ABSTRACT

Title of Thesis:	CONNECTED ENVIRONMENT: JOINT TRAFFIC SIGNAL AND VEHICLES SPEED OPTIMIZATION FOR OPTIMUM MOBILITY AND FUEL CONSUMPTION
	Romina Jahangiri, Master of Science, 2022
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A connected environment offers an effective solution to smart cities' current concerns. The performance of existing traffic signals and speed advisory technology can be improved by cooperation between traffic signal and speed system advisory in a connected environment. This research proposes a connected intersection where the traffic light and individual vehicles' speed can be optimized simultaneously. Traffic signal timing and arrival time of the vehicles at the beginning of each cycle can be calculated to find the optimum speed, brake force, and vehicle engine power each second. The main contribution of this thesis is to consider the optimization of the traffic signal and vehicles' velocity together at the same time at different penetration rates and demand levels to optimize total travel time, stop time, delay, and fuel consumption. Few research studies have considered these simultaneously. An analysis is conducted

to compare the result of this thesis with actuated and fixed-time traffic signals. The results show improvement in fuel consumption and mobility, specifically at the lower demand levels.

CONNECTED ENVIRONMENT: JOINT TRAFFIC SIGNAL AND VEHICLES SPEED OPTIMIZATION FOR OPTIMUM MOBILITY AND FUEL CONSUMPTION

By

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Acknowledgments

Two years ago, my journey for a Master of Science in transportation engineering started at the University of Maryland, College Park. Before even starting my first class, it was my great fortune that I met my advisor, Professor Ali Haghani, and Dr. Kaveh Farokhi Saadabadi. I searched and learned about their recent research areas. I was so excited to join their group and learn from them.

Since traffic control in urban areas in the presence of connected vehicles is considered a potentially challenging and relevant topic in academia and industry, I focused on optimizing travel time, stop time, delay, and fuel consumption in a signalized connected intersection in my thesis.

During the last three years, I had the opportunity to work as a research assistant with Dr. Farokhi at the Center for Advanced Transportation Technology. I took some relevant courses in transportation engineering. This coursework and research experience helped me get familiar with the transportation engineering area from different dimensions, and this opportunity expanded my knowledge.

My Master of Science experience at the University of Maryland was a little far from what I hoped to be due to the coronavirus pandemic situation. Although there were many restrictions and limitations in that period, classes were online, and my project was challenging enough to keep me motivated to continue it.

I want to express my gratitude to Professor Ali Haghani, who provided the opportunity to become familiar with optimization, and Dr. Kaveh Farokhi, who helped me as my research moved forward and responded to my concerns to overcome my difficulties.

Also, thank you to my thesis committee, Dr. Chenfeng Xiong, and Dr. Paul Schonfeld, who helped me in this research.

Center for Advanced Transportation Technology has sponsored this work as part of a project to enhance proficiency in optimizing vehicles' travel time, stop time, delay, and fuel consumption in the presence of connected vehicles.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Section 1.1: Research Motivation

Urban areas are faced with a dramatic increase in population, leading to increased transportation needs. The United Nations estimated 55% of people worldwide in 2018 resided in urban areas, and this amount will increase to 68% by 2050 [1]. Although urbanization has its benefits, pollution, population explosion, and traffic congestion are some side effects of living in urban areas. Fortunately, the boom in technology has helped form smart cities, which was considered an imaginary theory in the 20th century. Smart cities provide an area with efficient services and better quality of life. Apart from that, they help improve daily functions like commuting [2]. Improving the functionality can reduce the side effects of urbanization. There are many smart cities or plans for cities to become smart cities worldwide, such as New York, Beijing, Zurich, Amsterdam, Berlin, and Singapore [3].

Smart mobility can be considered a significant part of a smart city. Smart mobility makes more efficient, attractive, and innovative mobility, which helps increase travel quality and decrease wasting time and fuel consumption. The population increase in large cities has caused more car usage in the urban areas. This dramatic growth has caused more collisions, congestion, and fuel consumption. Motor vehicles were used 167% more in 2009 than in 1970 in the United States [4]. As the number of car usage has increased, urban areas have become more and more congested, resulting in more fuel consumption. In 2020, the congestion cost was $101 billion. However, there was a decrease in comparison with 2019. In 2019 congestion cost was $190 billion. Meanwhile, travel delays also decreased from 8.7 billion hours to 4.3 billion hours from 2019 to 2020 [5]. Motor vehicles used about 142.17 billion gallons of gasoline (or about 3.39 billion barrels) in 2019 in the USA, an average of about 389.51 million gallons (or about 9.27 million barrels) per day. There are 42 gallons in a barrel [4].

A connected environment can make a significant impact on smart cities. A connected environment includes communication between Vehicle and Vehicle, Vehicle and Infrastructure, and Vehicle and others like pedestrians. Connected and autonomous vehicles have been significant developments in smart mobility during recent decades. A connected environment can provide more information about traffic conditions (position, speed, fuel consumption parameters). Such extra information helps decrease congestion, reduce accident rates, maximize traffic flows, and minimize emissions by optimizing signal timing plans at an intersection, along a corridor, or in a region. Apart from that, connected vehicles can increase safety, warn drivers before crashes and reduce fatalities. So, these technologies can be beneficial for the entire smart cities. According to the American Association of State Highway and Transportation Officials (AASHTO), 90% of light vehicles will be equipped with at least one type of connected technology by 2040 [6]. Therefore, undoubtedly connected and autonomous vehicles will make a fundamental revolution in the smart mobility system. The connected environment is discussed in two dimensions; Intersection control and in-vehicle control.

Subsection 1.1.1: Intersection control

One part of the connected environment is the communication between infrastructures like traffic lights controllers and vehicles. Urban traffic control systems are updated frequently in smart cities to keep up with the traffic flows in urban areas. Traffic signal controllers rapidly adapt to different traffic patterns to control ever-growing traffic demands, help smooth traffic flow, and reduce traffic congestion. Traffic signals fall into three groups. Previously, traffic signals were pre-timed. They were uniform and constant in terms of phase sequence, cycle length, and all interval times from cycle to cycle, which was not efficient enough because different programs could be generated. For instance, the traffic flow is different during the day and night hours, even in the morning and evening peak hours, but the controller cannot respond to the fluctuations in vehicle arrivals. Actuated signal controls were developed later, which detected the presence of vehicles by detectors like loop detectors, radar, sonic, ultrasonic waves, and video detectors. These systems perform more efficiently than fixed-time traffic control because the green time can be extended to the maximum green split and can also be skipped if there is no other call from other parts of the roads or pedestrians. The actuated control system has its own weaknesses compared to the adaptive traffic signal control systems. Adaptive signal control systems are considered the newest technology in this area. This type of control uses the same pattern of actuated controls. They detect the current data, but the difference is they can proactively respond to traffic flow and use prediction models to get information about the vehicles' states, the arrival of vehicles, and the queue of the intersections.

In recent years, one of the practical technologies in signalized intersections that received attention in signal timing is communication with connected vehicles. This thesis analyzes a fixed-time traffic signal, and a fixed-cycle length actuated traffic signal control that can communicate in a connected environment. The actuated traffic signal is based on NO-recall, which means the actuated phase will only be activated when there is a call or, in other words, when there is a demand. The following assumptions are considered:

i. Since different penetration rates are to be considered, detectors are provided at a distance of 20 meters to an intersection in each section. These detectors count the vehicles even if the vehicles are unequipped and cannot share any information.

ii. To avoid collisions in the intersection, a dual-ring method is designed that includes two rings. Figure 1 shows the designed dual-ring method for this intersection.

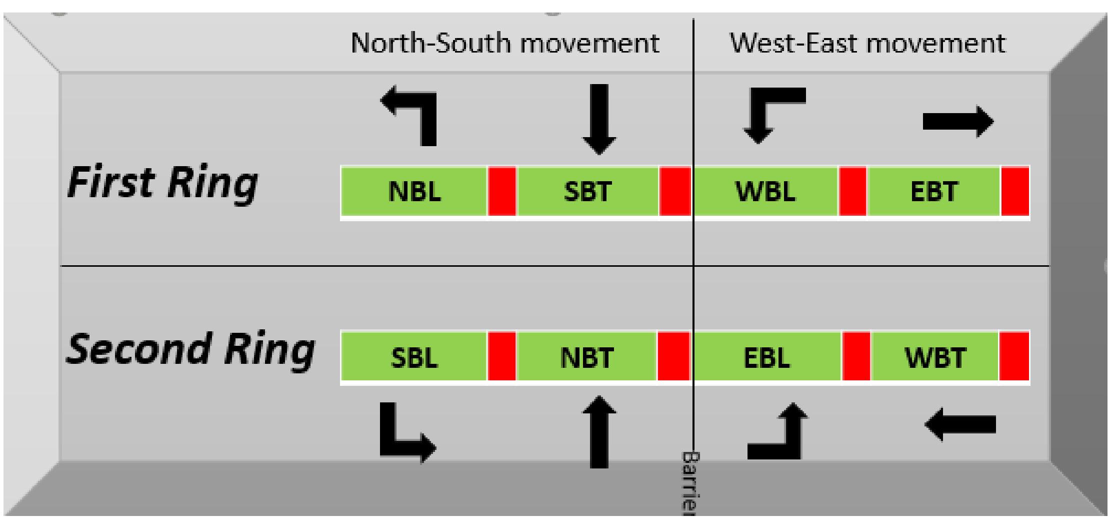


Figure 1: Dual-ring scheme design

iii. The right turn is always green in this intersection. No straight approach in the right lanes is considered.

Subsection 1.1.2: Vehicular technology

A communication system needs to be installed on vehicles and traffic signal controllers to connect vehicles and infrastructures. The vehicles' inter-vehicle network or mobile internet makes it possible for vehicles, infrastructures, and others to communicate with each other. The data from connected vehicles to infrastructures (Roadside equipment (RSE)) which is called basic safety messages (BSM), is broadcast by one of the communication types from on-board equipment (OBE) found on the vehicles. The aforementioned communication types are Dedicated Short Range Communication (DSRC), Cellular, WIFI, and Radio. The BSM is a safety message that includes location, speed, acceleration, deceleration, heading, and some more vehicle systems information that the Society of Automotive Engineers identifies (SAE) J2735 DSRC Message Set Dictionary [7]. RSE broadcast signal phase and time (SPaT) information and MAP information, and vulnerable road users (VRU) also broadcast personal safety messages (PSM). Recently, the United States and Europe have built a system named Vehicular ad-hoc network (VANE) to understand the interconnection of vehicles' operation statuses to solving traffic problems [9].

In this thesis, the vehicles are categorized as follows:

a) Connected Vehicles

Equipped or connected vehicles are some vehicle types that can communicate by V2I and V2V. These vehicles can broadcast their position, speed, acceleration, deceleration, direction, etc. In this type, it is assumed that vehicles strictly follow speed advice. These vehicles are considered above level 4 of automated vehicles. Automated vehicles categorization is described in table 1.

Table 1: Levels of Automation for Vehicles (NHTSA, 2018) [8]

Levels of automation	*Who does what and when*
Level 0	*The human driver does all the driving*
Level 1	*An advanced driver assistance system (ADAS) on the vehicle can sometimes assist the human driver with either steering or braking/acceleration, but not both simultaneously.*
Level 2	*An advanced driver assistance system (ADAS) on the vehicle can itself actually control both steering and braking/accelerating simultaneously under some circumstances. The human driver must continue to pay full attention ("monitor the driving environment") at all times and perform the rest of the driving task.*
Level 3	*An automated driving system (ADS) on the vehicle can itself perform all aspects of the driving task under some circumstances. In those circumstances, the human driver must be ready to take back control at any time when the ADS requests the human driver to do so. In all other circumstances, the human driver performs the driving task.*
Level 4	*An automated driving system (ADS) on the vehicle can itself perform all driving tasks and monitor the driving environment – essentially, do all the driving – in certain circumstances. Humans need not pay attention in those circumstances.*
Level 5	*An automated driving system (ADS) on the vehicle can do all the driving in all circumstances. The human occupants are just passengers and need never be involved in driving.*

b) Conventional Vehicles (Unequipped vehicles)

They are defined as vehicles that do not have the willingness or ability to communicate with other vehicles or controllers. These vehicles also are considered as level 0 of autonomy vehicles in which human drivers do everything. Thus, reaction time for drivers is considered.

Despite the benefits of these technologies in smart cities, there are still challenges that are summarized as follows:

1. The penetration rate of connected vehicles will increase gradually. There is limited information in the lower penetration rates, in connected environments, and sometimes more errors. Even though having a complete penetration rate might take a while, a lower penetration rate can have benefits compared to a zero penetration rate. It is beneficial to consider different penetration rates and demonstrate the advantages of having even a low penetration rate. There is a need to have more accurate methods for the lower penetration rates.
2. Urban transportation systems are usually large-scale and have different flow rates. Then, the transportation system needs to have a flexible model that can support different flow rates. Although much research has been conducted in this area, few simultaneously consider different demands with varying penetration rates.
3. The connected environment includes V2V, V2I, and V2X. A connection between vehicles and infrastructures like traffic lights is needed for better performance. According to the AASHTO, 80 percent (250,000) of traffic signal locations will be equipped with vehicle-to-infrastructure (V2I) by 2040 [6]. In recent years, one of the practical technologies in signalized intersections that has received increasing attention in signal timing is communication with connected vehicles. More research needs to be focused on decreasing the delay

time of vehicles in intersections because of red lights. This requires more robust control methods and more computational strategy.

Finding the solutions to these problems still remains a challenge. This thesis attempts to address these questions to improve connected vehicles' performance. This thesis will analyze a connected environment and traffic light estimation to maximize the benefits of connected vehicles in the system.

Section 1.2: Goal and Scope

Subsection 1.2.1: Research goals

This thesis aims to minimize vehicles' travel time, stop time, delay, and fuel consumption in a connected environment. In a connected environment, vehicles receive the data and get optimized in terms of fuel consumption and speed. Traffic lights get optimized in green light to decrease the total travel time before the intersection and the stopping time of vehicles behind the red light. This optimization will be done simultaneously. The objectives are listed below specifically.

1. Develop a signalized intersection in a traffic simulator and collect the trajectory data of vehicles in different demand levels. The information provided from simulations is used to exploit the benefits.
2. Propose traffic signal control to minimize total travel time, delay, stop time, and fuel consumption and locate the detectors to count the unconnected vehicles.

3. Consider different penetration rates for connected vehicles to be close to reality as much as possible.

The outcome of this thesis will provide a traffic control system in a connected environment by using the data that transfers between vehicles and vehicles and vehicles and infrastructures to optimize velocity for vehicles and green light for traffic lights simultaneously to minimize time and fuel usage.

Subsection 1.2.2: Research scope

This thesis's research scope is limited, as described briefly below.

1. Signal control strategies are proposed only in one intersection in an urban scenario. This is because traffic signals are an essential component of the transportation system. Properly timing traffic signals will decrease green lights and, as a result, reduce travel time and fuel consumption. Highways or urban area corridors are not considered but can be considered in future work.
2. Only three demand levels are considered, and they are distributed at the intersection. Low demand (1400 veh/hr), medium demand (2000 veh/hr), and high demand (2800 veh/hr) are considered.
3. Detectors are proposed to count the unequipped vehicles.
4. Data errors or potential issues like packet loss are not considered. It is assumed that all data will transfer wholly and faithfully. Hacking problems or cyber security attacks are not considered.
5. A car-following model is used to avoid accident occurrences.

6. Only fixed cycle length for traffic signals is considered. Free-cycle length could provide more adjustable traffic signals based on demands. This free-cycle length method will be suggested for future work.

Section 1.3: Research tasks

The following tasks are completed in this thesis:

1. Literature Review:

   Relevant previous papers and research is categorized and discussed in three parts.

   A. Traffic signals optimization research

   B. Speed optimization

   C. Traffic signal and speed optimization

   By reviewing these papers, it can be seen that most of the research focused solely on traffic signals optimization methods like optimizing green lights or vehicles' velocity, and acceleration/deceleration optimization. This thesis focuses on both of them to get a more efficient result.

2. Finding data

   After investigating the existing database USDOT CV pilot and Wejo movement, this research focused on the simulation and used the simulation result data because of the very low penetration rate of equipped vehicles in the urban areas. The data is generated in Matlab and simulation, optimized, and analyzed in Matlab.

3. Optimization

   The optimization of the data is done in Matlab. Travel time, stop time, delay, and the engine’s power and brake force are analyzed in this thesis.

Section 1.4: Software

In our analysis, the following software is used:

I. **Aimsun Simulation:** Aimsun traffic simulator (academic license) is used to simulate an intersection with actuated signal control. The optimized model will be compared with the output of the simulation.

II. **Matlab:** Matlab (academic license) is used to optimize the model by fmincon and generate the data for the lower penetration rate. The graphs and plots in the thesis have been produced using Matlab.

III. **DB Browser (SQLite):** The vehicle trajectory data volume is high and is based on SQLite format. After the simulation, the DB browser is used to read the output of the data and convert some of the tables to CSV format for analysis.

IV. **QGIS:** The vehicle trajectory waypoints of real data sources are shown on QGIS to find the segments and a visual overview of the data to see whether or not the data is helpful in this research.

V. **Open street map (OSM) and open source routing machine (OSRM):** OSM and OSRM are used to find the way ID from the waypoint or get an overview of waypoints in the map.

Section 1.5: Organization

Chapter 2 presents a comprehensive review of previous studies and defines the research gaps. This chapter contains the most important papers on optimizing traffic signals and vehicles speed. Chapter 3 describes the simulation details and proposes an optimization methodology to optimize total travel time, brake force, and engine power. Chapter 4 discusses the result and compares the result with the base model, and Chapter 5 concludes this thesis and illustrates the future work.

Chapter 2: Literature Review

This chapter provides a literature review and identifies the research gaps. Section 2.1 reviews the related literature for controlling traffic signals and speed advisory to minimize vehicles' total travel time or fuel consumption. Section 2.2 summarizes the research gap in this area, and section 2.3 presents the available data for this thesis.

Section 2.1: Literature review

Researchers in the connected environment area provide different strategies for minimizing fuel consumption, greenhouse gases, and critical air pollution emissions and maximizing mobility in the signalized intersection by reducing vehicle idling duration, the number of stops, and unnecessary vehicle accelerations and decelerations. Their surveys might be concentrated on one intersection or extended in a corridor or a network.

Subsection 2.1.1: Traffic signal optimization

As explained earlier, connected infrastructures can collect vehicle information, analyze them and decide how long each phase extends. The adaptive signal control system is the most efficient operation to decrease the idling time. Goodall et al. [10] chose a predictive microscopic simulation algorithm (PMSA) to control traffic signals. His strategy helps optimize delay, stops, and deceleration in a 15-seconds period by considering no delay in transferring the data (vehicles data transfer immediately). The study showed that this methodology is suitable for saturated and over-saturated demands. He et al. [11] solve this lousy condition. He proposed platoon-based arterial traffic signal optimization. His study was based on headway recognition, and a mixed-integer linear program was applied. The VISSIM simulation results showed a significant reduction in delay in saturated and oversaturated traffic conditions.

Lee et al. [12] developed a cumulative travel time strategy calculated every 5 seconds. The results showed that total delay and speed improved, and the minimum penetration rate needed to get efficiency was 30%. In this regard, some researchers consider different penetration rates to be close to the actual world. One of the concerns in optimizing traffic signal time is counting the number of unequipped vehicles in low penetration rates. This issue happens at lower penetration rates. Kalman filtering algorithm is a practical algorithm that researchers used in lower penetration rates, but there were some errors. In this regard, some researchers presented new techniques to improve counting errors.

Aljamal, Abdelghaffar, and Rakha [13] proposed adaptive Kalman filtering for real-time probe vehicles data and compared it with traditional methods. The results showed 29% more accuracy. Also, they proposed a neural network adaptive Kalman filtering, which helps to have a more accurate count of vehicles, but they are very sensitive to initial conditions. Rakha, Abdelghaffar, and Aljamal [14] presented new Kalman filtering work, which helped decrease the erroneous and robust vehicle count estimation. They compared it with a fixed-time and an adaptive phase split optimizer. They showed that their model was more accurate for fixed-time plans for low traffic demand levels, and for high traffic demand, their model was more accurate for the adaptive traffic signals.

Rakha and Abdelghaffar [33] proposed a new, improved Kalman filtering technique with higher estimation precision. They evaluated it using empirical and simulated data and loop detectors, and the results showed they got an accurate count of vehicles. Decreasing fuel consumption and energy is also among the significant performance measures researchers evaluate. Zhao et al. [15] proposed a V2I optimization to optimize fuel usage and delay by considering fuel consumption characteristics for each vehicle. In their research algorithm, the trajectory of each vehicle was predicted in each second.

Subsection 2.1.2: Vehicle Speed advisory

Controlling vehicles is based on the SPaT and MAP, including vehicles' location, speed, acceleration, deceleration, and traffic light information. Some researchers worked on green light optimization speed advisory in controlling vehicle speed. This system was used almost first by Katsaros, Kernchen, Dianati, and Rieck [16] and then used by many researchers (Suzuki and Marumo [17], Li and Dridi [18], and Koukoumidis, Shiuan Peh, and Martonosi [19] who made SIGNALGURU software based on the Glosa system). Vahidi and Asadi [20] proposed a method to control the speed at which vehicles reach intersections at a green light with minimum braking. They considered a safe gap between vehicles and cruise close to the predefined speed. Some researchers like Barth and Boriboonsomsin [27] focused on optimizing fuel consumption based on optimized speed in traffic congestion. Yang and Jin [36] presented a control theory in which, at first, the advice speed was done independently, then a cooperative eco-driving strategy was done for connected vehicles. They considered various speed limits determined by feedback of control strategy.

Subsection 2.1.3: Vehicle velocity and Traffic signal optimization

To the best of our knowledge, a limited number of papers considered controlling the speed of vehicles and signal timing simultaneously. Li and Elefteriadou [21] are regarded as pioneers in joint traffic light optimization and vehicle speed advisory. They considered a simple intersection with one lane in each approach with no turn. They also considered simple vehicle kinematics with fixed acceleration and deceleration. Xu and Ban [32] proposed cooperation between vehicles and traffic lights to simultaneously optimize traffic signals and vehicle speed. They calculated engine power and brake force to optimize vehicles' fuel consumption and optimized traffic signal timing and vehicles' arrival times to minimize trip time. They considered fixed cycle length, did not consider any vehicle lane changing, and focused on individual-based. Mahler and Vahidi [34] developed a SPaT prediction and then optimized velocity based on the signal phasing and timing for vehicles for three fixed-time and actuated signals to reduce fuel consumption and idling time. They used generic scenarios, and Monte Carlo simulation and AUTONOMIE for fuel evaluation. Autonomie is a simulation environment developed by the Argonne National Laboratory. They considered three scenarios: vehicles are not aware of front traffic lights. Vehicles know real-time information. Vehicles have full and exact traffic-signal timings data. Results showed in the second scenario; they get a 16% reduction in fuel consumption in fixed-time signals and 6% in actuated signals.

Chunhui and Yiheng [35] proposed an integrated optimization model for traffic signals and vehicles' speed in an intersection. They considered a mixed-integer linear programming (MILP) model. They avoid vehicle lane changing. They focused on platoon-based moving and trajectory planning only considered for leading vehicles. The results showed that co2 emission and average delay decreased more at the higher demand level. Pourmehrab and Elefteriadou [22] proposed a methodology to adjust the green time to consider unserved conventional vehicles in one intersection. They did not consider any lane changing and pedestrians. Hajbabaie [23, 24] considered two different ways to count the vehicles, based on which they optimized the traffic light.

Section 2.2: Research gaps

Based on the literature review in section 2.2, this research focused on optimizing a traffic signal and vehicle velocity simultaneously to minimize total travel time and stop time behind the red light and minimizing braking force and engine power. This research proposes computationally efficient cooperation between vehicles and infrastructures to capture the demand fluctuations in their signal cycle. Few works have integrated the optimization of vehicles' velocity and traffic signals simultaneously in the transition period when different levels of connected vehicles exist. So, different penetration rates are studied.

Section 2.3: Existing data sources

The next step is looking for existing data sources that might be useful. Two open data sources were found in Tampa, Florida. However, the common disadvantage of these databases is that there were not enough connected vehicles in this area at the time of the studies to start optimizing traffic signals efficiently.

Subsection 2.3.1: USDOT CV PILOT Tampa, FL

This data is available in ITS Public Data Hub Data Sandbox, which uses Public Amazon Web Services S3 Bucket to have access. This data source includes online data from Tampa, FL, NYC, and Wyoming. They provided RSU coverage for 300ft. This research focused on one of the RSUs named thea2 (Tampa Hillsborough expressway authority) in the location of 27.950591, -82.448949 for one hour on 06.02.2020, 16:00-17:00. Figure 2 shows the location of thea2 on google map. Three thousand five hundred twenty-one waypoints and 22 total journey IDs were received. So, there was almost one connected vehicle every 3 minutes, and it was not helpful to optimize the traffic light. Waypoints of one vehicle are shown in Figure 3 on the QGIS map.

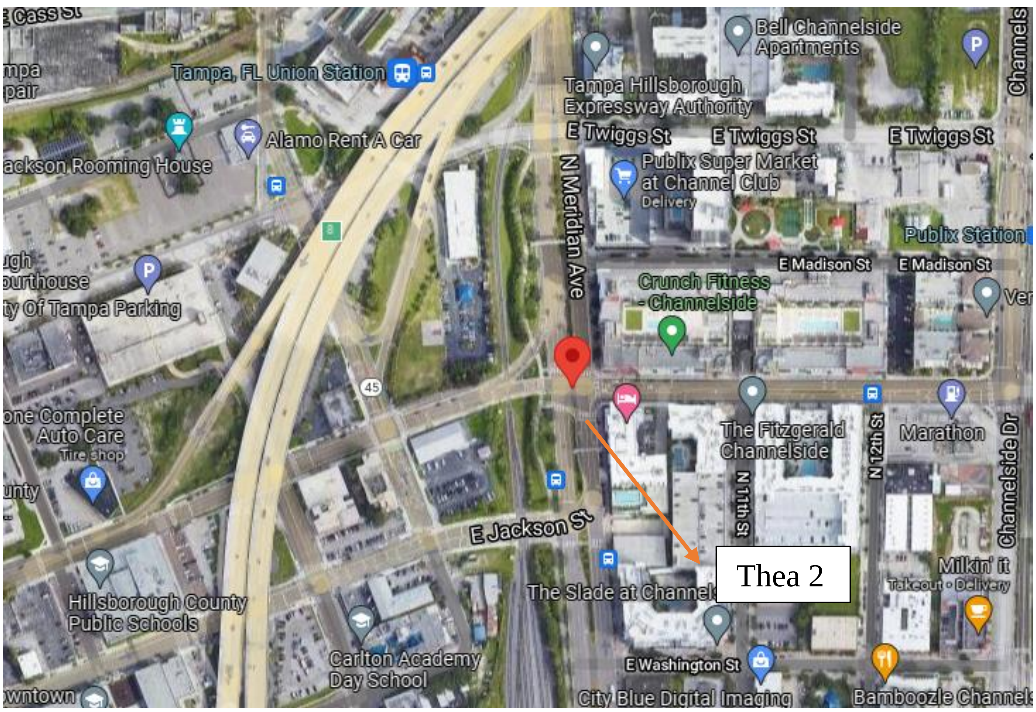


Figure 2: The locations of Thea two RSU on google map

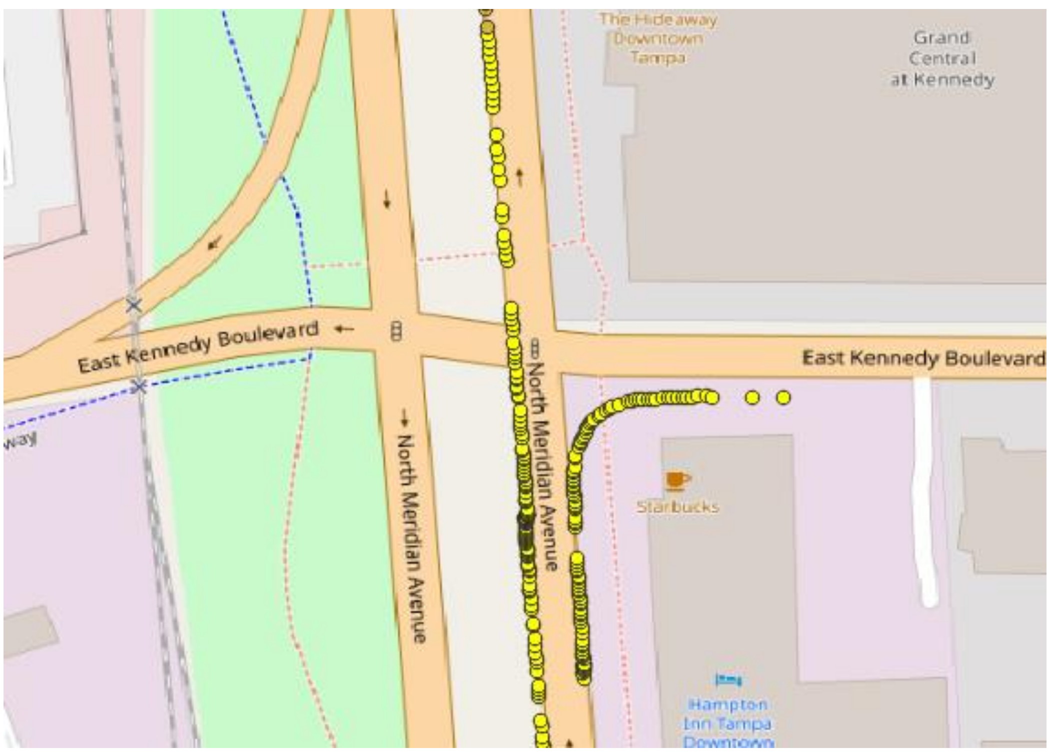


Figure 3: Waypoints of one vehicle in the CV pilot data

The New York City CV pilot data was also searched, but the location and time of the data are obfuscated because of privacy for the public and cannot be used at present.

Subsection 2.3.2: Wejo movement data Tampa, FL

This data source is from General Motors and consists of the trajectory data of Cadillac, Chevrolet, Buick, and GMC. They gathered these vehicles' trajectory data for the ones produced after 2015. Transmission of the information in these vehicles happens every 1-3 seconds, and one out of 28 vehicles in the US is considered in this database. During the time 06.02.2020, 16:00-17:00, there were 39346 waypoints and 416 journey IDs at the same location. The trajectory data of Wejo needed snapping. The waypoints of one vehicle are shown in Figure 4.

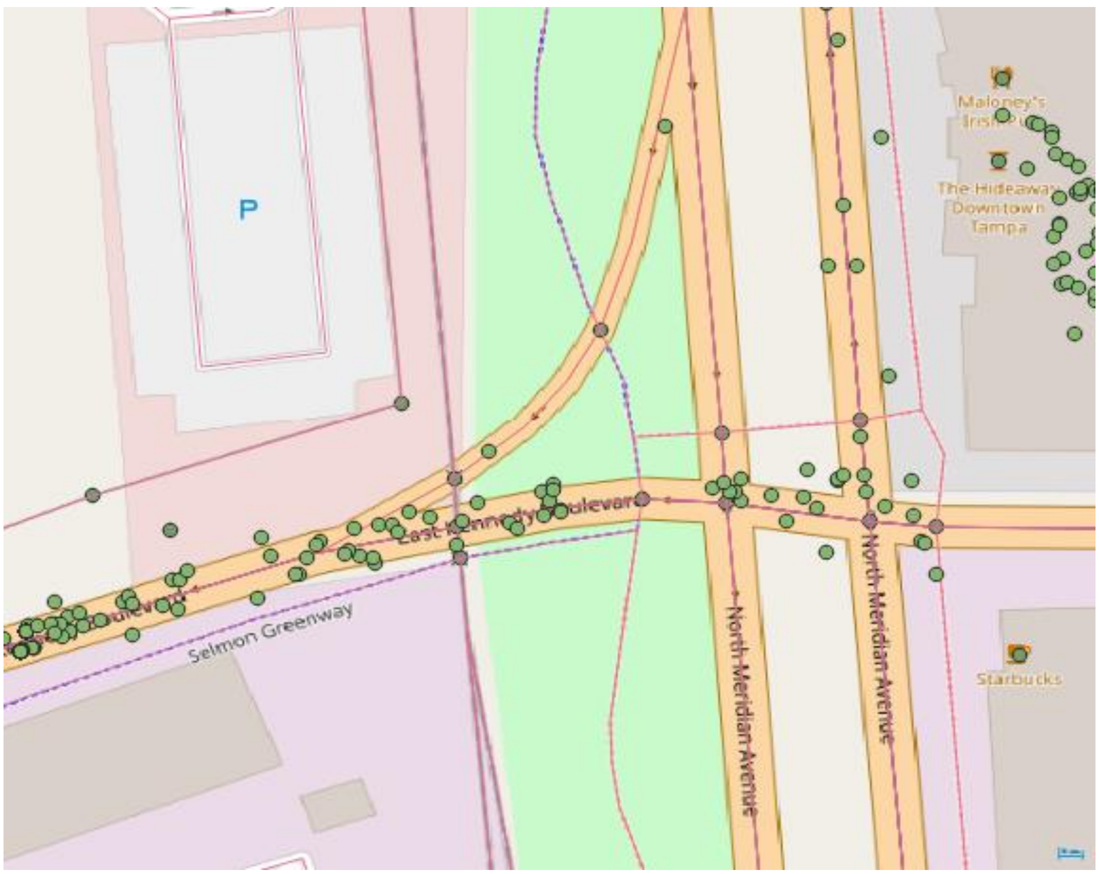


Figure 4: Waypoints of one vehicle in Wejo data

Open street map (OSM) and open source routing machine (OSRM) are used to route the waypoints. The first step is to find the latitude and longitude of these points. Then two end nodes covering each latitude and longitude need to be found. After that, the way-ID needs to be found. After cleaning and analyzing the data, the results showed that this data was not sufficient for this thesis.

Subsection 2.3.3: Simulated data

As seen in previous subsections, there was not enough data. So, an intersection is simulated, and a trajectory data set is generated for this research. In the next chapter, the details of the simulation and the results are discussed.

Chapter 3: Methodology framework

Since existing data was not enough for this research, new data was generated while maintaining the existing data features. An intersection in the simulation was implemented, and the available vehicles' trajectory data set features were used to optimize the traffic signal time and vehicles' speed. Aimsun simulation software academic license is used.

Section 3.1: Simulation

Subsection 3.1.1: Actuated traffic signal control

In the Aimsun simulator, an isolated four-legged intersection with three lanes was considered in each section (right lane, straight lane, and left lane}, with a length of 1000 meters for each leg. The designed intersection actuated controller can extend the green light based on the existence of vehicles. There are four detectors near the intersection on each leg. The length of each detector is 2 meters, and they are 20 meters far from the intersection and 978 meters far from the section's entrance. An overview of the intersection is shown in Figure 5. Blue lines in Figure 5 show the detectors. These detectors can count the number of vehicles, define the type of vehicles (equipped or unequipped) and request the extension of green time for the designated section and approach.

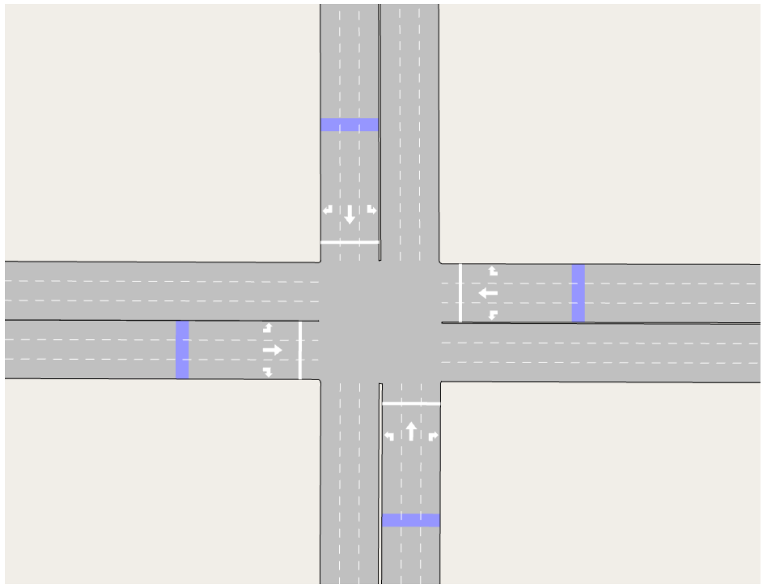


Figure 5: An overview of the studied intersection

First, a fixed time and an actuated traffic signal controller were assumed as base models to compare our results. The actuated traffic signal control is designed based on the dual ring scheme to avoid collisions. The dual ring design scheme method was shown previously in Figure 1.

There are some assumptions about the actuated traffic signals.

1. The actuated traffic signal always has a green light for right turns.
2. The actuated traffic signal has a fixed cycle length for each demand.
3. Only homogeneous vehicles are considered.
4. There are not any pedestrians or bicycles.

There are eight phases in which minimum green light and maximum green light are different based on the cycle length and demand. The green light can be extended by calling from detectors.

Three different demands (low-level, medium, and high-level) are considered. One type of vehicle with length and width of 4 and 2 meters respectively is considered. The maximum speed of vehicles on all streets is 60 km/hr. Maximum acceleration and deceleration are 3m/s2 and 6m/s2. The simulation is 1 hour, and the results for comparison are from an average of five replications for each demand level. Almost 60% of demand moves in east-west streets and 40% in the north-south streets. The cycle length was assumed to be fixed, and the Webster formula [26] was used to find the optimum cycle length.

The result of fixed time and actuated signal control are compared in this research.

Section 3.2: Traffic signal and vehicle cooperation

Subsection 3.2.1: Overview of the cooperation

The same four-legged and three lanes intersection was considered, but it needs to be mentioned that vehicles do lane changing before entering the study area. In other words, they drive to their desired destination from the entrance of the study area. However, they can have lane-changing after the intersection.

Eight movements are supposed because the right turn is always green, and as one lane for the right turn is considered, there is no conflict with other vehicles. Therefore, these eight movements include northbound left (NBL), northbound through (NBT), southbound left (SBL), southbound through (SBT), westbound left (WBL), westbound through (WBT), eastbound left (EBL), and eastbound through (EBT).

The same dual ring control method with fixed cycle length and clearance time is used for the traffic signal. In addition, each phase has an effective green interval. The vehicles can pass the stop line at the end of the effective green time. The phase sequence is the same as actuated. The first ring includes WBL, NBL, SBT, and EBT, and the second ring includes SBL, NBT, EBL, and WBT. In Figure 1, the effective green light for each approach is shown in green color, and the red one shows the clearance time. Clearance time includes yellow and all-red times. Then, $t_{NBL}, t_{SBT}, t_{WBL}, t_{EBT}, t_{SBL}, t_{NBT}, t_{EBL}\ and\ t_{WBT}$ show the passing time or phase time of vehicles on the NBL, SBT, WBL, EBT, SBL, NBT, EBL, and WBT, respectively. CL is the cycle length and $t_{NS}\ and\ t_{EW}$ show the phase time of the north-south and east-west.

Infrastructures can communicate with connected vehicles in the communication range area, gather the vehicles' information, calculate the optimum signal timing, and implement it. The communication between infrastructure and vehicles is considered V2I communication. Several communication platforms can support the transferred messages like dedicated short-range communication (DSRC), Bluetooth, 4G/5G, etc. As the latency result of 4G/LTE and DSRC (26) shows, DSRC has less delay in data transmission. In this study, the proposed algorithm is based on DSRC technology.

As shown in Figure 6, in cooperation between the traffic signal and approaching vehicle, the infrastructure acquires the connected vehicles' speed and the location at the end of each cycle. The controller optimizes traffic signal time and designs vehicles' arriving time by considering traffic signal lights and safety constraints. Then, the optimized arriving time is sent to the vehicles. The vehicles' on-board units receive the optimal arriving time based on optimal traffic signal timing and adjust the speed to optimize brake force and engine power to minimize fuel usage.

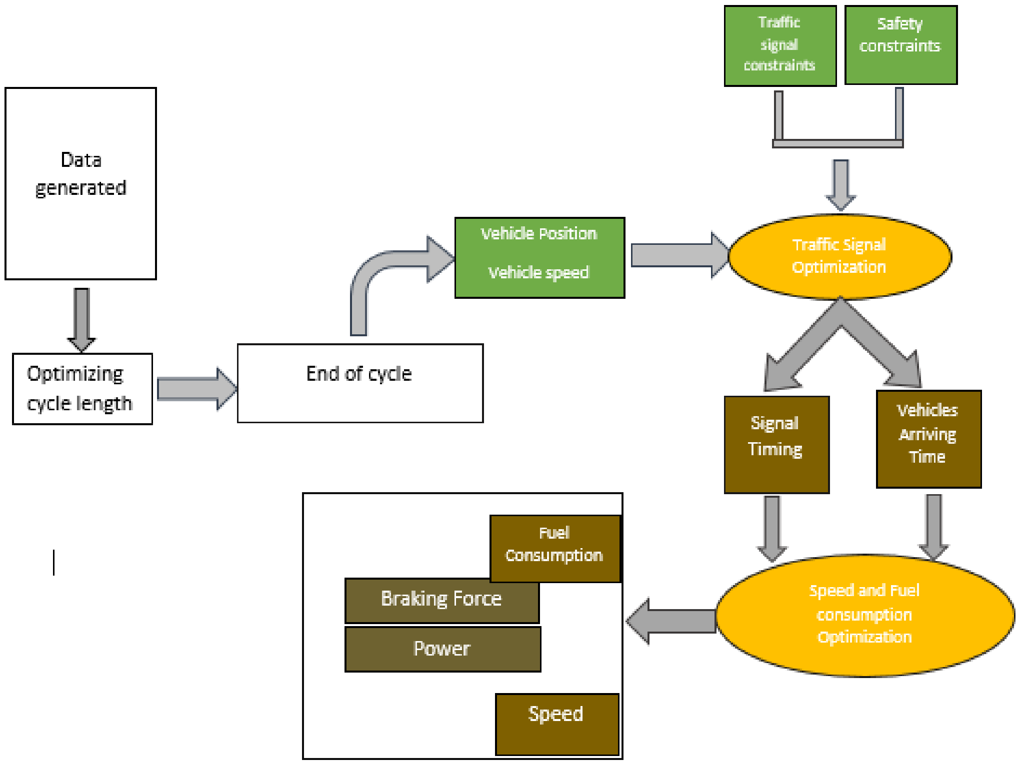


Figure 6: An overview of the methodology framework

Subsection 3.2.2: Traffic signal optimization

Each vehicle in the study belongs to one movement. So if L is considered as the movement of vehicles, L belongs to NBL, SBT, WBL, EBT, SBL, NBT, EBL, and WBT, and vehicles are from 1~N_L based on their distances to stop lines. N_L shows the total number of vehicles in movement L. Therefore, each vehicle is indicated as (L, i), which i shows the vehicle's number and $i \leq N_L$. There are some assumptions:

1. The degree of automation is considered above level 4.
2. The vehicles' arrival time at the stop bar is assumed to be in the green time interval.
3. There is a safety headway between vehicles.

Therefore, by considering t_L^i as the arrival time of vehicle i in movement L and g the green time interval; the arrival time of the vehicle in the green interval can be:

$$t_L^i \in g_L \quad (1)$$

Each vehicle's destination is the intersection's stop line in the vehicle's approach. The effective green interval of each approach can be written as:

$$g_{NBL} = K * CL \sim K * CL + t_{NBL} - R \quad (2)$$

$$g_{SBT} = K * CL + t_{NBL} \sim K * CL + t_{SBT} + t_{NBL} - R \quad (3)$$

$$g_{WBL} = K * CL + t_{SBT} + t_{NBL} \sim K * CL + t_{WBL} + t_{SBT} + t_{NBL} - R \quad (4)$$

$$g_{EBT} = K * CL + t_{WBL} + t_{SBT} + t_{NBL} \sim K * CL + t_{EBT} + t_{WBL} + t_{SBT} + t_{NBL} - R \quad (5)$$

$$g_{SBL} = K * CL \sim K * CL + t_{SBL} - R \quad (6)$$

$$g_{NBT} = K * CL + t_{SBL} \sim K * CL + t_{NBT} + t_{SBL} - R \quad (7)$$

$$g_{EBL} = K * CL + t_{SBL} + t_{NBT} \sim K * CL + t_{SBL} + t_{NBT} + t_{EBL} - R \quad (8)$$

$$g_{WBT} = K * CL + t_{SBL} + t_{NBT} + t_{EBL} \sim K * CL + t_{SBL} + t_{NBT} + t_{EBL} + t_{WBT} - R \quad (9)$$

R represents the clearance time, K is the cycle number, and CL is the cycle duration. The cycle duration is fixed and determined based on the demand. The cycle length can be calculated by the Webster formula [26].

Phase time constraints based on the dual ring method can be considered as:

$$t_{SBT} + t_{NBL} - t_{NBT} - t_{SBL} = t_{NS} \quad (10)$$

$$t_{EBT} + t_{WBL} - t_{WBT} - t_{EBL} = t_{EW} \quad (11)$$

$$t_{NS} + t_{EW} = CL \quad (12)$$

The effective green time interval should be between minimum green time and maximum green time for each phase. Minimum and maximum green times are assumed to be the same as the base actuated traffic signal.

$$g_{min} \leq \ t_{NBL}, t_{SBT}, t_{WBL}, t_{EBT}, t_{SBL}, t_{NBT}, t_{EBL}, t_{WBT} \ \leq g_{max} \tag{13}$$

To avoid collisions, safety constraints are considered. The following vehicle needs to have a safe time headway with the preceding vehicle. In this thesis, 2 seconds of safety time headway is considered.

$$t_L^i - t_L^{i-1} \geq \min time\ headway, \forall 2 \leq i \leq N_L \tag{14}$$

Some complex nonlinear models generally represent the vehicle's engine and transmission.

Simple kinematic models are used. Vehicles accelerate or decelerate to the desired speed and then continue with a uniform speed. The simple kinematic models are listed as follows.

$$d^{\cdot} = -v \tag{15}$$

$$v^{\cdot} = a \tag{16}$$

$$a = \begin{cases} a(t), if\ v \neq v_{target} \\ 0, if\ v = v_{target} \end{cases} \tag{17}$$

$$v \leq v_{max} \tag{18}$$

$$a \leq a_{max} \tag{19}$$

d shows the vehicle's distance to the intersection, v is the vehicle's speed at each time, and a represents the acceleration. If the vehicle's speed does not match the desired speed, the speed accelerates to reach the target speed. The maximum speed is the same as the simulation, 60 km/hour, and the maximum acceleration is 4 m/s. When a vehicle is far from the preceding vehicle and far from the intersection, it can move at the maximum speed limit. The minimum arriving time can be calculated as follows.

$$t_{L\,min}^{i} = \frac{2a_{max}d_L^i + \left(v_{max} - v_L^i\right)^2}{2a_{max}v_{max}}, if\ d_L^i \geq v_{max}^2 - {v_L^i}^2 \tag{20}$$

If the vehicle is not far from the preceding vehicle or intersection, the minimum arrival time can be calculated as follows.

$$t_{L\,min}^{i} = \frac{-v_L^i + \sqrt{{v_L^i}^2 + a_{max}d_L^i}}{2a_{max}v_{max}}, if\ d_L^i \leq \frac{v_{max}^2 - {v_L^i}^2}{2a_{max}} \tag{21}$$

Obviously, the arrival time should be greater than the minimum arriving time.

$$t_L^i \geq t_{L\,min}^i, \forall i \leq N_L \tag{22}$$

In optimizing the traffic signal, the aim is to optimize the phase time and the arrival time of vehicles.

$$Minimize \sum_{i=1}^{N_L} t_L^i \tag{23}$$

Subject to:

$Constraints$: (1)~(23) [32]

Fmincon optimization function in Matlab software for this optimization is used. The result of this optimization will cover the optimum arrival time of vehicles, effective green time, and phase time.

Subsection 3.2.3: Vehicle optimization

After optimizing at the end of each cycle for upcoming vehicles, each vehicle’s speed will be optimized to minimize the engine power and brake force. Therefore, the longitudinal dynamic model for the vehicle model is assumed [25].

$$s^{\cdot} = -v \tag{24}$$

$$v^{\cdot} = \frac{1}{m}[\frac{p}{v} - F_b - 0.5C_D A\rho_a v^2 - mgf cos\alpha - mg sin\alpha] \tag{25}$$

Where P is engine power, m is vehicle mass, v is speed, $F_b$is braking force, C_D means the drag coefficient, A is the vehicle frontal area, $\rho_a$is the air density, f is the rolling resistance coefficient for tires, g is the gravitational acceleration, α is the road slope, v is the vehicle speed, and s in formula 24 is the vehicle displacement. Virginia Tech's comprehensive power-based fuel consumption model [28] is used to adjust the vehicles' speed to optimize engine power and brake force.

$$F_c = \begin{Bmatrix} \alpha_0 + \alpha_1 P + \alpha_2 P^2, if\ P > 0 \\ \alpha_0, if\ P \leq 0 \end{Bmatrix} \tag{26}$$

In formula (26), $F_c$is fuel consumption rate for vehicles and $\alpha_0, \alpha_1\ and\ \alpha_2$ are coefficients.

α_0=0.59,

α_1=0.057,

α_2=0.00014.

To have operations, when two vehicles follow each other, if the following vehicle is equipped, a basic safe distance formula between them is needed. In contrast, a car-following model needs to be implemented if the following vehicle is unequipped. Formula (27) shows the safe distance between two equipped vehicles, and formula (28) defines the car-following model when the following vehicle is not equipped.

$$L(t) - L(t)_p \geq d_0 \tag{27}$$

Formula (27) shows the safe distance between two vehicles. L is the location of the vehicle and L_p is the location of the preceding vehicle at each time.

Car-following model needs to have a safe distance between a preceding equipped and an unequipped vehicle. Gipps [29] car-following model is implemented in simulation and Matlab. This model includes two components, acceleration, and deceleration. V_a Represents the speed that a vehicle desires to achieve and V_b shows the vehicle's speed, which is influenced by the preceding vehicle's speed.

$$v_a(n, t+T) = v(n,t) + 2.5a(n)T\left(1 - \frac{v(n,t)}{v^*(n)}\right)\sqrt{0.025 + \frac{v(n,t)}{v^*(n)}} \quad (28)$$

Gipps car following model shows the maximum speed of vehicle n in time period t+T. n is the number of vehicles, and t represents time. So, v(n,t) shows the speed of vehicle n in time t. a is the acceleration and v^* is the desired speed. A free acceleration rate less than a maximum pre-defined number is used. T is the reaction time.

At the same time, the maximum speed that a vehicle can reach considering the preceding vehicle's speed can be calculated as follows.

$$v_b(n, t+T) = d(n)T + \sqrt{d(n)^2T^2 - d(n)\big(2(x(n-1),t) - s(n-1) - x(n,t)\big) - v(n,t)T - \frac{V(n-1,t)^2}{d^{\cdot}(n-1)}}) \quad (29)$$

Where d (n) is the deceleration of vehicle n and less than 0. x(n,t) is the position of vehicle n in time t. x(n-1,t) is the position of vehicle n-1 in time t. s(n-1) is the effective length of vehicle n-1, and $d^{\cdot}(n-1)$ is the estimation of deceleration for vehicle n-1. Also, a free deceleration rate of more than the minimum is assumed.

Therefore, the speed for vehicle n can be determined by the minimum ofv_a and v_b.

$$v(n, t+T) = min\{v_a(n, t+T), v_b(n, t+T)\} \tag{30}$$

The initial position and speed of vehicle n are considered 0 andv_0.

$$s(0) = 0 \tag{31}$$

$$v(0) = v_0 \tag{32}$$

The distance the vehicle passes during the optimization time defined in traffic signal optimization should be the same as the distance between the vehicle's initial position and the intersection's stop line.

$$s(t_f) = d \tag{33}$$

$$t_f = t_L^i \tag{34}$$

Finally, the optimization can be done on brake force and engine power.

$$Minimize\ k_1 \int_0^{t_f} F_c(t)dt - k_2 v(t_f)^2 \tag{35}$$

$constraints$ (24)~(35) [32]

The results of this optimization are the optimum engine power and brake force. $k_1\ and\ k_2$ are the weight coefficients of fuel usage and vehicle kinetic energy. In the base model (actuated traffic signal), fuel consumption is calculated by equation (26), and engine power at each time can be calculated by equation (36) [30]. R(t) is the resistance force which will be expressed later. m is the vehicle's mass, and a(t) and v(t) show the acceleration and speed at each time. η_d is the driveline efficiency, which is between 85% and 95%, and 90% is presumed in this thesis [31].

$$P(t) = \left(\frac{R(t) + 1.04ma(t)}{3600\eta_d}\right) v(t) \tag{36}$$

Resistance force at each time can be gained by equation (37). C_h is the correction factor for altitude and will be calculated by equation (38), in which H shows the altitude in kilometer base. $C_r, c_1 \ and \ c_2$ are rolling resistance parameters considered 1.75, 0.0328, and 4.575, respectively [31]. G(t) is the gradient of the road at each time.

$$R(t) = \frac{\rho_a}{25.92} C_D C_h A v(t)^2 + 9.8066m \frac{C_r}{1000}(c_1 v(t) + c_2) + 9.8066m * sinG(t) \quad (37)$$

$$C_h = 1 - 0.085H \quad (38)$$

Chapter 4: Result

Three different demand levels (low, moderate, and high) in traffic simulator Aimsun and Matlab for a fixed time and actuated traffic signal are regarded. Table 2 shows the demand levels.

Table 2: Demand levels

Low	Moderate	High
1400	**2000**	**2800**

Figure 7 shows the demand division.

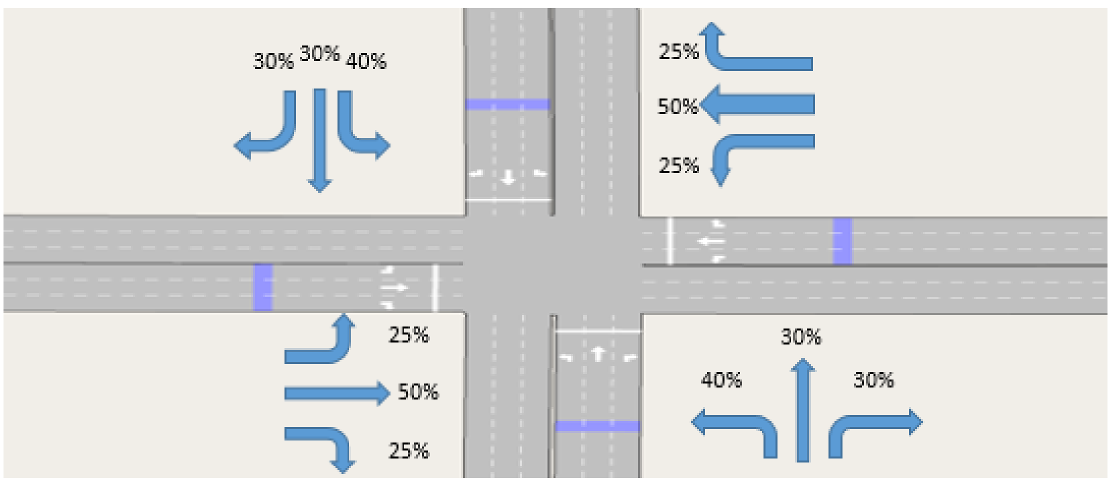


Figure 7: the percentage of demand for each movement in all approaches

The intersection has 1000 meters in length in each section and a 1000-meter communication range. The fixed time and actuated traffic signal control (ASC) in the simulation are performed as base models to verify the signalizing method (CTV) cooperation between a traffic signal and vehicle speed. Vehicles and traffic signal parameters and assumptions are listed below.

Vehicle's mass=3300 lbs,

Drag coefficient= 0.4,

Vehicle frontal area= 1.5m^2,

Air density= 0.0749 lb/ft^3,

Rolling Resistance coefficient= 0.015,

Maximum power = 130kw,

Three different demand levels are considered 1400, 2000, and 2800 vehicles per hour for the entire intersection. All demands are divided based on Figure 7. The cycle length, minimum, and maximum green time will change based on the demand levels.

Section 4.1: Comparison between actuated traffic signal control and traffic signal and vehicle cooperation

The speed profiles, acceleration/ deceleration, braking force, and engine power after the optimization time (end of the cycle) and before the intersection of the same vehicle in actuated traffic signal control and traffic signal with vehicle cooperation are compared. Figure 8 shows that the vehicle in traffic signal and vehicle cooperation method does not stay behind the red line in the intersection.

Figure 9 illustrates the acceleration/ deceleration of the vehicle in the first cycle. As seen, the vehicle's speed in the traffic signal and vehicle cooperation control method has decreased in the 80th second, and finally, in the 85th second, it reached 7m/s. In contrast, the vehicle brakes around the 93rd second and reaches 0 before the 100th second in actuated signal control. This sudden decline in the velocity results in a higher brake force. Before the 80th second, both methods had the same speed, which is not shown in the figure.

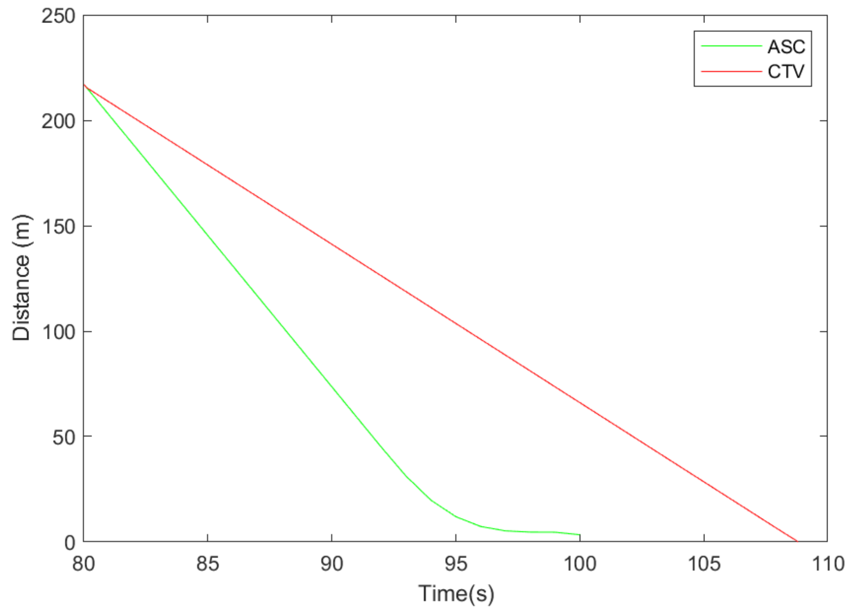


Figure 8: Comparison of the trajectory of one vehicle in the ASC and the traffic signal and vehicle cooperation control methods

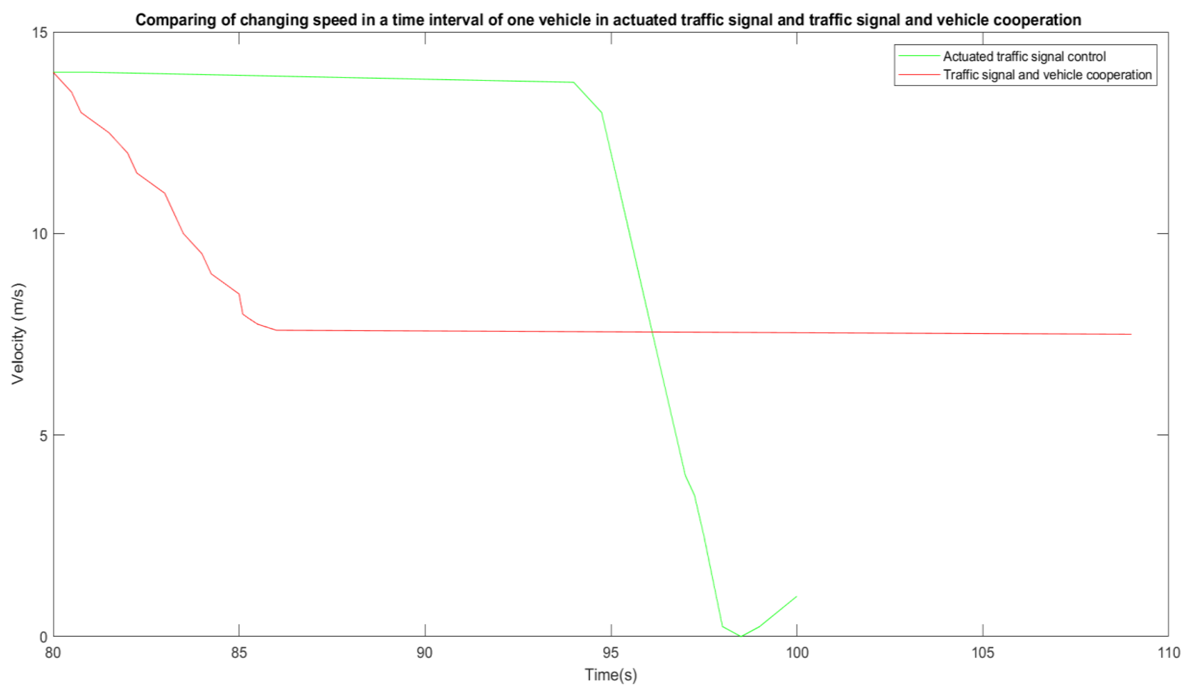
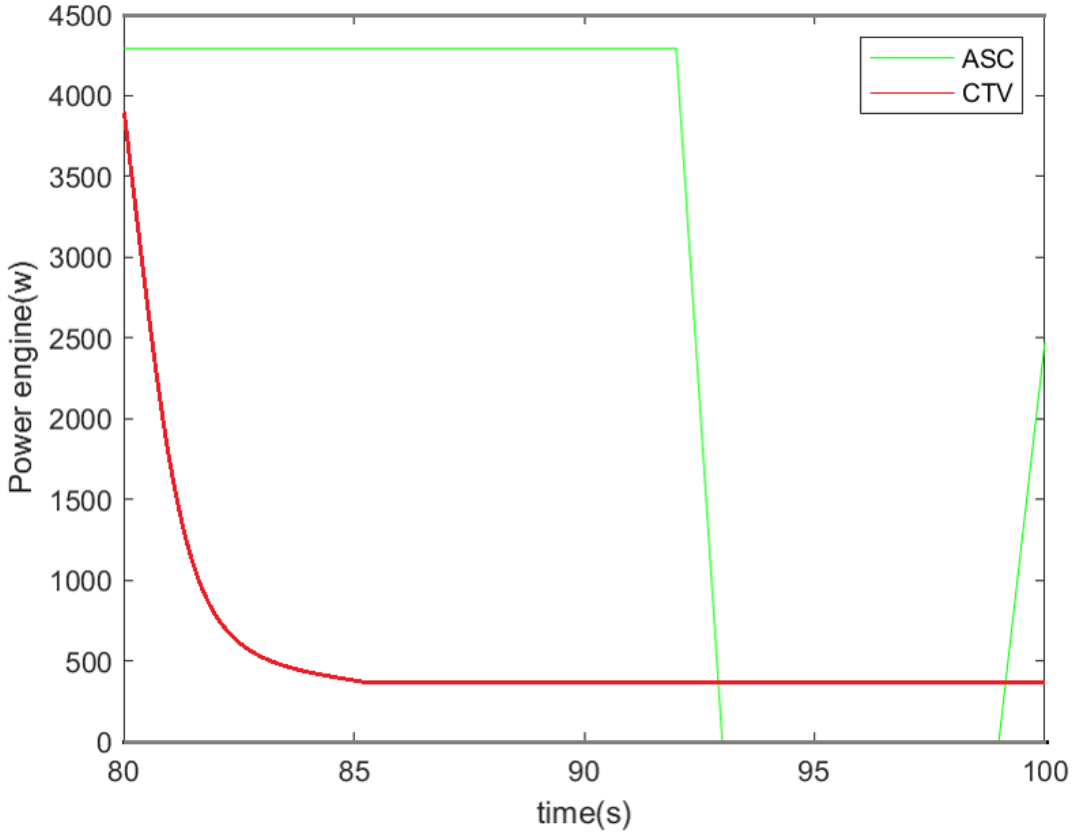


Figure 9: Comparison of changing speed in a time interval of one vehicle in the ASC and the traffic signal and vehicle cooperation control methods

Figure 10 compares this vehicle's engine power and brake force. Engine power in actuated traffic signal method decreased sharply around time 94 seconds from more than 4KW to 0W. However, in the traffic signal and vehicle cooperation control method, it never reached 0W. The engine power decreased smoothly to around 500W. On the second graph that shows brake force, the brake force in actuated traffic signal method increased to 5000 N, while the braking force between time around 85 and 100 seconds is less than 0N, and before that, there is an increase of less than 1000N.



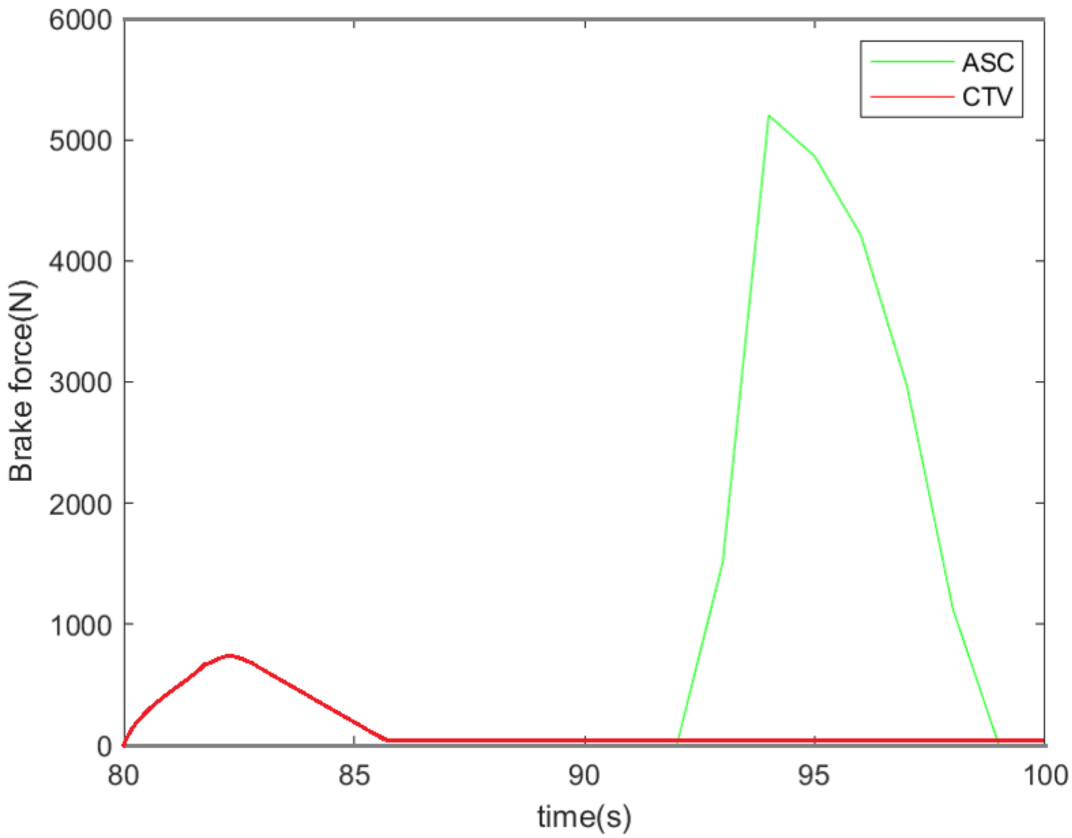


Figure 10: Comparison of changing brake force in a time interval of one vehicle in the ASC and the traffic signal and vehicle cooperation control methods

There are three vehicles in one approach (NBT) in the first cycle, and their trajectories are considered. Figure 11 illustrates these three vehicles' trajectories on one graph. As can be seen, all three vehicles have stopped behind the traffic light in the actuated traffic signal control method. In contrast, they did not have any stop behind the red light in the traffic signal and vehicle cooperation method.

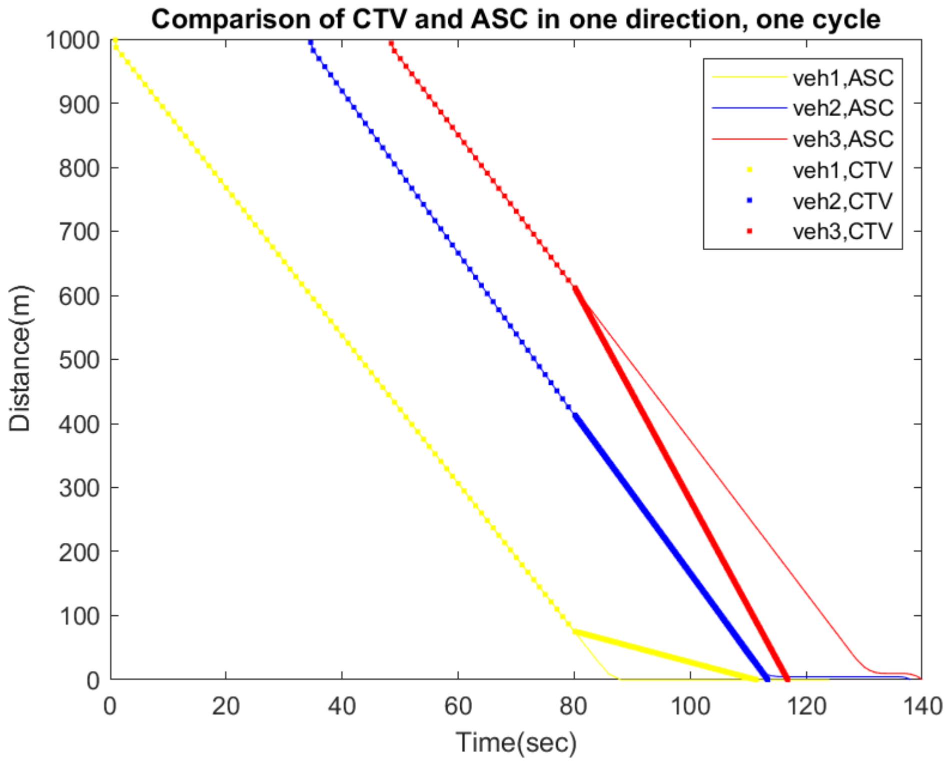


Figure 11: Comparison of the traffic signal and vehicle cooperation and the ASC methods in the northbound left approach in one cycle

To look more widely, one cycle in Figure 12 is shown. The first cycle is chosen to compare the difference between vehicles' trajectories on a graph. In this cycle, vehicles are moving in the EBT, SBL, NBT, and EBL approaches and are shown by blue, green, yellow, and cyan colors, respectively. As can be seen in the following graphs, none of the vehicles is standing behind the red light in the traffic signal and vehicle cooperation method. The traffic signal is optimized at the 80seconds, which is the end of the cycle, and the arrival time is defined for each vehicle to avoid the stopping time behind the stop line. While, in the actuated traffic signal control method, most of the vehicles are stopping behind the stop line.

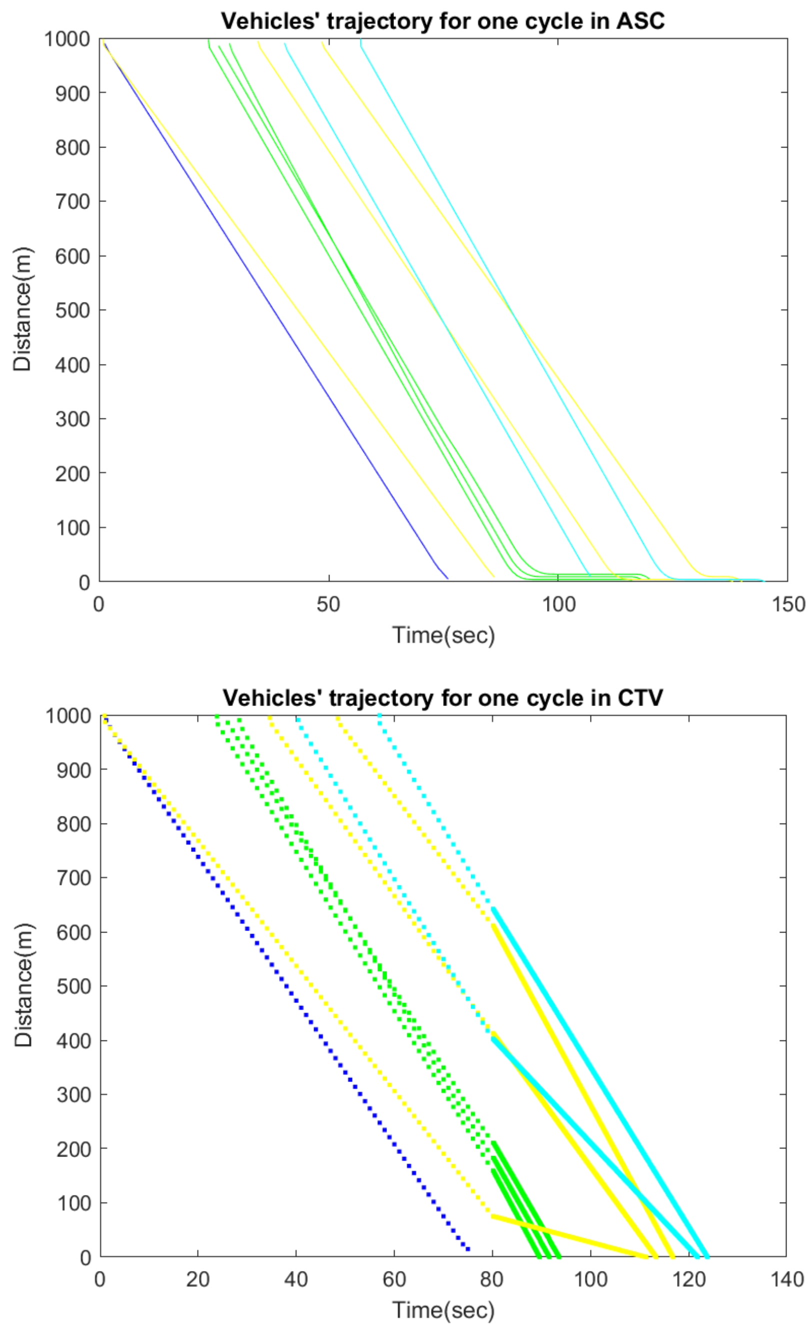


Figure 12: Trajectory of a cycle for the ASC and the traffic signal and vehicle cooperation control methods

The trajectory for all vehicles for lower demand levels is illustrated in the next step. In the lower demand level, 400 veh/hr in the east approach, 400 veh/hr in the west approach, 300 veh/hr in the north, and 300 veh/hr in the south approach are presumed.

The cycle length is 80 seconds. The minimum green time is 7 seconds, and the maximum is 50 seconds.

Figures 13, 14, 15, and 16 show the trajectories for all vehicles when all are considered connected (traffic signal and vehicle cooperation) and when all are not connected (actuated traffic signal control) for the first ring and second ring separately. Vehicle trajectories in traffic signal and vehicle cooperation methods are shown by solid lanes and in actuated traffic signal control by dotted lines. As seen in Figures 14 and 16, there are some irregular mixed colors in less than 100 meters in actuated traffic signal control in both rings, which means more vehicles stop behind the stop line in the actuated traffic signal control method.

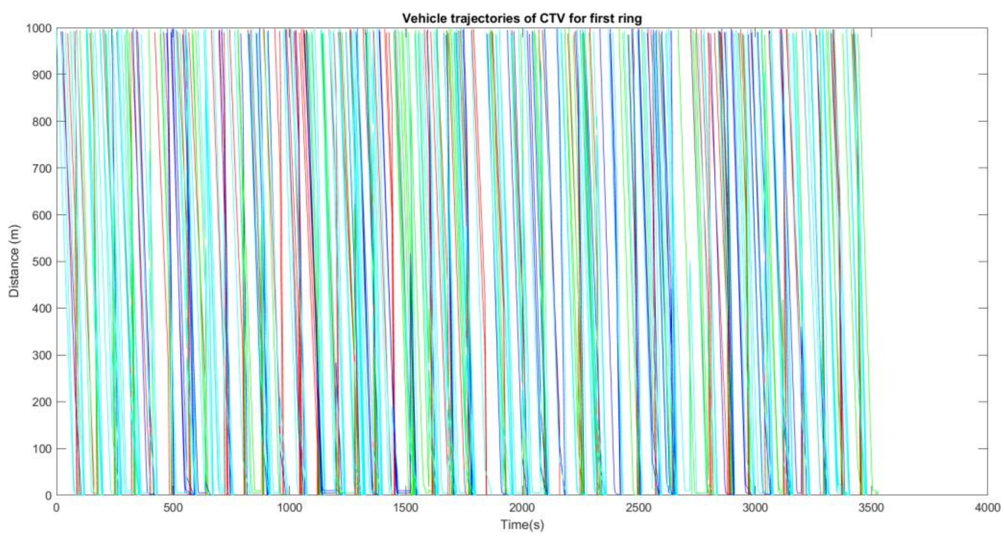


Figure 13: Vehicles trajectories of the traffic signal and vehicle cooperation control method for the first ring

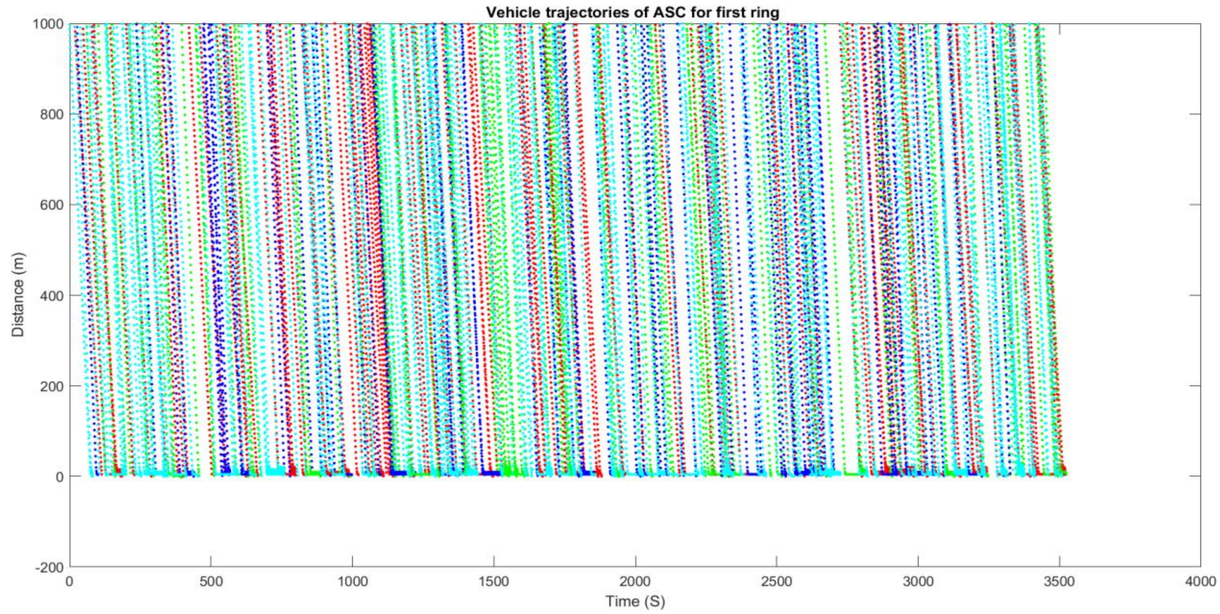


Figure 14: Vehicles trajectories of the ASC method for the first ring

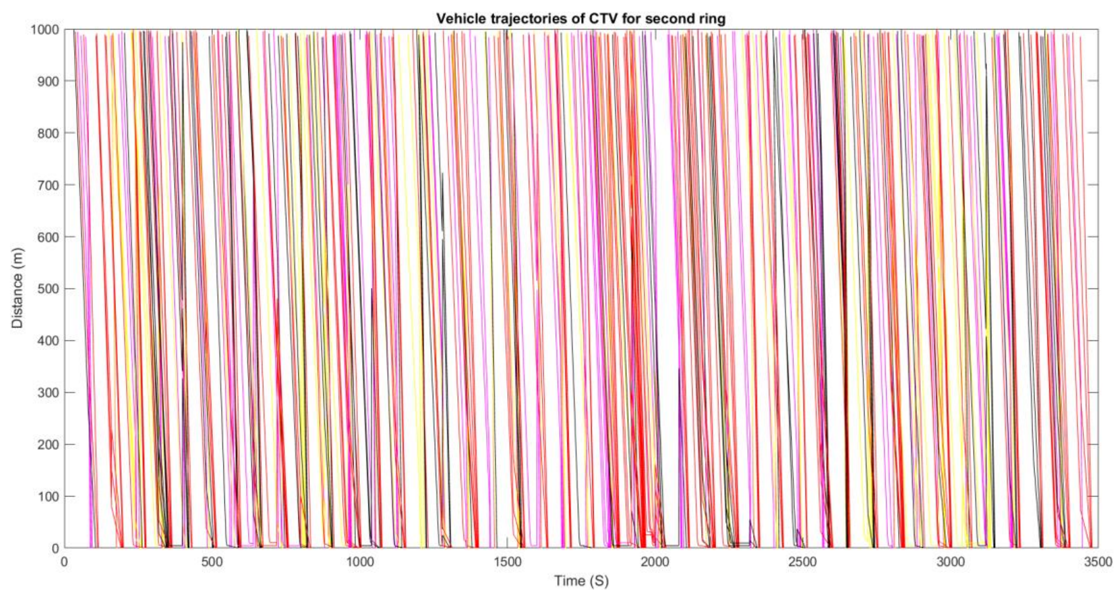


Figure 15: Vehicles trajectories of the traffic signal and vehicle cooperation control method for the second ring

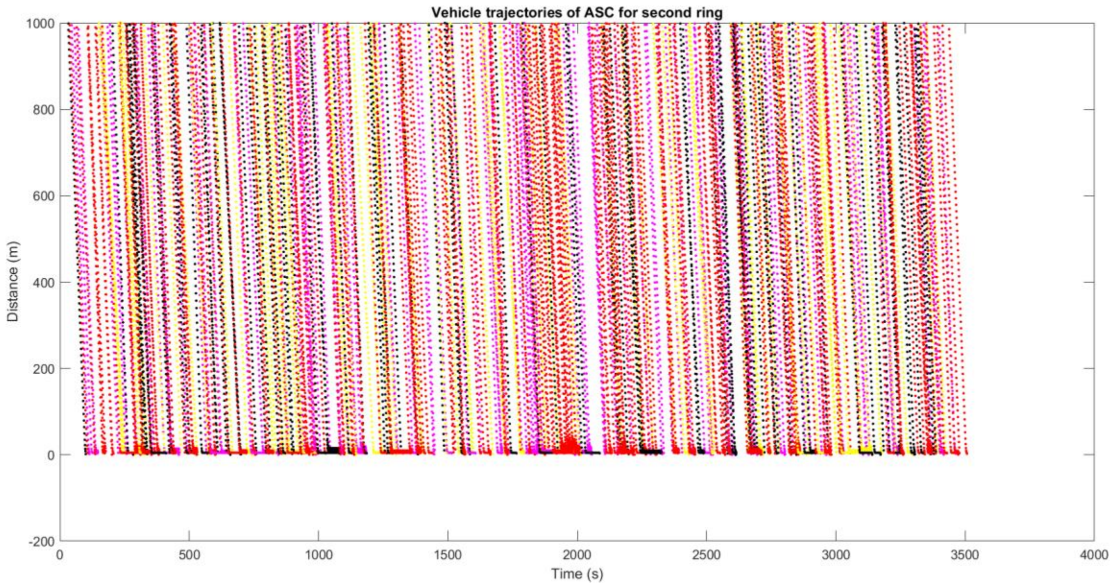


Figure 16: Vehicles trajectories of the ASC method for the second ring

<u>*Section 4.2: Total Travel Time Comparison*</u>

The total travel time comparison for the traffic signal and vehicle cooperation, fixed time, and actuated traffic signal control for the three demand levels is illustrated in Figure 17. The result for each demand level is the average of five replications. The bar charts show that an increase in the demand level results in an increase in the total travel time in all three scenarios. Overall, the traffic signal and vehicle cooperation method performs better in all scenarios. More precisely, the traffic signal and vehicle cooperation method performs better than the actuated traffic signal method in higher demand levels with a 25.9% more decrease in total travel time. The performance rate superiority compared to the actuated traffic signal control decreases to 22.9% and 17.4% in moderate and lower demand levels. The comparison between the fixed time and traffic signal and vehicle cooperation methods shows better performance in higher (29.8%), lower (28.7%), and moderate (25.7%) demand levels, respectively. It is noticed that in comparison between total travel time of actuated traffic signal control, traffic signal and vehicle cooperation, and fixed time methods, the fixed time method shows better results in the moderate demand level, and the actuated traffic signal control method shows better result in lower demand level.

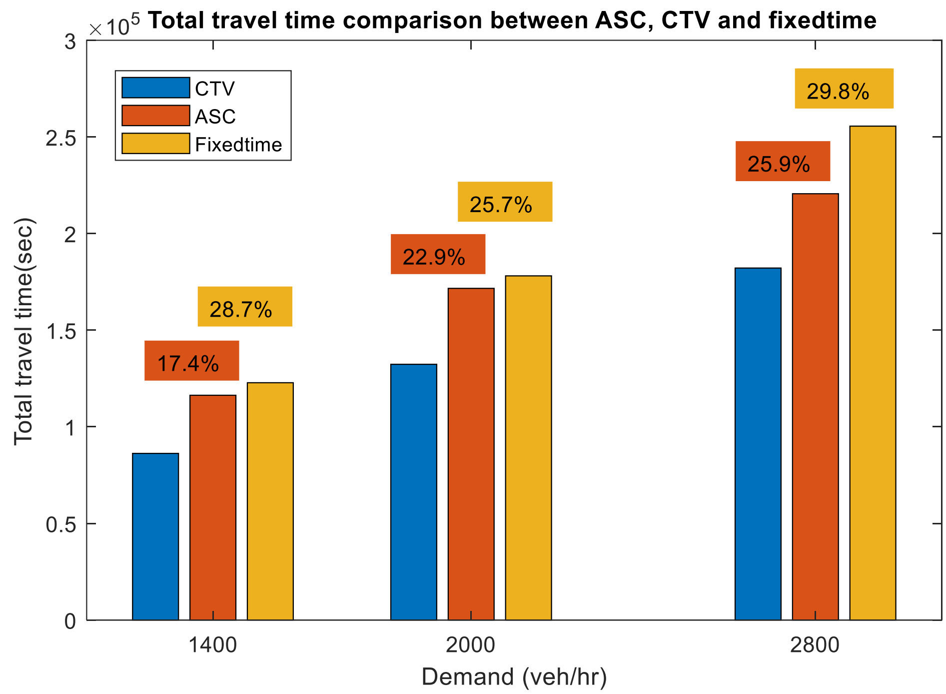


Figure 17: Comparison of the total travel time between the ASC, the traffic signal and vehicle cooperation, and the fixed time control methods at different demand levels

The result of the comparison of the total travel times in different penetration rates for all three-demand levels is shown in Figure 18. The result shows the efficiency of the traffic signal and vehicle cooperation method compared with the actuated traffic signal control method. 100% means all vehicles are connected, and 0% means there is no connected vehicle. 0% is considered the actuated traffic signal control, which is only based on detectors and does not rely on connected vehicles. The scatter plot illustrates the result of each replication of each demand level, and the line graph shows the average of the total travel time of each penetration rate in the demand levels. Each penetration rate is replicated five times at each demand level. As the penetration rate increases, there is a downward pattern in total travel time.

Interestingly, the total travel time slope in higher demand levels is less than those in moderate and lower demand levels. This means the performance of connected vehicles is much better in lower demand levels than in higher demand levels. However, this trend is different when there is an 80% penetration rate and a 100% penetration rate. The difference between the total travel time between 80% and 100% penetration rate increases as the demand level decreases.

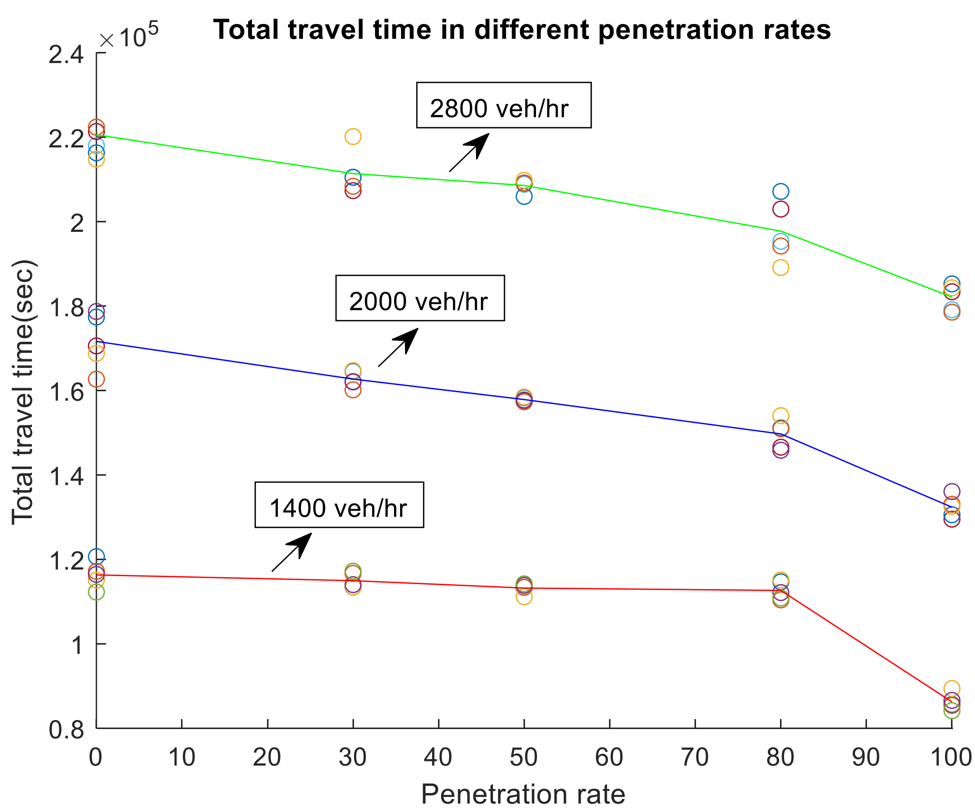


Figure 18: Comparison of the ASC and the traffic signal and vehicle cooperation control methods' total travel time for different penetration rates at different demand levels

Section 4.3: Total Stop Time Comparison

Total stop time is compared between the actuated traffic signal control, fixed time, and the traffic signal and vehicle cooperation methods in Figure 19. The comparison shows significant differences between the traffic signal and vehicle cooperation and the other two methods, and the amount of difference increases as the demand increases. Overall, the traffic signal and vehicle cooperation method shows the total stop time in three demand levels less than 10000 seconds, much lower than the actuated traffic signal control and fixed time methods' stop times. The fixed time traffic signal and actuated traffic signal control methods have almost the same stop time in moderate and higher demand levels. However, the actuated traffic signal method shows a better result in the lower demand level.

Figure 20 illustrates the total stop times in various demand levels at different penetration rates. The scatter points show the total stop time in each replication. Each demand level has been replicated five times in each penetration rate. The lines show the average total stop time pattern in all demands. The total stop time pattern is shown by green, blue, and red colors in high, medium, and low demand levels, respectively. The result shows there is a downward pattern in the total stop time. As the penetration rate increases, the total stop time decreases. This pattern can be seen in all demand levels. When all vehicles are connected, the total stop time decreases significantly. All demand levels in all connected vehicles have less than 10000 seconds of total stop time. It is noted that total stop time when all vehicles are not connected in higher demand levels is almost two times more than the lower demand level.

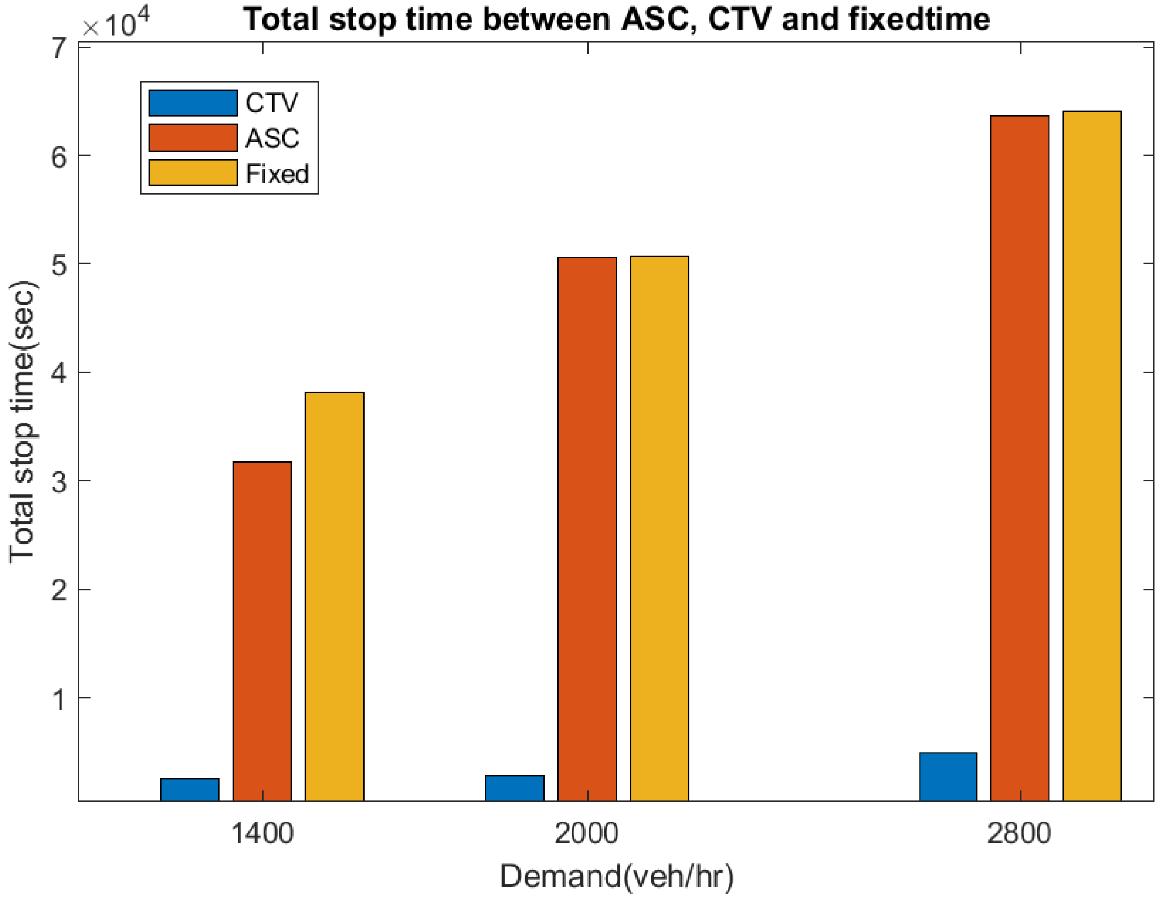


Figure 19: Comparison of the total stop time between the ASC, the traffic signal and vehicle cooperation, and fixed time methods at different demand levels

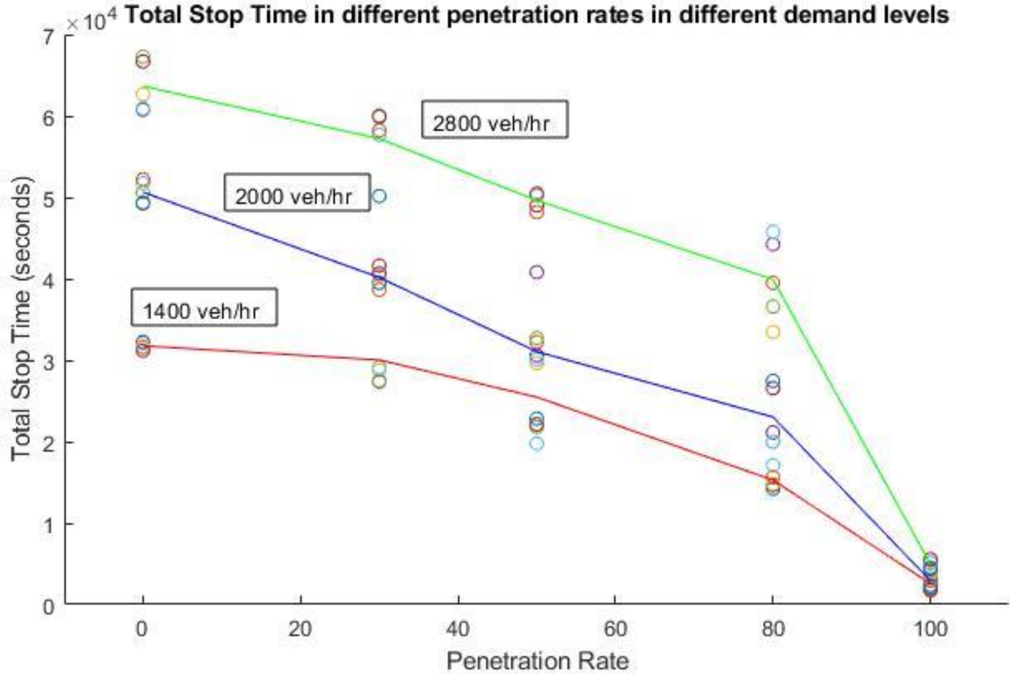


Figure 20: Comparison of the ASC and the traffic signal and vehicle cooperation methods' total stop time for different penetration rates at different demand levels

<u>*Section 4.4: Total Fuel Consumption Comparison*</u>

Fuel usage is compared between the actuated traffic signal control, fixed time, and traffic signal and vehicle cooperation methods, and the results are shown in Figure 21. At all demand levels, the traffic signal and vehicle cooperation method shows better performance in comparison to the other two methods.

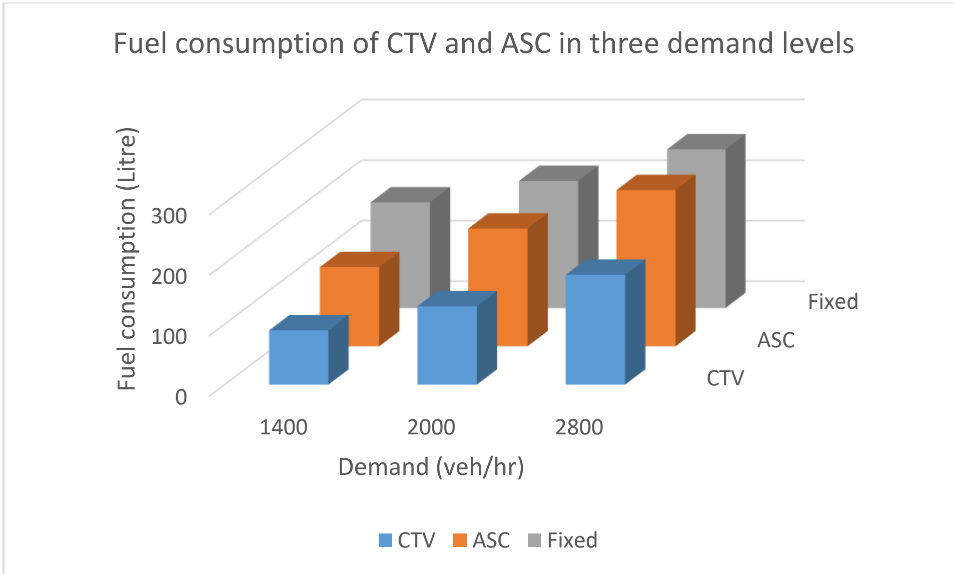


Figure 21: Comparison of the fuel usage between the ASC and the traffic signal and vehicle cooperation methods at different demand levels

Fuel consumption is compared between different penetration rates in different demand levels in Figure 22. As it is seen, fuel usage increases as demand increases. There is a downward pattern in fuel usage at each demand level. As penetration rate increases, fuel usage decreases. The slope is less in the lower demand level.

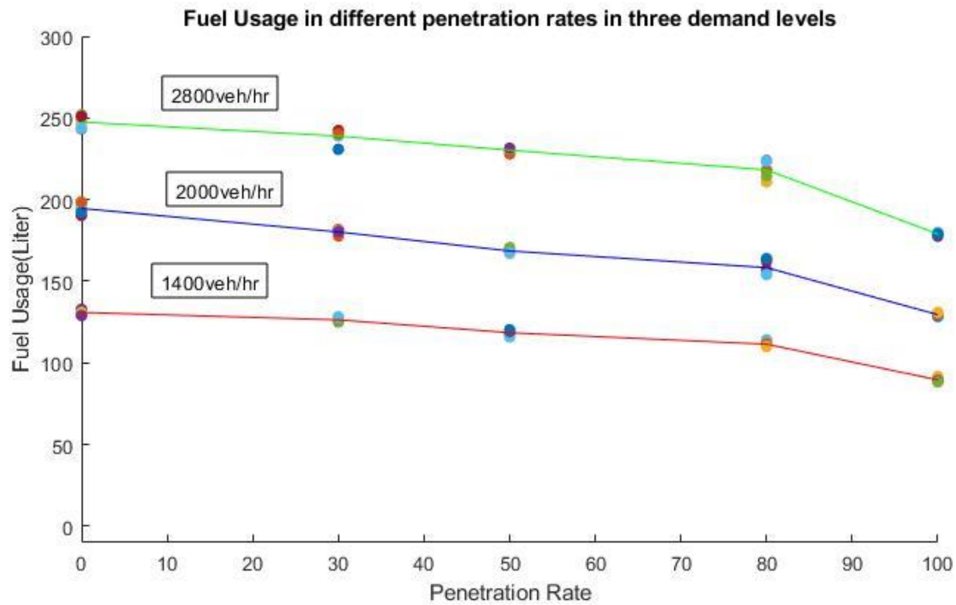


Figure 22: Comparison of the actuated traffic signal and the traffic signal and vehicle cooperation methods' fuel usage for different penetration rates at different demand levels

Section 4.5: CO2 Comparison

CO2 emission is evaluated based on gasoline consumption. Considering CO2 is 19.564 lbs/gallon of gasoline (Energy Information Administration), the amount of CO2 in different scenarios is computed in Table 3.

Table 3: Amount of CO2 production

CO2(lbs)			
Demand level	1400	2000	2800
CTV	462.7971	668.9382	937.7426
ASC	676.2284	1005.013	1333.842
Fixed	901.4706	1084.597	1354.101

Section 4.6: Total Delay Time Comparison

Delay time is the extra time drivers spend negotiating the intersection compared to going through it at the speed limit without stopping. Delay time is compared between the actuated traffic signal, fixed time, and the traffic signal and vehicle cooperation methods and is shown in Figure 23. As can be seen, the difference between the delay time of the traffic signal and vehicle cooperation method and the other two methods decreases as the demand level increases, which means the traffic signal and vehicle cooperation method shows better performance in lower demand levels in terms of reducing delay time.

Delay time is compared in different penetration rates at different demand levels in Figure 24. Delay time increases as the penetration rate decreases. There is a similarity in the pattern of delay time for moderate and high demand levels. It is noted that a 100% penetration rate decreases the delay time significantly. As illustrated, there is a decrease even in 30% penetration rates in all demand levels. In lower demand levels, the difference between delay times at lower penetration rates is less observed. Specifically, there is an almost steady pattern in the delay time in less than 100% penetration rate at lower demand levels.

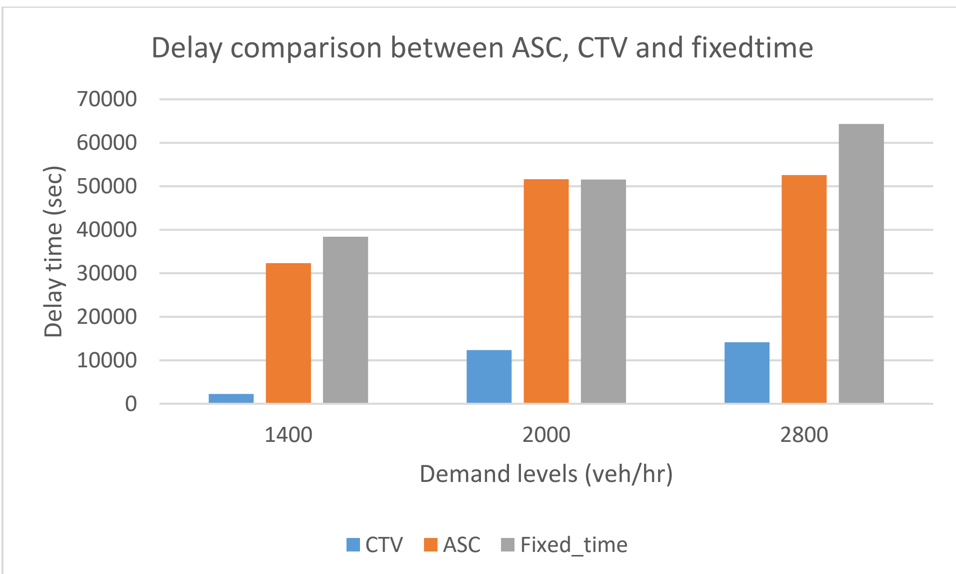


Figure 23: Comparison of delay time in the traffic signal and vehicle cooperation, the actuated traffic signal control, and the fixed time methods at different demand levels

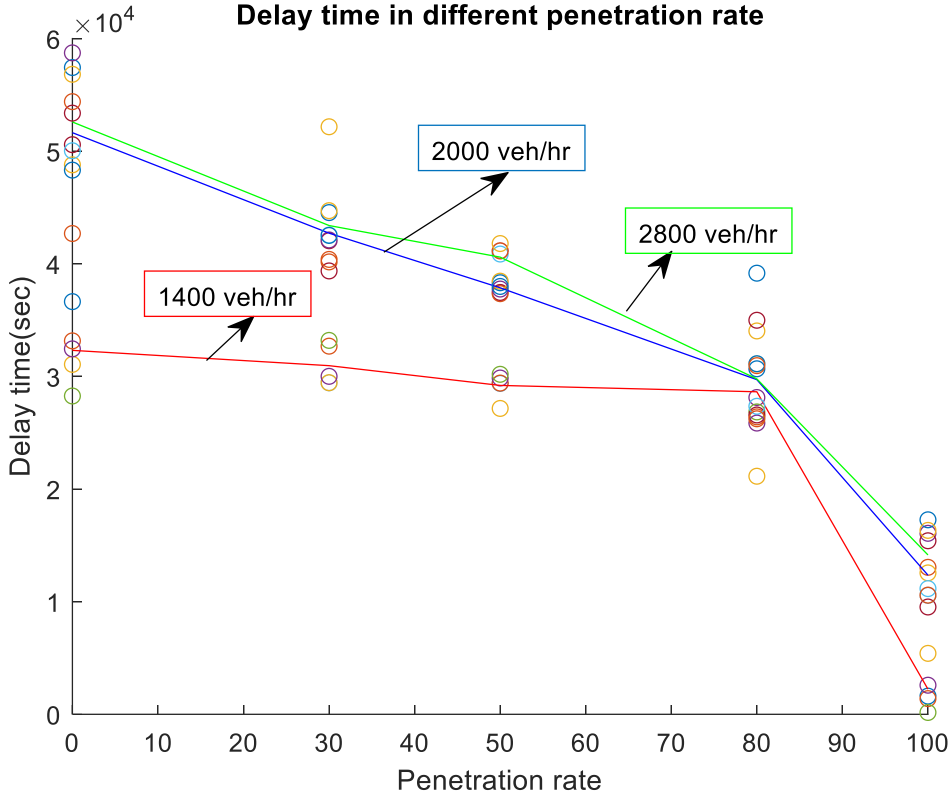


Figure 24: Comparison of the actuated traffic signal control and the traffic signal and vehicle cooperation methods' delay time for different penetration rates at different demand levels

Chapter 5: Conclusion and outlook

Section 5.1: Conclusion

This thesis was devoted to a novel control strategy in which a traffic signal and vehicles' speed are optimized simultaneously to optimize fuel consumption and mobility.

First, two different available data sets were examined. Like most raw data sets, these two data sets required some pre-processing and cleaning. After cleaning, visualizing, and analyzing the data sets, the result showed that the number of connected vehicles in the study area was insufficient for this research. Therefore, new datasets were generated in Matlab and Aimsun simulation by considering the features of the available data sets. The generated data were studied and analyzed in Matlab, and the optimization was done by the Fmincon function. The results of the control method proposed in this study with the actuated traffic signal control and fixed time traffic signal control are compared. The study area focused on one signalized intersection.

In this research, traffic signal timing is optimized at the end of each cycle based on the location and speed of vehicles for the upcoming cycle. Based on the traffic signal timing and phasing, arrival times are suggested for the vehicles. Based on the traffic signal timing and arrival time information, the vehicles' brake force and engine power are also optimized per second to optimize fuel consumption, delay, stop time, and total travel time.

Three different demand levels were considered to compare the results in different demand levels (1400, 2000, and 2800 vehicles per hour). To be close to reality, five different penetration rates were considered. The result showed that total travel time, stop time, delay, and fuel consumption can decrease significantly when all vehicles are connected. There is an even better performance in lower penetration rates in comparison with zero penetration rates. The result showed that there is better performance in all measurements, even at a 30% penetration rate. A zero percent penetration rate is considered the actuated traffic signal control method since actuated traffic signal is based on detectors and does not rely on connected vehicles. All three control methods showed better results in the lower demand level.

Section 5.2: Outlook

Optimizing the traffic signal and vehicles' speed simultaneously is still considered to be at the initial stage and needs more research. In this thesis, there are some limitations that need to be considered as future steps for research. First, in this thesis, one intersection with three lanes is assumed. Corridor and network scales with different intersection types, such as those with more lanes and legs, are worth researching. Second, lane changing was considered to be done before the communication area and can be considered in a future study. Third, only homogeneous vehicles in this study are researched. In reality, there are different kinds of vehicles that can impact fuel consumption and travel time. This can be focused on in future research. Fourth, two types of vehicles (connected with level 4+ of autonomy and non-connected with level 0 of autonomy) are searched, but different levels of autonomy impact the total travel time. Other suggestions for future work can be increasing the capacity or considering saturated intersections. The focus of this thesis was only on light to moderately congested intersections. Finally, yet importantly, the optimization in this thesis was implemented in Matlab with the Fmincon function. The computation time was significantly high, and this thesis can be considered only as a proof of concept. There is definitely a need for a rapid computational method for real applications, and this is an important area for future research.

Appendices

Table 4: Total travel time summary

		Total	Travel	Time		
		0%	30%	50%	80%	100%
1400 veh/hr	Mean	32.31008	31.9325	31.445	31.28833	23.95371
	STD	0.759953	0.456749	0.295477	0.537901	0.490554
	Var	0.719338	1.600475	0.137977	3.21601	0.582707
2000 veh/hr	Mean	47.67889	45.2005	43.85267	41.58711	36.76533
	STD	1.634602	0.475665	0.124402	0.851126	0.627502
	Var	2.671925	0.226257	0.015476	0.724416	0.393759
2800 veh/hr	Mean	61.27611	58.72222	57.94278	54.93839	50.59722
	STD	0.848138	1.265099	0.371453	1.793324	0.763352
	Var	0.577528	0.20862	0.087307	0.289338	0.240643

Table 5: Total stop time summary

Total Stop Time						
		100%	80%	50%	30%	0%
1400 veh/hr	Mean	0.710428	4.246056	5.963667	7.786944	8.824278
	STD	0.192061	0.284031	0.297787	0.209979	0.108012
	Var	0.036888	0.080674	0.088677	0.044091	0.011667
2000 veh/hr	Mean	0.781361	5.841556	8.628111	11.15694	14.06622
	STD	0.07735	0.774877	0.336656	0.280719	0.336546
	Var	0.005983	0.600435	0.113337	0.078803	0.113263
2800 veh/hr	Mean	1.372233	15.40711	15.45328	16.00144	17.68367
	STD	0.124619	0.919878	1.238614	1.065504	0.777564
	Var	0.01553	0.846176	1.534164	1.1353	0.604605

Table 6: Total fuel consumption summary

Total Fuel Consumption						
		100%	80%	50%	30%	0%
1400 veh/hr	Mean	89.60435	111.4698	118.5153	126.3549	130.9278
	STD	1.172041	1.44577	1.499564	1.350658	1.264275
	Var	1.373681	2.09025	2.248691	1.824276	1.598392
2000 veh/hr	Mean	129.5163	154.8878	168.546	180.17	194.5854
	STD	0.923155	3.874045	1.364205	1.340092	3.124192
	Var	0.852215	15.00823	1.861057	1.795845	9.760574
2800 veh/hr	Mean	181.5608	242.2034	245.6317	248.6875	258.2514
	STD	0.865583	5.527498	4.890465	5.071965	3.091635
	Var	0.749234	30.55323	23.91664	25.72483	9.55821

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