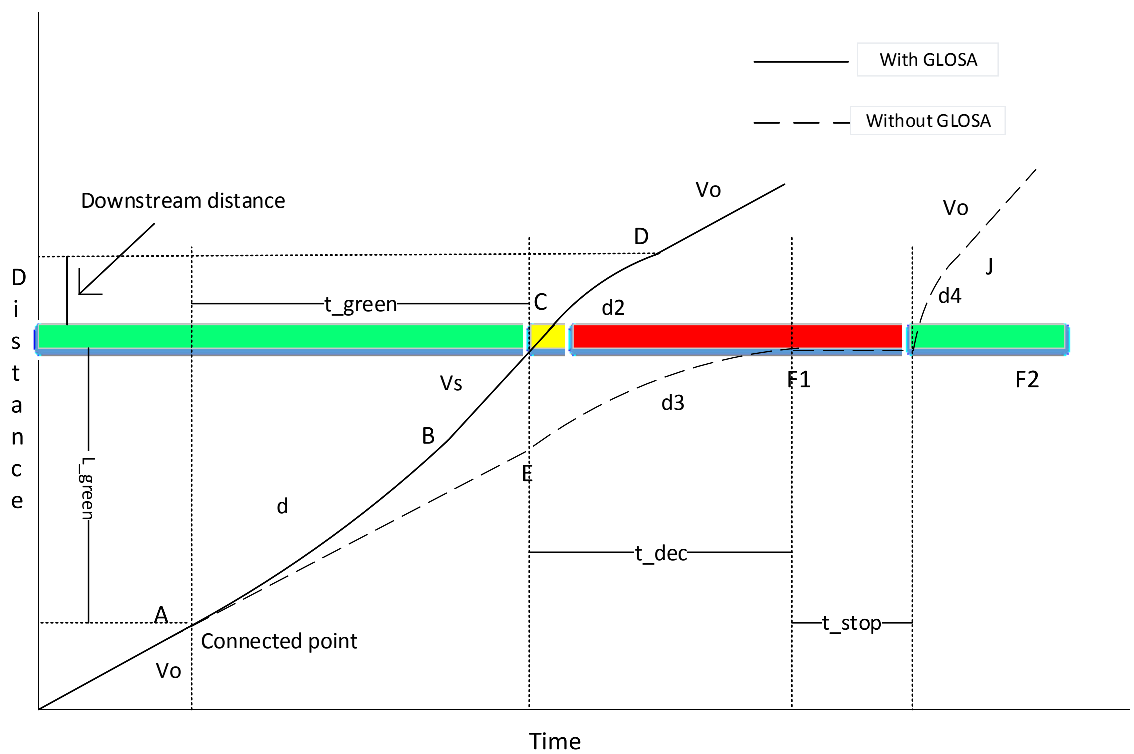

Figure 7 Relationship of Green Light Optimal Speed and Distance

3.5.1 Green Light Scenario with GLOSA

If the vehicle follows the advice of system, then the fuel consumption is consisted of acceleration (AB), uniform speed (BC) and deceleration (CD) stages.

$$F_1 = \mathrm{F_{AB}} + \mathrm{F_{BC}} + F_{CD} \tag{11}$$

The fuel consumption of the acceleration stage can be got from the following integration formula.

$$F_{AB} = \int_0^{\frac{v_S - v_O}{d}} (e^{\sum_{i=0}^{3} \sum_{j=0}^{3} (L_{i,j} * (d*t+v_0)^i * d^i)} * \sigma_t) \tag{12}$$

For the uniform speed stage, the acceleration rate is zero and the speed is a constant, thus the uniform speed stage can be got from the formula (13).

$$F_{BC} = e^{\sum_{i=0}^{3} \sum_{j=0}^{3} (L_{i,j} * v_S^i)} * (t_m - \frac{v_S - v_O}{d}) \tag{13}$$

The recover stage, the vehicle has to slow down to its original speed after passing the intersection. The fuel consumption can be calculated as the formula (14).

$$F_{CD} = \int_0^{\frac{v_S - v_O}{d_2}} (e^{\sum_{i=0}^{3} \sum_{j=0}^{3} (M_{i,j} * (v_0 - d_2 * t)^i * d_2^j)} * \sigma_t) \tag{14}$$

Where d is the acceleration rate to speed up and d_2 is the general deceleration rate when the vehicle slows down to the original speed, it can be calculated as:

$$a_{dr} = -k_3 v^2 + k_2 v + k_1 \tag{15}$$

Where $a_{dr}$is the deceleration rate, $k_3 = 0.005, k_2 = 0.154, k_1 = 0.493$, v is the current speed[33]. Different drivers and vehicles may have different deceleration rate at this situation. It may possible to get the real time dynamic deceleration rate using acceleration sensor or smartphone. But this research will use a general deceleration rate based on the real time speed. It’s easier to implement and can be accurate at most situations.

So the total fuel consumption for a vehicle going through an intersection is

$$F_1 = \int_0^{\frac{v_S - v_O}{d}} (e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j} * (d*t+v_0)^i * d^i\right)} * \sigma_t) + e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j} * v_S^i\right)} * \left(t_m - \frac{v_S - v_O}{d}\right) + \int_0^{\frac{v_S - v_O}{d_2}} (e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(M_{i,j} * (v_0 - d_2 * t)^i * d_2^j\right)} * \sigma_t) \quad (16)$$

Total running distance consists of the distance when the vehicle is connected to the RSU and the deceleration distance after passing the intersection.

$$L_1 = \mathrm{x} + \frac{v_S^2 - v_O^2}{2d_2} \quad (17)$$

The final fuel consumption objective function is:

$$f_1 = \mathrm{Min}(F_1/L_1) \quad (18)$$

3.5.2 Green Light Scenario without GLOSA

For the vehicle without GLOSA system, it will encounter the red signal. To pass the intersection, firstly the vehicle will approach to intersection at uniform speed (AE), then deceleration to stop before intersection (EF1) and stop for the green signal (F1F2), finally will accelerate to the original speed (F2D). So the fuel consumption calculated by:

$$F_2 = F_{AE} + F_{EF1} + F_{F1F2} + F_{F2D} \quad (19)$$

The constant speed stage can be got from formula (20)

$$F_{AE} = e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j} * v_0^i\right)} * t_{ave} \quad (20)$$

The time lasts for the constant speed stage can be calculated from (21)

$$t_{ave} = (\mathrm{x} - \frac{v_0^2}{2d_3})/v_0 \quad (21)$$

The deceleration stage when after the driver notices the signal changed to red.

$$F_{EF1} = \int_0^{t_{dec}} (e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(M_{i,j} * (v_0 - d_3 * t)^i * d_3^j\right)} * \sigma_t) \quad (22)$$

The following formula calculates the time for the deceleration stage.

$$t_{dec} = v_0/d_3 \quad (23)$$

The driver has to wait at the stop bar until the signal changes to green and usually the engine is still running. The fuel consumption for this stage can be got from the following formulas.

$$F_{F1F2} = e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j})} * t_{stop} \quad (24)$$

The stop time depends on the red signal remaining time when connected to RSU, the total red signal time, the constant speed time and the deceleration time.

$$t_{stop} = t_m + T_{red} - t_{ave} - t_{dec} \quad (25)$$

The driver will speed up when he or she notices the signal changed to green. The fuel consumption can be got by:

$$F_{F2D} = \int_0^{\frac{v_O}{d_4}} (e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j}*(d_4*t)^i*d_4^j\right)} * \sigma_t) \quad (26)$$

Where d_3 is the general deceleration rate for vehicle at specific speed, can be calculated from formulate (15). d_4 is the general acceleration rate for vehicle at specific speed. It's similar to the previous situation, different vehicles and drivers may have different deceleration and acceleration rates. We set it as the general ones and the acceleration rate can be got from the following:

$$a_{acc} = ae^{bv} \quad (27)$$

Where a=1.70, b= -0.04, v is the vehicle speed[34].

So the Total fuel consumption for vehicle without GLOSA system at this scenario is

$$F_2 = e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}*v_0^i)} * t_{ave} + \int_0^{t_{dec}} \left(e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(M_{i,j}*(v_0-d_3*t)^i*d_3^j\right)} * \sigma_t\right)$$

$$+ e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j})} * t_{stop} + \int_0^{\frac{v_O}{d_4}} (e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j}*(d_4*t)^i*d_4^j\right)} * \sigma_t) \quad (28)$$

The total distance consists of vehicle to pass the intersection and recover the previous status is

$$L_2 = x + \frac{v_0^2}{2d_4} \quad (29)$$

The fuel consumption per kilometer is

$$f_2 = {}^{F_2}/_{L_2} \tag{30}$$

The fuel saving rate can be calculated as:

$$f_{saving} = \frac{f_2 - f_1}{f_2} * 100\% \tag{31}$$

3.6 Red Light Scenario Objective Function

For the fourth scenario, the signal is red now, and still will be red when the vehicle reaches the intersection if it keeps the current speed. However, it may pass the intersection if it slows down a little bit. For vehicle with and without GLOSA, the speed profiles illustrates as the following figures. For vehicle following the GLOSA, it will firstly slows down and keep the lower speed until passing the intersection. After that, it will speed up to the original speed. For vehicle without GLOSA, it will keep the current speed and then slow down to prepare the stop of red signal. The vehicle either is completely stopped or during the deceleration stage when the signal is changing to green. After that, the vehicle will speed up to the original speed.

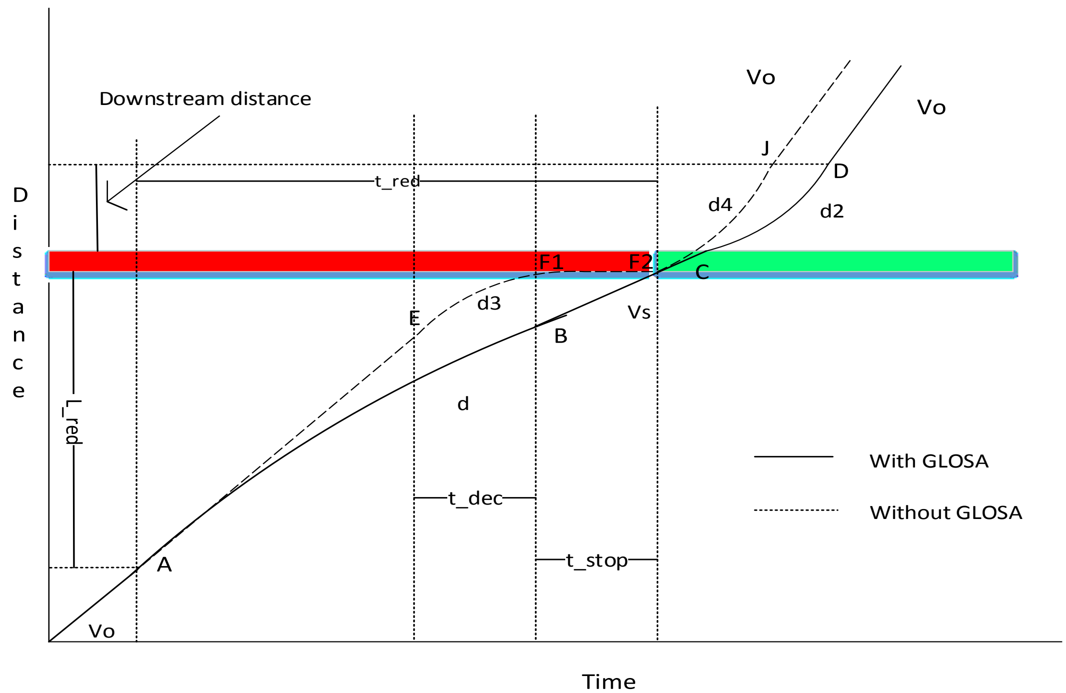

Figure 8 Relationship of Red Light Optimal Speed and Distance

3.6.1 Red Light Scenario with GLOSA

It is red signal now, but the vehicle can pass intersection without stop if it stops a little bit. For vehicle with GLOSA, the speed profile includes the deceleration (AB), constant speed (EC) and acceleration (CD) stages. Thus the total fuel consumption can be got as:

$$F_1 = F_{AE} + F_{EC} + F_{CD} \tag{32}$$

The deceleration stage fuel consumption can be got from the following integration formula.

$$F_{AE} = \int_0^{\frac{v_0 - v_s}{d}} \left(e^{\sum_{i=0}^{3} \sum_{j=0}^{3} \left(M_{i,j} * (v_0 - d * t)^i * d^i \right)} * \sigma_t \right) \tag{33}$$

For the constant speed stage, the speed is constant and acceleration rate is zero, thus the fuel consumption can be calculated using (34).

$$F_{EC} = e^{\sum_{i=0}^{3} \sum_{j=0}^{3} \left(L_{i,j} * v_s^i \right)} * (t_m - (v_0 - v_s)/\mathrm{d}) \tag{34}$$

In the acceleration stage, the vehicle needs to recover to its original speed and the fuel consumption can be got from (35).

$$F_{CD} = \int_0^{\frac{v_0-v_s}{d_2}} (e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j}*(d_2*t)^i*d_2^j\right)} * \sigma_t) \quad (35)$$

Where d_2 is the general acceleration rate for vehicle to speed up to its original speed and can be calculated from formulate (27).

Thus the total fuel consumption is

$$F_1 = \int_0^{\frac{v_0-v_s}{d}} \left(e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(M_{i,j}*(v_0-d*t)^i*d^i\right)} * \sigma_t\right) + e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j}*v_s^i\right)} * \left(t_m - \frac{v_0-v_s}{\mathrm{d}}\right) + \int_0^{\frac{v_0-v_s}{d_2}} (e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j}*(d_2*t)^i*d_2^j\right)} * \sigma_t) \quad (36)$$

Total distance consists of the distance when the OBE is connected to the RSU and the acceleration stage after passing the intersection.

$$L_1 = x + \frac{v_0^2 - v_s^2}{2d_2} \quad (37)$$

The final fuel consumption objective function is

$$f_1 = Min(\frac{F_1}{L_1}) \quad (38)$$

3.6.2 Red Light Scenario without GLOSA

For vehicle without GLOSA system, the total fuel consumption includes the constant speed (AB), deceleration (BF1), possibly the stopped waiting stage (F1F2) and acceleration (F2D) stages.

Thus the total fuel consumption is calculated by:

$$F_2 = F_{AB} + F_{BF1} + F_{F1F2} + F_{F2D} \quad (39)$$

The fuel consumption of constant speed stage:

$$F_{AB} = e^{\sum_{i=0}^{3}\sum_{j=0}^{3}\left(L_{i,j}*v_0^i\right)} * t_{ave} \quad (40)$$

We assume the driver will begin to decelerate at the appropriate distance at a general deceleration rate. Thus the constant speed time can be calculated as:

$$t_{ave} = (x - v_0^2/(2d_3))/v_0 \quad (41)$$

The signal may turn green as the vehicle is decelerating to a fully stop. And also the signal can be green after the vehicle fully stopped. The fuel consumption for deceleration stage stopped waiting stage and the acceleration stage can be got separately from (42), (43), and (44).

$$F_{BF1} = \int_0^{t_{dec}} \left(e^{\sum_{i=0}^{3} \sum_{j=0}^{3} \left(M_{i,j} * (v_0 - d_3 * t)^i * d_3^i \right)} * \sigma_t \right) \quad (42)$$

$$F_{F1F2} = e^{\sum_{i=0}^{3} \sum_{j=0}^{3} \left(L_{i,j} \right)} * t_{stop} \quad (43)$$

$$F_{F2D} = \int_0^{t_{acc}} (e^{\sum_{i=0}^{3} \sum_{j=0}^{3} \left(L_{i,j} * (d_4 * t)^i * d_4^j \right)} * \sigma_t) \quad (44)$$

If $t_{ave} + {}^{v_0}/_{d_3} \le t_m$, the vehicle will fully stop before signal turn green. Then

The vehicle speed when the signal changes to green:

$$v_{green} = 0 \quad (45)$$

The deceleration lasts time:

$$t_{dec} = {}^{v_0}/_{d_3} \quad (46)$$

The stopped waiting time:

$$t_{stop} = t_m - t_{ave} - {}^{v_0}/_{d_3} \quad (47)$$

The acceleration time:

$$t_{acc} = {}^{v_0}/_{d_4} \quad (48)$$

If $t_{ave} + {}^{v_0}/_{d_3} > t_m$, the signal will turn green before the vehicle stopped. Then

$$v_{green} = v_0 - d_3 * t_{dec} \quad (49)$$

$$t_{dec} = t_m - t_{ave} \quad (50)$$

$$t_{stp} = 0 \quad (51)$$

$$t_{acc} = v_{green}/d_4 \quad (52)$$

Where d_3 is the general deceleration rate, can be got using formulate (X). And d_4 is the general acceleration rate, can be got from formulate (X). v_{green} is the vehicle speed when the signal turn green.

The total distance consists of the distance when OBE connected the RSU and the acceleration stage.

$$L_2 = x + (v_0^2 - v_{green}^2)/d_4 \tag{53}$$

So the fuel consumption per kilometer for vehicle to pass the intersection without GLOSA is

$$f_2 = {F_2}/{L_2} \tag{54}$$

The fuel saving rate can be calculated as:

$$f_{saving} = \frac{f_2 - f_1}{f_2} * 100\% \tag{55}$$

3.7 GLOSA Logic at Intersections

This section will discuss about the advisory logic of the Eco-driving. The inputs of the model are vehicle speed, vehicle distance, vehicle acceleration and remaining signal time. Based on the input, the GLOSA will make decide what message to provide.

3.7.1 Green Signal Scenario

It's green for the signal intersection, and remain green time is t_{green} , the distance between the vehicle and intersection isL_{green} , the current speed for the vehicle is v_0. The vehicle may get the following situations:

1. If $\frac{L_{\text{green}}}{v_0} < t_{green}$, the vehicle can pass the intersection without stop, the system suggest the vehicle to keep the current speed.

2. If $\frac{L_{green}-\frac{v_{max}^2-v_0^2}{2*a_r}}{v_{max}}+\frac{v_{max}-v_0}{a_{ar}} \leq t_{green} < \frac{L_{green}}{v_0}$, the vehicle can't pass the intersection with current speed, but it will pass it without stop if speeds up to an allowed speed.

3. If $\frac{L_{green}-\frac{v_{max}^2-v_0^2}{2*a_r}}{v_{max}}+\frac{v_{max}-v_0}{a_{ar}} > t_{green}$, the vehicle can't pass the intersection even it speeds up.

Where a_{ar} is the vehicle general average acceleration at the current speed and the value of a_{ar} can be calculated from formula (27).

3.7.2 Red Signal Scenario

It's red for the signal intersection, and the remain red time is t_{red}, the distance between the vehicle and intersection is L_{red}, the current speed is v_0. The vehicle may encounter the following situations:

1. If $\frac{L_{red}}{v_0} > t_{red}$, the vehicle will pass the intersection without stop. The system recommends the vehicle to keep the current speed.

2. If $\frac{L_{red}}{v_0} < t_{red} < \frac{L_{red}-\frac{v_0^2-v_s^2}{2*a_{dr}}}{v_s}+\frac{v_0-v_s}{a_{dr}}$, the vehicle can pass the intersection if it slows down a little bit.

3. If $\frac{L_{red}-\frac{v_0^2-v_{min}^2}{2*a_{dr}}}{v_{min}}+\frac{v_0-v_{min}}{a_{dr}} \leq t_{red}$, the vehicle is unable to pass the intersection and will meet the red signal even it slows down bit.

Where a_{dr} is the deceleration rate for general condition and v_{min} is the minimum speed limit, there is no minimum speed limit in Canada, general we make the minimum speed as half of the max speed limit.

3.7.3 GLOSA Working Logic

The following figure shows the basic logic of the GLOSA application. Once the OBE in the vehicle is connected to the RSU and received data, the OBE will send data to the smartphone. If it's green, then check whether it's able to pass the intersection with current speed. If no, then the provided voice message will be red ahead. If yes, then check whether speed up is needed. For red signal, the idea is almost the same. Check whether it's possible to pass without stop. If no, then red ahead message will be provided. If yes, then check whether slowdown is needed.

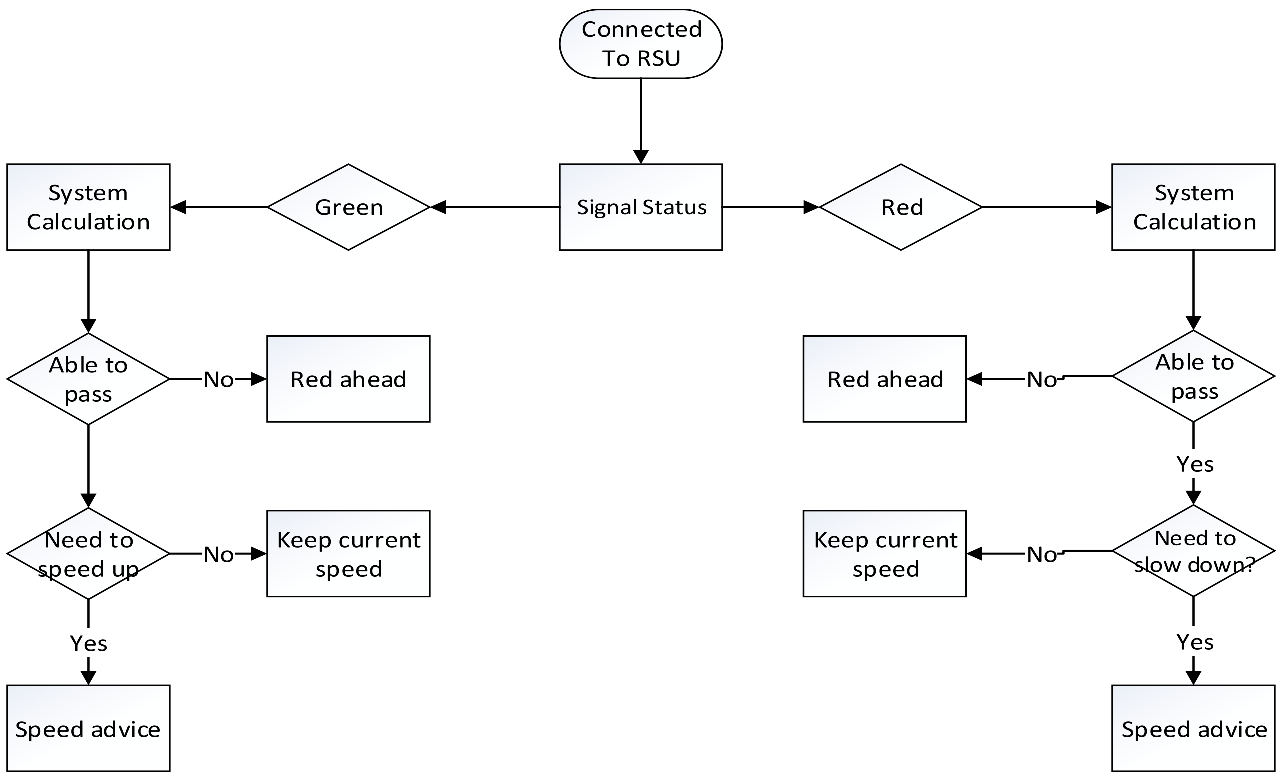

Figure 9 GLOSA Working Logic

CHAPTER 4 EXPERIMENT AND SIMULATION

This section will introduce the experiments and simulation of this thesis. The experiments contain two specific scenarios that the vehicle may encounter. The comparisons of fuel consumption between the vehicle with GLOSA and without GLOSA will be introduced.

4.1 Experiments for Green Signal Scenario

For green signal, we set the vehicle at a specific condition where the vehicle speed is 20 m/s, the remaining time is 14 second, but the distance to the intersection is 300 meter. So the vehicle may need to speed up a little bit in order to catch the green light. Based on different acceleration rate, the fuel consumption will be different. FIGURE 10 shows the relationship of acceleration ad fuel consumption.

As we can see from the figure, fuel consumption is going to decrease as the acceleration rate increase. And the fuel consumption for vehicle without GOSA, we set the acceleration rate at a general acceleration rate using formula (27). The general acceleration rate is 0.76 m/s^2 at speed of 20 m/s. And we can see that the vehicle with GLOSA will saving fuel only if the acceleration rate is greater than 0.25 m/s^2. The fuel saving can be up to 15.7%. But the figure also shows that if the vehicle accelerates to catch the green signal at a very low acceleration rate, the more fuel will be used. From others' research conclusions, we know it's reasonable. As the driver accelerates at a low acceleration rate, it takes more time to speed up in order to catch the green signal. The vehicle fuel consumption increases when it accelerates.

The mode input parameters are as follows:

$v_0 = 20m/s$, $t_m = 14\ s$, x = 300 m, $v_{max} = 80\ km/h$, $T_{red} = 60\ s$, $T_{green} = 60\ s$

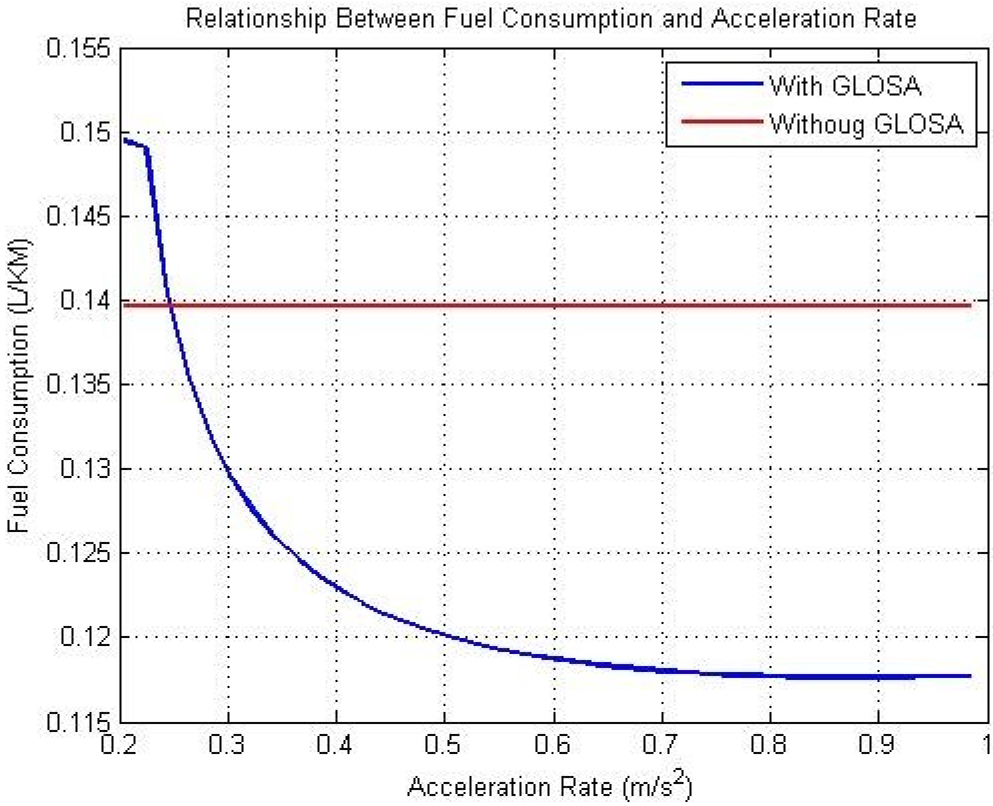

Figure 10 Relationships of Acceleration and Fuel Consumption

4.2 Experiments for Red Signal Scenario

For red signal, the specific condition is set as the vehicle speed at 20 m/s, vehicle distance to the intersection 300 meter and remaining red time is 20 second. The vehicle will encounter red signal if it keeps current speed approaching to the intersection. The vehicle has to slow down a little bit to wait for the signal turns green. The fuel consumption varies as the deceleration varies. FIGURE 11 shows the relationship of deceleration and fuel consumption. The figure shows that the fuel consumption increases as the deceleration rate increases. As long as the deceleration rate is smaller than 1.65 m/s^2, the vehicle will save fuel if it follows the advice of GLOSA application. The deceleration rate for vehicle without GLOSA is set to a general deceleration rate at speed 20 m/s. The general deceleration rate is 1.57 m/s^2 and can be got from formula (15). The experiment result indicates that the fuel consumption can be up to 60%. The reason for the high fuel saving percentage maybe the avoidance of the red light stop and start which consume fuel at a high rate.

The model input parameters are as follows:

$v_0 = 20m/s$, $t_m = 20\ s$, x $= 300$ m, $v_{max} = 80\ km/h$, $T_{red} = 60\ s$, $T_{green} = 60\ s$

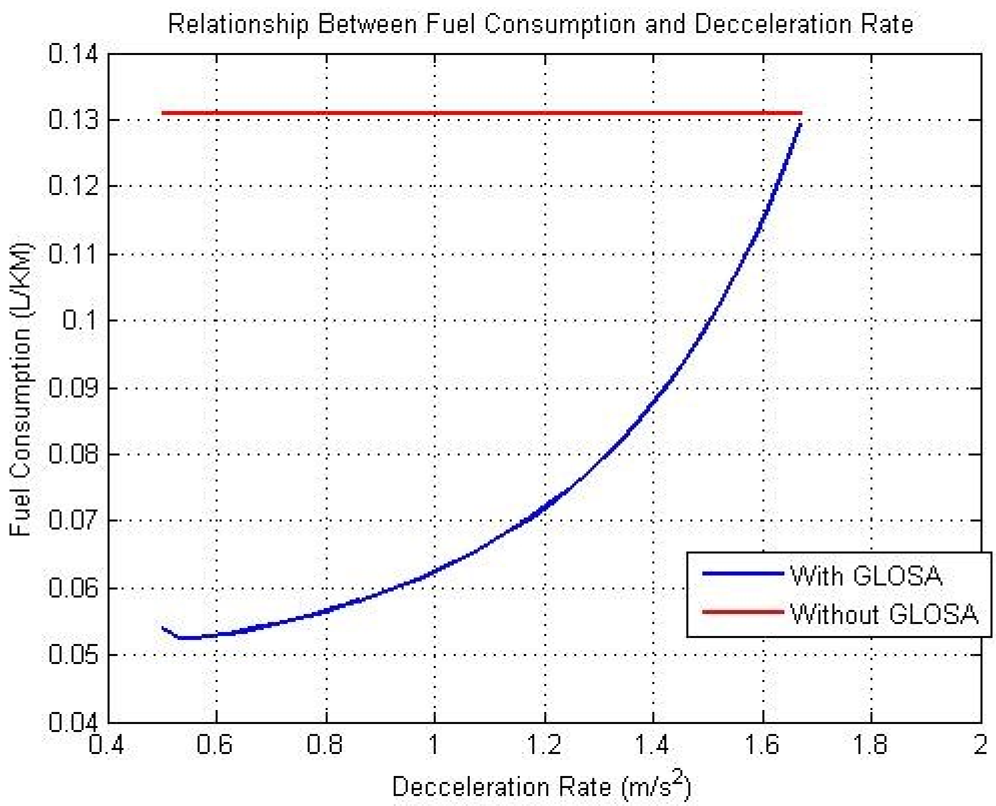

Figure 11 Relationships of Fuel Consumption and Deceleration Rate

4.3 MATLAB Simulation

The previous experiments only consider the specific conditions which the parameters are set. It gives a preliminary view of the fuel consumption. However, a more general simulation which considers all possible conditions should be implemented. In this section, simulation for 100,000 times of passing through an intersection is simulated in MATLAB[35].

The vehicle speed is set as a random value at the range of 10 to 16 m/s. The intersection signal cycle is set to be 120 seconds. Green time is 60 seconds, red time is 57 seconds and yellow is 3 seconds. In the simulation, we consider yellow signal as red. Thus, the green signal lasts for 60 seconds and red lasts for 60 seconds and remaining signal time is set to be a random value at the range of 1 second to 60 second. The maximum speed of this segment is set to be 60 km/s. Even though there is no minimum speed limit in Canada. The connected distance was set as a random value from 200 to 300 meter. To avoid the block of traffic, the minimum speed is set to be half of the vehicle's current speed.

For each time, a vehicle approaches to an intersection; all the inputs in the model are simulated by random values. Table 5 shows the inputs values range. Totally 100,000 times of simulations had run in MATLAB.

Table 3 Simulation Model Inputs

Original speed	Remaining signal time	Connected distance	Maximum speed	Minimum speed	Signal Color
v_0 (m/s)	t_m (s)	x (m)	v_max (m/s)	v_min(m/s)	T_light_color
[10,16]	[1,60]	[200,300]	60/3.6	30/3.6	0/1

*signal color: 0 indicates red signal, 1 indicates green signal

Comparing the with-GLOSA control to the without-GLOSA control in both scenario 1 and scenario 2, Table 4 and Figure 12 shows significant fuel consumption savings. The mean value of fuel consumption shows GLOSA saves about 56% fuel in scenario 1 and 21% in scenario 2. To investigate the significance of improvement by the proposed GLOSA, a statistical study was conducted: the t-test. In the t-test, it was assumed that the sample of the results followed the normal distribution and 0.05 was selected as the significance level. As shown in Table 4, the GLOSA can achieve significant fuel saving on both two scenarios[36 37].

Table 4 t-test of Simulation Results

Control Type	Scenario 1		Scenario 2	
	Average Fuel Consumption (L/KM)	Fuel Saving (L/KM)	Average Fuel Consumption (L/KM)	Fuel Saving (L/KM)
Without GLOSA	0.093	NA	0.061	BA
With GLOSA	0.041	-0.052	0.048	-0.013
t value	3.329e+02		1.099e+02	
t critical value	1.646		1.646	
Confidence Level	95%		95%	
p value	0		0	
Significant improvement?	Yes		Yes	

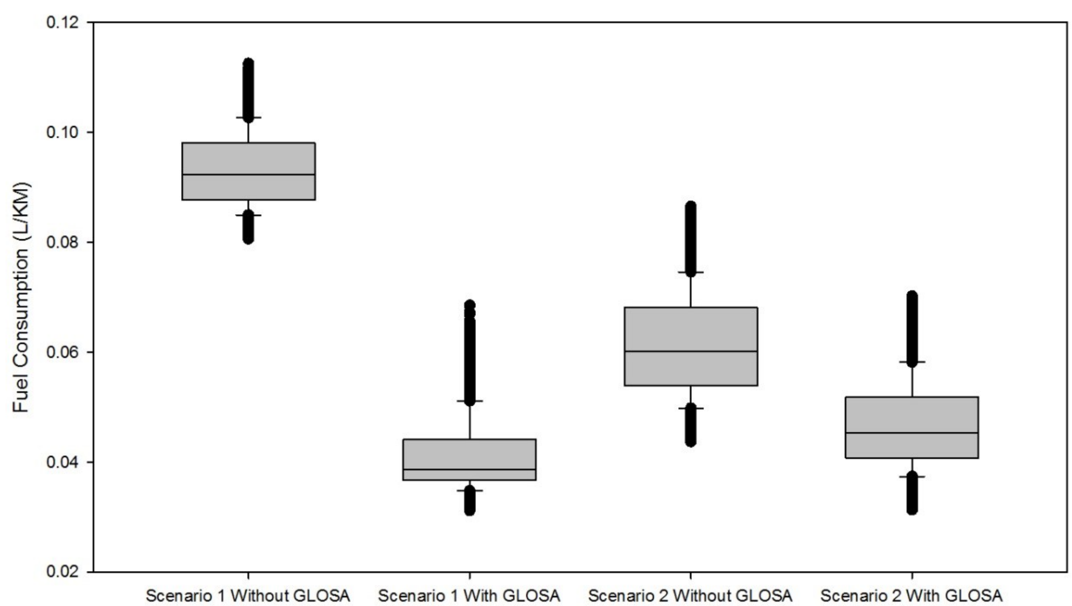

Figure 12 Box Plot of Fuel Consumption in Different Scenarios

Sensitivity analysis is conducted to investigate the impact of maximum speed on the fuel savings, as shown in Figure 13. Firstly, it is obvious that the fuel consumptions increase significantly with increased maximum speed, except for scenario 1 without GLOSA. When the signal is green (Scenario 1), the fuel savings decrease obviously when the maximum speed increases; however, when the signal is red (Scenario 2), the fuel savings increase obviously when the maximum speed increases.

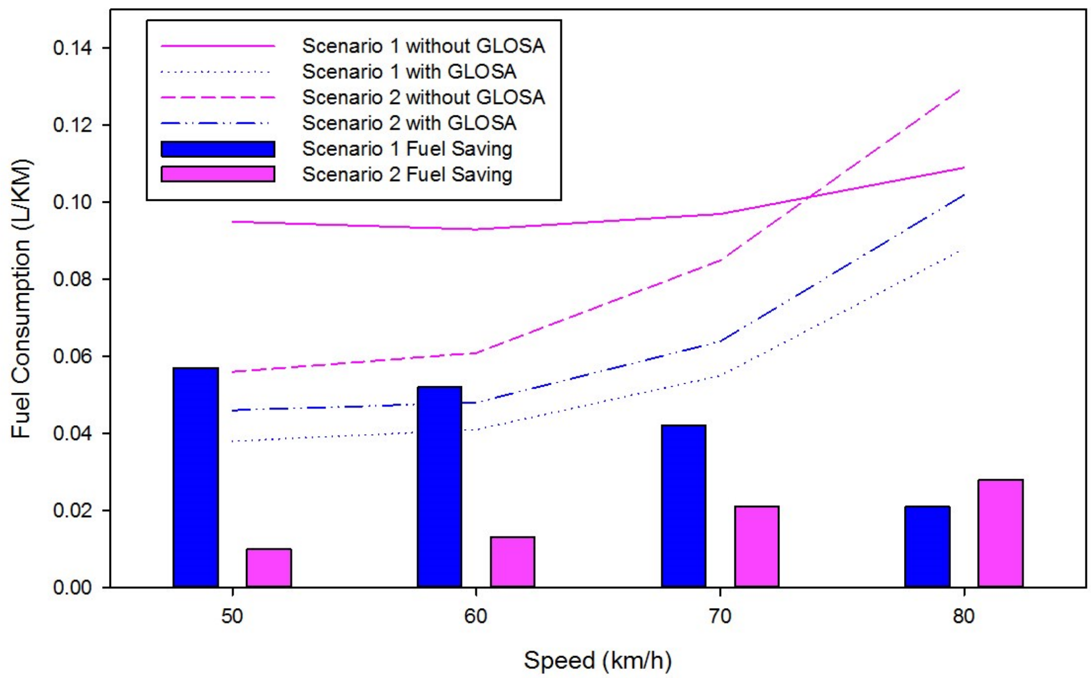

Figure 13 Impact of Maximum Speed on Fuel Savings

4.4 Field Test and Results

The field test was conducted in a CV environment. As shown in Figure 4, the real-time traffic signal phase and timing (SPaT) information is provided to vehicles with OBE approaching signalized intersections. It is on the basis of a DSRC (Dedicated Short-Range Communication) wireless transceiver that could broadcast information very dependably and with low latency. Then the SpaT information is transferred to the smartphone through Bluetooth communication[38] [39] [40].

An android smartphone application has been developed to collect data. Vehicle speed, distance to the intersection and acceleration were collected when the vehicle was approaching to intersection. There is a speedometer in the app. When the speed indicator is located at the green color range, it means the vehicle can pass the next intersection at current speed. And if it locates at the red color range, then it will encounter red signal ahead and it impossible for the vehicle to pass the intersection at current speed. The color ranges will be updated each second based on the vehicle speed, remaining signal time and distance to the intersection. And also once the OBE is connected to the RSU when approaching to the intersection, the advice speed which helps the driver save most fuel will be provided to the diver via voice message

4.4.1 Smartphone App

There is a speedometer in the app. When the speed indicator is located at the green color range, it means the vehicle can pass the next intersection at current speed. And if it locates at the red color range, then it will encounter red signal ahead and it impossible for the vehicle to pass the intersection at current speed. The color ranges will be updated each second based on the vehicle speed, remaining signal time and distance to the intersection. And also once the OBE is connected to the RSU when approaching to the intersection, the advice speed which helps the driver save most fuel will be provided to the diver via voice message[41].

Figure 14 Eco-Driving Smartphone APP

4.4.2 Test Intersection

The field test intersection is 87 Avenue & 111 Street in Edmonton, Alberta, Canada, as shown in the marked cycle in Figure 7. The field test is conducted around 11:00 PM on three days in July, 2015, and the arrows show driving directions of the test vehicle. The signal timing of the intersection is fixed. The cycle length is 100 seconds; green time is 50 seconds, red time is 47 seconds; and yellow is 3 seconds.

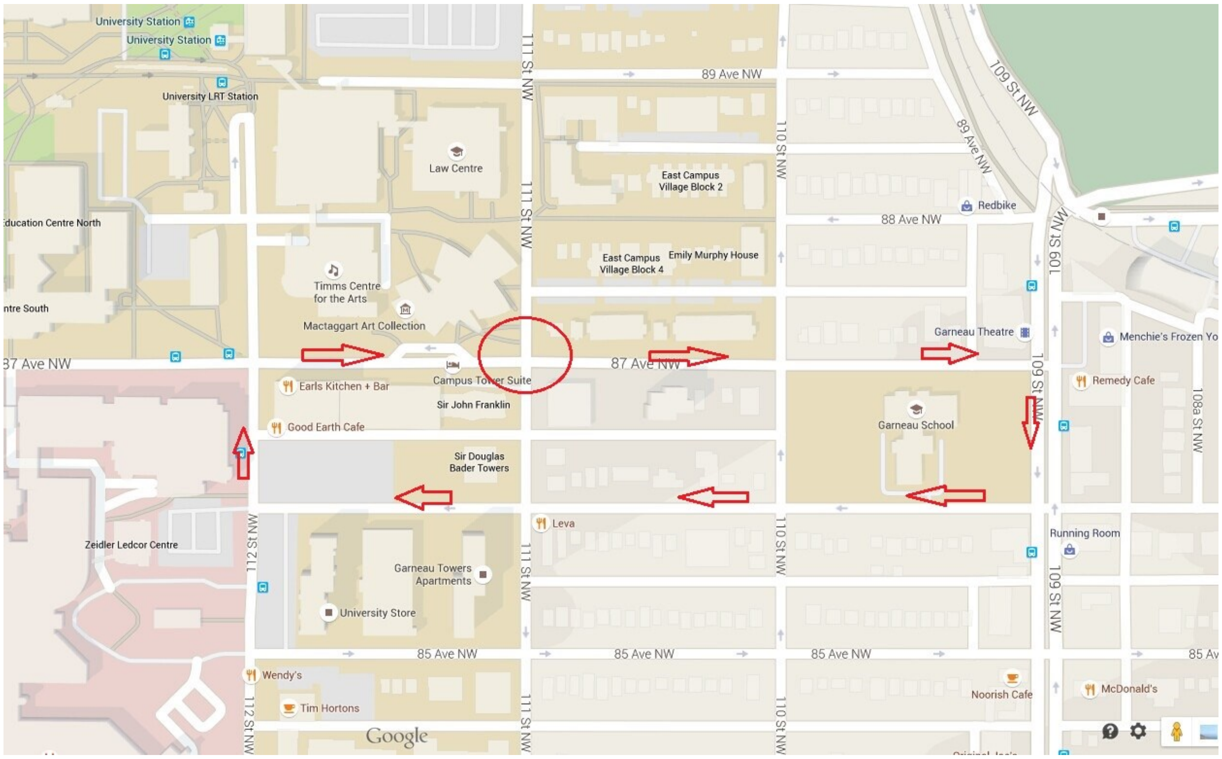

Figure 15 Test Intersection Map

4.4.3 Field Test Results

Table 7 and Figure 8 show significant fuel consumption savings in the field test. The mean value of fuel consumption shows GLOSA saves about 14% fuel. To investigate the significance of improvement by the proposed GLOSA, a statistical study was conducted: the t-test. In the t-test, it was assumed that the sample of the results followed the normal distribution and 0.05 was selected as the significance level. As shown in Table 3, the GLOSA can achieve significant fuel saving.

Table 5 t-test of Field Test Results

Control Type	Average Fuel Consumption (L/KM)	Fuel Saving (L/KM)
Without GLOSA	0.053	
With GLOSA	0.046	-0.007
t value	3.786	
t critical value	1.703	
Confidence Level	95%	
p value	3.885e-04	
Significant improvement?	Yes	

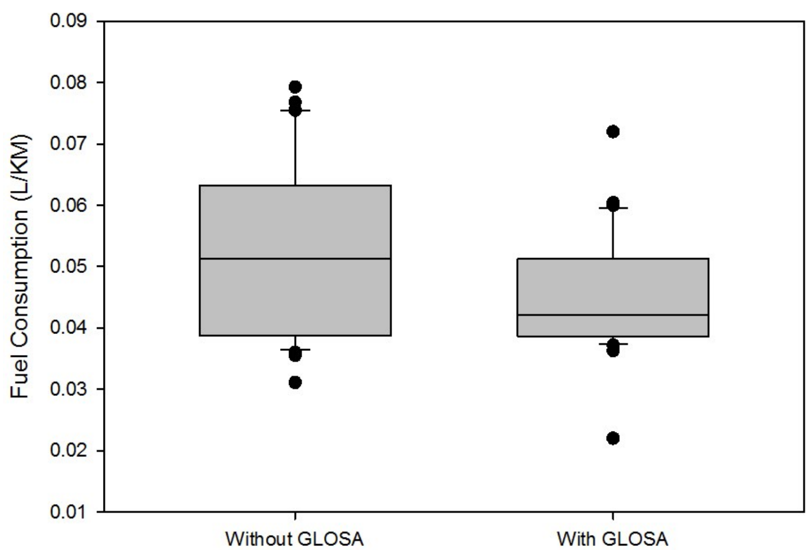

Figure 16 Box Plot of Fuel Consumption in Field Test

CHAPTER 5 CONLUSIONS

Fuel consumption is directly related to the acceleration/deceleration patterns of the vehicles traveling on the arterial and the idling at traffic signals. By taking advantage of the recent developments in communication between vehicles and road infrastructure, it is possible to obtain the signal phase and timing information. Using this real-time signal information, this study developed explicit objective functions to measure the fuel consumption, and a fuel saving strategy for vehicle passing through the intersection safely. The experiment results indicates that the GLOSA application has a significant positive effect on reduce of fuel consumption. The average saving of fuel is 56% for green signal scenario, 21% for red signal scenario, and 14% for field test.

5.1 Limitation

As we can see that there is a gap between the fuel saving results of field test and simulation. There are maybe several reasons for this. Firstly, the driver in the field test needs response time to react to the speed advice voice message while it's not considered in the simulation. This could make the vehicle with GLOSA consume more fuel than that in the simulation. Secondly, the distance between the field test intersection and its upstream intersection is only 150 meters while it's 200 to300 meters in the simulation. This can also increase the fuel consumption compared to simulation. Thirdly, the driver in the field actually can't keep the speed exactly as the voice message advised. All these factors have affected the field test results.

Besides, there are also some limitations in this research. Firstly, the parameters of VT emission model are not generated by the research field test and vehicle conditions. This will bring bias to the fuel consumption results. Secondly, this research only considers single intersection and single vehicle. This makes the application here impractical. Besides that, the field test intersection is too close to the upstream intersection may also affected the field test results since the test vehicle didn't have the same connection distance as it was in simulation conditions.

5.2 Future Work

For the future work, we may need to select another intersection which has a more similar traffic condition as the simulation. Also GLOSA needs to be tested with different signal cycle lengths. As both the cycle lengths and green phase duration increase, vehicles have more chances to pass intersections without stop or slowing down. A set of field experiments will be carried out to determine fuel savings from having a low penetration rate of GLOSA equipped vehicles in the traffic stream. After the single intersection and single vehicle step, the GLOSA system should consider queues and multiple vehicles in the intersection.

REFERENCES

[1] WWF-Canada 2012, Road Transportation Emission Reduction Strategies, WWF Climate Change and Energy Program.

[2] https://www.fueleconomy.gov/feg/tech_adv.shtml, accessed by 2015 May 30, 2015.

[3] Katsaros, K (2010), Performance study of a Green Light Optimal Speed Advisory (GLOSA) Application Using an Integrated Cooperative ITS Simulation Platform. Sciences New York, 918–923.

[4] Seredynski, M., Dorronsoro, B., & Khadraoui, D. (2013). Multi-Segment Green Light Optimal Speed Advisory Marcin. IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, 2187–2192.

[5] Koukoumidis, E., Peh, L.-S., & Martonosi, M. R. (2011). SignalGuru: leveraging mobile phones for collaborative traffic signal schedule advisory. Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services - MobiSys '11, 127.

[6] Kyoungho Ahn, Emission Models Comparison, Dissertation for Master of Science, Virginal Polytechnic Institute and State University, 2001.

[7] Post, K., Kent, J. H. H., Tomlin, J., Carrtuthers, N., & Carruthers, N. (1984). Fuel consumption and emission modelling by power demand and a comparison with other models. Transportation Research Part A: General, 18(3), 191–213.

[8] http://sumo.dlr.de/wiki/Models/Emissions/PHEMlight, accessed by June 3, 2015.

[9] Kraschl-Hirschmann, K., Zallinger, M., Luz, R., Fellendorf, M., & Hausberger, S. (2011). A method for emission estimation for microscopic traffic flow simulation. 2011 IEEE Forum on Integrated and Sustainable Transportation Systems, FISTS 2011, 300–305.

[10] http://www.ermes-group.eu/web/leading_EU_models, accessed by June 3, 2015.

[11] Rakha, H., Ahn, K., & Trani, A. (2004). Development of VT-Micro model for estimating hot stabilized light duty vehicle and truck emissions. Transportation Research Part D: Transport and Environment, 9(1), 49–74.

[12] Rakha, H., & Kamalanathsharma, R. K. (2011). Eco-driving at signalized intersections using V2I communication. IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, 341–346.

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

[14] De Nunzio, G., Canudas de Wit, C., Moulin, P., & Di Domenico, D. (2013). Eco-driving in urban traffic networks using traffic signal information. 52nd IEEE Conference on Decision and Control, 892–898.

[15] Kundu, S., Wagh, A., Qiao, C., Li, X., Kundu, S., Sadek, A., … Wu, C. (2013). Vehicle Speed Control Algorithms for Eco-Driving, (c), 931–932.

[16] Mahler, G., & Vahidi, A. (2012). Reducing idling at red lights based on probabilistic prediction of traffic signal timings. American Control Conference (ACC), 6557 – 6562. Retrieved from.

[17] Stevanovic, A., Stevanovic, J., & Kergaye, C. (2013). Green Light Optimized Speed Advisory Systems. Transportation Research Record: Journal of the Transportation Research Board, 2390, 53–59.

[18] Tielert, T., Killat, M., Hartenstein, H., Luz, R., Hausberger, S., & Benz, T. (2010). The impact of traffic-light-to-vehicle communication on fuel consumption and emissions. 2010 Internet of Things, IoT 2010.

[19] Bradaï, B., Garnault, A., Picron, V., & Gougeon, P. (n.d.). A Green Light Optimal Speed Advisor for reduced CO2 emissions, 1–6.

[20] Li, J., Dridi, M., & El-moudni, A. (2014). Multi-Vehicles Green Light Optimal Speed Advisory Based On The Augmented Lagrangian Genetic Algorithm.

[21] Rakha, H., & Kamalanathsharma, R. K. (2011). Eco-driving at signalized intersections using V2I communication. IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, 341–346. http://doi.org/10.1109/ITSC.2011.6083084.

[22] http://www.itsa.org/industryforums/connectedvehicle, accessed by June 5, 2015.

[23] http://www.its.dot.gov/factsheets/dsrc_factsheet.htm, accessed by June 8, 2015.

[24] SAE International, DSRC Implementation Guide. A guide to users of SAE J2735 message sets over DSRC.

[25] http://www.aradasystems.com/locomate-rsu/, accessed by June 9, 2015.

[26] http://www.aradasystems.com/locomate-obu/, accessed by June 9, 2015.

[27] http://safetran-traffic.com/index.php/products/controllers/rackmount/#rackmount, accessed by June 9, 2015.

[28] Shladover, S. E. (2011). Investigating the Potential Benefits of Broadcasted Signal Phase and Timing (SPAT) Data under IntelliDrive - Task 4: Investigating Potential Benefits, 1–15.

[29] Systems, I. T. (2012). SAE J2735 DSRC Message g Dictionary y Overview SAE J2735 DSRC Message Dictionary Overview.

[30] Alsabaan, M., Naik, K., & Khalifa, T. (2013). Optimization of fuel cost and emissions using V2V communications. IEEE Transactions on Intelligent Transportation Systems, 14(3), 1449–1461.

[31] Ahn, K., Rakha, H., Trani, A., & Van Aerde, M. (2002). Estimating Vehicle Fuel Consumption and Emissions based on Instantaneous Speed and Acceleration Levels. Journal of Transportation Engineering, 128(2), 182–190

[32] Alsabaan, M., Naik, K., & Nayak, A. (2010). Applying Vehicular Ad Hoc Networks for Reduced Vehicle Fuel Consumption, 84, 217–228.

[33] Maurya, A. K., & Bokare, P. S. (2012). Study of Deceleration Behaviour of Different Vehicle Types. *International Journal for Traffic and Transport Engineering*, *2*(3), 253–270.

[34] Mehar, A., Chandra, S., & Velmurugan, S. (2013). Speed and acceleration characteristics of different types of vehicles on multi-lane highways. European Transport - Trasporti Europei, (55), 1–12.

[35] http://www.mathworks.com/help/matlab/, accessed by August 14, 2015.

[36] Statistics for applications, Lecture, Section 7, MIT Open Course Ware, fall 2006.

[37] http://www.pik-potsdam.de/~petri/planwaveresonance/matlab-2010b-ttest2-help.pdf, Matlab 2010b ttest help Documents, accessed by August 14, 2015.

[38] A guide to users of SAE J2735 message sets over DSRC, DSRC Implementation Guide.

[39] LocoMate Programmer's Guide, August 2012, version 2.3, ARADA System Confidential documents .

[40] LocoMate User's Guide, February 25, 2013, version 1.25, ARADA System Confidential documents.

[41] http://developer.android.com/intl/ja/reference/org/w3c/dom/Document.html, Android Development Documents.

Appendix

The following code is the MATLAB Simulation code. There are five files. The main_simulation.m is the simulation start file.

Main_Simulation.m

```
clear;clc;
N_test=100000;

Simulation_Results=zeros(N_test,6);

for i=1:1:N_test

    v_0=randi([14,19]);
    t_m=randi([1,60]);
    x=randi([200,300]);
    v_max=70/3.6;
    v_min=v_max/2;
    d_ar=1.7*exp(-0.04*v_0);
    d_dr=0.005*v_0^2+0.154*v_0+0.493;
    % signal light color, 1 represente green, 0 represente red
    T_light_color=randi([0,1]);

    Simulation_Results(i,1)=v_0;
    Simulation_Results(i,2)=t_m;
    Simulation_Results(i,3)=x;

    if T_light_color==1
        if x/v_0 <t_m
            Simulation_Results(i,4)=normal_keep_status(v_0,t_m,x);
            Simulation_Results(i,5)=normal_keep_status(v_0,t_m,x);
            Simulation_Results(i,6)=1;
        elseif x/v_0 >t_m && ((x-(v_max^2-v_0^2)/(2*d_ar))/v_max+(v_max-v_0)/d_ar) <= t_m
            output=get_fuel_saving_acc(v_0,t_m,x);
            Simulation_Results(i,4)=output(1);
            Simulation_Results(i,5)=output(2);
            Simulation_Results(i,6)=2;
        else
            Simulation_Results(i,4)=get_normal_fuel_acc(v_0,t_m,x);
            Simulation_Results(i,5)=get_normal_fuel_acc(v_0,t_m,x);
            Simulation_Results(i,6)=3;
        end
```

```
    else
        if x/v_0 >t_m
            Simulation_Results(i,4)=normal_keep_status(v_0,t_m,x);
            Simulation_Results(i,5)=normal_keep_status(v_0,t_m,x);
            Simulation_Results(i,6)=4;
        elseif x/v_0<t_m && (x-(v_0^2-v_min^2)/(2*d_dr))/v_min+(v_0-v_min)/d_dr >t_m
            output=get_fuel_saving_dec(v_0,t_m,x);
            Simulation_Results(i,4)=output(1);
            Simulation_Results(i,5)=output(2);
            Simulation_Results(i,6)=5;
        else
            Simulation_Results(i,4)=get_normal_fuel_dec(v_0,t_m,x);
            Simulation_Results(i,5)=get_normal_fuel_dec(v_0,t_m,x);
            Simulation_Results(i,6)=6;
        end
    end
    i
end
Simulation_Results=real(Simulation_Results);
```

Get_fuel_saving_acc.m

```
function [ fuel_consumption ] = get_fuel_saving_acc(v_0,t_m,x )
%GET_FUEL_SAVING_ACC Summary of this function goes here
%   Detailed explanation goes here
fuel_consumption=zeros(2,1);
v_max=80;
T_red=60;

% Coefficients of Composite VehicMe FueM Consumption;
L=[-8.1668,-0.0114,0.00029,-1E-06;
   -0.0786,0.02286,-0.0003,1.1E-06;
   0.07634,-0.0067,0.00011,-4E-07;
   -0.0058,0.0005,-8E-06,2.1E-08];
L1=[-7.73452,0.02799,-0.0002228,1.09E-06;
0.22946,0.0068,-0.00004402,4.80E-08;
-0.00561,-0.00077221,7.9E-07,3.27E-08;
9.77E-05,0.00000838,8.17E-07,-7.79E-09];

M=[-8.1668,-0.0114,0.00029,-1E-06;
    0.00809,-0.0076,0.00027,-1E-06;
    -0.0028,-0.0004,2E-05,-9E-08;
    -0.0002,-3E-06,3.6E-07,-2E-09];
M1=[-7.73452,0.02804,-0.00021988,1.08E-06;
-0.01799,0.00772,-0.00005219,2.47E-07;
-0.00427,0.00083744,-7.44E-06,4.87E-08;
```

```
0.00018829,-0.00003387,2.77E-07,3.79E-10];

d1=1.7*exp(-0.04*v_0);
d3=-0.005*v_0^2+0.154*v_0+0.493;
t_dec=v_0/d3;
d4=1.7*exp(-0.04*0)*3.6;
fun4= @(t)
exp(L(1,1)+L(1,2)*(d4*t)+L(1,3)*(d4*t).^2+L(1,4)*(d4*t).^3+d3*L(2,1)+d3*L(2,2)*(d4*t)+d3
*L(2,3)*(d4*t).^2+d3*L(2,4)*(d4*t).^3+d3^2*L(3,1)+d3^2*L(3,2)*(d4*t)+d3^2*L(3,3)*(d4*t).
^2+d3^2*L(3,4)*(d4*t).^3+d3^3*L(4,1)+d3^3*L(4,2)*(d4*t)+d3^3*L(4,3)*(d4*t).^2+d3^3*L(4
,4)*(d4*t).^3);
F_acc=quadl(fun4,0,v_0*3.6/d4);

t_ave=(x-v_0^2/(2*d3))/v_0;
t_stop=t_m-t_ave-t_dec+T_red;
d3=d3*3.6;
x=x/1000;
v_0=v_0*3.6;
F_ave=exp(sum(L,1)*[1,v_0,v_0^2,v_0^3]')*t_ave;
fun3= @(t) exp(M(1,1)+M(1,2)*(v_0-d3*t)+M(1,3)*(v_0-d3*t).^2+M(1,4)*(v_0-
d3*t).^3+d3*M(2,1)+d3*M(2,2)*(v_0-d3*t)+d3*M(2,3)*(v_0-d3*t).^2+d3*M(2,4)*(v_0-
d3*t).^3+d3^2*M(3,1)+d3^2*M(3,2)*(v_0-d3*t)+d3^2*M(3,3)*(v_0-
d3*t).^2+d3^2*M(3,4)*(v_0-d3*t).^3+d3^3*M(4,1)+d3^3*M(4,2)*(v_0-
d3*t)+d3^3*M(4,3)*(v_0-d3*t).^2+d3^3*M(4,4)*(v_0-d3*t).^3);
F_dec=quadl(fun3,0,v_0/d3);
F_stop=exp(sum(sum(L)))*t_stop;

L_distance_normal=x+(v_0^2)/(2*d4*3600);
F_normal=(F_ave+F_dec+F_stop+F_acc)/L_distance_normal;


%d_0=(2*(x*1000)-2*(v_0/3.6)*t_m)/t_m^2;


  d=d1*3.6;
  v_s = v_0+ d.*t_m-sqrt(d.*(d.*t_m*t_m+2*t_m*v_0-2*x*3600));
  if v_s> v_max
    v_s=v_max;
  end
  d2=(-0.005*(v_s/3.6)^2+0.154*(v_s/3.6)+0.493)*3.6;
  fun1= @(t)
exp(L(1,1)+L(1,2)*(v_0+d*t)+L(1,3)*(v_0+d*t).^2+L(1,4)*(v_0+d*t).^3+d*L(2,1)+d*L(2,2)*(
v_0+d*t)+d*L(2,3)*(v_0+d*t).^2+d*L(2,4)*(v_0+d*t).^3+d^2*L(3,1)+d^2*L(3,2)*(v_0+d*t)+
d^2*L(3,3)*(v_0+d*t).^2+d^2*L(3,4)*(v_0+d*t).^3+d^3*L(4,1)+d^3*L(4,2)*(v_0+d*t)+d^3*L
(4,3)*(v_0+d*t).^2+d^3*L(4,4)*(v_0+d*t).^3);
```

```
   F1 = quadl(fun1, 0, (v_s-v_0)/d);
   F2=exp(sum(L,1)*[1,v_s,v_s^2,v_s^3]')*(t_m-(v_s-v_0)/d);
   F_up=F1+F2;
   fun2 =  @(t) exp(M(1,1)+M(1,2)*(v_s-d2*t)+M(1,3)*(v_s-d2*t).^2+M(1,4)*(v_s-
d2*t).^3+d2*M(2,1)+d2*M(2,2)*(v_s-d2*t)+d2*M(2,3)*(v_s-d2*t).^2+d2*M(2,4)*(v_s-
d2*t).^3+d2^2*M(3,1)+d2^2*M(3,2)*(v_s-d2*t)+d2^2*M(3,3)*(v_s-
d2*t).^2+d2^2*M(3,4)*(v_s-d2*t).^3+d2^3*M(4,1)+d2^3*M(4,2)*(v_s-
d2*t)+d2^3*M(4,3)*(v_s-d2*t).^2+d2^3*M(4,4)*(v_s-d2*t).^3);

   F_down=quadl(fun2,0,(v_s-v_0)/d2);
   F=F_up+F_down;
   L_disance=x+(v_s^2-v_0^2)/(2*d2*3600);
   F=F/L_disance;

fuel_consumption(1)=F;
fuel_consumption(2)=F_normal;

end
```

get_fuel_saving_dec.m

```
function [ fuel_consumption ] = get_fuel_saving_dec( v_0,t_m,x )
%GET_FUEL_CONSUMPTION_DEC Summary of this function goes here
%   get the fuel saving data

% Coefficients of Composite VehicMe FueM Consumption;
L=[-8.1668,-0.0114,0.00029,-1E-06;
  -0.0786,0.02286,-0.0003,1.1E-06;
  0.07634,-0.0067,0.00011,-4E-07;
  -0.0058,0.0005,-8E-06,2.1E-08];
L1=[-7.73452,0.02799,-0.0002228,1.09E-06;
0.22946,0.0068,-0.00004402,4.80E-08;
-0.00561,-0.00077221,7.9E-07,3.27E-08;
9.77E-05,0.00000838,8.17E-07,-7.79E-09];

M=[-8.1668,-0.0114,0.00029,-1E-06;
   0.00809,-0.0076,0.00027,-1E-06;
   -0.0028,-0.0004,2E-05,-9E-08;
   -0.0002,-3E-06,3.6E-07,-2E-09];
M1=[-7.73452,0.02804,-0.00021988,1.08E-06;
-0.01799,0.00772,-0.00005219,2.47E-07;
-0.00427,0.00083744,-7.44E-06,4.87E-08;
0.00018829,-0.00003387,2.77E-07,3.79E-10];

d3=-0.005*v_0^2+0.154*v_0+0.493;
t_dec=v_0/d3;
```

```
t_ave=(x-v_0^2/(2*d3))/v_0;
d3=d3*3.6;
v_0=v_0*3.6;
x=x/1000;
F_ave=exp(sum(L,1)*[1,v_0,v_0^2,v_0^3]')*t_ave;
F_dec=0;
F_stop=0;
F_acc=0;
v_current=0;
d4=0;
fun3= @(t) exp(M(1,1)+M(1,2)*(v_0-d3*t)+M(1,3)*(v_0-d3*t).^2+M(1,4)*(v_0-
d3*t).^3+d3*M(2,1)+d3*M(2,2)*(v_0-d3*t)+d3*M(2,3)*(v_0-d3*t).^2+d3*M(2,4)*(v_0-
d3*t).^3+d3^2*M(3,1)+d3^2*M(3,2)*(v_0-d3*t)+d3^2*M(3,3)*(v_0-
d3*t).^2+d3^2*M(3,4)*(v_0-d3*t).^3+d3^3*M(4,1)+d3^3*M(4,2)*(v_0-
d3*t)+d3^3*M(4,3)*(v_0-d3*t).^2+d3^3*M(4,4)*(v_0-d3*t).^3);
if  t_ave+t_dec <= t_m
   F_dec=quadl(fun3,0,v_0/d3);
   t_stop=t_m-t_ave-t_dec;
   F_stop=exp(sum(sum(L)))*t_stop;
   d4=1.7*exp(-0.04*0)*3.6;
   fun4= @(t)
exp(L(1,1)+L(1,2)*(d4*t)+L(1,3)*(d4*t).^2+L(1,4)*(d4*t).^3+d3*L(2,1)+d3*L(2,2)*(d4*t)+d3
*L(2,3)*(d4*t).^2+d3*L(2,4)*(d4*t).^3+d3^2*L(3,1)+d3^2*L(3,2)*(d4*t)+d3^2*L(3,3)*(d4*t).
^2+d3^2*L(3,4)*(d4*t).^3+d3^3*L(4,1)+d3^3*L(4,2)*(d4*t)+d3^3*L(4,3)*(d4*t).^2+d3^3*L(4
,4)*(d4*t).^3);
   F_acc=quadl(fun4,0,v_0/d4);
elseif t_ave+t_dec>t_m
   F_dec=quadl(fun3,0,(t_m-t_ave));
   v_current=(v_0/3.6-(d3/3.6)*(t_m-t_ave))*3.6;
   d4=1.7*exp(-0.04*v_current/3.6)*3.6;
   fun5= @(t)
exp(L(1,1)+L(1,2)*(v_current+d4*t)+L(1,3)*(v_current+d4*t).^2+L(1,4)*(v_current+d4*t).^3+
d3*L(2,1)+d3*L(2,2)*(v_current+d4*t)+d3*L(2,3)*(v_current+d4*t).^2+d3*L(2,4)*(v_current+
d4*t).^3+d3^2*L(3,1)+d3^2*L(3,2)*(v_current+d4*t)+d3^2*L(3,3)*(v_current+d4*t).^2+d3^2*
L(3,4)*(v_current+d4*t).^3+d3^3*L(4,1)+d3^3*L(4,2)*(v_current+d4*t)+d3^3*L(4,3)*(v_curre
nt+d4*t).^2+d3^3*L(4,4)*(v_current+d4*t).^3);
   F_acc=quadl(fun5,0,(v_0-v_current)/d4);
end
L_distance_normal=x+(v_0^2-v_current^2)/(2*d4*3600);
F_normal=(F_ave+F_dec+F_stop+F_acc)/L_distance_normal;


   d=d3;
   v_s = v_0- d.*t_m+sqrt(d.*(d.*t_m*t_m-2*t_m*v_0+2*x*3600));
   d2=1.7*exp(-0.04*v_s/3.6)*3.6;
```

```
    fun1= @(t) exp(M(1,1)+M(1,2)*(v_0-d*t)+M(1,3)*(v_0-d*t).^2+M(1,4)*(v_0-
d*t).^3+d*M(2,1)+d*M(2,2)*(v_0-d*t)+d*M(2,3)*(v_0-d*t).^2+d*M(2,4)*(v_0-
d*t).^3+d^2*M(3,1)+d^2*M(3,2)*(v_0-d*t)+d^2*M(3,3)*(v_0-d*t).^2+d^2*M(3,4)*(v_0-
d*t).^3+d^3*M(4,1)+d^3*M(4,2)*(v_0-d*t)+d^3*M(4,3)*(v_0-d*t).^2+d^3*M(4,4)*(v_0-
d*t).^3);
    F1 = quadl(fun1, 0, (v_0-v_s)/d);
    F2=exp(sum(L,1)*[1,v_s,v_s^2,v_s^3]')*(t_m-(v_0-v_s)/d);
    F_up=F1+F2;
    fun2 =  @(t) exp(L(1,1)+L(1,2)*(v_0-d2*t)+L(1,3)*(v_0-d2*t).^2+L(1,4)*(v_0-
d2*t).^3+d2*L(2,1)+d2*L(2,2)*(v_0-d2*t)+d2*L(2,3)*(v_0-d2*t).^2+d2*L(2,4)*(v_0-
d2*t).^3+d2^2*L(3,1)+d2^2*L(3,2)*(v_0-d2*t)+d2^2*L(3,3)*(v_0-
d2*t).^2+d2^2*L(3,4)*(v_0-d2*t).^3+d2^3*L(4,1)+d2^3*L(4,2)*(v_0-
d2*t)+d2^3*L(4,3)*(v_0-d2*t).^2+d2^3*L(4,4)*(v_0-d2*t).^3);

    F_down=quadl(fun2,0,(v_0-v_s)/d2);
    F=F_up+F_down;
    L_disance=x+(v_0^2-v_s^2)/(2*d2*3600);
    F=F/L_disance;
fuel_consumption(1)=F;
fuel_consumption(2)=F_normal;

end
```

get_normal_fuel_acc.m

```
function [ output_fuel_consumption ] = get_normal_fuel_acc( v_0,t_m,x)
%GET_NORMAL_FUEL_ACC Summary of this function goes here
%   Detailed explanation goes here

T_red=60;

% Coefficients of Composite VehicMe FueM Consumption;
L=[-8.1668,-0.0114,0.00029,-1E-06;
   -0.0786,0.02286,-0.0003,1.1E-06;
   0.07634,-0.0067,0.00011,-4E-07;
   -0.0058,0.0005,-8E-06,2.1E-08];
M=[-8.1668,-0.0114,0.00029,-1E-06;
    0.00809,-0.0076,0.00027,-1E-06;
    -0.0028,-0.0004,2E-05,-9E-08;
    -0.0002,-3E-06,3.6E-07,-2E-09];
d3=-0.005*v_0^2+0.154*v_0+0.493;
t_dec=v_0/d3;
d4=1.7*exp(-0.04*0)*3.6;
fun4= @(t)
exp(L(1,1)+L(1,2)*(d4*t)+L(1,3)*(d4*t).^2+L(1,4)*(d4*t).^3+d3*L(2,1)+d3*L(2,2)*(d4*t)+d3
*L(2,3)*(d4*t).^2+d3*L(2,4)*(d4*t).^3+d3^2*L(3,1)+d3^2*L(3,2)*(d4*t)+d3^2*L(3,3)*(d4*t).
```

```
^2+d3^2*L(3,4)*(d4*t).^3+d3^3*L(4,1)+d3^3*L(4,2)*(d4*t)+d3^3*L(4,3)*(d4*t).^2+d3^3*L(4
,4)*(d4*t).^3);
F_acc=quadl(fun4,0,v_0*3.6/d4);

t_ave=(x-v_0^2/(2*d3))/v_0;
t_stop=t_m-t_ave-t_dec+T_red;
d3=d3*3.6;
x=x/1000;
v_0=v_0*3.6;
F_ave=exp(sum(L,1)*[1,v_0,v_0^2,v_0^3]')*t_ave;
fun3= @(t) exp(M(1,1)+M(1,2)*(v_0-d3*t)+M(1,3)*(v_0-d3*t).^2+M(1,4)*(v_0-
d3*t).^3+d3*M(2,1)+d3*M(2,2)*(v_0-d3*t)+d3*M(2,3)*(v_0-d3*t).^2+d3*M(2,4)*(v_0-
d3*t).^3+d3^2*M(3,1)+d3^2*M(3,2)*(v_0-d3*t)+d3^2*M(3,3)*(v_0-
d3*t).^2+d3^2*M(3,4)*(v_0-d3*t).^3+d3^3*M(4,1)+d3^3*M(4,2)*(v_0-
d3*t)+d3^3*M(4,3)*(v_0-d3*t).^2+d3^3*M(4,4)*(v_0-d3*t).^3);
F_dec=quadl(fun3,0,v_0/d3);
F_stop=exp(sum(sum(L)))*t_stop;

L_distance_normal=x+(v_0^2)/(2*d4*3600);
F_normal=(F_ave+F_dec+F_stop+F_acc)/L_distance_normal;
output_fuel_consumption=F_normal;
end
```

get_normal_fuel_dec.m

```
function [ output_fuel_consumption ] = get_normal_fuel_dec( v_0,t_m,x)
%GET_NORMAL_FUEL_DEC Summary of this function goes here
%   Detailed explanation goes here
L=[-8.1668,-0.0114,0.00029,-1E-06;
   -0.0786,0.02286,-0.0003,1.1E-06;
   0.07634,-0.0067,0.00011,-4E-07;
   -0.0058,0.0005,-8E-06,2.1E-08];

M=[-8.1668,-0.0114,0.00029,-1E-06;
    0.00809,-0.0076,0.00027,-1E-06;
    -0.0028,-0.0004,2E-05,-9E-08;
    -0.0002,-3E-06,3.6E-07,-2E-09];
d3=-0.005*v_0^2+0.154*v_0+0.493;
t_dec=v_0/d3;
t_ave=(x-v_0^2/(2*d3))/v_0;
d3=d3*3.6;
v_0=v_0*3.6;
x=x/1000;
F_ave=exp(sum(L,1)*[1,v_0,v_0^2,v_0^3]')*t_ave;
F_dec=0;
F_stop=0;
```

```
F_acc=0;
v_current=0;
d4=0;
fun3= @(t) exp(M(1,1)+M(1,2)*(v_0-d3*t)+M(1,3)*(v_0-d3*t).^2+M(1,4)*(v_0-
d3*t).^3+d3*M(2,1)+d3*M(2,2)*(v_0-d3*t)+d3*M(2,3)*(v_0-d3*t).^2+d3*M(2,4)*(v_0-
d3*t).^3+d3^2*M(3,1)+d3^2*M(3,2)*(v_0-d3*t)+d3^2*M(3,3)*(v_0-
d3*t).^2+d3^2*M(3,4)*(v_0-d3*t).^3+d3^3*M(4,1)+d3^3*M(4,2)*(v_0-
d3*t)+d3^3*M(4,3)*(v_0-d3*t).^2+d3^3*M(4,4)*(v_0-d3*t).^3);
if  t_ave+t_dec <= t_m
   F_dec=quadl(fun3,0,v_0/d3);
   t_stop=t_m-t_ave-t_dec;
   F_stop=exp(sum(sum(L)))*t_stop;
   d4=1.7*exp(-0.04*0)*3.6;
   fun4= @(t)
exp(L(1,1)+L(1,2)*(d4*t)+L(1,3)*(d4*t).^2+L(1,4)*(d4*t).^3+d3*L(2,1)+d3*L(2,2)*(d4*t)+d3
*L(2,3)*(d4*t).^2+d3*L(2,4)*(d4*t).^3+d3^2*L(3,1)+d3^2*L(3,2)*(d4*t)+d3^2*L(3,3)*(d4*t).
^2+d3^2*L(3,4)*(d4*t).^3+d3^3*L(4,1)+d3^3*L(4,2)*(d4*t)+d3^3*L(4,3)*(d4*t).^2+d3^3*L(4
,4)*(d4*t).^3);
   F_acc=quadl(fun4,0,v_0/d4);
elseif t_ave+t_dec>t_m
   F_dec=quadl(fun3,0,(t_m-t_ave));
   v_current=(v_0/3.6-(d3/3.6)*(t_m-t_ave))*3.6;
   d4=1.7*exp(-0.04*v_current/3.6)*3.6;
   fun5= @(t)
exp(L(1,1)+L(1,2)*(v_current+d4*t)+L(1,3)*(v_current+d4*t).^2+L(1,4)*(v_current+d4*t).^3+
d3*L(2,1)+d3*L(2,2)*(v_current+d4*t)+d3*L(2,3)*(v_current+d4*t).^2+d3*L(2,4)*(v_current+
d4*t).^3+d3^2*L(3,1)+d3^2*L(3,2)*(v_current+d4*t)+d3^2*L(3,3)*(v_current+d4*t).^2+d3^2*
L(3,4)*(v_current+d4*t).^3+d3^3*L(4,1)+d3^3*L(4,2)*(v_current+d4*t)+d3^3*L(4,3)*(v_curre
nt+d4*t).^2+d3^3*L(4,4)*(v_current+d4*t).^3);
   F_acc=quadl(fun5,0,(v_0-v_current)/d4);
end
L_distance_normal=x+(v_0^2-v_current^2)/(2*d4*3600);
F_normal=(F_ave+F_dec+F_stop+F_acc)/L_distance_normal;
output_fuel_consumption=F_normal;
end
```