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DEVELOPMENT OF AN ECO APPROACH AND DEPARTURE APPLICATION TO IMPROVE ENERGY CONSUMPTION OF A PLUG-IN HYBRID VEHICLE IN CHARGE DEPLETING MODE

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DEVELOPMENT OF AN ECO APPROACH AND DEPARTURE APPLICATION TO IMPROVE ENERGY CONSUMPTION OF A PLUG-IN HYBRID VEHICLE IN CHARGE DEPLETING MODE

By

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Definitions and Abbreviations

T = Torque (Nm)

$\mathrm{F_0}$ = Road Load Coefficient (N)

$\mathrm{F_1}$ = Road Load Coefficent (N/kph)

$\mathrm{F_2}$ = Road Load Coefficent ($\mathrm{N/kph^2}$)

V = Velocity (m/s)

m = Mass (kg)

a = Acceleration ($\mathrm{m/s^2}$)

g = gravitational acceleration ($\mathrm{m/s^2}$)

Θ = Road Grade(radians)

α = Angular Acceleration($\mathrm{rad/s^2}$)

$\mathrm{R_{wheel}}$ = Radius of Wheel (m)

E = Energy (kJ)

dt = Interval Time Elapsed (s)

$\mathrm{P_{aux}}$ = Auxilary Load (kW)

$\mathrm{V_k}$ = Velocity over Current Interval(m/s)

$\mathrm{V_{k-1}}$ = Velocity over Previous Interval(m/s)

$\mathrm{t_k}$ = Time Elapsed over Current Interval (s)

$\mathrm{t_{k-1}}$ = Time Elapsed over Previous Interval(s)

$\mathrm{a_k}$ = Acceleration during Current Interval ($\mathrm{m/s^2}$)

dx = Dynamic Programming Discretization (m)

X = Distance between Vehicle and Intersection (m)

MTU = Michigan Technological University

EV = Electric Vehicle

PHEV = Plug-in Hybrid Electric Vehicle

CAV = Connected and Autonomous Vehicle

Eco AnD = Eco Approach and Departure

MTUDC = Michigan Technological University Drive Cycle

BSM = Basic Safety Message

SPaT = Signal Phase and Timing

DSRC = Dedicated Short-Range Communications

RSU = Road-side Unit

SQP = Sequential Quadratic Programming

MPC = Model Predictive Control

CD Mode = Charge Depleting Mode

V2V = Vehicle to Vehicle

V2I = Vehicle to Infrastructure

DP = Dynamic Programming

HMI = Human Machine Interface

t_{open} = Time a Green Phase Begins

t_{close} = Time a Green Phase Ends

t_{sig} = Time Remaing unitl the Current Phase Ends

t_{clear} = Time Requried to Clear an Intersection at the Current Speed

Acknowledgements

I’d like to express my appreciation for all the support and insights provided by Dr. Jeff Naber over the course of this project. He has provided me with great opportunities to develop new skills and evolve as an Engineer. He has provided me with the perfect balance of guidance and freedom to explore on my own throughout the research process.

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Abstract

A recent study at Michigan Technological University as part of the NEXTCAR DOE APRA-E Project was conducted to determine the potential energy savings of a plug-in hybrid electric vehicle (PHEV) equipped with various Connected and Automated Vehicle (CAV) Technologies. One aspect of this study focused on the development of an Eco Approach and Departure (Eco AnD) Application that would further reduce the energy consumed around a signalized intersection.

Many modern intersections are equipped with traffic signals that can broadcast Basic Safety (BSM), MAP, and Signal Phase and Timing (SPaT) message sets that contain intersection ID, location, current phase, and cyclic timing information. This data can then be used as inputs to an optimization algorithm that will predict the most energy efficient maneuver for a vehicle as it approaches and departs from an intersection.

This Eco AnD Application has been developed to allow a test vehicle to interface with the traffic signals, run the optimization routine, and then relay the information back to the driver in the form of a velocity profile. Benefits of an Eco Approach and Departure Application have been evaluated on six different intersections on the Michigan Technological University Drive Cycle (MTUDC). A driver, given information about the cyclic timing and offsets of each intersection, drove through each intersection numerous times collecting data that would be used to show energy consumption of the vehicle.

The energy consumption using the human driver was then compared to the maneuvers generated by the Eco AnD Application. Energy reduction benefits could then be

determined on an intersection-by-intersection basis, for a subset of the MTUDC, and for the entire MTUDC. Thus far, the Eco AnD Application has been used to experimentally demonstrate 2-4% energy savings on the MTUDC.

1 Introduction

Several hybrid vehicle platforms exist in today's automotive market. [1] Recent developments in advanced power electronic technologies have made hybrid and electric vehicles a viable option for automotive manufacturers searching for new ways to continue to meet increasingly stringent government regulations. As new technologies make their way to market, the trend will move from hybrid vehicles towards completely electric vehicles (EV). Currently, limitations on the total range of electric vehicles are among the most prohibitive factors preventing them from becoming popular amongst consumers. Improving the range of electric vehicles would greatly increase their appeal and likely grow their sales volume in automotive markets globally. [2]

1.1 Motivation

The Department of Energy ARPA-E NEXTCAR project at Michigan Technological University seeks to improve energy consumption of plug-in hybrid electric vehicles (PHEVs) and EVs utilizing connected and autonomous vehicle (CAV) technologies. A team of students and faculty have worked to develop advanced control strategies and optimization algorithms that will reduce energy consumption of a PHEV by 21% over the Michigan Technological University Drive Cycle (MTUDC) and extend the range of an EV by 9%.

This thesis will focus primarily on the Eco Approach and Departure (Eco AnD) Application from development to integration. The Eco AnD Application is one of several

CAV technologies developed by the NEXTCAR Team to reduce energy consumption of a test vehicle around signalized intersections. This application determines the optimal maneuver for a vehicle to clear an intersection in a way that minimizes the energy the vehicle will consume. The optimization routine requires information broadcast from the traffic signals using Direct Short-Range Communication (DSRC). With information about the intersection's location, current phase, and timing estimate, the optimizer generates the most efficient maneuver subject to traffic laws and relays the information back to the driver in the form of a predicted velocity profile.

The Eco AnD application, like the other CAV technologies included in this study, were tested and validated on the MTU Drive Cycle. This drive cycle includes five signalized intersections. This section of the drive cycle will be referred to as the RSU Loop, as it is the section that contains the five signalized intersections and Road-Side Units (RSU). One intersection is traversed from north to south, and then again from west to east for a total of six vehicle/intersection interactions. RSUs at each intersection are used to transmit DSRC messages, which will be received by the test vehicle.Data collected during the testing and validation phase has been analyzed to characterize the Eco AnD Application's performance on an intersection-by-intersection basis, as well as its performance over the entire MTUDC.

The remainder of this Thesis is structured to provide details on the development and testing process of the Eco AnD Application. This will be addressed in the Materials and Methods section to follow. Models and Simulations will be discussed in the Methods and Materials sections as well, but a complete list of key parameters is included in the

Appendix. After a description of how the application was developed, the Results section will elaborate on the information gathered from the test data and how it characterizes the effectiveness of this application. The findings of this study related to the Eco AnD Application will be summarized in the conclusion section at the end of this article.

2 Eco Approach and Departure Application as a Connected Vehicle Technology

CAV Technologies have become a focal point for research in areas where reducing energy consumption of a vehicle is a priority. As part of the DoE ARPA-E NEXTCAR program, several studies have been conducted at Michigan Technological University to develop several CAV Technologies, including an Eco-Routing Application, Speed Harmonization, In-Situ Vehicle Parameter Characterization, etc. Each technology contributed to a combined goal of reducing overall vehicle energy consumption by 21% and increase the total range of Charge Depleting Mode by 6% along the MTUDC. [3]

Additional works related to Connected Vehicles and Eco Approach and Departure research have been conducted at various universities around the world. A deep exploration into the ways in which a Connected Vehicle would interact with intersections has been provided by Xia et al. from UC Riverside. He explains the potential maneuvers and notes several key parameters associated with DSRC communication with the intersection. Several CAV technologies are explained within this article, providing insights into the simulated fuel savings for each. The Eco AnD Application discussed in this paper has been simulated to show fuel saving of 11 to 19% on an arterial roadway. [4]

With an understanding of how intersection phase cycles are scheduled, the green phase can be predicted. Since the vehicle can only clear an intersection during a green phase, an optimization algorithm can be used to predict a velocity trajectory to clear the intersection legally, and consuming the least amount of energy. Lou et al. suggest using a Genetic Algorithm for determining a velocity trajectory that meets these conditions. The Genetic Algorithm they suggest is a type of dynamic programming that is used offline for simulation purposes. Fuel savings proposed by this work suggest a potential fuel savings of 16%. [5]

Nunzio et al. makes use of another DP optimization approach when developing an Eco AnD model. This study comments on an application of Dijkstra's Algorithm to solving the energy minimization problem, as well as a Pruning Algorithm. The Pruning Algorithm is employed to search for the feasible times in which the vehicle can cross the intersection. This is defined in a way that is not very computationally intense. Dijkstra's Algorithm is then used to search for the minimal costs listed in a feasibility chart. This work has noted an average reduction in energy consumption of about 10%. [6,7]

Another study by Huang and Peng, use a Sequential Convex Optimization strategy in an Eco AnD Application. For this work, they use a conventional vehicle with a spark ignited engine. The optimization problem is defined by using a multi-objective optimization problem, solved at each step using an SQP method. Their method balances weighting factors to influence how aggressively the vehicle accelerates, which ultimately plays a role in the time the maneuver requires and fuel consumption. Average fuel savings for their work is noted as 12%, while they have in some cases found simulated fuel consumption values to be reduced by as much as 35%. [8]

Barik briefly touched upon the potential benefits of an Eco AnD Application in his work on CAV Technologies. He too used an SQP method to define maneuvers a vehicle would follow to reduce the energy consumed by a vehicle as it passes through a signalized intersection. His work was able to simulate vehicle interactions with one or two traffic lights. Ultimately, he was able to predict that his Eco AnD Controller could increase a vehicle's mpg by 10 to 30 mpg. [9]

HomChaudhuri, Lin, and Pisu took a very different approach when developing their version of an Eco AnD Application. Like several other works, they too rely on V2V communication for input into their algorithm, but they chose to develop a hierarchal control strategy for a hybrid vehicle. This work details the process for developing a controller that reduces the overall energy of a hybrid-electric vehicle as it interacts with signalized intersections. Their "high level" controller predicts the green phase they aim to clear the intersection, while their "low level" MPC determines the velocity profile their vehicle will take to maneuver through the intersection(s). Their controller has shown to increase vehicle mpg by 15 mpg compared to a regular non-connected vehicle. [10]

Like the other technologies developed by Michigan Tech, the Eco AnD Application could help reduce overall energy consumption of a vehicle by generating an optimal velocity profile to safely pass through an intersection. An optimal velocity maneuver would favor conserving energy and would benefit Charge Depleting (CD) Mode range as well. The remainder of this article will address the development of an Eco AnD Application and how it can be used towards achieving the goals set for the Michigan Tech's NEXTCAR program.

2.1 Overview of Infrastructure to Vehicle Communication

An Eco Approach and Departure Application can be used to generate optimal velocity maneuvers for a vehicle as it passes through an intersection. Before a maneuver can is created, the controller must first understand the current status of the intersection the vehicle is approaching. Critical information about the intersection, such as the location of the intersection, the current phase or color of the traffic light, and how long until the current phase ends is broadcast from an intersection using DSRC communication.

Instances where an intersection is sending data to a vehicle is typically is also referred to as I2V Communication. It is also possible to transmit information from vehicle to vehicle using DSRC messages, and that is commonly referred to as V2V communication. Both I2V and V2V related message sets are defined in the SAE J2735 [11] Standard for DSRC communication applications. The majority of this application will focus on I2V communication, specifically SPaT and MAP messages. Information being broadcast from a signalized intersection in either of these message sets will include some, if not all of the signals shown in Figure 2.1.

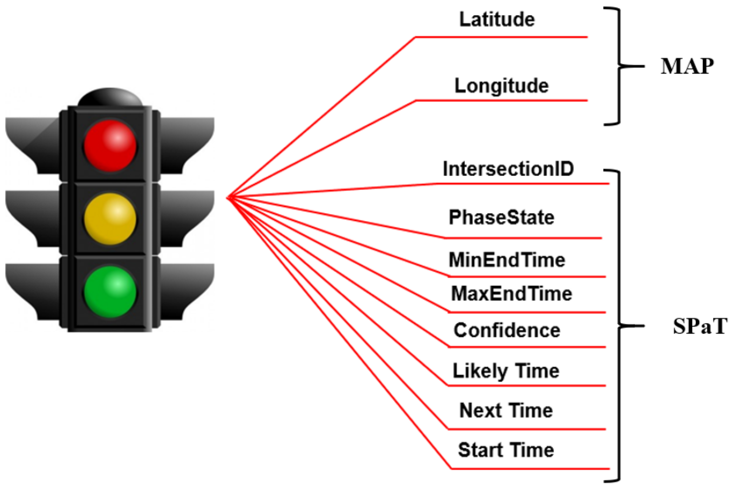

Figure 2.1 Key Signals Broadcast by an Intersection

It is important to note that each signalized intersection may broadcast different signals depending the several characteristics of the intersection, or the way the traffic light controller has been set up. [11] For example, every intersection will broadcast a unique IntersectionID value, but the intersection shown on the left in Figure 2.2 is likely to broadcast fewer Movement States than the one on the right. Each Movement State should be thought of as a maneuver through the intersection and will contain information related to its own current Phase State, and timing information.

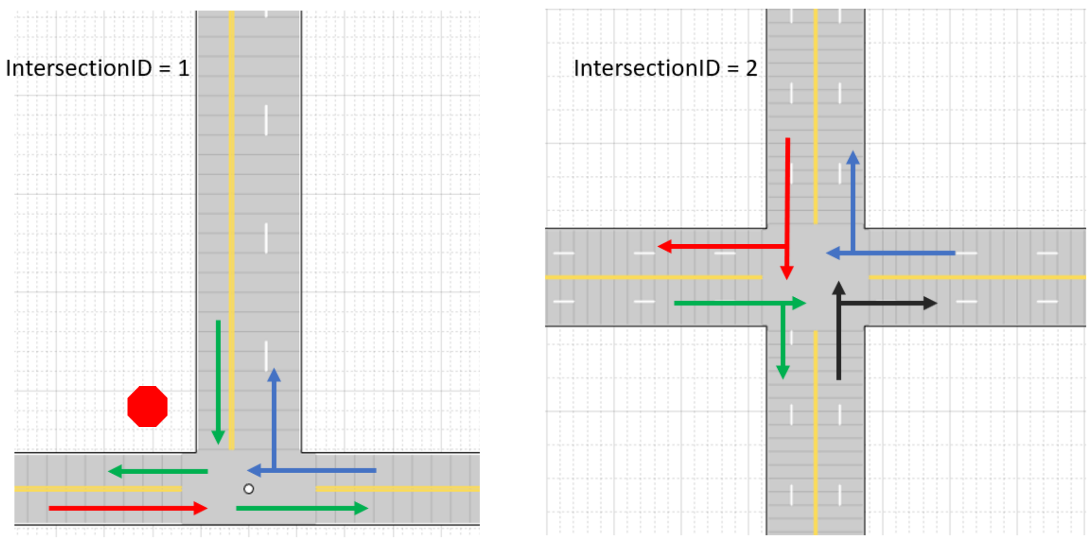

Figure 2.2 Intersection Comparison between a T-shaped intersection (left) and a 4x4 Intersection (right). Each arrow represents a Movement State in each scenario.

In the case study in Figure 4, the T-Shaped Intersection is shown to have different flows of traffic. If the top of the figure is considered to be North, the blue arrow indicates that a vehicle may either proceed through the intersection heading West, or turn to travel North. Unless there is a traffic light specifically designating the vehicle to turn towards the North, both blue patterns would likely be considered the same maneuver and therefore the same Movement State. These types of intersections are common around Michigan Tech, and by using them as an example, the green arrow turning either East or West would be permitted after stopping at a stop sign. This example would show that this intersection is likely to have either two, or three Movement States and two or three different phase cycles.

The 4x4 Intersection on the right is also common around Michigan Tech. In this example, there are 4 different Movement States. Note that both lanes traveling in either direction is generally included in the same Movement State. Comparing the two intersections, they are different in that the number of Movement States and phase cycles are different.

Different signalized intersections may also broadcast different timing signals. Generally speaking, every signalized intersection relay information about the Minimum End Time, or the soonest time until the current phase ends. However, there is no guarantee that every intersection will broadcast other timing information such as the Likely Time, Next Time, or Start Time. [11]

2.2 Test Vehicle and Instrumentation

This Eco Approach and Departure Application is one of several CAV technologies developed to meet the DoE ARPA-E NEXTCAR goals for reducing energy consumption and extending the range of EV operation. MTU NEXTCAR Team's partnership with General Motors has made it possible to develop and test each of these CAV technologies using 2nd Generation Chevy Volts.

The 2nd Gen Chevy Volt is a plug-in hybrid electric vehicle that uses a Dual Mode Power Split propulsion system. The propulsion system is configured with two electric machines and engine. The vehicle can operate in Charge Sustaining mode where torque can be supplied by a combination of the electric machines and engine, or it can operate in Charge Depleting Mode. In the case of Charge Depleting Mode, only the electric machines are used to drive the vehicle. The scope of this study focuses on a 2nd Gen Chevy Volt operating exclusively in Charge Depleting Mode.

The Volt test vehicles are also equipped with additional sensors and a data acquisition system. Some of the sensors include LIDAR, radar, a GNSS/RTK system, and a DSRC receiver. The Eco AnD Application makes use of the GNSS/RTK system for determining a more precise location of the vehicle than the stock GPS unit can provide. The Volt has been instrumented with the DSRC receiver so that it can listen and decode the SPaT, MAP, and BSM messages broadcast from an intersection. Figure 2.3 depicts a high-level I/O diagram for instrumentation in the Chevy Volt.

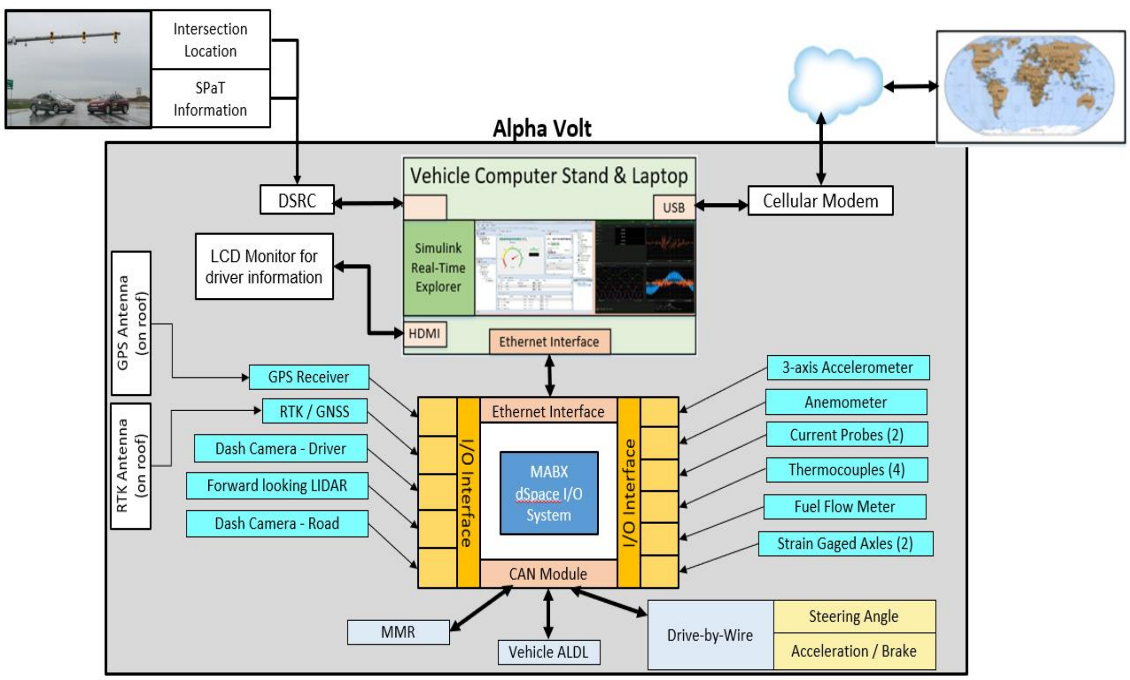

Figure 2.3 I/O Diagram for Instrumentation On-board 2nd Gen. Chevy Volt. The connections and interfaces between the hardware devices are shown with black arrows indicating the flow.

The Volt is also equipped with a Micro Auto Box II. This is used not only for data acquisition, but also for running models in real time. ControlDesk is a software package by dSpace that allows users to set up an instrumentation panel and data recorders. While using the Eco AnD Application, data pertaining to the intersection and the velocity profile generated by the application is displayed for the driver. The Micro Auto Box II, along with the Cohda MK5, and GNSS system are shown installed in the vehicle in Figure 2.4.

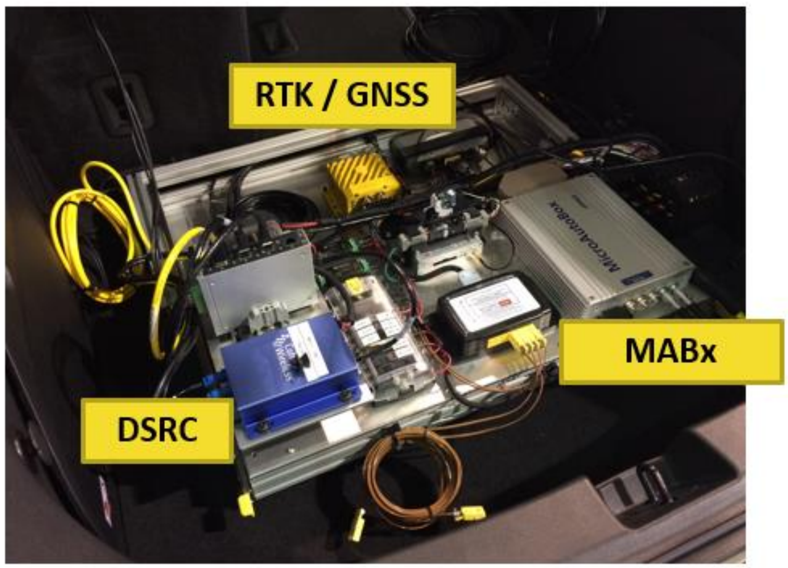

Figure 2.4 Hardware installed inside the 2nd Gen Chevy Volt test vehicle. The Micro Auto Box (MABx), RTK/GNSS system, and Cohda MK5 are installed on a hardware rack in the trunk of the vehicle.

3 Development of an Eco AnD Application

Development of this Eco Approach and Departure Application spanned just over a year, beginning with preliminary testing for potential impact on energy savings followed by a simulation phase, and finally implementation. Each phase of the development process posed unique issues, but ultimately led to a more profound understanding of the problem and a more robust application.

The Eco AnD Application has been developed to minimize a cost function calculating overall energy consumed by the Chevy Volt for a minimal solution. Optimization of the velocity profiles is performed using a Dynamic Programming (DP) method. An open source Matlab function has been used along with an accompanying custom model file to implement the DP algorithm. Special considerations have been made to reduce computational time while running the DP optimizer, without significant impact on the validity of the solution.

Before testing the Eco AnD Application on-road, significant simulation studies were conducted to ensure the application not only generates minimal energy consuming profiles, but also generates profiles that follow traffic laws. This involved developing simulations for the different intersections along the MTUDC, and developing a version of the optimizer that could be ran offline in addition to the online version. The remainder of this section will discuss the Eco AnD Application from a high level, while explaining the Dynamic Programming optimization, and simulation studies in greater detail.

3.1 Overview of Application

An Eco Approach and Departure Application can be used to generate maneuvers a driver could follow to pass through a signalized intersection while consuming the least amount of energy. In order for the application to create the most appropriate maneuver, it must be knowledgeable about key parameters of the intersection, the vehicle, and the relevant traffic laws. This Eco AnD Application receives information from a signalized intersection, and accepts several signals from the Controller Area Network (CAN) bus on the vehicle. With the required input information available, the Eco AnD Application follows a process for determining the least costly maneuver through an intersection while obeying traffic laws.

The first step in the process to generate a minimal energy maneuver is for the application to collect information from an intersection. This Eco AnD Application uses a Cohda MK5 radio as a receiver for DSRC messages. SPaT and MAP messages are among the most important messages. SPaT messages include signals like *CurrentPhase* which is the current color of the traffic light, and *MinEndTime* which tells how long until the current phase ends. MAP messages include the location of the intersection. With this information, the Eco AnD Application can begin to interpret the situation at hand.

The Eco AnD Application generates maneuvers that will minimize energy consumption using a Dynamic Programming optimization. Dynamic Programming is implemented to compute several variables and apply a large number of constraints for this type of problem. The Eco AnD Application's optimizer accepts phase, end time, distance to the intersections and the current vehicle speed as inputs, and generates a maneuver for both the approach and departure. The velocity profiles generated by the Dynamic Programming is relayed back to the driver through ControlDesk. The driver is then expected to follow the profile displayed on the HMI. Figure 3.1 depicts the HMI as it is positioned in the vehicle.

Figure 3.1 HMI display (circled) positioned in the front passenger seat of the vehicle.

3.1.1 Vehicle Maneuvers

The vehicle's interaction with signalized intersections can be categorized in one of four ways. The vehicle can pass through the intersection while maintaining the current speed, the vehicle may have to slow down as it approaches the intersection, the vehicle may have to accelerate, or the vehicle may have to come to stop at the intersection. Maintaining a constant speed is the most favorable type of maneuver, while coming to a stop is the least favorable maneuver. Figure 3.2 depicts the different maneuvers a vehicle may perform as it approaches an intersection.

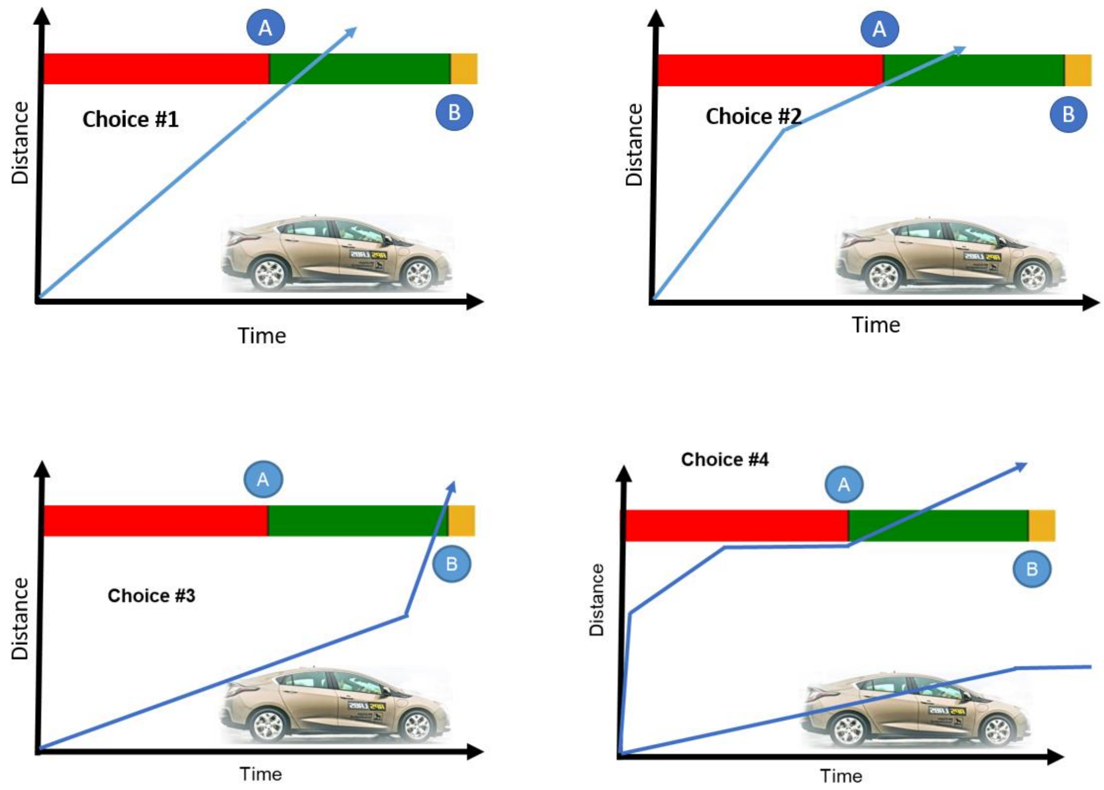

Figure 3.2 Vehicle Maneuver Choices: 1 – Maintain Current Speed, 2 – Decelerate, 3 – Accelerate, 4 – Stop

“A” in Figure 3.2 represents the opening of the green phase, while “B” represents the closing on the green phase in time. To legally proceed through the intersection, the vehicle must clear the intersection in between points A and B.

3.2 MTUDC and RSU Loop

Effectiveness of the Eco AnD Application in reducing overall energy consumption of a passenger vehicle has been determined for the MTUDC. The MTUDC is roughly 36 kilometers of varying road grades, speed limits, and traffic densities. The southern section of the MTUDC circled in Figure 3.3, is of specific interest with the Eco AnD Application as it is the only section of the MTUDC where signalized intersections are present. DSRC transmitters are often referred to as Road-Side Units, and for that reason the southern subsection of the MTUDC will be referred to as the RSU Loop.

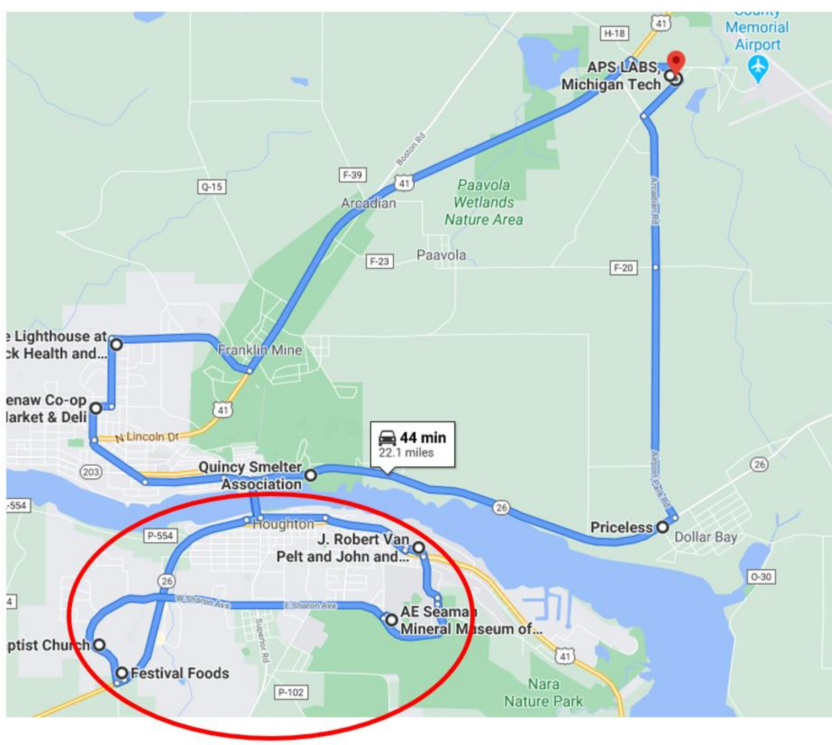

Figure 3.3 Map of the MTUDC with the RSU Loop is circled in red.

3.2.1 Intersections

The RSU Loop subsection of the MTUDC contains five signalized intersections. The vehicle will pass through one intersection traveling south, and then again heading east. Therefore, there are a total of 6 interactions between the test vehicle and signalized intersections. Each of the six interactions will be treated as separate intersections when evaluating the impact and effectiveness of the Eco AnD Application.

Each intersection is unique and should be considered separately. In some cases, the test vehicle will pass straight through an intersection without turning. The vehicle is expected to turn left at one intersection and right at another. These maneuvers, as well as the individual intersections' cyclic phase and timing, offsets, and grades need to be considered. It is also possible that the speed limit approaching the intersection may differ from the departure speed limit in some cases. The RSU Loop is shown in Figure 3.4, illustrating the direction of travel and link distances between intersections. Enclosure A Intersection Modelling Information, lists the critical parameters observed for each intersection on the MTUDC.

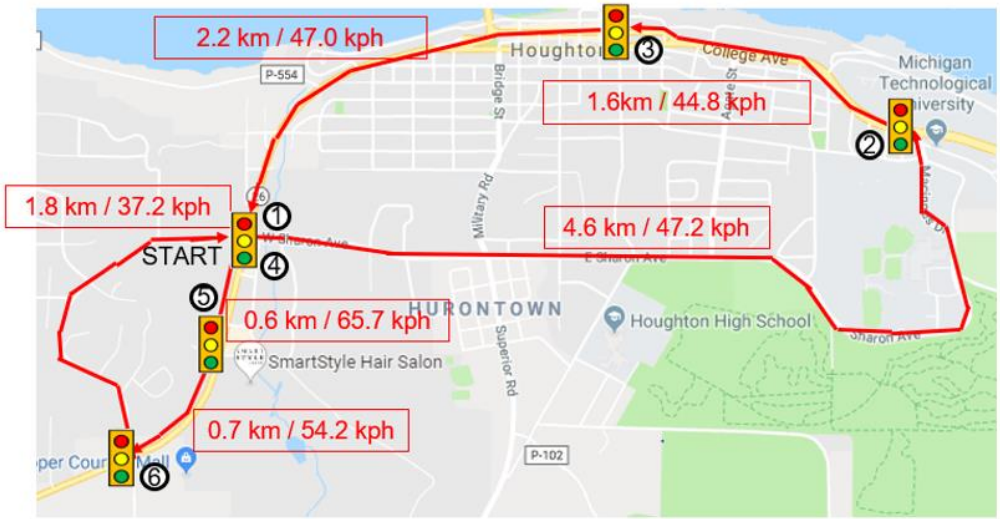

Figure 3.4 Map of RSU Loop detailing the direction traveled, link distances, and average link speeds.

One similarity all intersections have in common is the range of DSRC Communication. which is limited to 300 meters, unobstructed. This means a test vehicle instrumented with a DSRC receiver must be within 300 meters to received SPaT and MAP data. Figure 3.5 depicts 300 meters before and after the intersections, outlining the anticipated range of DSRC Communication on the RSU Loop.

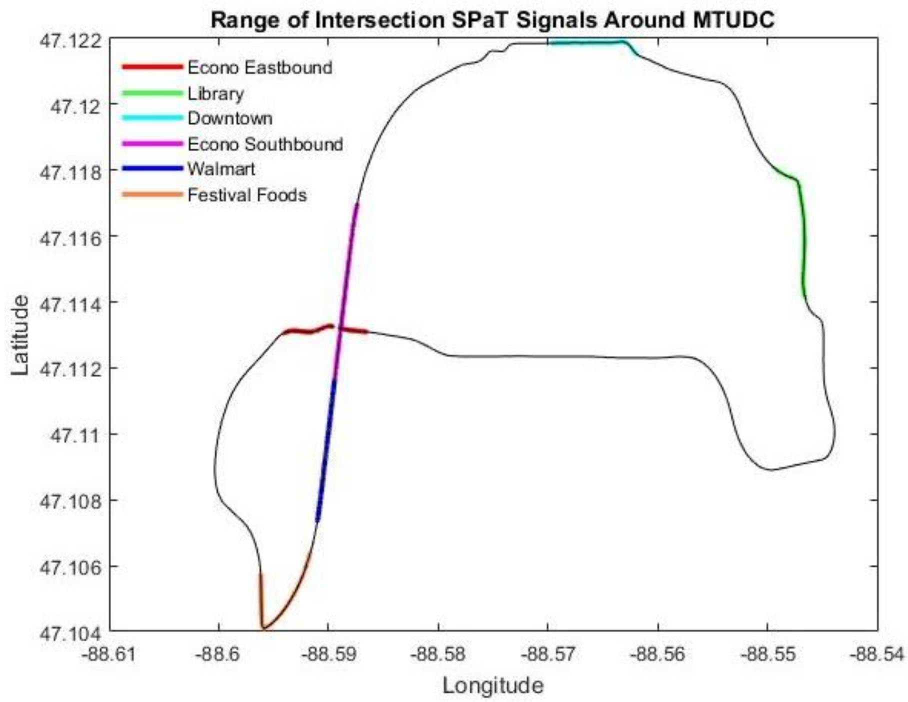

Figure 3.5 Range of DSRC Communication for each of the signalized intersections along the RSU Loop. Note: Econo Eastbound and Econo Southbound are the same intersection, though it is treated as though they are separate.

3.2.2 Preliminary Studies for Eco AnD Application Impact

Two initial studies were done to determine the potential impact of an Eco AnD Application prior to development. The first was a study to determine how stopping at intersections on the RSU Loop effects the overall energy consumption of the vehicle as it completes one lap around the RSU Loop. The second study shows an estimate of an energy penalty associated with stopping at each intersection.

Both studies were conducted using a human driver who was given information regarding the cyclic timing and offset of each intersection, and the distance between the intersections. This made it possible for the driver to negotiate the RSU Loop, while controlling the number of times they stopped.

The results of the first preliminary experiment show that stopping at more intersections generally results in a higher overall energy consumption. The results are shown in Figure 3.6. *Case A* is taken to be the best-case scenario, where *Case B* is accepted as the worst-case scenario.

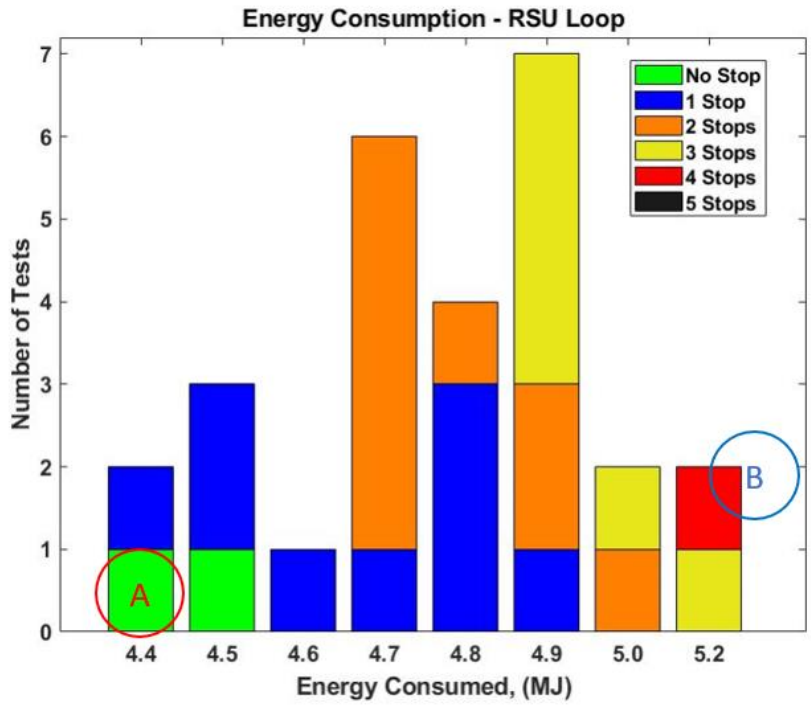

Figure 3.6 On-road Data Collected from preliminary experiments around the RSU Loop. Scenario "A" indicates the most favorable result, where it shows not stopping at any intersection yields a lower overall energy consumption. Point "B" is given as the worst-case scenario where a total of 4 stops leads to the largest overall energy consumption.

Not only was the effect of stopping considered for the RSU Loop, but the same tests could be used to show the impact of stopping on overall energy consumption on an intersection-by-intersection basis. As in the case with the RSU Loop, energy consumption on an intersection-by-intersection basis was typically observed to be higher in scenarios where the vehicle came to a stop before proceeding through the intersection. Figures 3.7 and 3.8 show the results of these studies for two different intersections on the RSU Loop.

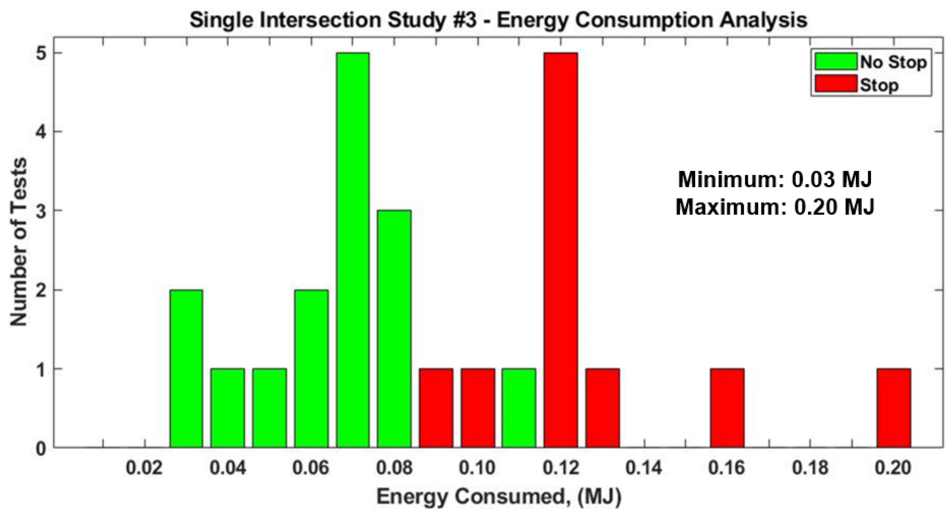

Figure 3.7 Intersection-by-intersection preliminary analysis of the third intersection on the RSU Loop (Downtown Intersection). The data follows the trend supporting the claim that stopping at an intersection is more costly in terms of energy consumption.

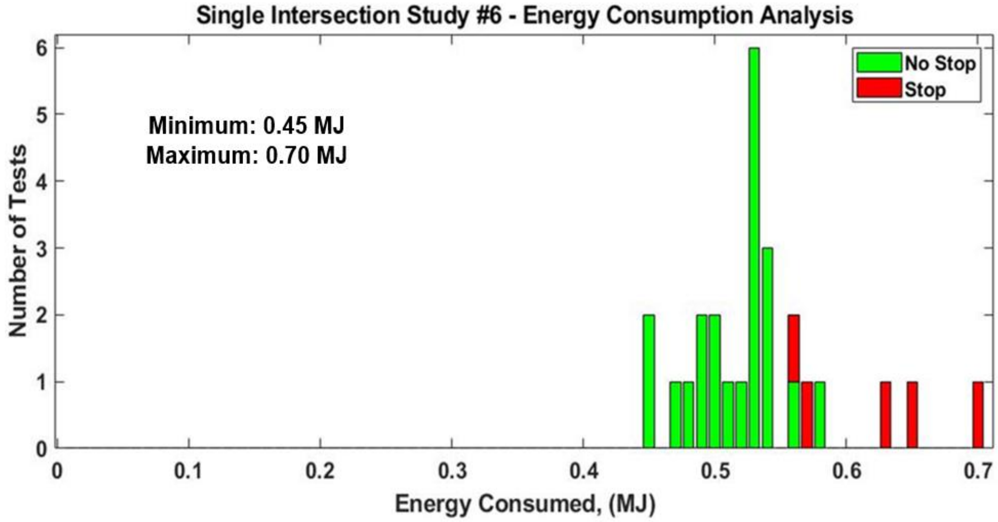

Figure 3.8 Intersection-by-intersection case study modelling the preliminary analysis data for Intersection #6. (Festival Foods) This intersection proved to be easy to time, ultimately requiring less instances where a stop was required. The data shows stopping at the intersections generally results in a larger energy consumption.

The same results from this preliminary test on the RSU Loop can be used to predict the impact on energy consumption for the entire MTUDC. Equations 3.1a, 3.1b, and 3.1c are used to compute the energy difference for the entire MTUDC. Results from this preliminary experiment as it pertains to the entire MTUDC are tabulated in Table 3.1.

$$MTUDC_{best} = \left(MTUDC_{avg} - SI_{avg}\right) + SI_{best} \qquad \textit{Eq. 3.1a}$$

$$\Delta E_{consumed} = MTUDC_{best} - MTUDC_{avg} \qquad \textit{Eq. 3.1b}$$

$$Savings(\%) = \left(\frac{\Delta E_{consumed}}{MTUDC_{avg}}\right) * 100 \qquad \textit{Eq.3.1c}$$

Where $MTUDC_{best}$ is given as the best-case scenario achieved for the entire MTU Drive Cycle. $MTUDC_{avg}$ is the average energy consumed for the MTUDC, and SI_{avg} represents the average Single Intersection energy consumption value. $\Delta E_{consumed}$ is given as the difference in energy consumption between the best and average scenarios for the entire MTUDC

Table 3.1. Preliminary Experiment Energy Reduction Results

	RSU Loop	MTU DC
Regular Driver Average Consumption	5.0 – 5.2 MJ 165 –156MPGe	19.4 MJ 143 MPGe
Best RSU Loop Scenario (No Stops)	4.4 MJ 186 MPGe	18.6 MJ 149 MPGe
Median Energy Savings	7.7%	2.1%
Max Savings (A to B)	15.4%	4.2%

The second experiment was used to determine estimates for energy penalties associated with stopping at each intersection. A data mining exercise showed the differences in various energy consumption values associated with the best-case scenarios, worst case scenarios, and various profiles in between. Energy penalties determined from this preliminary test are tabulated in Table 3.2.

Table 3.2. Energy Penalties Associated with Intersections Along the RSU Loop

Intersection	Energy (kJ) , Stop	Energy (kJ), No Stop	Energy Saved, (%)	Time Reduction, (sec)
Library	306	216.5	29.2	-10.9
Downtown	163.5	141.4	13.5	-26.0
Econo Southbound	350.0	292.4	16.5	-2.5
Walmart	365.6	203.5	44.3	-2.0
Festival Foods	89.5	67.95	24.1	-2.5

3.3 Dynamic Programming

The Eco AnD Application utilizes a Dynamic Programming optimization strategy for determining minimal energy maneuvers for a vehicle as it passes through an intersection. Dynamic Programming allows for the consideration of several variables while applying a large number of constraints. Typically, Dynamic Programming is synonymous with large computational times and complexity, but several considerations have been made to reduce computational time and make implementation more feasible.

3.3.1 Defining the Problem

Before discussing how the DP algorithm will generate the optimal velocity profile for a maneuver, it is important to understand the problem at a high level. The Eco AnD Application is meant to minimize the energy consumption of the vehicle in Charge Depleting Mode as it passes through a signalized intersection. Therefore, the focus will be placed on the energy being taken from the battery, and the scope of the problem will be restricted to 300 meters before and after an intersection.

Each intersection broadcast information regarding the location, current phase, and time until the current phase ends. The current phase dictates whether the vehicle is permitted to cross the intersection. Legally, a vehicle is permitted to pass through an intersection while the phase represents a green light. A vehicle may also pass through while the light is yellow, but this Eco AnD Application will consider a yellow light as part of the red and will not allow the vehicle to clear during that phase.

The time until the current phase ends provides a time-based constraint for the maneuver. The Eco AnD Application must generate a maneuver that will clear the intersection only during a green phase. Therefore, it is critical that the application understands when the green phase occurs. The time at which a green phase begins will be referred to as the "opening time" and the time the green phase ends will be referred to as the "closing time."

Some intersections may broadcast a "NextTime" signal. If it does, this signal provides an estimate in time for when the current phase will begin again. If this signal is not available, it may be necessary to rely on estimate for how long the phase or next set of phases will last. Since the length of individual phases are not broadcast (i.e. green = 20 seconds, yellow = 4 seconds, red = 20 seconds) it may be necessary to make assumptions for these values or record observations to better estimate the opening time of a green phase.

When it comes to the Eco AnD Application and testing on the RSU Loop, the cyclic timing information has been observed and recorded for each intersection. The intersections along the RSU Loop are fixed timing intersections, meaning their phase lengths do not change. This makes it easy to hard code those values into the Eco AnD Application as a look-up table based on Intersection ID. If the individual phase lengths are known ahead of time, a method described in the following equations can be implemented to estimate the time until the green phase opens and closes.

$$t_{open} = 0 \qquad \textit{Eq. 3.2a}$$

$$t_{close} = t_{sig} \qquad \textit{Eq. 3.2b}$$

$$t_{open} = t_{sig} + t_{red} \qquad \textit{Eq. 3.3a}$$

$$t_{close} = t_{sig} + t_{red} + t_{green} \qquad \textit{Eq.3.3b}$$

$$t_{open} = t_{sig} \qquad \textit{Eq. 3.4a}$$

$$t_{close} = t_{sig} + t_{green} \qquad \textit{Eq.3.4b}$$

Equations 3.2a and 3.2b predict the opening and closing of the green phase when the current phase is already green. Equations 3.3a and 3.3b are used to calculate the green phase opening and closing times when the current phase is given to be yellow. Finally, Equations 3.4a and 3.4b predict the opening and closing of the green phase when the current phase is red. In these equations, t_{sig} is given as the variable name for the Minimum End Time value of the current phase.

With this information, the Eco AnD Application can determine when it can cross the intersection. When it can legally cross through the intersection, and how long it has to clear the intersection play significant roles when it comes to generating a maneuver. Depending on the current speed of the vehicle and how much time the vehicle has before it can clear the intersection, the DP algorithm will determine the maneuver that most effectively limits the energy consumption of the vehicle.

3.3.2 Calculations

The DP optimizer outputs a minimal energy consumption maneuver in the form of a velocity profile. The optimizer does this by splitting the complete problem into separate segments. In this case, the approach and departure maneuvers are spatially discretized into five-meter intervals. Like previous Dynamic Programming implementations for vehicle dynamics and racing applications, the spatially discretized model allows for minimizing the cost function where there may not be a consistent time interval. [14]

In the case of the Eco AnD Application, the DSRC communication range limits the scope of the maneuvers to 600m. The full 600 meters however, is not always used to define the problem. DSRC communication can be obstructed or the vehicle may not necessarily receive the first message at 300 meters away from the intersection. Each time the optimizer is run, a preceding calculation is performed to determine how far the vehicle is away from the intersection. This calculation is shown in Equation 3.5, where the function is taken from the Matlab Mapping Toolbox.

$$dist\ to\ intersection = distance(Lat_{int}, Long_{int}, Lat_{veh}, Long_{veh}) \quad Eq.3.5$$

Lat_{veh} and $Long_{veh}$ are given as the vehicle's latitude and longitude coordinates received by the GNSS/RTK system. Lat_{int} and $Long_{int}$ are the latitude and longitude coordinates of the intersection. The latitude and longitude coordinates for the intersections are received and decoded from MAP messages.

The Dynamic Programming in the Eco AnD Application is used to minimize a cost function. In this case, the cost function is an energy model for a 2^{nd} Generation Chevy Volt in Charge Depleting Mode. The cost function has been simplified so that is comprised of a series of coefficients, torque, velocity, and time. The coefficients were generated through a curvefit procedure using on-road data. [12] This simplified model is used to reduce the complexity of the cost function by including key powertrain parameters and efficiencies within the coefficients. Equation 3.5 represents a common LVD equation for calculating torque output and Equation 3.6 is the cost function. A typical model function for a hybrid electric vehicle would include consideration for the fuel consumed, however this Eco AnD Application focuses on a vehicle in CD Mode.

[13] Therefore, it is sufficient that the six coefficients in Equation 3.6 only relate to the battery and electric machines.

$$T = \left(F_0 + F_1V + F_2V^2 + ma + mgsin(\theta) + (I_{eff} * \alpha)/R_{wheel}\right) * R_{wheel} \qquad Eq.3.5$$

$$E = (C_1 + C_2T + C_3V + C_4TV + C_5T^2 + C_6V^2) * dt + P_{aux} * dt \qquad Eq.3.6$$

Where F0, F1, F2 are the road load coefficients for the Chevy Volt, m is the mass of the vehicle, a is the acceleration, g is gravity, I_{eff} is the effective inertia term, and R_{wheel} is the radius of the wheel. The P_{aux} term is used to account for auxiliary loads during the drive cycle such as the HVAC system, seat or steering wheel heaters, radio, etc. This also serves as a weighting value for time for the cost function. The higher the auxiliary load, the more emphasis the optimizer will put on minimizing the time it takes to complete a maneuver.

Dynamic Programming optimizers, like the one used for this Eco AnD Application, use a regressive calculation method. That is to say, the model is first solved for the last interval, and then the problem is worked in reverse until it reaches the initial interval. When generating the output, or the velocity profiles, the DP optimizer determines the best value for a control input that results in the minimization of the cost function. That control value is then used to determine the value of the preceding state. [14,15,16]

The Eco AnD Application's Dynamic Programming consists of two state variables and one control variable. The state variables are velocity and time, while the control variable is acceleration. Equation 3.7 states the update function for the velocity state, and

Equation 3.8 shows the time update calculation. In this model, time is merely calculated so that a time-based constraint can be applied.

$$V_k = \sqrt{V_{k-1} + 2a_k dx} \quad Eq.3.7$$

$$t_k = \frac{dx}{V_k} \quad Eq.3.8$$

In Equations 3.7 and 3.8 V_k and t_k are the current segments velocity and time value. Acceleration, given as a_k is the control input variable. The DP algorithm applies final value constraints, as well as grid size selection for the velocity and time states to ensure the vehicle crosses the intersection during the green interval and does not exceed the speed limit of the departure.

3.3.3 Optimization Constraints

While the DP optimization is centered around a spatially based model, the optimization performed by the Eco AnD Application is subject to both distance and time-based constraints. Constraints must be applied to prevent the application from generating a profile that would recommend the driver break traffic laws. Additional constraints can be applied to restrict the search region which limits the time it takes to run the DP algorithm.

Among the distance-based constraints are the distance to the intersection and vehicle speed. The approach of the vehicle is defined as the distance between the vehicle and the intersection before the vehicle arrives at the intersection. The approach can be 300 meters at most, but may be shorter depending on when the vehicle receives the messages transmitted by the intersection. It is imperative that none of the maneuvers generated by the application cause the vehicle to stop before the intersection or after the vehicle crosses into the intersection. The vehicle must also not cross the intersection when the light is red.

Each intersection has both an approach speed limit and a departure speed limit. In some cases, the approach speed limit may differ from the departure speed limit. Approach and departure speed limits are hard coded in this Eco AnD Application for the intersections along the RSU Loop. Figure 3.9 shows one intersection along the RSU Loop where the vehicle crosses heading south and then again heading east, while Figure 3.10 shows an intersection where the vehicle turns left and heads west. These intersections illustrate three different scenarios where the vehicle encounters different speed limits before and after an intersection, as well as, one instance where the approach and departure speed limits are the same.

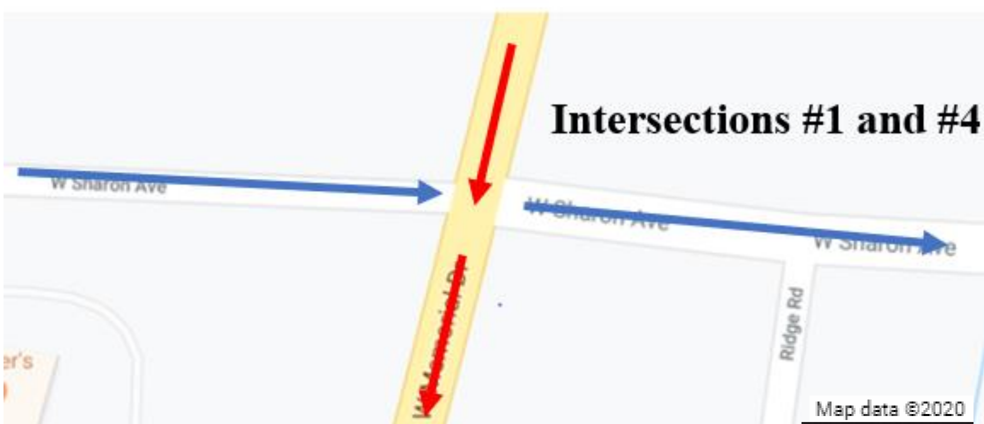

Figure 3.9 Intersections 1 and 4. (Econo Eastbound and Southbound)
Original image taken from Google Maps

Figure 3.10 Intersection 2 (MTU Library) Original image taken from Google Maps

Time based constraints are considered to ensure the vehicle does not pass through an intersection when a non-permissible phase is active. That is to say, the vehicle can only cross an intersection during a green phase so the time to clear the intersection must be greater than the opening time, and less than the closing time. The time to clear the intersection at a given speed is shown in Equation 3.9. The time-based constraint is then given in Equation 3.10.

$$t_{clear} = \frac{X}{V} \qquad Eq.3.9$$

$$t_{open} \leq t_{clear} \leq t_{close} \qquad Eq.3.10$$

In Equation 3.9 t_{clear} is given as the time it takes the vehicle to clear the intersection based on the vehicle's current speed, V in meters per second. The current distance from the vehicle to the intersection in meters is given as X.

Finally, the last constraint imposed on the model is placed on acceleration. Acceleration is the control input variable for the model and is limited between -3 and 3 m/s^2. This is not the maximum physical limits of acceleration or deceleration for a Chevy Volt, but it has been chosen for driver comfort concerns related to jerk.

3.3.4 Dynamic Programming in Matlab

The Dynamic Programming optimization responsible for determining the optimal velocity profile has been implemented using three different Matlab scripts. The first is the "dpm" function available for download through MathWorks's website. [17] The other two scripts have been created specifically for the Eco AnD Application. One script names parameters for the optimization which include sample size, number of samples, state/control constraints, and the function call handle for the "dpm" function. The other script is a model file. The state update equations and the cost functions are stored in this script.

The Eco AnD Application runs in a loop for each interval, regressively calculating the optimal combination of control input values and resulting states that contribute to a minimal energy consumption maneuver. The DP algorithm requires a user to specify the grids, or ranges, in which the state and control input values can be selected. The velocity state grid spans speeds between 0 m/s and the speed limit on the road, while the time state grid spans from 0 seconds to time the time the green phase closes.

Special considerations were made when defining the time state grid for this problem. First, the time state value is only calculated for the approach maneuver. This is because the vehicle must clear the intersection during a green phase, and this implementation makes it easier to apply the time-base constraints. Also, limiting the size of the time grid to the closing time narrows the space in which the optimizer will search for the solution.

Several parameters have been set to reduce the computational time required to run the DP optimizer. First, the problem is discretized into 5 meter segments. Depending on when the Eco AnD Application receives its first DSRC message, the vehicle will be within 300 meters of the intersection. The number of intervals in the problem are then taken as the distance divided by the discretization size. When we consider the approach and departure, the number of samples increases, which will result in a greater runtime.

The size of the state and control input grids have an impact not only and the resolution of the solution, but the runtime as well. DP algorithms calculate the cost for each control input value. The default input grid for the Eco AnD Algorithm spans -3 to 3 m/s^2 by 0.2 m/s^2 steps. Refining the discretization to 0.1 m/s^2 further increases the DP optimization time. Figures 3.11 and 3.12 show the time to run the DP optimizer with different numbers of samples in the problem and multiple state grid sizes. Table 3.3 lists the number of intervals in each test for Figure 3.11 and the discretization values for Figure 3.12.

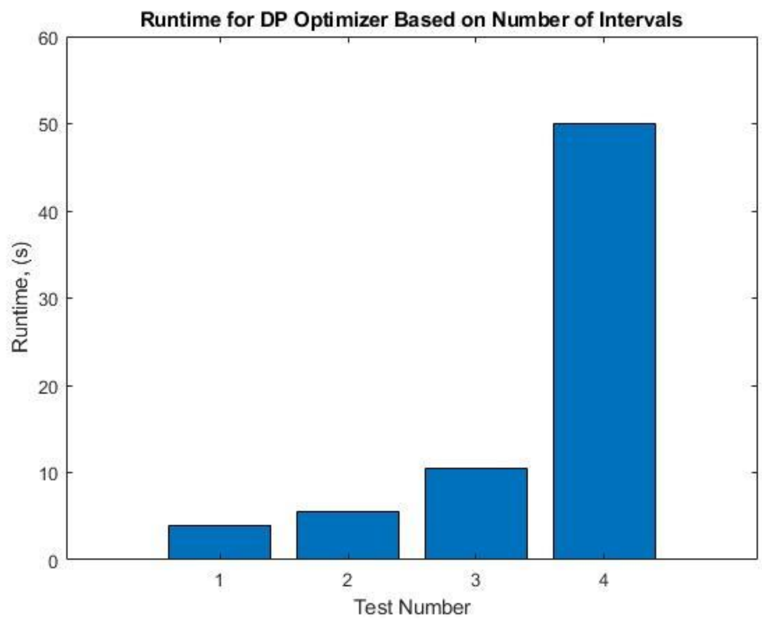

Figure 3.11 Runtimes for DP optimizer based on the number of intervals in the problem. Of the four tests conducted, test number one had the fewest intervals and ran the fastest.

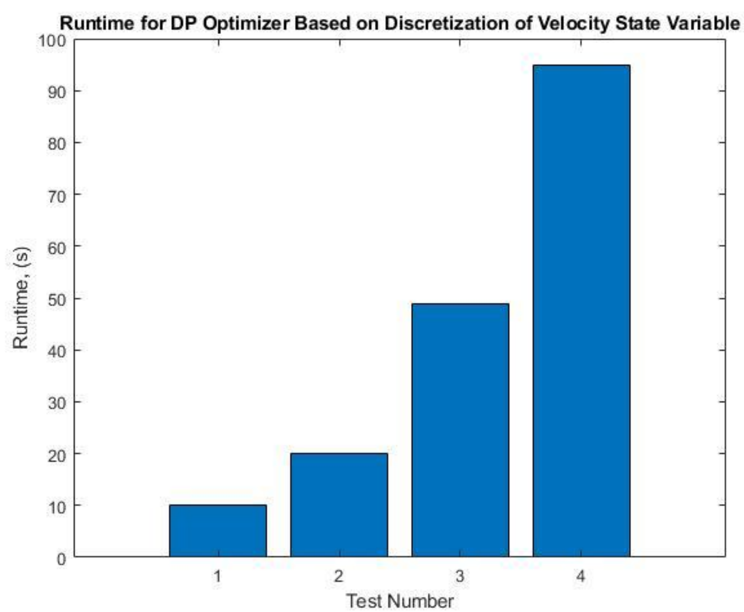

Figure 3.12 Runtimes for DP optimizer based on the level of discretization of the velocity state variable. Of the four tests conducted, test number one had the coarsest discretization at 1 m/s and ran the fastest.

Table 3.3. Test Parameters for test shown in DP Runtime Evaluation

Test Number	Dependent Parameter
Figure 3.11 Test #1	30 Intervals
Figure 3.11 Test #2	60 Intervals
Figure 3.11 Test #3	120 Intervals
Figure 3.11 Test #4	600 Intervals
Figure 3.12 Test #1	1 m/s Discretization
Figure 3.12 Test #2	0.5 m/s Discretization
Figure 3.12 Test #3	0.2 m/s Discretization
Figure 3.12 Test #4	0.1 m/s Discretization

3.4 Simulation / Comparison

The impact of the Eco AnD Application has been evaluated by using simulation tools, as well as through comparisons between generated profiles and on-road data collected by a human driver. Simulation studies have been conducted to determine effective means of eliminating velocity trajectories based on traffic laws and cyclic offsets in intersection timing and distances. A version of the Dynamic Programming has been created to run on a desktop where a user can input initial conditions for an intersection and vehicle, to which a velocity profile will be generated. That profile can then be compared to on-road data to determine how much energy can be saved using the Eco AnD Application.

3.4.1 Simulated Intersections and RSU Loop

A model for each intersection has been created using Matlab and Simulink. Each intersection is then set to be a reference model within an RSU Loop model. Every intersections' timing, distance, and grade is set within the respective models. Tables 3.3 and 3.4 lists the parameters for Intersection #4, while Figure 3.13 illustrates an intersection modeled using Matlab's Autonomous Vehicle Toolbox.

Table 3.4. Intersection #4 Timing Parameters (Econo Southbound)

Traffic Light Timing Info		
Intersection	**Phase**	**Timing (sec)**
Econo (N/S)	**Red**	**43**
	Yellow	**5**
	Green	**21**

<u>Table 3.5. Intersection #4 Modelling Parameters</u>

Speed Limit	**Approach**	**45 mph**
	Departure	**45 mph**
Change in Elevation (m)	**27.7**	
Avg. Maneuver Time, (s)	**52.3**	
Avg. Distance (m)	**600 ± 1**	

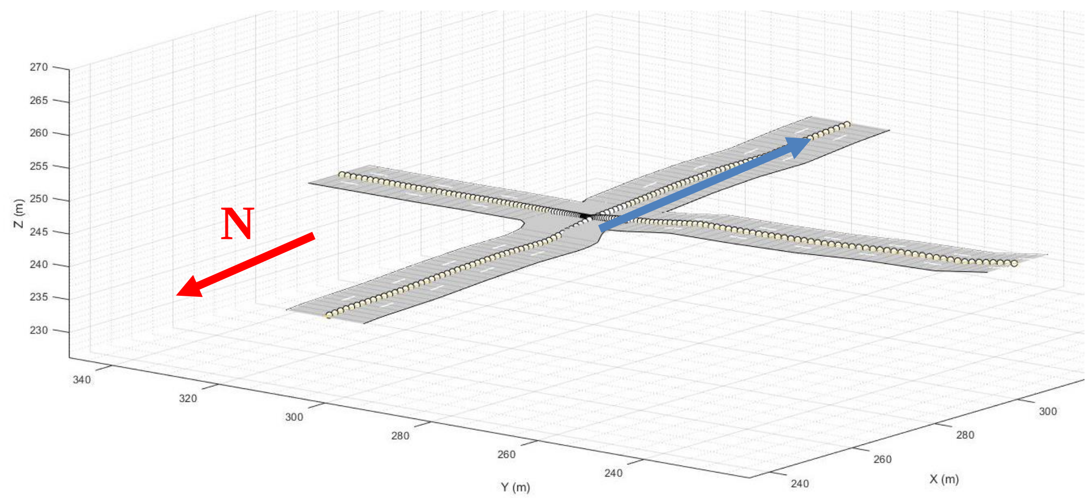

Figure 3.13 3D Rendering of the Econo Southbound Intersection using elevation and location data recorded on-road. Model and plot created using Matlab's Autonomous Driving Toolbox. Direction of travel for traffic flow is shown with a blue arrow.

The same process has been followed for creating models for the other five intersections. This model has been designed to allow for testing with on-road data velocity profiles as well as optimized velocity profiles. The velocity trajectory input to this model is then checked for overall energy consumption, in addition to how well the profile follows the traffic laws. Figure 3.14 depicts the output of the RSU Loop model, where it compares an on-road velocity profile with an optimizer generated profile. This allows for comparing real world experimental profiles with optimized simulation profiles. At the same time, this tool quickly allows the user to check that the optimized profiles adhere to traffic laws and pass through the intersections when permitted.

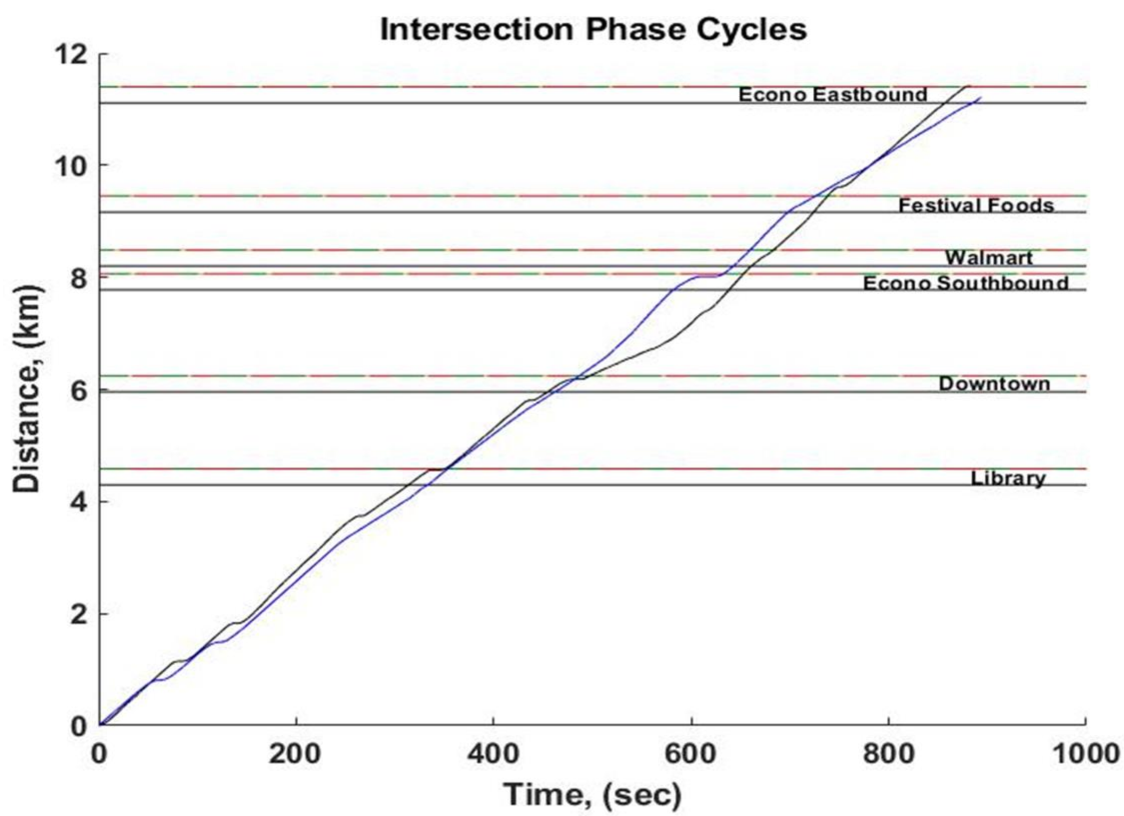

Figure 3.14 Resulting data shown for comparing two velocity profiles of a vehicle in the simulated RSU Loop environment. Profiles are checked for energy consumption, as well as whether or not it violates any traffic laws. In this example, the black line is the on-road data, while the blue line represents a simulated profile.

3.4.2 Eco AnD Application Compared to On-Road Data

To evaluate the effectiveness of the Eco AnD Application's optimized velocity profiles, the generated profiles can be compared to data collected during on-road testing. The Eco AnD Application will accept the same conditions the human driver faced on the road during testing, and output a velocity trajectory that minimizes the overall energy consumption. The effectiveness of the Eco AnD Application can be evaluated by comparing its resulting energy consumption to the measured energy consumption in the on-road data.

Measurements have been collected for several approach and departure maneuvers for five of the six intersections on the RSU Loop. Only approach maneuvers were collected for the sixth intersection. Table 3.5 lists the preliminary tests results showing the potential impact of a human driver who is knowledgeable about the cyclic timing and offsets of each intersection. These tests were conducted on an intersection-by-intersection basis to assess the potential impact an Eco AnD Application could have on overall energy consumption of the vehicle.

Table 3.6. Prelim Results of Eco AnD Impact for Intersection #4

	Potential Energy Savings	Potential Increase, (MPGe)
Single Intersection	0.26 MJ / 29.9%	+20.9
RSU Loop	5.0%	+8.1
MTU DC	1.3%	+1.9

The same data sets collected in the preliminary tests could also be used for comparison with the Eco AnD Application. The prelim testing showed that there was indeed a potential for reducing the energy consumption of a vehicle, but those tests still involved a human driver. The Eco AnD Application was used as part of a simulation study to compare to the human driver. Parameters like current phase, time required to complete the maneuver, whether the vehicle stopped, etc. were all taken into consideration when developing the profiles using the Eco AnD Application. Data was recorded for the human driver beginning 300 meters before the intersection, and 300 meters after the intersection. To match this, the Eco AnD Application was constrained to travel a total of 600 meters assuming the intersection is located at the end of the first 300 meter segment.

The results of the comparison showed that there was still room for improvement beyond the human driver's capability. Ensuring that the simulated vehicle traversed the same distance in the same time, with or without stopping, and subject to realistic acceleration constraints, the simulations continually proved that the Eco AnD Application was capable of further reducing the overall energy consumption of the vehicle. The results for two intersection are listed by intersection in Table 3.6.

Table 3.7. Comparison of On-road Energy Consumption and Eco AnD Optimized Profiles

Intersection	Test	On-Road Energy, (kJ)	Optimizer Energy, (kJ)	Change in Energy, (kJ)
4	1	732	695	-37
4	2	827	681	-146
4	3	763	681	-82
4	4	673	602	-71
4	5	781	667	-114
5	1	733	575	-158
5	2	889	620	-269
5	3	767	612	-155
5	4	822	651	-171
5	5	845	667	-178

The negative values in the Change in Energy column represent energy recovered back to the battery. For Intersections 4 and 5 (Econo Southbound and Walmart) all five tests concluded that the Eco AnD Application can further reduce energy consumption beyond that of a human driver.

Figure 3.15 has been provided to represent the different velocity trajectories used by the human driver and the Eco AnD Application. Of important note, the human driver tends to make more sudden accelerations or decelerations while the application decides to change speed more gradually. In both cases the vehicle does not need to stop at the intersection, but both the driver and the simulated vehicle are subject to speed limits imposed on the road.

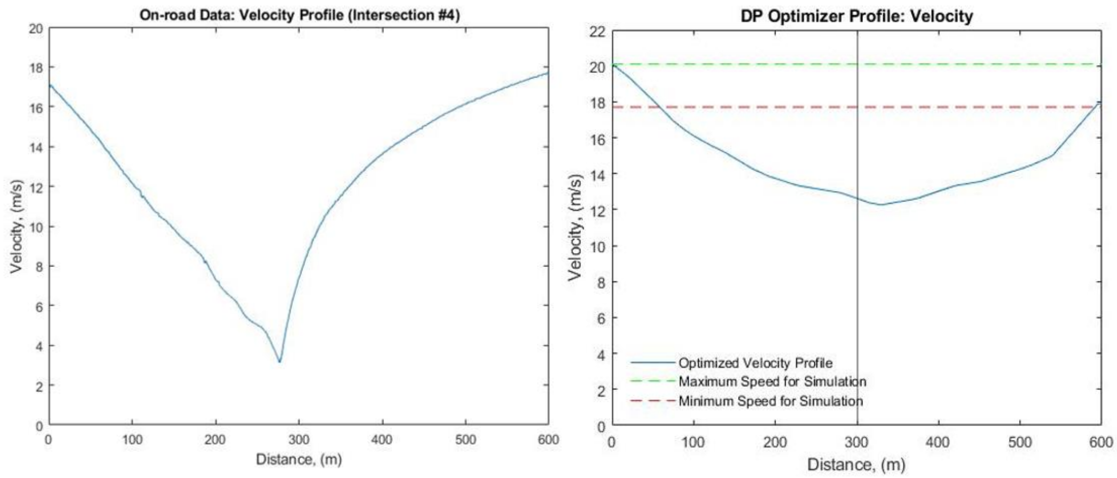

Figure 3.15 Comparison between on-road maneuver and the Eco AnD Application's DP optimizer output trajectory. The DP optimizer's profile changes speed more gradually. Both vehicles complete the maneuver at the same final velocity.

In order to compare both profiles, the DP optimizer was given the characteristics of the on-road maneuver and adjusted to match. The final speed has been constrained to meet the same final speed as the on-road maneuver, spanning the same distance. The DP optimized profile, while starting at a slightly higher velocity saves 37 kJ of energy compared to the on-road maneuver. In the plot on the right, the green line represents the speed limit of the maneuver and the red line represents the final speed indicated by the on-road data.

Analysis of the Eco AnD Application's impact on energy consumption for each intersection shows further energy reduction is possible beyond the preliminary testing results. Table 3.8 lists the results of using the Eco AnD Application to simulate not only the impact on the energy consumption while in Charge Depleting Mode, but also anticipated results for other operating conditions. Data provided in Table 3.8 is given for the entire MTUDC.

Table 3.8. Preliminary Experiment Energy Reduction Results

	Average Driver, (MJ)	Eco AnD App, (MJ)	Energy Savings, (%)
Charge Depleting Mode	19.4	18.5	4.6
Blended Mode - 31% SOC	38.9	38.0	2.3
CS Mode - Lower Limit SOC	60.8	59.9	1.5
CD-CS Mode - 26 to 29% SOC	48.6	47.7	1.9
CD-CS Mode - 26 to 29% SOC (Hold Mode)	49.8	48.9	1.8

4 Implementation of the Eco AnD Application

After developing the Eco AnD Application, simulating maneuvers offline, and comparing the results to on-road data, the application is ready to be implemented into a 2nd Generation Chevy Volt. The integration process begins with creating a Simulink model that will establish the flow of information through the model, and call the Dynamic Programming to perform optimizations as necessary. Once the Simulink model is complete it must be downloaded to the vehicle's Micro Auto Box II so that it can be run in real time while the vehicle navigates the drive cycle. Finally, data must be relayed back to the driver via the HMI screen and recorded for post processing. This section will discuss each step of the implementation process and offer insights into technical details related to online usage of the Eco AnD Application.

4.1 Integration of the Eco AnD Model with the Vehicle

The Eco AnD model is not only intended to be used for offline simulations, but also for online use onboard a test vehicle. The offline simulation model has been built into a Simulink model so that it can be used for online testing.

The Eco AnD Simulink model acts as an interface for the input signals received from the Cohda radio and CAN messages, as well as the output velocity profile created by the optimizer. The required input signals received from SPaT and MAP messages are decoded using dSpace V2X Blockset within the Simulink Model. Figure 4.1 illustrates the flow of data from the intersection to the Eco AnD optimizer.

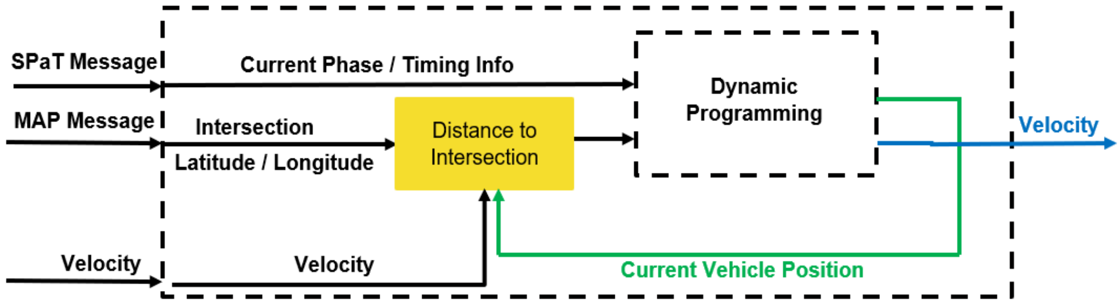

Figure 4.1 Flow Chart for Data input and output from the Eco AnD optimizer. The application requires information from SPaT and MAP messages, as well as CAN signals such as velocity and the vehicle's location.

4.2 Using the Application On-Road

The Eco AnD Application can be used on-road to help reduce the overall energy consumption of a Chevy Volt. After the Simulink model has been downloaded to the Micro Auto Box, data recorders and instrumentation panels can be created specifically for Eco AnD testing. These data recorders and instrumentation panels are created in dSpace's ControlDesk.

Data recorders in the ControlDesk Application from dSpace can be assigned to run continuously, or as triggered events. The Eco AnD Application's evaluation will require the data recorders to collect data continuously. The data recorder designed for the Eco AnD Application will monitor vehicle signals from the CAN bus such as velocity, location, battery current and voltage, etc. It will also need to record the relevant information from the DSRC messages. The same signals discussed in previous sections related to the inputs to the DP optimizer, will be recorded.

As the Eco AnD Application generates maneuvers, the velocity predictions must be relayed back to the driver. The driver must then be able to quickly identify what actions must be taken to follow the maneuver. To accomplish this, the predicted velocity, as well as other intersection information will be displayed on a HMI screen in the drivers field of view.

The data that will be displayed on the HMI's panel must be selected in ControlDesk and added to a "layout." The layout for the Eco AnD Application consists of a speedometer with three needles, a traffic light identifying the phase, and a readout for how long until the current phase ends.

5 Conclusion and Future Works

The work described in this thesis has been done to develop an Eco Approach and Departure Application that can be used to reduce the overall energy consumption of a hybrid-electric test vehicle along a predetermined drive cycle. The test vehicle in this study was driven in Charge Depleting Mode. This thesis has covered the development of an Eco AnD Application, from preliminary analysis to determine the potential impact of this type of application, to the low-level technical details of the applications functionality, and finally the on-road evaluation of the Eco AnD Application's performance.

The on-road evaluation will be performed at the American Center for Mobility (ACM) in Ypsilianti, MI. The demonstration will consist of a static test to show the vehicle is capable of receiving and decoding SPaT Messages, as well as a dynamic test where the vehicle will drive along a route where it will encounter a signalized intersection and active the Eco AnD application. The signalized intersection will be a six-by-six intersectin broadcasting eight Movement States. Depending on the information received from the traffic light, the optimizer will generate a maneuver for the driver to follow. The driver will follow the maneuver suggested, ensuring it does not violate any traffic laws while collected data to determine the energy consumption of the vehicle.

5.1 Conclusions

The Eco Approach and Departure Application relies heavily on information collected from messages received through DSRC communication. Chapter 2 provides insights into what DSRC communication is and what aspects of the messages pertain to this application. Due to range limitations of DSRC communication, the Eco AnD Application's use is also confined to 300 meters before and after a traffic light while on-road.

An offline calculation version of the Eco AnD Application has been developed to test generated maneuvers in a simulation environment. Knowing the intersection parameters, each intersection could be modeled and added to the simulation. A larger simulation model has been developed to include all six intersections and the Dynamic Programming optimizer.

Chapter 3 has provided an overview of the simulation capabilities. Specific considerations were discussed where it comes to developing the simulation models. A low-level dive into the DP optimizer including how it was developed, use cases, and technical details was also provided. Thus far, the Eco AnD Application has been used to show simulated savings in various modes of operation for the Chevy Volt. In scenarios where the Chevy Volt is operating in CD Mode, the Eco AnD application has demonstrated the largest energy savings of 4.6 percent. Even though the application was not originally developed for use with Charge Sustaining operation, the Eco AnD application nearly reaches the 2 to 4 percent goal, resulting in 1.8 percent energy savings in Hold Mode scenarios.

Finally, the implementation of the Eco AnD Application into a 2nd Generation Chevy Volt was discussed in Chapter 4. The application was originally created and tested offline using Matlab. The same functions that make up the Eco AnD Application were then added to a Simulink model using S-function blocks. The Simulink model, when downloaded to the Micro Auto Box II on the Volt, allows the application to be ran on-road. The Eco Approach and Departure Application has been demonstrated at the American Center for Mobility using the six-by-six intersection.

5.2 Future Work

While developing this Eco Approach and Departure Application, a few points of interest were noted as avenues for future development. Potential points of improvements include adaptations of the optimizer, further development of more compressive driver feedback systems, and updates to the simulation environment to increase robustness.

Like other DP algorithms, the Eco AnD Application's optimizer can be considered a "greedy optimization." This is to say that the optimizer will minimize the cost function for this vehicle. As discussed in Chapter 3, the DP algorithm will minimize the energy consumed by slowing the vehicle down so that it crosses the intersection later in time.

Extending the time of the maneuver may be favorable in terms of energy consumption, but the maneuvers may not be suitable for every on-road scenario. Of important concern is the likelihood to aggravate the drivers following behind the test vehicle. The optimizer will ensure the test vehicle makes it through the intersection, but slowing down to meet the end of the green phase may cause the drivers behind the test vehicle to get stopped at the intersection. This may be resolved by introducing additional constraints to limit how much a test vehicle may slow down.

One other solution would be to add a factor into the model to account for a following vehicle. Using BSM messages, another DSRC message transmittable from vehicle to vehicle, the test vehicle may be able to receive information about the following vehicle and account for that vehicle in the optimizer as well. To that effect, the energy consumption of a platoon of vehicles could then be considered in addition to the overall energy consumption of the test vehicle.

The current implementation of the Eco AnD Application provides a profile for the driver to follow on the HMI display shown in Chapter 4. Through testing, this has proved to be difficult at times when traffic density is higher, at higher speeds, and in scenarios where the intersection's phase changes more suddenly. Developing additional features or tools to make relaying the recommended maneuver to the driver would benefit the testing and evaluation process by making it easier for the driver to follow the maneuver.

Finally, the Eco AnD Application's simulation environment should be updated as often as possible. Including models for more intersections would increase the number of scenarios that can be simulated. As discussed in Chapter 3, intersection models can quickly be created or updated using Matlab's Mapping Toolbox. Intersection models have already been created for the intersections on the MTUDC, but additional intersections could be made to include the intersections at ACM as that is where the Eco AnD Application will also be tested.

6 Reference List

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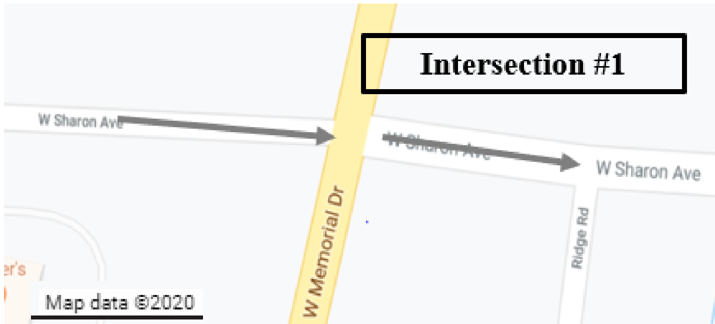
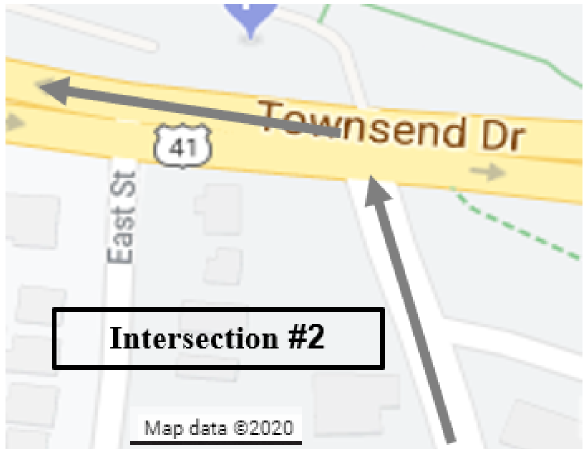
A Intersection Model Parameters



Traffic Light Timing Info		
Intersection	Phase	Timing (sec)
Econo (E/W)	R	50
	Y	3
	G	20

Speed Limit	Approach	25 mph
	Departure	35 mph
Change in Elevation	- 200 m	
Avg. Maneuver Time	28 Sec	
Avg. Distance	300m ± 10m	

Intersection #1 - Parameters for Econo Eastbound Intersection Model. (Original image collected from Google Maps)



Traffic Light Timing Info		
Intersection	**Phase**	**Timing (sec)**
Library (N/S)	R	40
	Y	4
	G	25

Speed Limit	Approach	25 mph
	Departure	30 mph
Change in Elevation	- 35.8 m	
Avg. Maneuver Time	71.1 sec	
Avg. Distance	600m ± 1m	

Intersection #2 - Parameters for MTU Library Intersection Model. (Original image collected from Google Maps)

Traffic Light Timing Info		
Intersection	**Phase**	**Timing (sec)**
Downtown (W)	**R**	**24**
	Y	**4**
	G	**32**

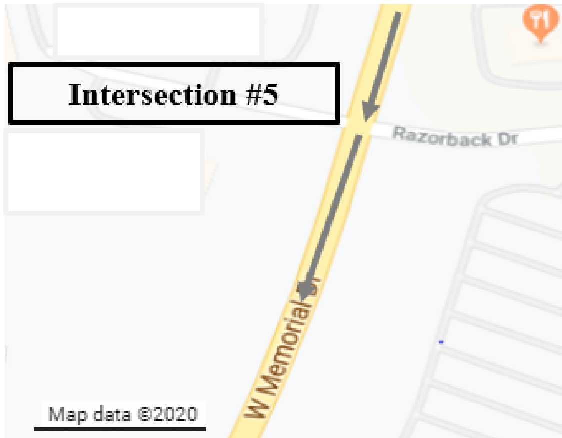
Speed Limit	**Approach**	**25 mph**
	Departure	**25 mph**
Change in Elevation	**-5.2 m**	
Avg. Maneuver Time	**69 sec**	
Avg. Distance	**600m ± 1m**	

Intersection #3 – Parameters for Downtown Intersection Model. (Original image collected from Google Maps)

Traffic Light Timing Info		
Intersection	**Phase**	**Timing (sec)**
Econo (N/S)	**R**	**43**
	Y	**5**
	G	**21**

Speed Limit	**Approach**	**45 mph**
	Departure	**45 mph**
Change in Elevation	**27.7 m**	
Avg. Maneuver Time	**52.3 sec**	
Avg. Distance	**600m ± 1m**	

Intersection #4 – Parameters for Econo Southbound Intersection Model. (Original image collected from Google Maps)



Traffic Light Timing Info		
Intersection	**Phase**	**Timing (sec)**
Walmart(N/S)	R	31
	Y	5
	G	31

Speed Limit	Approach	45 mph
	Departure	45 mph
Change in Elevation	24.7 m	
Avg. Maneuver Time	33.7 sec	
Avg. Distance	600m ± 1m	

Intersection #5 – Parameters for Walmart Intersection Model. (Original image collected from Google Maps)

Traffic Light Timing Info		
Intersection	**Phase**	**Timing (sec)**
Festival Foods (E/W)	R	44
	Y	3
	G	22

Speed Limit	Approach	45 mph
	Departure	25 mph
Change in Elevation	26.4 m	
Avg. Maneuver Time	50 sec	
Distance	600m ± 1m	

Intersection #6 – Parameters for Festival Foods Intersection Model. (Original image collected from Google Maps)