An Analysis of EcoRouting Using a Variable Acceleration Rate Synthesis Model

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Academic Abstract

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Automotive manufacturers are facing increasing pressure from legislative bodies and consumers to reduce fuel consumption and greenhouse gas emissions of vehicles. This has led to many automotive manufacturers starting production of Plug-in Hybrid Electric Vehicles (PHEV's) and Battery Electric Vehicles (BEV's). Another method that helps to reduce the environmental effect of transportation is EcoRouting.

The standard Global Positioning System (GPS) navigation offers route alternatives between user specified origin and destination. This technology provides multiple routes to the user and focuses on reducing the travel time to reach to the destination. EcoRouting is the method to determine a route that minimizes vehicle energy consumption, unlike traditional routing methods that minimize travel time. An EcoRouting system has been developed as a part of this thesis that takes in information such as speed limits, the number of stop lights, and the road grade to calculate the energy consumption of a vehicle along a route.

A synthesis methodology is introduced that takes into consideration the distance between the origin and destination, the acceleration rate of the vehicle, cruise speed and jerk rate as inputs to simulate driver behavior on a given route. A new approach is presented in this thesis that weighs the energy consumption for different routes and chooses the route with the least energy consumption, subject to a constraint on travel time. A cost function for quantifying the effect of travel time is introduced that assists in choosing the EcoRoute with an acceptable limit on the travel time required to reach the destination.

The analysis of the EcoRouting system with minimum number of conditional stops and maximum number of conditional stops is done in this thesis. The effect on energy consumption with the presence and absence of road-grade information along a route is also studied. A sensitivity study is performed to observe the change in energy consumption of the vehicle with a change in acceleration rates and road grade. Three routing scenarios are presented in this thesis to demonstrate the functionality of EcoRouting. The EcoRouting model presented in this thesis is also validated against an external EcoRouting research paper and the energy consumption along three routes is calculated. The EcoRoute solution is found to vary with the information given to the variable acceleration rate model. The synthesis and the results that are obtained show that parameters such as acceleration, deceleration, and road grade affect the overall energy consumption of a vehicle and are helpful in determining the EcoRoute.

General Audience Abstract

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The automotive industry is undergoing a major transformation throughout the world in terms of regulations on greenhouse gas emissions and fuel consumption. There is a significant amount of research being done on reducing emissions of cars while maintaining safety, performance and consumer acceptability of vehicles with an emphasis on cost and innovation. Vehicle manufacturers have started manufacturing Plug-In Hybrid Electric Vehicles (PHEV's) and Battery Electric Vehicles (BEV's) with a focus on reducing petroleum use.

While a lot of work is being done on manufacturing cars that help reduce emissions, significant research is also being conducted to help navigate cars in an energy efficient manner. EcoRouting is defined as the method that helps to route cars efficiently and conserve energy.

EcoRouting helps to increase fuel efficiency without any modifications to the vehicle powertrain and can be customized to any vehicle. A simulation study to analyze the effects of EcoRouting in different driving conditions with an emphasis on the effects of road grade and stop lights on energy consumption is presented. The EcoRoute solution is found to vary with the road grade, the maximum allowed acceleration, and the number of conditional traffic lights. The synthesis and the results that are obtained show that external parameters such as road grades, speed limits, and stop lights affect the overall energy consumption of a vehicle and that EcoRouting can significantly reduce vehicle energy consumption.

The EcoRouting research done in this thesis focuses mainly on analyzing the effect of changes in road grade and accelerations on the energy consumption of a vehicle. A sensitivity study is performed to study the change in energy consumption of a vehicle with a change in road grade and acceleration. It is found that the net difference in elevation between the origin and the destination plays a significant role in determining the energy consumption of a vehicle. This thesis also focuses on formulating a cost function for the maximum permissible travel time required to reach the destination and shows how travel time is an important metric to determine an EcoRoute. Three case studies are presented which provide a demonstration of the discussed methods and typify a working EcoRouting model.

Dedication

Dedicated to my parents, for all the sacrifices they made for my education.

Acknowledgements

I would like to thank Dr. Douglas Nelson for being an outstanding mentor, a disciplined professor and most importantly, a good friend during my tenure while working with him as a grad student. The ability to always go above and beyond of what is expected of us is something that Dr. Nelson has taught me and will leave an indelible impression on me. I am grateful to Dr. Baumann for having faith in my abilities as the ECE Graduate Research Assistant and letting me teach a few of his sophomore micro-controller classes. I would also like to thank him for the conversations in his office about world politics and introducing me to American idioms.

I would like to thank my parents, for helping me and supporting me in this journey at Virginia Tech. The constant support and encouragement that they provided has helped me to overcome many hurdles in the past couple of years. The sacrifices that they have had to make for me to reach this position have been truly exceptional and no words could do justice to them. Aai and Baba, we accomplished this!

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I would also like to thank Matt Moniot, for always being patient and helping me to understand his velocity profile model, and always being ready to play a game of ping pong.

Last but not the least, I would like to thank Pramit Baul, for introducing me to the topic of EcoRouting and for being a good friend, throughout my entire journey at Virginia Tech. I had no idea that a random encounter in a Computer Vision class would lead to such a beautiful friendship.

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1) Chapter One- Introduction

Fuel regulations in the automotive industry are getting stricter by the day. Corporate Average Fuel Economy (CAFE) standards set by the United States government dictate the fuel economy of an automobile for driving in the United States. The tighter restrictions by the government on fuel economy for cars has provided an impetus to the research and development of efficient electric powertrains. Many automobile manufacturers are actively looking to manufacture a larger fleet of electric vehicles and increase their market share in the world of electric vehicles. The efforts to reduce fuel consumption are not restricted to the powertrain level itself. Research is being carried out currently to improve the fuel efficiency of a vehicle with a focus on powertrain agnostic methods. EcoRouting is one such method that helps reduce fuel emissions.

EcoRouting is defined as the determination of a route that minimizes vehicle energy consumption, unlike traditional routing methods that minimize travel time (TT) as shown in Figure 1-1. While EcoRouting may not always provide the shortest possible route, it aims to provide a route that consumes minimum energy.

Hybrid electric and battery electric vehicle sales have dropped in recent years [1], which has been attributed to falling fuel prices [2]. However, the drop is temporary and several studies forecast a rise in fuel prices by 2018 [3]. The 2018 fuel cost environment will likely encourage adoption of this technology by industry and subsequently consumers.

EcoRouting also has the potential to give rise to an entirely new field in the automotive industry. The EcoRouting module can be customized to each vehicle using a model of basic vehicle parameters to estimate energy consumption over a routing scenario. The benefits of EcoRouting include the potential to make almost any car more fuel efficient by using an online cost model that takes real time traffic information from an on-board computer or by using a centralized Vehicle to Infrastructure (V2I) system to evaluate efficient routes.

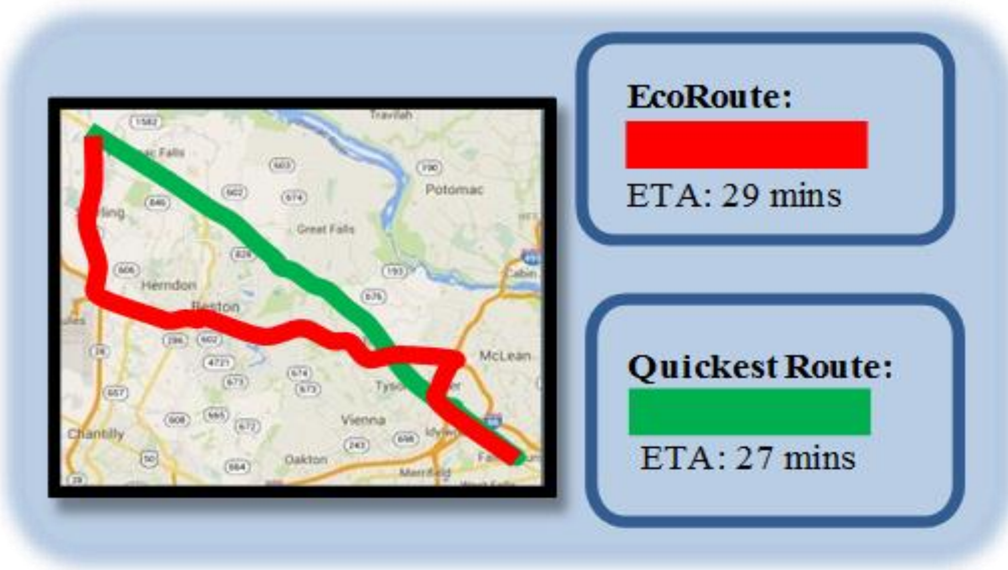

Figure 1-1: Arterial and Highway Routes used for Energy Consumption [4]

EcoRouting depends on external factors such as distance of the destination from the source, the speed limits of the travel path, road grade, and the total idle time required to reach the destination. There are other factors, such as the weather conditions, humidity and the speeds of other vehicles, that impact energy consumption. However, these factors are out of scope for this thesis.

The branch of graph theory which deals with effective routes to reach a destination is commonly referred to as Path Planning. Path Planning algorithms are commonly used in robotics to find the most efficient paths to reach the destination. The most commonly used Path Planning algorithm is Dijkstra's Algorithm [5]. Dijkstra's algorithm is a greedy algorithm which often fails to provide the optimum solution to reach the destination. Other algorithms that are commonly used in the Path Planning literature are the A* algorithm [6] and the Bug algorithms [7]. Lost Cow problems [8] and the traveling salesman problem [9] are being intensively studied to find computationally efficient methods for path planning.

With the advent of autonomous vehicles, automobile manufacturers are considering the class of algorithms related to dynamic routing of vehicles [10] and trying to implement Rendezvous algorithms [11] that help vehicles to communicate with one another and reach an optimal solution by utilizing the least amount of time and distance.

EcoRouting analysis is essentially a path planning problem with the cost function being energy instead of distance. EcoRouting can be classified as being closely aligned to the set of Vehicle Routing Problems (VRP). The travelling salesman problem also fits into the category of VRP.

However, the travelling salesman problem is an NP complete problem in some scenarios. This makes it impossible to reach a globally optimal solution in finite polynomial time. The EcoRouting problem is not an NP complete problem and sub-optimal solutions to it can be found in a finite, deterministic amount of time.

1.1) Current State of EcoRouting Technology

EcoRouting is a topic that is currently being researched by many leading automotive manufacturers. The need for energy efficient vehicles has led to the research and development of different EcoRouting modules. A part of the EcoRouting system also emphasizes improving overall driver behavior to focus on energy efficient driving. The technology that provides feedback to the driver to focus on energy consumption is popularly referred to as EcoDriving. EcoDriving modules also help to estimate future cost savings and provide the driver a detailed feedback for adopting energy efficient driving practices.

EcoRouting modules can be broadly classified into two categories: powertrain-based and powertrain-agnostic. Powertrain-based modules for EcoRouting take into consideration the different powertrain architectures of vehicles and provide the EcoRoute based on the energy requirements of the vehicle powertrain. These modules provide a detailed analysis of how much energy is being consumed by the vehicle and the efficient driving practices that should be adopted based on the powertrain architecture. Powertrain based modules for EcoRouting take into consideration the effect of internal parameters of the vehicle like grid energy, thermal energy etc., as well as the effect of external parameters like traffic data, elevation of the routes, weather etc. Powertrain agnostic modules usually account for the effect of external factors only to calculate the EcoRoute and provide a generalized feedback of efficient driving practices.

Major automotive manufacturers like Ford, Nissan, General Motors, Toyota, Honda, Hyundai etc. are quickly making a foray into the area of EcoRouting. Most of the research in EcoRouting revolves around conventional vehicles and battery electric vehicles. Automobile manufacturers provide an option to the driver to use an “Eco” mode to conserve energy and increase fuel savings. The eco-routing module used by Ford provides an option to the driver to choose between the shortest route, fastest route and the most energy efficient route. The driver may choose the routes depending upon his/her need. Real-time traffic information is also used by Ford’s proprietary eco-routing module called MyTouch™ [12] to estimate the amount of time and fuel required to reach the destination. The data provided by this module is updated in real time and the eco-route may also be changed dynamically depending on the traffic scenario at that time. This module can be used by the driver when he/ she switches to the option of driving in the “Eco” mode.

The EcoRouting strategy used by Nissan for routing its battery electric vehicles adds a unique constraint. The EcoRouting strategy takes into consideration the locations of electrical charging points while determining the most energy efficient path. The module used by Nissan is called CARWINGS ™ [13] and it is currently used in the Nissan Leaf. CARWINGS also provides the data of available charging stations to the driver when it provides the eco-route. The research in

EcoDriving also involves changing the pedal map strategy to conserve energy. Hyundai Sonata and Toyota Prius have incorporated a different pedal map strategy that is more suitable for improving the overall fuel economy of a vehicle. Reinforcement techniques like ‘rewarding’ the driver with green leaves and providing an estimate of the total money saved are also used by car manufactures to encourage people to drive in an eco-friendly manner. Honda Insight is one such example where drivers are ‘rewarded’ if they consistently adopt a fuel-efficient path to drive.

There is a significant amount of research being done for conventional vehicles and battery electric vehicles, however, not all automotive manufacturers have implemented EcoRouting strategies for Hybrid Electric vehicles. Chevrolet Volt has a “Mountain Mode” feature which helps to form an eco-driving strategy based on either the Charge depleting or the Charge sustaining modes. General Motors has also filed a patent for their own proprietary Eco- routing module. This patent involves commanding the powertrain to shift from the charge-sustaining mode to the charge-depleting mode when the hybrid vehicle has traveled a distance that is greater than or equal to the charge-depleting operating threshold. Garmin has developed their own eco-routing module called the “Garmin Mechanic” [14] which connects to the On-Board Diagnostics (OBD) port of the vehicle and provides feedback to the driver about the fuel consumption and the costs that were saved over a period of one week. This module can be used for hybrids as well and provides good eco-driving feedback to the driver.

A scalable powertrain model was developed by Courtney Tamaro [15] which uses publicly available data to calculate energy consumption results for conventional vehicles, battery electric vehicles and hybrid electric vehicles. This model accounts for the effect of external and internal parameters on energy consumption and helps to obtain the EcoRoute. A variable acceleration rate synthesis model was developed by Matt Moniot [16] and is used in conjunction with Tamaro’s model to accurately carry out the EcoRouting analysis for a hybrid electric vehicle.

1.2) Terminology

The starting point for the journey is defined as the source whereas the end-point is defined as the destination. A route is defined as any path between the source and destination. Every route between the source and the destination is broken into small segments with the help of placeholders, commonly referred to as nodes. The nodes for every route are unique and consist of an ID along with the knowledge of their geographical position represented in the form of their latitude, longitude and elevation. This representation of routes as a cluster of nodes is commonly used in graph theory.

Graphs are classified into two categories: Directed and Undirected graphs.

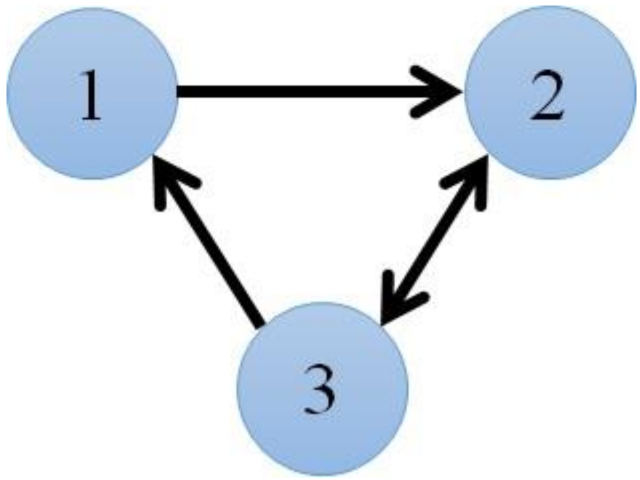

Figure 1-2: Directed Graph

Directed graphs are graphs represented in a two- dimensional manner that is a set of vertices connected by edges, where the edges have a directionality vector associated with them. Like most roads, which have a direction associated with them, directed graphs help us to find the direction from one node to the other. In a directional graph, one cannot move from one node to another if they do not have a directed edge.

The number of nodes that can be reached from a single node is defined as the degree of the graph. As shown in Figure 1-2, the nodes 1 and 2 have a degree of one whereas the node labeled 3 has a degree of two, since it is possible to go from node 3 to node 1 and node 2.

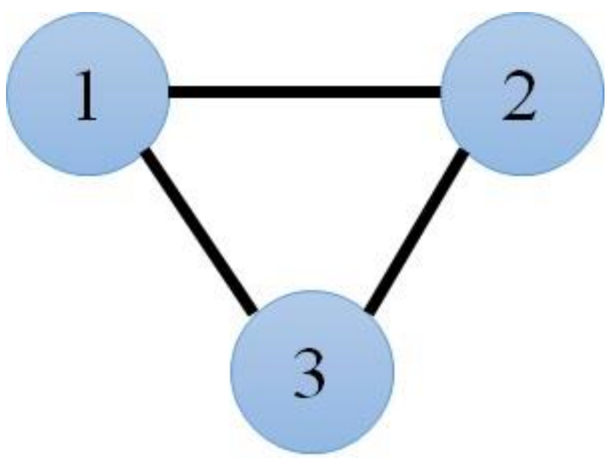

Figure 1-3: Undirected Graph

Figure 1-3 shows an undirected graph. This type of a graph allows travel from one node to another irrespective of the direction of the edge. It is possible to travel in any direction and thus greater complexity is associated with undirected graphs compared to directed graphs. For routing and path planning purposes, a directed graph is always considered as it helps us to reach the solution in a finite amount of time.

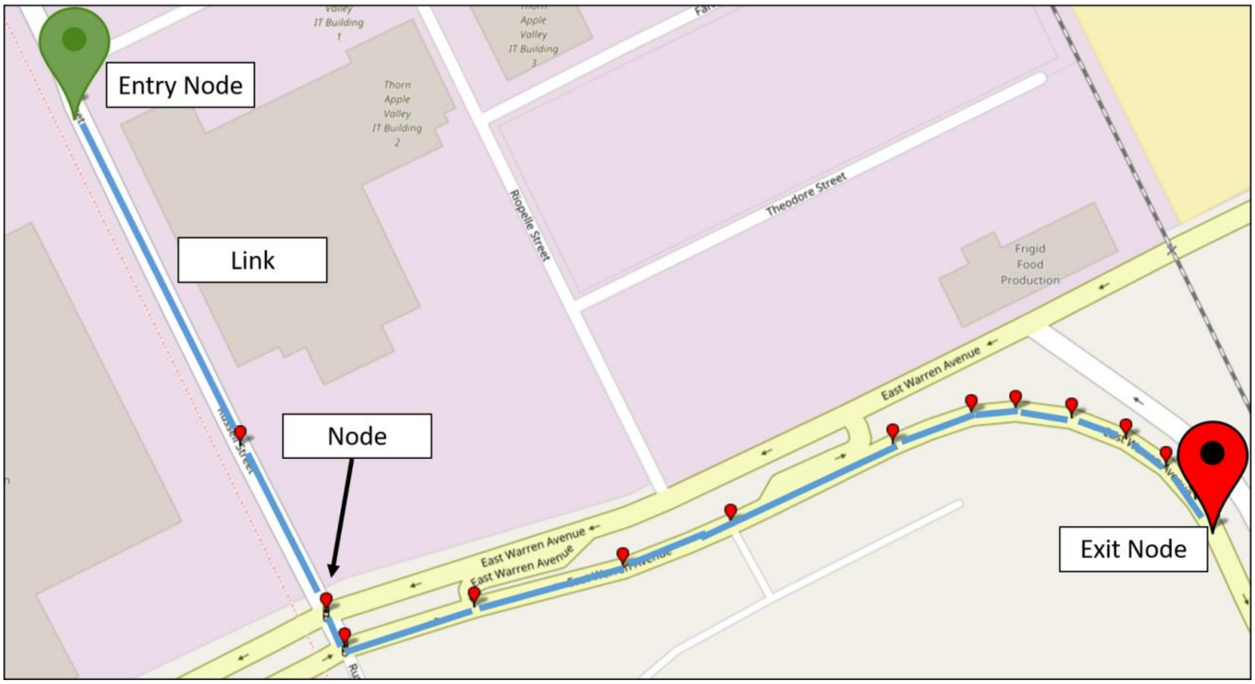

Figure 1-4: Visualization of basic route terminology [17]

As shown in Figure 1-4, every route can be looked as a set of nodes and edges. The discretization of routes helps us to calculate the energy expended by a vehicle between two nodes. The total energy is obtained by cumulatively adding the energy between the nodes. The cost function to calculate energy between two nodes is also obtained through the process of discretization of routes.

1.3) Geographical Coordinate Systems

For this thesis, information about latitude, longitude and the grade between two adjacent nodes is of prime importance. These parameters help us to define the precise geographical location of each node in the network of routes. The geographical information of each node is obtained through open source platforms. These parameters constitute the Geographic Co-ordinate Systems (GCS). GCS data is a standardized set of data that can be used worldwide. The GCS data is typically obtained from Global Positioning System (GPS) satellites.

The three types of GCS systems used as a part of route information in this thesis are:

1) World Geodetic Systems (WGS84)
2) Earth Centered Earth Fixed (ECEF) Systems, and
3) Shuttle Radar Topography Mission (SRTM) data.

1.3.1) WGS84 data

The World Geodetic System 84 (WGS84) system is a standard which is used in GPS and cartography that takes into account the curvature of the earth to give distance between two specific points. The WGS84 system approximates the earth to be elliptical in shape and considers the sea level height to be the baseline for calculating elevations. Thus, by considering the earth as an ellipsoid and the sea level as the baseline, the WGS84 system helps to calculate the latitude, longitude and the elevation data of any given point on the earth.

Figure 1-5 illustrates how the WGS84 system approximates the earth to be an ellipsoid. The geoid is then used to mark the sea levels on the earth and set up a reference point to obtain the latitudes and longitudes of any point on earth.

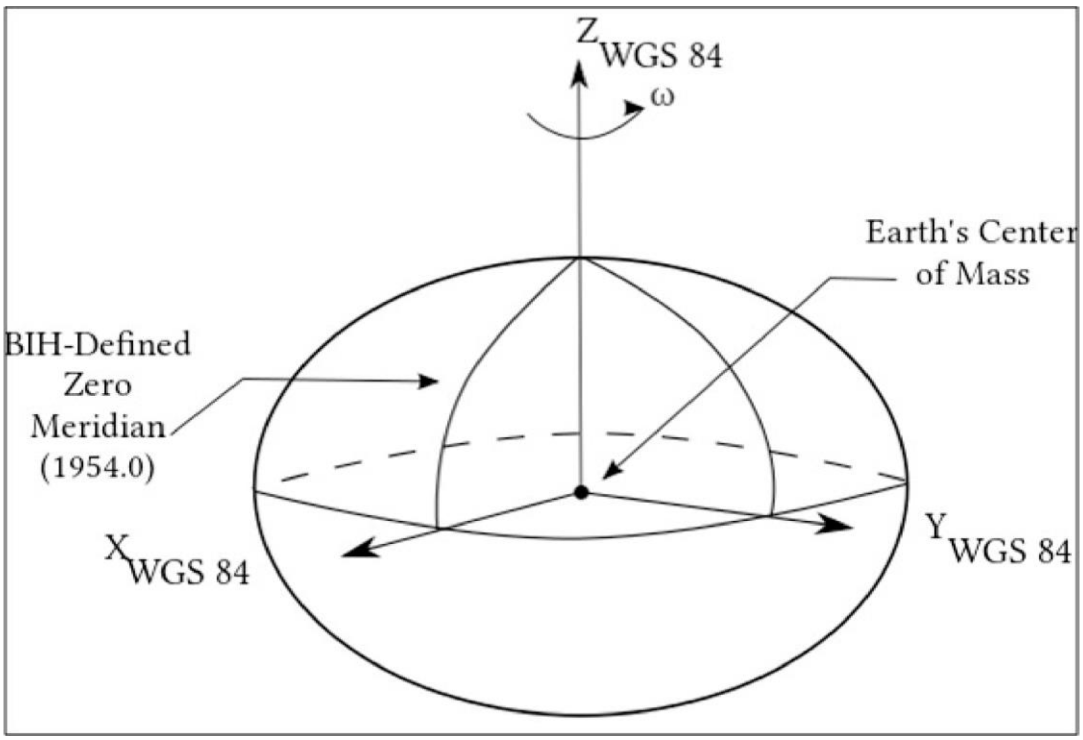

Figure 1-5: WGS84 coordinate official diagram [18] (Public Domain)

1.3.2) Earth Centered Earth Fixed Co-ordinate System

The ECEF system is used to find the Euclidian distance between two points obtained through the WGS84 system. The ECES system uses a Haversine Transform to convert the difference between the latitudes and longitudes of two different points and find the Euclidian distance in SI units. The ECEF system uses only the center of the earth and the orientation of the axes to calculate the distances and is thus widely used in various satellite measurements.

Figure 1-6 gives a representation of how the ECES uses the transforms to find the exact distances between the latitudes and the longitudes of two points on the surface of the earth.

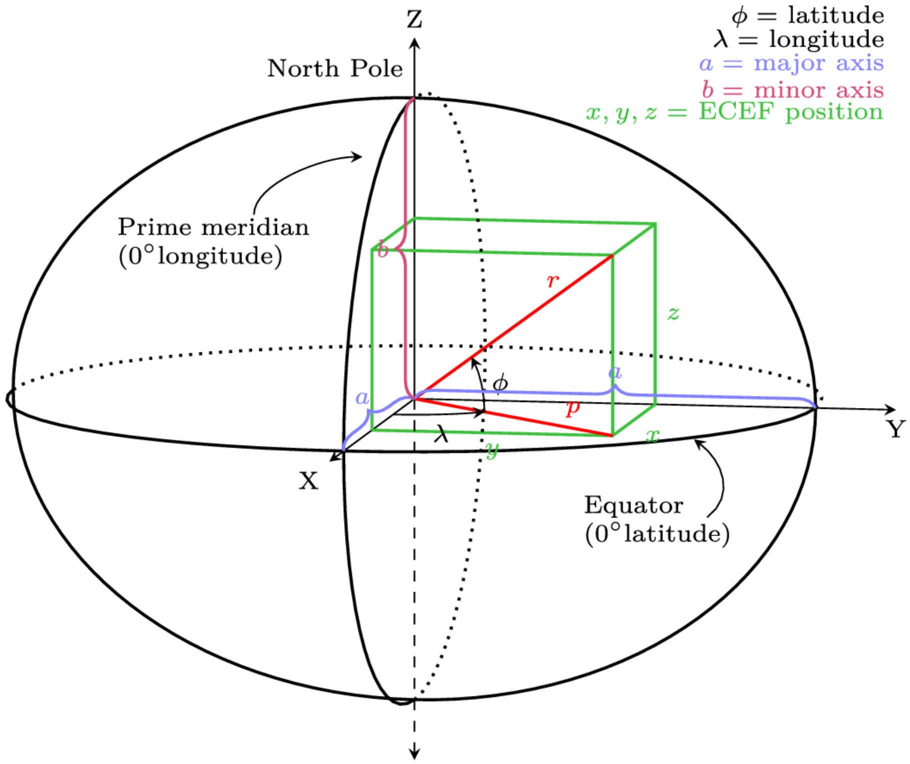

Figure 1-6: Relation between ECEF coordinates [19] (Public Domain)

1.3.3) Shuttle Radar Topography Mission (SRTM) data

Satellite Radar Topography Mission is a mission launched by NASA to accurately find the elevation of all points on the earth. A resolution of 30 metres is achieved by NASA in the SRTM database. The data obtained from SRTM database and the ECEF system is used to find the road grade. The elevation data between two points on a road and the Euclidian distance between them helps us to find the road grade accurately. Most parts of the world are covered in the SRTM database except for some regions in North Africa and the Middle East.

The SRTM data for the Sierra Nevada region is illustrated in Figure 1-7 below to give an idea of how the topography data looks. A resolution of 30 metres is also obtained on this data.

Figure 1-7: SRTM data for Sierra Nevada, Spain [20]. (Public Domain)

1.4) Speed Limits

Speed limits form a major part of the EcoRouting analysis. Driver behavior is heavily dependent on the speed limit of a given route. The driver behavior for the EcoRouting analysis is simulated by taking into consideration the maximum speed limits between each node. The speed limit for a given region is obtained from OpenStreetMaps©, an open source online platform that generates an osm file which contains values of the maximum speed limit of a given region. Speed limits for a given region are obtained by comparing the information about the latitude and longitude for a specific route.

1.5) Mandatory and Conditional Stops

Along with the effect of road grade and speed limits, the effect of idle time spent at stop lights and stop signs forms a major part of the EcoRouting analysis. Stops introduce a deceleration and acceleration, that contributes to an increase in energy consumption as well as time.

As a part of this thesis, stop signs are referred to as mandatory stops and stop lights are referred to as conditional stops. The number of stops with idle time on a route plays an important part in determining the energy expended by a vehicle. Stops also play a huge part in driver behavior as drivers will always show a proclivity for routes that minimize idle time. Typically, idle time is increased due to traffic conditions, stop lights and stop signs. The parameters of stop signs are added to the obtained route parameters using Google Maps ©. The addition of external vehicle parameters to the model helps to simulate driver behavior and consequently the amount of energy that would be expended on the route.

1.6) Powertrain Model

The powertrain model developed by Tamaro [15] is used to calculate the energy consumption along the route. This backward facing powertrain model is built from publicly available data and can be used for conventional, battery electric and plug-in hybrid electric vehicles. The inputs for this powertrain model are distance of the route, road grade, velocity of the car and the idle time expended on mandatory and conditional stops. The velocity of the car is obtained from a variable acceleration model developed by Moniot [16].

Tamaro used a constant acceleration model to simulate driver behavior as does the EcoRouting analysis based on it carried out by Pramit Baul [17]. This thesis builds upon the work of Baul and Tamaro and uses Moniot's variable acceleration model to carry out the EcoRouting analysis for a set of routes.

1.7) Contributions of this thesis

An EcoRouting system has been developed as a part of this thesis that takes in information such as speed limits, the number of stop lights, and the road grade to calculate the energy consumption of a vehicle along a route. The EcoRouting research done in this thesis focuses on analyzing the effect of the change in road grade and accelerations on the energy consumption of a vehicle and the analysis with minimum and maximum number of conditional stops.

Three simulation studies to analyze the effects of EcoRouting in different driving conditions with an emphasis on the effects of road grade and stop lights on energy consumption are presented. A synthesis methodology is introduced that takes into consideration the distance between the origin and destination, the acceleration rate of the vehicle, cruise speed and jerk rate as inputs to simulate driver behavior on a given route. A new approach is presented in this thesis that weighs the energy consumption for different routes and chooses the route with the least energy consumption, subject to a constraint on travel time.

This thesis also focuses on formulating a cost function for the maximum permissible travel time required to reach the destination and shows how travel time is an important metric to determine an EcoRoute. A sensitivity study is performed to observe the change in energy consumption of the vehicle with a change in acceleration rates and road grade. It is found that the net change in elevation between the origin and the destination plays a significant role in determining the energy consumption of a vehicle.

2) Chapter Two- Literature Review

The current research in EcoRouting deals with analysis of external factors like grade, weather conditions, dynamic traffic routing and vehicle to vehicle (V2V) communication as well as internal factors like changing the pedal map and making modifications to the powertrain architecture of a vehicle. The analysis of EcoRouting on highway vs city driving and the energy consumption associated with it forms the majority of the research in this thesis.

2.1) EcoRouting research in conventional vehicles

This section of the literature review talks about the current state of the technology that is used in EcoRouting. The papers and studies presented in these sections give a brief overview of the current challenges that we are facing in the field of EcoRouting.

The analysis of EcoRouting strategies in two different environments and the quantitative impact of EcoRouting on network-wide fuel consumption and emission levels are discussed in [21]. The authors conducted case studies in the cities of Cleveland and Columbus, Ohio to analyze the effect of EcoRouting over a larger network. This paper shows that a combined fuel savings ranging from 3-9% is obtained if the eco-route is always chosen to reach the destination. The authors have also found that the eco-routing algorithm always aims at minimizing the distance travelled to reach the destination and in most cases the shortest time path and the shortest distance path are the same. However, the authors have not considered the effect of external factors like grade, and the change in cost function on EcoRouting.

For this paper, Rakha et al. use INTEGRATION, a proprietary software to simulate a network of roads with traffic data. Driver behavior is also simulated with the help of this software along with the estimation of fuel consumption and traffic flow. The paper also considers the difference in city vs. highway driving, traffic congestion and market penetration to estimate the effect that EcoRouting will have in the future. The EcoRouting analysis in this paper is carried out on conventional cars and no battery electric vehicles or hybrid electric vehicles are used to calculate the energy consumption.

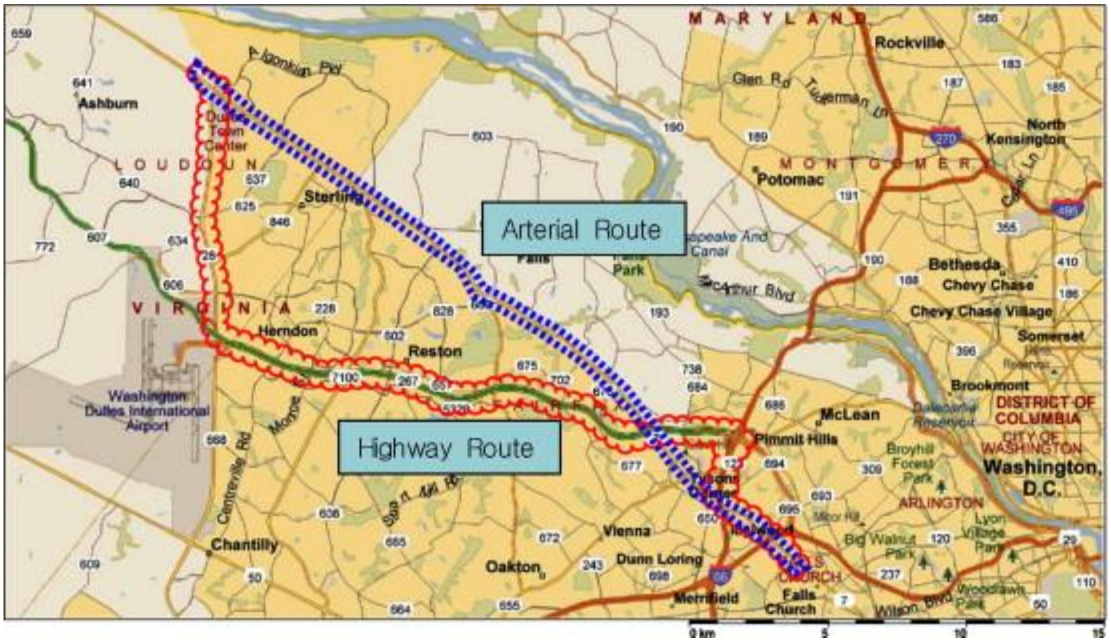

Figure 2-1: Highway and Arterial study corridors [4] (Fair Use)

The importance of choosing the right set of routes to optimize fuel consumption and travel time forms a major part of the analysis in [4]. The authors have analyzed the tradeoff between energy consumption and time but they have not developed a bounded solution for time. Developing a time-bounded solution is critical for EcoRouting to be commercially viable. As shown in the figure above, the authors studied the impact of EcoRouting on a Highway route and an Arterial route. GPS data information is used to calculate the length of the routes and incorporate their features of traffic flow into calculating the fuel consumption of the vehicle. The authors have shown that choosing the arterial path gives an 18% increase in fuel efficiency and a 16% increase in time. The results show that choosing a faster highway route may not always be the most energy efficient choice and could cause greater environmental concerns in the future.

The effect of external factors on the performance of the car is shown in [22]. The authors conducted their tests in the town of Chieri, Italy over a period of four weeks and achieved fuel savings of 15% in more than 50% of the test cases.

The authors have made certain assumptions in their calculations and the results show a proclivity for certain types of driving strategies. The dataset that is considered for this study does not compare the effect of their strategy for different network scenarios. The experimental study also relies on the use of artificial neural networks to predict the energy cost functions, but there is no clear explanation about the type of kernel functions that are used for their predictions

The seminal paper on EcoRouting is written by Ericson et al. [23]. The paper aims to optimize route choice based on the lowest fuel consumption. 15,437 routes are used to estimate the fuel consumption patterns of the city of Lund, Sweden. The authors use Esri [48], a mapping software, that provides external tools like ArcGIS, ArcVIEW and external modules to compare the energy consumption results between the shortest time path, shortest distance path and the most fuel-efficient path. The major conclusions are that 46% of the trips chosen by the drivers were not the most fuel- efficient routes and that an 8.2% fuel consumption reduction could be achieved if a navigation system designed to save fuel were used. Figure 2-2 provides a brief overview of the architecture used in this paper to calculate energy consumption.

Tamaro [15] uses a similar model to calculate the energy consumption of vehicles. 30 inputs are used in the model to calculate the energy at every point in the powertrain. The model can also be customized to calculate the energy consumptions of Battery Electric Vehicles and Plug-In Hybrid Electric Vehicles based on publicly available vehicle powertrain data.

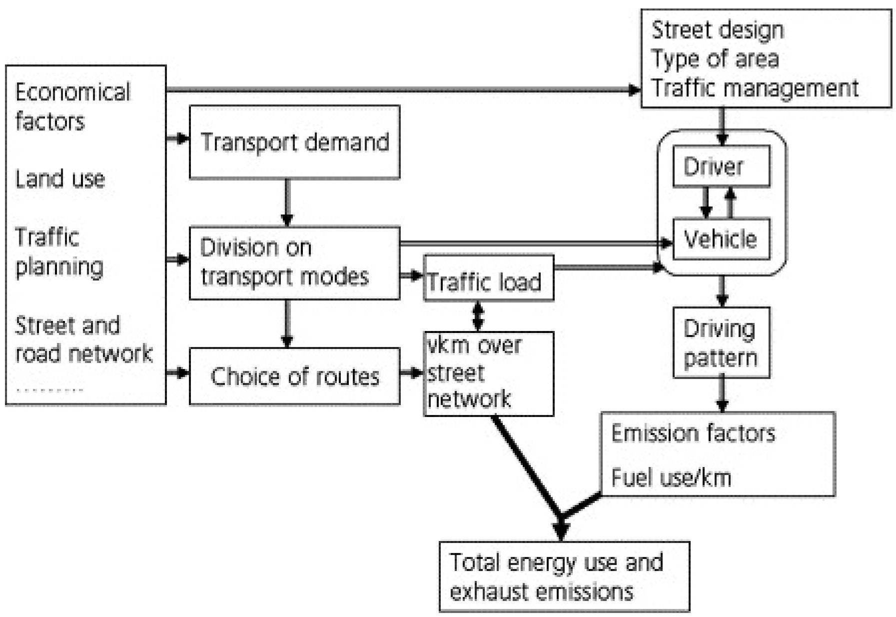

Figure 2-2: Architecture to calculate fuel consumption. [23] (Fair Use).

2.2) EcoRouting in PHEV and BEV

This section of the literature review lays the basic foundations of the research that will be carried forward in this thesis. The papers and studies presented in these sections give a brief overview of the current challenges with plug-in hybrids and battery electric vehicles. The results and conclusions of each study are analyzed and presented in these sections.

Comparative studies have shown that vehicles that are purely electric skew the EcoRouting algorithm to excessively favor routes with regenerative braking resulting in high savings in energy at the cost of a high increase in commute TT [24].

The study conducted by Wisniewski et al. [25] to compare the effects of EcoRouting shows that a fuzzy logic based control strategy could be used to choose a path depending on factors such as grades and speed limits. Linguistic variables are used by the authors in this paper to define the nature of the road, driving conditions, desired driving events, and "green" ratings of driving routes to account for the fuzzy logic based eco-routing strategy. A non-additive rule based Mamdani model is used in this paper. The trapezoidal and the triangular membership functions are used in this paper and the analysis of choosing routes using these functions is done. The authors have found that the triangular membership function performs better and gives good fuel savings than the trapezoidal membership function for a given network of routes. This paper helps us to understand the importance of having a decision- based strategy to determine the EcoRoute from a given set of routes.

Mackanic et al. [26] clearly show in their paper that there is a relationship between static parameters, like road grade and speed limits, and dynamic parameters, like traffic conditions and stop lights, to determine the route used for travelling from source to a destination. The authors have simulated energy savings of more than 13% by including the impacts of external parameters.

A driving study [27] of over 100 vehicles noted that 20% of fuel is consumed during acceleration. 117 drivers were used as part of this study to travel more than 342,000 kilometers combined. The key point to note is that events involving acceleration constitute only 6% of the distance traveled. Similarly, deceleration affects the energy consumption of a vehicle. The study also found that 78% of the fuel consumption occurs when the acceleration and deceleration does not exceed 0.55 m/s^2. Studying the effects of acceleration and deceleration forms an integral part of the analysis in this thesis.

The powertrain model used in this work for simulating results is outlined by [17] and requires grade and distance information as an input to generate energy consumption results. Route information outlining speed limits, stop locations, grade, etc. is useful, but not enough information for the powertrain model to generate results. An intermediate step of synthesizing velocity profiles is required between establishing route parameters and the calculation of energy consumption.

Existing research involving EcoRouting has shown that using only speed limit information and failing to accurately model speed transitions can lead to selecting the incorrect path [4]. Additionally, describing speed transitions by using constant acceleration or deceleration rates also fails to accurately approximate real-world behavior; studies have shown that acceleration decreases as velocity increases [28].

A more refined synthesis model is required that accepts route parameters as inputs and outputs an appropriate velocity profile that adheres to route and driver constraints (speed limits, accelerations during speed transitions, etc.). This model presents a more realistic driving behavior of driving between two stops. The selected synthesis methodology is outlined in depth in [16]. A summary follows outlining the chosen process which expands route parameters into representative velocity and acceleration profiles, facilitating energy consumption results.

Baul et al. [29] simulated 5-8% fuel savings at a maximum increase of 15% in travel time by incorporating the model used in [15]. The results in this paper confirmed that the shortest time path may not always be the most energy efficient path. A travel time increase of 7 seconds was found in the most energy efficient route showing that the increase in time may be minimal compared to the improvements in fuel consumption.

The comparison of EcoRoutes and shortest time routes for battery electric vehicles and conventional vehicles is discussed in [24]. The effect of internal parameters like vehicle powertrain and the external parameters like the condition of traffic at a time of the day and the topology of the streets is studied. Battery electric vehicles are found to give the maximum efficiency with a 22.7% improvement in energy consumption by considering the shortest time route as the baseline for all evaluations. Plug-In hybrid electric vehicles provided a 12% improvement in fuel consumption whereas conventional vehicles performed relatively poorly as compared to other vehicle types, by giving a fuel improvement of only 9%. This paper provides a good baseline to compare the results obtained for a battery electric vehicle. The analysis of road grade and acceleration is carried out in this thesis and the results show a similar trend for energy efficiency of battery electric vehicles. An important point to note in this paper is that the EcoRoute tends to vary depending on the type of the vehicle that one drives. The effect of internal parameters of the vehicle on deciding the most energy efficient route is an interesting area of research on which more work needs to be done.

2.3) Eco-driving research

The area of EcoRouting that involves changing driver behavior to drive in an eco-friendly way and conserve more fuel is known as EcoDriving. EcoDriving focuses on adopting good driving practices to improve the long-term fuel economy of the vehicle. Recent studies have shown that driving practices vary significantly even amongst drivers who are highly motivated to adopt good eco-driving practices. The study conducted in [30] shows that there is a large variance in fuel efficiency even amongst drivers who tend to show above average fuel economy. The variances in the aggressive driving practices and smooth driving practices has been shown among 39 drivers and the effect on fuel economy has been studied. A variance of 22% in fuel economy is shown for the sample size of 39 drivers.

The authors have developed an eco-driving architecture given in Figure 2-3 which explains the strategy behind how eco-driving can be implemented to change driver behavior.

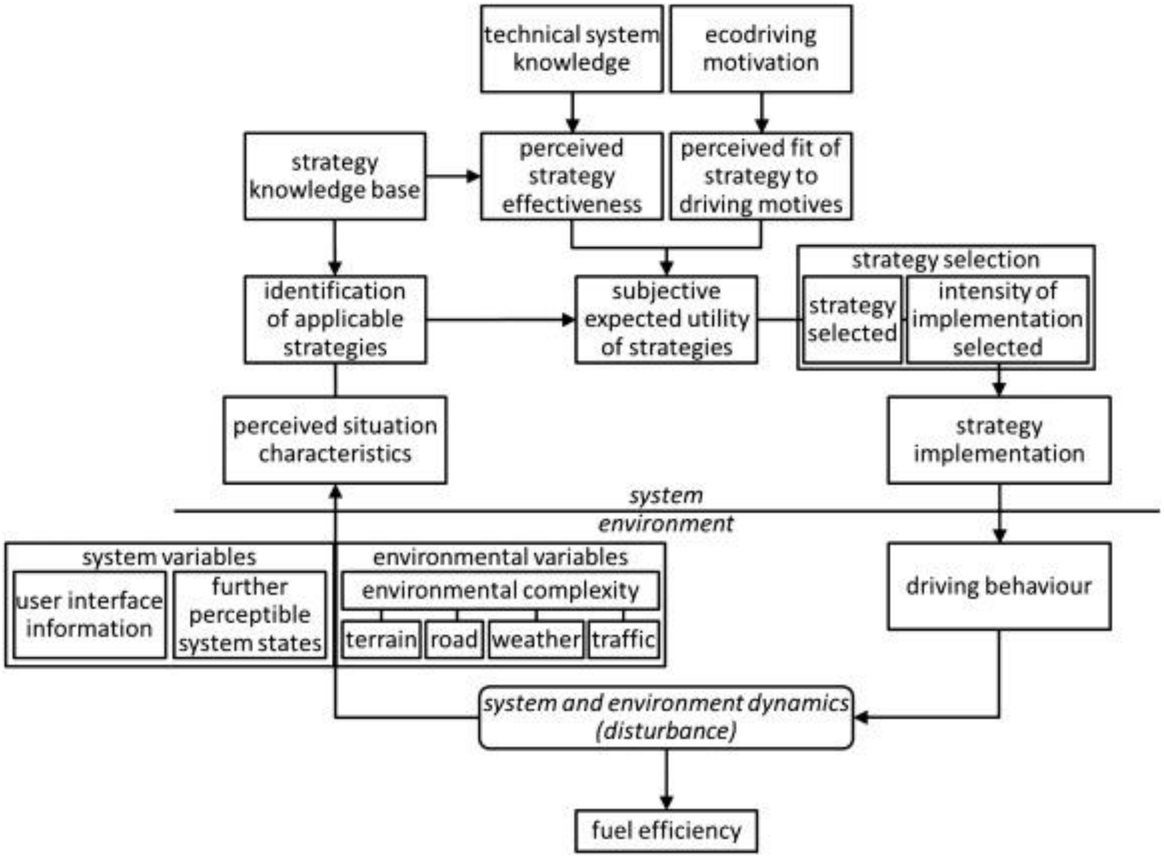

Figure 2-3: Adaptive control eco-driving strategy framework [30] (Fair Use)

However, it should be noted that not all studies find eco-driving to be an important parameter to improve fuel consumption as it may also lead to negative implications. A study on the impact of driver inattention on the risk of crashing was reported to the National Highway Traffic Safety Administration (NHTSA) [31]. This study shows that engagement of the driver in secondary tasks and glancing away from the road are the two major causes of inattention that lead to accidents.

A study conducted by the National Renewable Energy Laboratory (NREL) [32]shows that the impact caused by eco-driving modules is negligible and that there is not a significant change in the way people tend to drive their vehicles. However, there is a significant difference in energy consumption when time taken to reach the destination is considered with eco- driving. This report shows that there is a 20% difference in fuel economy for aggressive driving strategies and only a difference of 5-6% for moderate urban- environment focused driving strategies. Figure 2-4 below shows the conclusions drawn from this study where most of the fuel was consumed when the acceleration was found to be within the range of 0.75 to 1.5 m/s^2. This data was used by [15] and [16] in their research to synthesize speed profiles and simulate driver behavior.

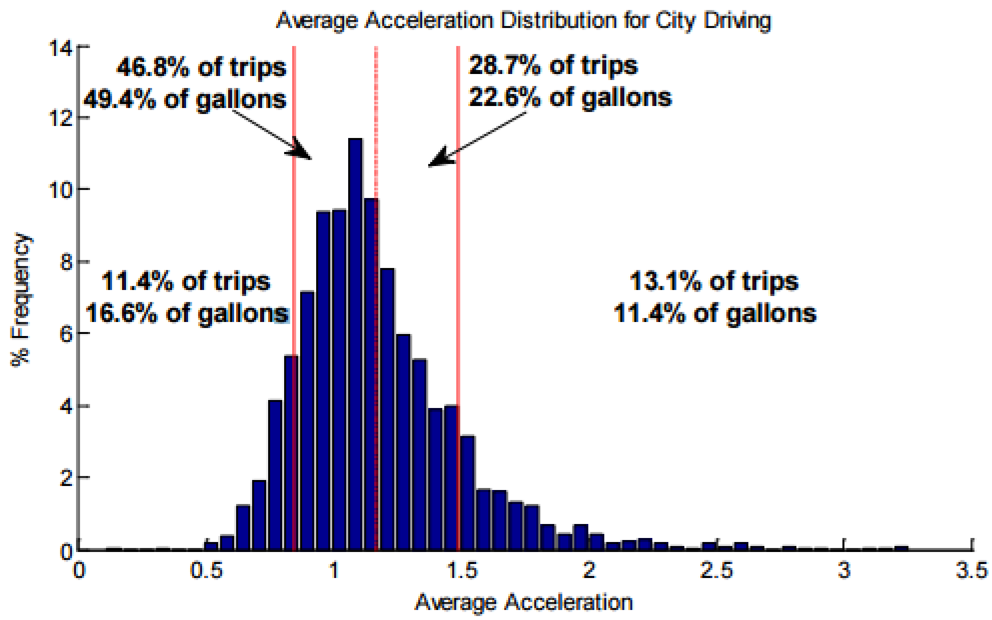

Figure 2-4: Acceleration distribution for Urban Driving [32] (Fair Use)

2.4) Research in simulating velocity profile

The results obtained in this thesis are based on the velocity profiles generated by Tamaro [15] and Moniot [16]. Tamaro uses a simplified trapezoidal model to simulate driver behavior. As seen from the Figure 2-5, this simplified model consists of simulating driver behavior between two stops. The velocity profile is primarily composed of three sections: acceleration, cruise speed and deceleration. The acceleration in these models is varied depending upon the distance between the two stops and the cruise velocity that can be attained between these stops.

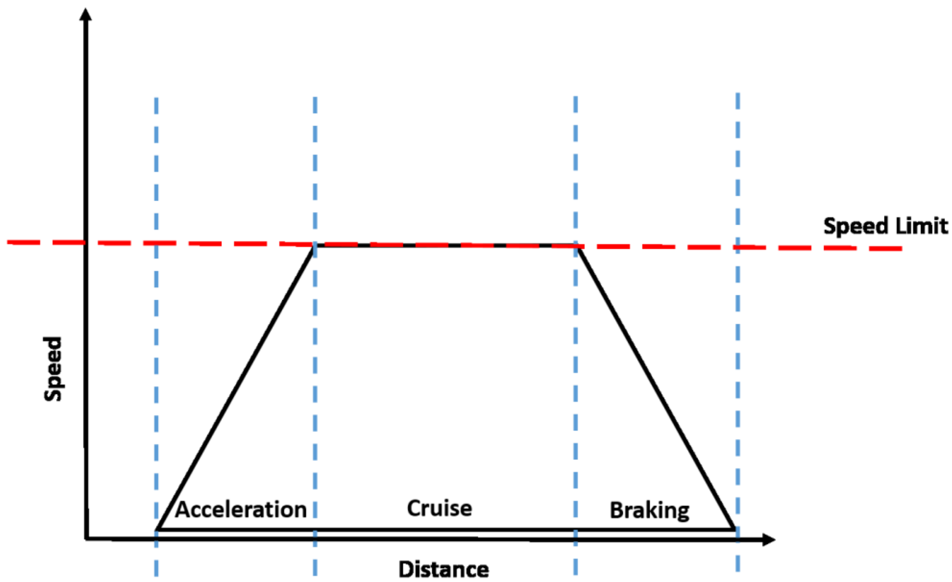

Figure 2-5: Simplified trapezoidal model for velocity profile.

As can be clearly seen, Figure 2-5 is based on a constant acceleration model. Although this model helps us to get started with understanding velocity profiles between two stops, it does not provide with an accurate representation of how vehicles are driven. The model presented by Moniot is based on the principle of using a variable acceleration strategy to simulate a velocity profile. This model provides a more accurate representation of how vehicles are driven in real-life. The velocity profile is made of seven different regions that are obtained from seven different equations. A clear explanation of this model is provided in the methodology section of this thesis. The velocity profile that is obtained is found over time whereas the velocity profile obtained by Tamaro varies with distance.

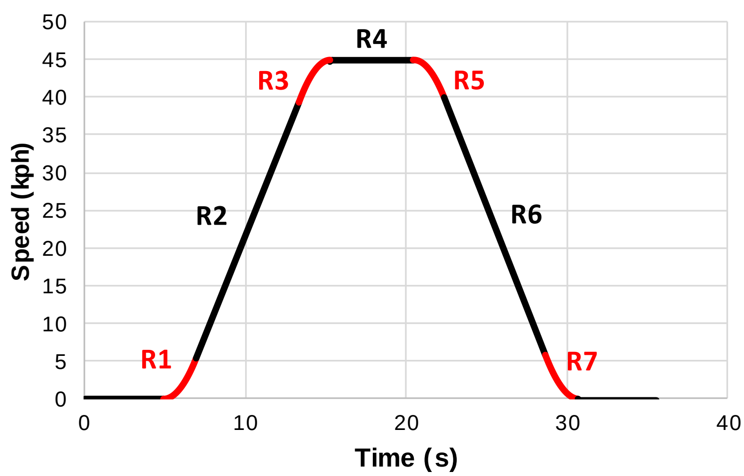

Figure 2-6: Variable acceleration based velocity profile [16]

2.5) Vehicle to infrastructure (V2x) in EcoRouting

The impact of using the Vehicle to Infrastructure (V2X) for EcoRouting is studied in [32] by Gonder et al. This study is a part of the collaboration between General Motors and the National Renewable Energy Laboratory (NREL) to analyze the impact of EcoRouting on the Chevrolet Bolt. The V2x architecture helps vehicles to gather traffic data and communicate with each other to find the optimized path to reach the destination. This strategy is commonly used in robotics as a part of the dynamic vehicle routing. This study identified target roads and extracted features such as road grades to incorporate with the driver behavior. Driver aggression is also considered in this study to account for the variations in speed with respect to the different routes. 43,000 Origin-Destination (O-D) routes were considered as a part of this study and it was found that the fastest route is not the most energy efficient route in 37% of the total cases. The difference in fuel economy is found to be 12.3% with an increase of 14.4% in travel time. These results are equated to the cost of fuel and it is found that the people who value their time at $35/hour would reduce energy consumption by 1% for a negligible increase in time. The results clearly show that drivers tend to prefer EcoRouting when there is not much change in the time taken to reach the destination.

The impact of using V2X and Vehicle to vehicle (V2V) architectures with Dedicated Short-Range Communication (DSRC) technologies is presented in [33]. This paper discusses the impact of routing vehicles at “smart” intersections. When vehicles arrive at an intersection, they are made to communicate with another and formulate an optimized routing strategy based on a predetermined algorithm. This algorithm has found to be working effectively for a four-lane road and gives us an idea of how this technology can be used in the future by autonomous vehicles. The results from this research also warrant studies with regards to incorporating non-CACC (Co-operative Adaptive Cruise Control) vehicles into the system and studies pertaining to tackling unexpected system changes, pedestrian movements etc. The authors state that this research can be used in the future to develop a state-of-art architecture in terms of intelligent vehicles and routing them by effectively making them communicate with one another and remove all human intervention.

2.6) Summary of EcoRouting Literature review

The literature review consists of 5 different sections. Sections 1 and 2 of the literature review talk about the current state of the technology that is carried out in EcoRouting. These sections lay the basic foundations of the research that will be carried forward in this thesis. The papers and studies presented in these sections give a brief overview of the current challenges that we are facing in the field of EcoRouting. The results and conclusions of each study are analyzed and presented in these sections.

Section 3 introduces the current research in terms of EcoDriving and how driving a vehicle also impacts the energy consumption. This section consists of case studies which present the impact of EcoDriving and compares the advantages and the disadvantages of EcoRouting against each other. This section also stresses on the adoption of less aggressive driving behaviors to save more energy.

Section 4 introduces us to the simulation of velocity profiles that are used a part of this thesis. Although a tremendous amount of literature review exists in this field, it is not relevant in the scope of this thesis. A complete literature review of the research in velocity profiles is presented by Tamaro [15] as a part of her Master’s thesis.

Section 5 introduces us to the new and emerging technologies that will be implemented in the future in conjunction with the existing technology. This section talks about using the Vehicle-to-Infrastructure architecture to route vehicles efficiently using a centralized server. This section also talks about how vehicles can communicate with one another effectively and find an optimized solution to reach the destination by utilizing minimum time and fuel consumption.

3) Chapter Three- Methodology

The collection of external and internal parameters that impact the vehicle is an important part of the EcoRouting analysis. The EcoRouting analysis is carried out in three steps: finding the route parameters, using the route parameters in the velocity simulation model, and calculating the net grid energy of the vehicle for a combination of routes. The input parameters that are needed to calculate the energy expended by the vehicle are distance of a route, the speed of the vehicle, the road grade and the amount of idle time spent at a stop.

The EcoRouting analysis can be carried out on different urban and highway driving scenarios based on the information obtained about the internal and external parameters for a route. This can help us to quantitatively evaluate the efficacy of EcoRouting and draw a conclusion about whether EcoRouting makes a significant impact in improving fuel economy of a vehicle. This section discusses the methodology that is carried out in this thesis and lays down the basic terminology used. A graphical representation of the drive cycles and the equations behind constructing a variable acceleration drive cycle are also discussed in this section.

3.1) Route Parameters

The starting point for the journey is defined as the source whereas the end-point is defined as the destination. A route is defined as any road between the source and destination. Every route between the source and the destination is broken into small segments with the help of placeholders, commonly referred to as nodes. The nodes are obtained from open source software and are unique for every route in the world. The nodes consist of an ID along with the knowledge of their geographical position presented in the form of their latitude and longitude.

The information about the elevation of every node from sea level is obtained through open source platforms. The nodes can be uniformly or non-uniformly distributed along the route depending upon the topology of the region from where this data is obtained. The horizontal distance between two consecutive nodes is referred to as the resolution between the two nodes. By using the information about the elevation of nodes and the resolution between them, we can calculate the grade between two nodes as shown in equation 1.

$$Grade(\%) = (\frac{Rise}{Run} * 100) \tag{1}$$

Where, $Rise =$ Difference of elevations between two nodes,

and $Run =$ Resolution between two nodes.

The areas which have a varying elevation also possess a varying amount of grade. For example, downtown San Francisco, which consists of mostly steep elevations at relatively closer distances has a variable grade associated with its roads. On the other hand, cities like Chicago which are relatively flat have a grade that is almost negligible in comparison. For the scope of this thesis, the elevation information is obtained from the Shuttle Radar Topology Mission (SRTM) database. This database is available online using different open source software. The section below gives an idea of how this data is obtained and utilized for this thesis.

3.2) Route Export

The parameters for the route are taken from open source online services called OpenRouteService© [34], OpenStreetMaps© [35] and GPS Visualizer© [36]. OpenRouteService provides us with a gpx file that contains information about the nodes and their respective unique identification numbers. The information about the latitudes and the longitudes for these nodes are also obtained through this platform. The information about the elevation data is obtained through the GPS visualizer platform. This information is used to calculate the grades between two nodes. Finally, the information about the speed limits is obtained through the OpenStreetMaps database and this is information is again used in a MATLAB script to help us find the exact location of the routes. A brief introduction of these platforms is given below.

3.2.1) Open Route Service

OpenRouteService is a platform that provides a gpx file as an output which contains the information about nodes. Cartographic information is obtained from OpenRouteService by entering the source and destination. OpenRouteService also provides a Graphical User Interface (GUI) as shown in Figure 3-1 for adding any waypoints to the path to find the route going through a region of interest in the map. The latitudes and longitudes are generated as outputs in the gpx file. The gpx file generated through OpenRouteService is fed as an input to the GPS Visualizer platform to get information about the elevation at the specified latitude and longitudes. The total length of the route is obtained from the OpenRouteService engine and then divided by the total number of nodes within the route to calculate the unit distance between two nodes and obtain the resolution of the chosen route. The resolution between unequally spaced nodes can also be obtained by considering the individual distance between adjacent nodes.

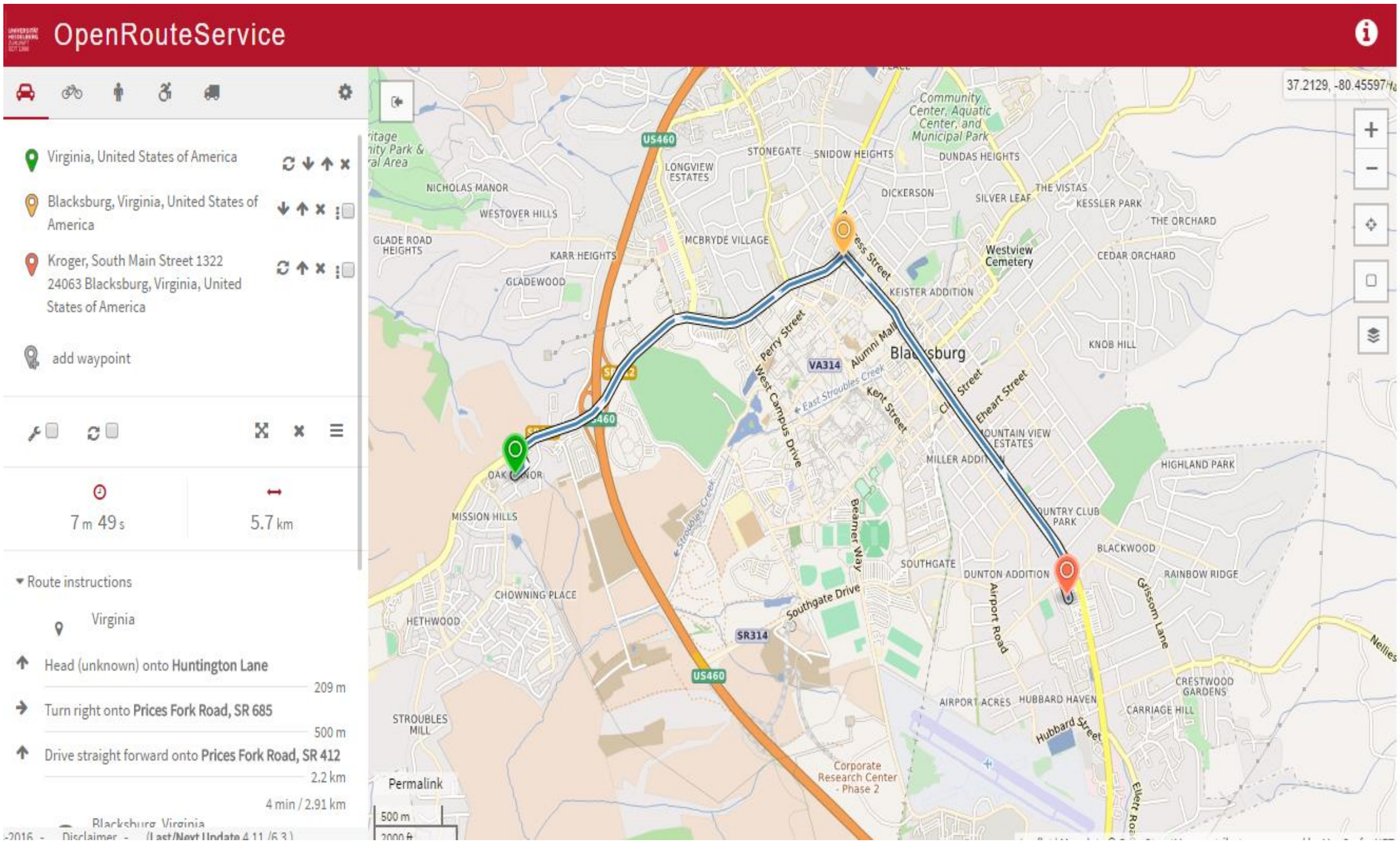

Figure 3-1: Interface of OpenRouteService platform

3.2.2) GPS Visualizer

The elevation data is obtained through the GPS Visualizer web service which uses the SRTM (Shuttle Radar Topography Mission) standard database. The SRTM database provides elevation data using high resolution radar sensing through a satellite. SRTM data can be obtained for resolutions of 30 metres, 60 metres and 90 metres. For this thesis, the resolution of 30 metres is chosen to calculate the elevations of the nodes on a route. The output of GPS Visualizer is also a gpx file which contains all the external parameters of a route.

3.2.3) OpenStreetMaps

OpenStreetMaps is one of the most popular open-source tools used in the field of Geographic Information Systems (GIS). OpenStreetMaps contains databases of almost all the routes in the world, which are constantly updated by active users. The OpenStreetMaps platform allows us to know the exact speed limits on the routes and the location of traffic signals. This information is obtained from the OpenStreetMaps platform in the form of an osm file. The osm file is then used to calculate the exact location of the signals. This parsed output is then fed into the vehicle powertrain sheet along with other parameters to calculate the energy consumed by a vehicle along a given set of routes.

OpenStreetMaps also gives an osm file which contains values of the maximum speed limit of a given region. Speed limits for a given region are obtained by comparing the information about the latitude and longitude for a specific route. The script for comparing the osm file with that of the gpx file is written to implement the process of finding speed limits for a given set of routes.

The data obtained about the latitude, longitude and elevation is fed into a MATLAB script. The distance parameters obtained through latitude and longitude are obtained in a WGS84 format. The process for converting these parameters into the Cartesian format is carried out to account for the curvature of the earth. The Haversine formula is used to correlate the WGS84 data format into Cartesian data format.

3.2.4) Mandatory and Conditional Stops

Mandatory and conditional stops constitute a major part of EcoRouting. The number of stops with idle time spent on a route plays an important part in deceleration and acceleration of a vehicle along a given route. Typically, idle time is increased due to traffic conditions, stop lights and stop signs. The parameters of stop lights and stop signs were added to the obtained route parameters using OpenStreetMaps©. The addition of idle time parameters to the model helps to simulate driver behavior and consequently the amount of energy that would be expended on the route.

The total number of routes from the source to destination is decided by using Yen's algorithm. Yen's Algorithm finds the N-Shortest paths in the system. After knowing the total number of routes, the topographic information is obtained through the above methods. A file is generated consisting of information regarding the total distance, the resolution of the path, the speed limits for every part of the route and the places where stop signs and stop lights occur. The route parameters that are obtained are then fed as input to the model which synthesizes a drive cycle based on a variable acceleration strategy.

3.3) Model Synthesis

Rather than employing a piecewise acceleration model (constant acceleration for positive speed transitions, zero acceleration for cruise, and constant deceleration for negative speed transitions), a piecewise jerk model is selected instead, where jerk represents the change in acceleration versus time as shown in equation 2.

$$j(t) = \frac{da(t)}{dt} \tag{2}$$

Where $j(t)$ = jerk as a function of time,
and $a(t)$ = acceleration as a function of time.

Controlling the acceleration by using a piecewise jerk constraint solves many of the problems faced by other speed transition models – accurate acceleration behavior can be tuned without complex modeling required. Acceleration begins at zero at the initial speed, increases to a maximum value during the transition, and tapers back to zero as the final speed is reached. Figure 3-2 shows an example speed transition between two speed limits with a maximum acceleration of 1.5 m/s^2 and an average acceleration of 0.79 m/s^2. In the example, a change in the roadway speed from 55 mph to 65 mph occurs at the 0.12- mile mark (from information retrieved from the route parameters).

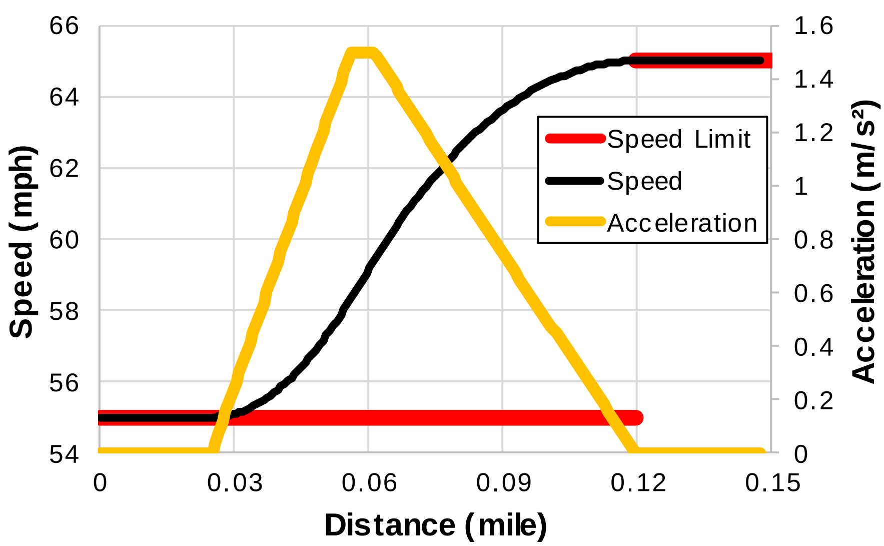

Figure 3-2. Speed transition in response to a speed limit change within a route.

In the speed limit transition, note the shape of the velocity transition. A constant acceleration would produce a linear profile between the initial speed limit and the final speed limit; the jerked nature of the acceleration creates a more realistic velocity profile.

The acceleration is timed such that the vehicle reaches the upcoming speed limit as the sign is passed. To ensure this timing, the acceleration distance is calculated from the synthesis model and subtracted from the location of the speed transition. Equations 3-9 describe the expressions for calculating the overall acceleration distance.

$$t_1 = \frac{a_{max}}{j_{max}} \tag{3}$$

$$t_2 = \frac{v_f - v_0}{a_{max}} - \frac{a_{max}}{2j_{max}} - \frac{a_{max}}{2j_{min}} + \frac{a_{max}}{j_{min}} \tag{4}$$

$$t_3 = -\frac{a_{max}}{j_{min}} \tag{5}$$

$$x_1 = \frac{j_{max} * t_r^3}{6} + v_0 * t_1 \tag{6}$$

$$x_2 = a_{max} * \frac{t_r^2}{2} + v_1 * t_2 + x_1 \tag{7}$$

$$x_3 = \frac{j_{min} * t_3^3}{6} + \frac{a_{max} * t_3^2}{2} + v_2 * t_3 + x_2 \tag{8}$$

$$x_t = x_1 + x_2 + x_3 \tag{9}$$

Where t_1 = positive jerk time,
t_2 = maximum acceleration time,
t_3 = negative jerk time,
x_1 = positive jerk distance,
x_2 = maximum acceleration distance,
x_3 = negative jerk distance,
x_t = speed transition distance,
v_f = final velocity,
v_0 = initial velocity,
a_{max} = maximum acceleration rate,
j_{max} = maximum positive jerk rate,
and j_{min} = maximum negative jerk rate.

The speed transition consists of three regions: 1, a period during which the acceleration jerks from zero to a_{max} at a rate of j_{max}; 2, a period of zero jerk and constant acceleration at a_{max}; and 3, a period during which the acceleration jerks from a_{max} to zero at a negative rate of j_{min}. The total time and distance for the speed transition is simply the sum of the time and distance spent in each of the three regions.

Generating the speed transition in Figure 3-2 using Equations 3-9 requires prescribing three variables: a_{max}, j_{max}, and j_{min}. Additionally, synthesizing speed transitions involving deceleration also requires defining a fourth parameter: a_{min}. Several assumptions are made to minimize the large number of inputs. First, it is assumed that the vehicle will accelerate and decelerate at the same maximum intensity as shown in equation 10. Second, it is assumed that driver aggressiveness and maximum acceleration will scale with maximum jerk (Equation 11); drivers who accelerate at a higher rate are also assumed to jerk at a higher rate. Finally, the maximum negative jerk is assumed to be related to the maximum positive jerk by a constant (Equation 12). The constant n dictates the curvature of speed transitions by affecting the amount of time spent in all three regions. A large n value results in an aggressively shaped speed transition while a small n value creates the more tapered shape present in Figure 3-2. Tuning of this constant in [16] against real world driving behavior revealed a value of 0.3 as ideal. Derivation of Equations 10-12 can be found in [16] as well.

$$a_{max} = -a_{min} \tag{10}$$

$$j_{max} = 0.5 * a_{max} \tag{11}$$

$$j_{min} = -n * j_{max} \tag{12}$$

Where a_{min} = maximum deceleration rate,
and n = tuning constant.

Equations 10-12 allow for the full description of a velocity synthesis between two known speeds using a single parameter: a_{max}. Increasing a_{max} affects every portion of the velocity synthesis by positively impacting the magnitude of the deceleration, positive jerk rate, and negative jerk rate. Similarly, the driver aggressiveness can be scaled back by reducing a_{max}. Figure 3-3 shows the example of the impact of the prescribed maximum acceleration on a speed transition from rest. Note how increasing a_{max} reduces the amount of time required to accelerate to the final speed and impacts the shape of the velocity profile. Increasing the maximum acceleration also impacts the average acceleration of the speed transition. In Figure 3-3, maximum accelerations of 1.5 m/s^2, 2.5 m/s^2, 3.5 m/s^2 correspond to average accelerations of 1.06 m/s^2, 1.49 m/s^2, and 1.78 m/s^2 respectively.

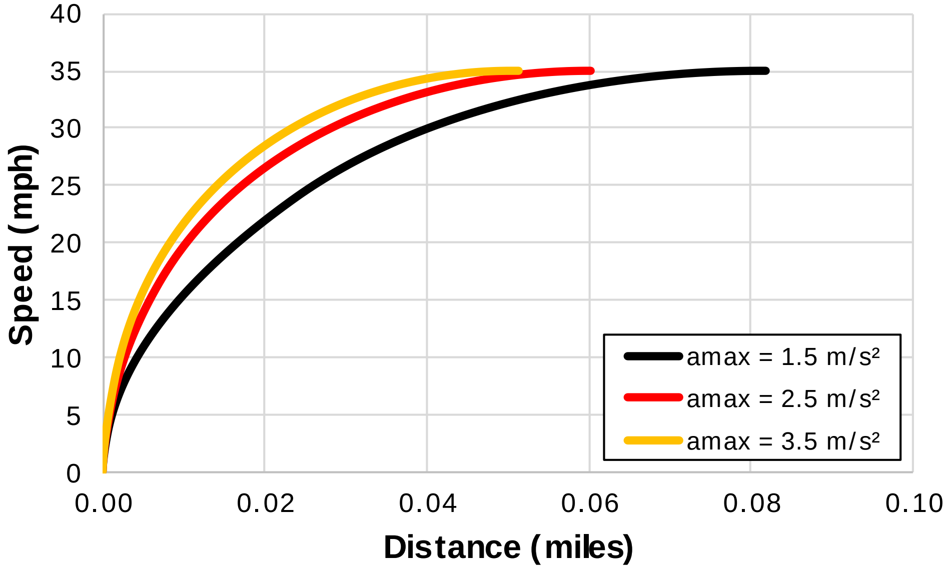

Figure 3-3. Impact of a_{max} on speed transition aggressiveness.

The synthesis method described in this section can be used successively to construct velocity profiles for entire route alternatives. Outputs from the velocity model are used as inputs for the powertrain model described in [15] to determine the least energy intensive path. The following section outlines an example of an EcoRouting application using these methods to obtain route parameters, velocity profiles, and energy consumption results.

3.4) Cost Function for Travel Time

The most energy efficient route to reach the destination may not always be the shortest- time route. The most energy efficient path might take a longer time to reach the destination and cause inconvenience to some drivers. In this thesis, we define the EcoRoute to be the most energy efficient route to reach the destination subject to a time constraint. The time taken by the driver to reach the destination is an important metric to consider. This section provides a cost function of the maximum travel time that would be permissible on a route to consider it as an EcoRoute.

The analysis of travel time is done by considering the minimum time required to reach the destination and finding the maximum permissible travel time for a set of routes. The maximum permissible travel time is a function of minimum travel time and is expressed in terms of percentage of minimum travel time.

$$Maximum\ Permissible\ Travel\ Time\ (MPTT) = t_{min} + t_{min} * x\% \tag{13}$$

Where, t_{min}= Minimum travel time,

and x= Percentage of minimum travel time

The travel time for shorter time routes is observed to be closer to the minimum travel time from the data that we have obtained. However, for longer routes the travel time varies considerably. The maximum permissible time for shorter routes is calculated as a higher percentage of minimum travel time, while for longer routes a smaller percentage of minimum travel time is considered. Thus, the value of x is higher for shorter travel time routes and lower for longer travel time routes. Table 3-1 below shows the value of x for different ranges of minimum travel time.

Table 3-1: Travel Time Range

Range of minimum travel time (minutes)	**Value of x (%)**	**Range of MPTT (minutes)**
0-5	40	0-7
5-10	30	6.5- 13
10-20	20	12-24
20-60	15	23-69
60-120	10	66-132
120+	5	126+

4) **Chapter Four- Results**

This section discusses the results obtained from two case studies where the EcoRouting analysis is performed. The town of Blacksburg, Virginia and the city of San Francisco, California are chosen to conduct the EcoRouting analysis because they consist of roads having variable grade and thus, the effect of grade on EcoRouting can be studied on real-world routes. The information about the traffic lights is also easily available from open source platforms and this makes the two places conducive to perform EcoRouting analysis. The subsequent results and conclusions obtained are presented below.

4.1) Case Study: Blacksburg

The analysis of EcoRouting using the variable acceleration model synthesis is done on 3 routes in the town of Blacksburg, Virginia, USA. The source and the destination are the same for the 3 routes but the driving environment is considerably different. There are 15, 11, and 7 potential stops present within Route 1, Route 2, and Route 3 respectively. Stops are distinguished as either conditional (a stoplight which could be green or red) or mandatory (a stop sign or a traffic circle). An average idle time of 25 seconds is assigned to a stop light. A detailed summary of all the routes is presented in Table 4-1. The parameters that are used for the input of the synthesis are presented.

Table 4-1: Summary of Blacksburg Routes

Route	Length (km)	Max speed (mph)	No. of Stops	Idle Time (seconds)	Max Grade (%)
1	5.6	40	15	300	5.61
2	9.1	65	11	225	5.6
3	5.6	65	7	75	5.67

Route 1 consists of driving through downtown Blacksburg and like most urban routes, it contains many locations where idle time can increase due to traffic lights and stop signs. The total length of Route 1 is 5.6 kilometers and the waypoints for Route 1 are placed at a resolution distance of 118 meters from each other. As Route 1 consists of driving through the city, the speed limit of the route is always below 40 mph. The constraints on speed limit and increase in stops with idle time leads to increased TT for Route 1.

Route 2 consists of driving through mostly highway scenarios to reach the destination. The number of stop lights is greatly reduced in this route. The total length of Route 1 is 9.1 kilometers and the waypoints for Route 2 are placed at a resolution distance of 118 meters from each other. The speed limit for this route goes as high as 65 mph. However, the decrease in stops with idle time and increase in speed limits do not change the TT as the distance is increased for this route. As the speed limits in Route 2 vary over a wide range, the effect of road grade and idle time plays a large part in deciding whether this route is indeed the EcoRoute.

A mixture of city and highway driving is observed in Route 3. Route 3 has speed limits going as high as 65 mph and going as low as 25 mph. The total length of route 3 is 5.6 kilometers and it consists of waypoints placed at a resolution of 118 meters from each other until the halfway point, followed by a resolution of 51 meters for the next half. The combination of highway and city driving gives a good opportunity for studying the feasibility of EcoRouting in different scenarios and seeing the effect of road grades and traffic time on the energy consumption of the vehicle. Figure 4-1 shows that the TT for all the routes is approximately the same in reaching the same destination from the same source.

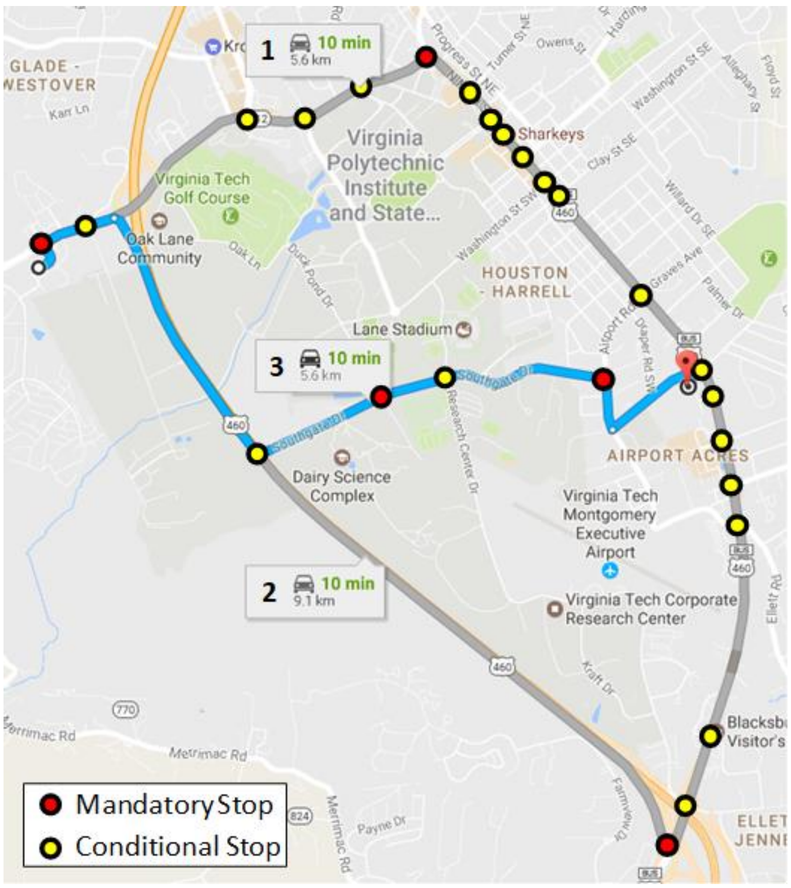

Figure 4-1: Routes used for EcoRouting analysis in Blacksburg

A comparative analysis is done on the three routes and the effects of road grades and conditional stops with idle time are studied. The EcoRoutes are chosen according to the energy consumed by the vehicle in reaching the destination. The results for the EcoRouting model are presented below.

4.1.1) Results obtained for Blacksburg Case Study

A 2013 Nissan Leaf is representative of typical EVs and is selected as the simulation vehicle using the validated powertrain model in [15]. Synthesized routes are input into the powertrain model and various parameters are output including tractive energy, battery terminal energy, etc. Table 4-2 contains the battery terminal energy required to propel the vehicle through each of the selected routes.

The data is segregated by two categories: whether conditional stops are applied within the route syntheses as shown in Figure 4-1 and whether grade data is considered for the powertrain results. Multiple simulations under different conditions provide the basis for exploring the potential impacts of stops and grade on the selection of the optimal route. The energy consequences of route stops will be evaluated followed by the impact of route grade.

Table 4-2: Terminal energy results for route alternatives under multiple conditions.

Route	**Energy expended without grade considered**			**Energy expended with grade considered**		
	No Cond. Stops (kJ)	All Cond. Stops (kJ)	Energy Diff. (kJ)	No Cond Stops (kJ)	All Cond. Stops (kJ)	Energy Diff. (kJ)
1	**2159**	2478	319	**2146**	**2450**	304
2	4326	4490	164	4639	4780	141
3	2441	**2450**	9	2640	2648	8

Battery terminal energy varies between each of the three routes. Route 1, consisting of mostly urban driving, requires far less energy than Route 2 which is a predominately highway route with higher speeds. Route 3, featuring urban and highway characteristics, also requires less energy than Route 2. The selection of the EcoRoute between Routes 1 and 3 is largely influenced by the route parameters of conditional stops and road grade. Total travel time is also heavily influenced by conditional stops, but there is no relationship between travel time and grade as shown in Figure 4-2.

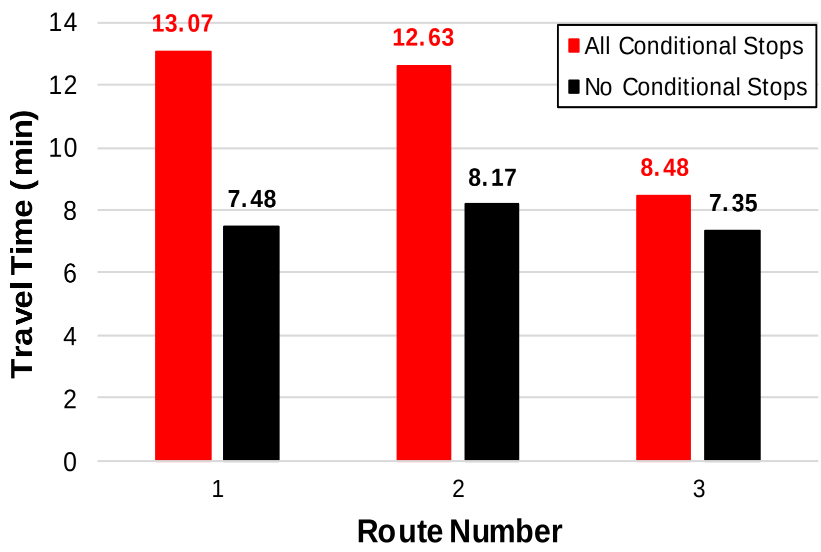

Figure 4-2: Travel time of each route with all conditional stops and with no conditional stops.

Conditional stops heavily influence both travel time and energy consumption for all three routes. Route 1 experiences the largest energy consumption and travel time inflation due to stops out of the three alternatives due to the large number of conditional stops. Route 1 contains 12 conditional stops compared to the 8 and 3 conditional stops present within Route 2 and Route 3 respectively. Specifically, conditional stops cause a 14.8% increase in energy consumption for the Route 1 compared to a 0.4% increase for Route 3 for the simulations without grade data considered. These disparate increases in energy consumption caused the EcoRoute to change; Route 1 is identified as the EcoRoute with all green traffic signals while Route 3 is the EcoRoute with all traffic signals appearing as red.

The 8 conditional stops within Route 2 also increased energy consumption (3.8% increase), but the prolonged highway speeds within the route prevent it from becoming competitive with the other alternatives. Note that the conclusions within this section do not fully apply to the powertrain results when grade is included.

For the case with no conditional stops, t_{min} = 7.35 minutes.

Therefore, Maximum Permissible Travel Time= 7.35 + (7.35) * (30%) = 9.55 minutes.

Route 1 is the route that has the minimum energy consumption and has a travel time less than the MPTT. Therefore, Route 1 is the EcoRoute in the case when no conditional stops are considered.

For the case with all conditional stops, t_{min}= 8.48 minutes.

Therefore, Maximum Permissible Travel Time= 8.48 + (8.48) * (30%) = 11.02 minutes.

Route 3 is the route that has the minimum energy consumption and has a travel time less than the MPTT for the case with all conditional stops. Therefore, Route 3 is the EcoRoute in the case when all conditional stops are considered.

These conclusions show there is a strong relationship between the impact factors of grade and acceleration on energy consumption.

Table 4-2 facilitates similar investigations regarding the impact of grade on the selection of the EcoRoute. In both alternatives of Route 1 (zero and all conditional stops), the influence of grade reduces the requisite terminal energy consumption. However, the terminal energy consumption required for Route 2 and Route 3 rises due to the influence of grade. These results confirm that the presence of grade can be a deciding factor of the EcoRoute (despite not swaying the determination of the EcoRoute in this analysis). Thus, a reliable and comprehensive EcoRouting strategy would require roadway grade data to accurately select the correct route in a real-world setting.

It is important to restate the presence of regenerative braking. The ability to capture energy from braking reduces the impact of both grade and traffic signals on energy consumption. Stops and grade would be more influential on the energy consumption of internal combustion engine vehicles (ICEV) which cannot recover braking energy. The figures given below show the synthesized velocity profiles for all six route alternatives with state of charge (SOC) results overlaid. SOC results are shown for both simulations of each route – with and without grade considered as an input. The impact of grade is especially noticeable during periods of cruising, which feature otherwise equivalent road load forces between the two traces. The major drawback behind using open source software to calculate grade is that a difference of 25 meters in elevation was observed in the destination points of the Routes 1 and 2.

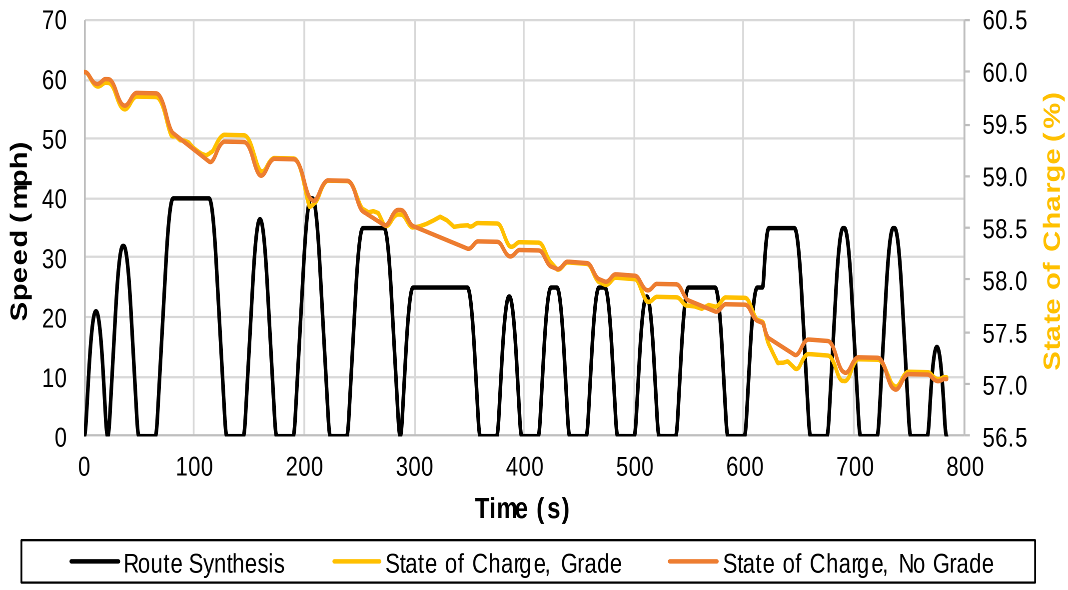

Figure 4-3: Route 1 synthesis with all conditional stops applied.

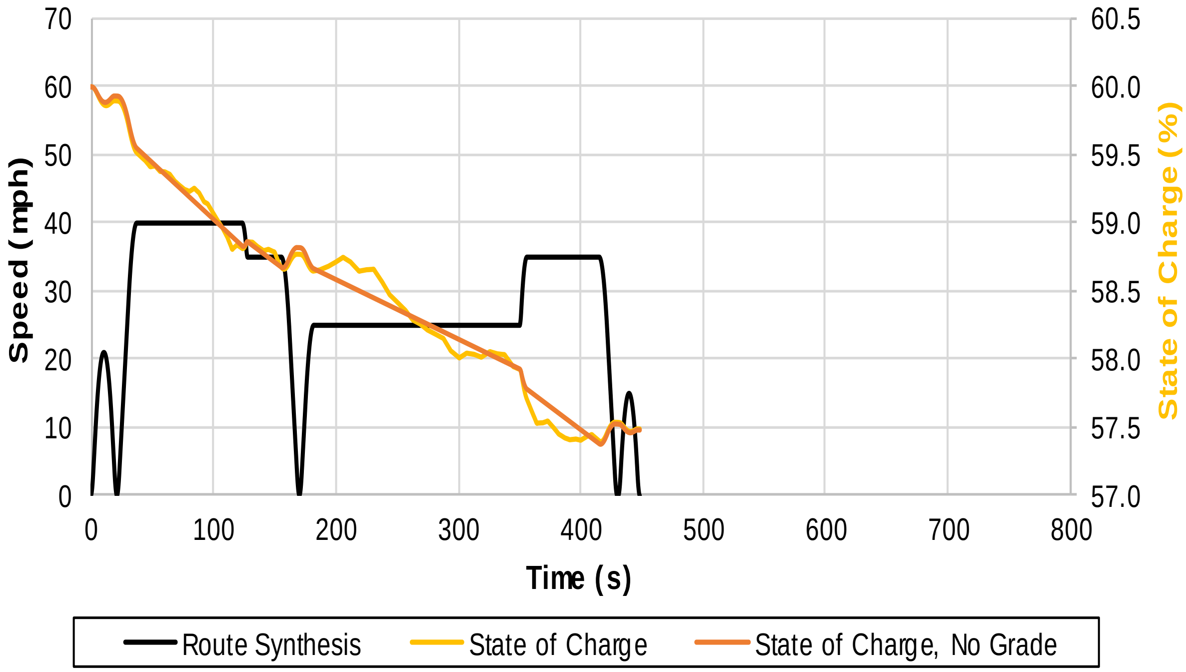

Figure 4-4: Route 1 synthesis with no conditional stops applied.

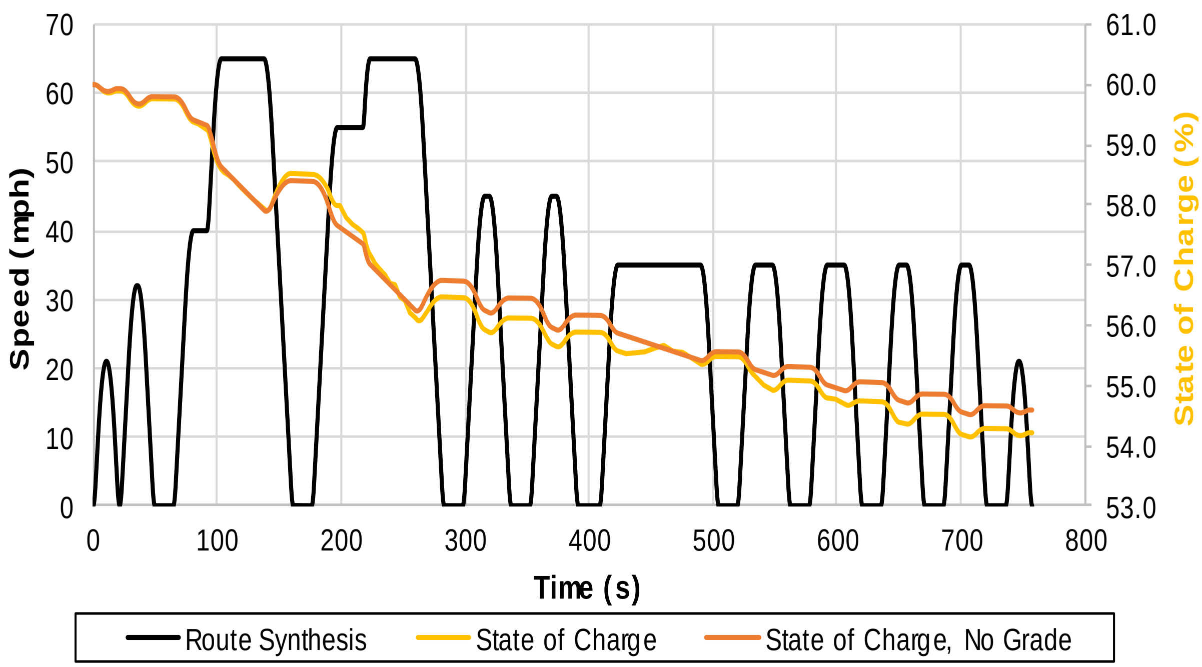

Figure 4-5: Route 2 synthesis with all conditional stops applied.

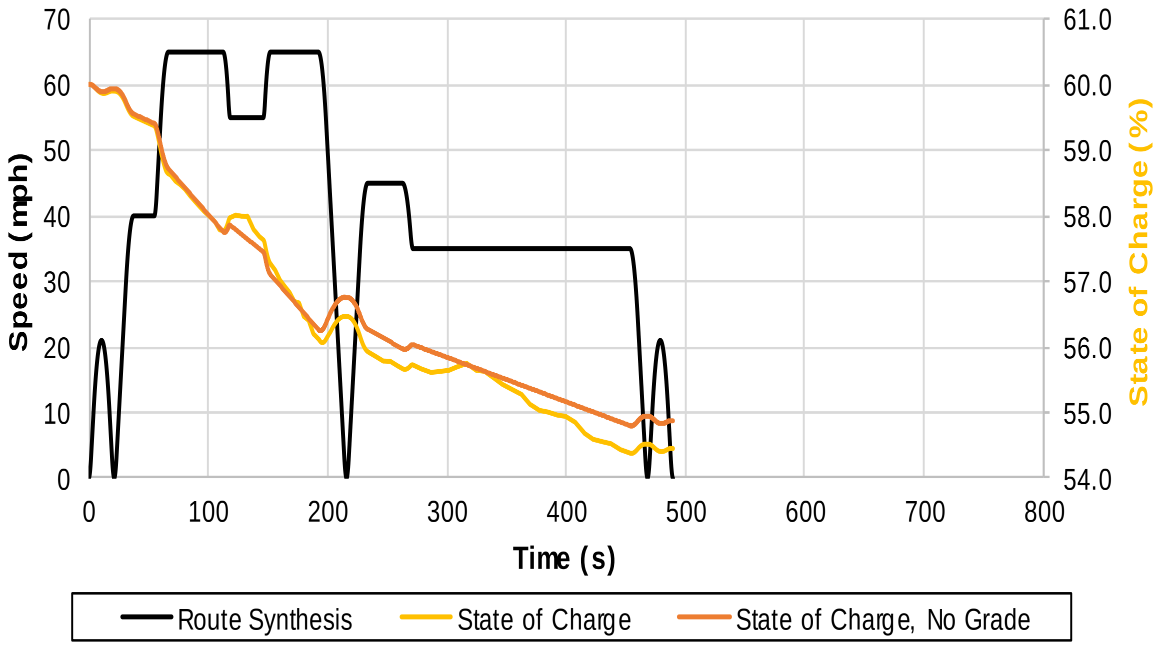

Figure 4-6: Route 2 synthesis with no conditional stops applied.

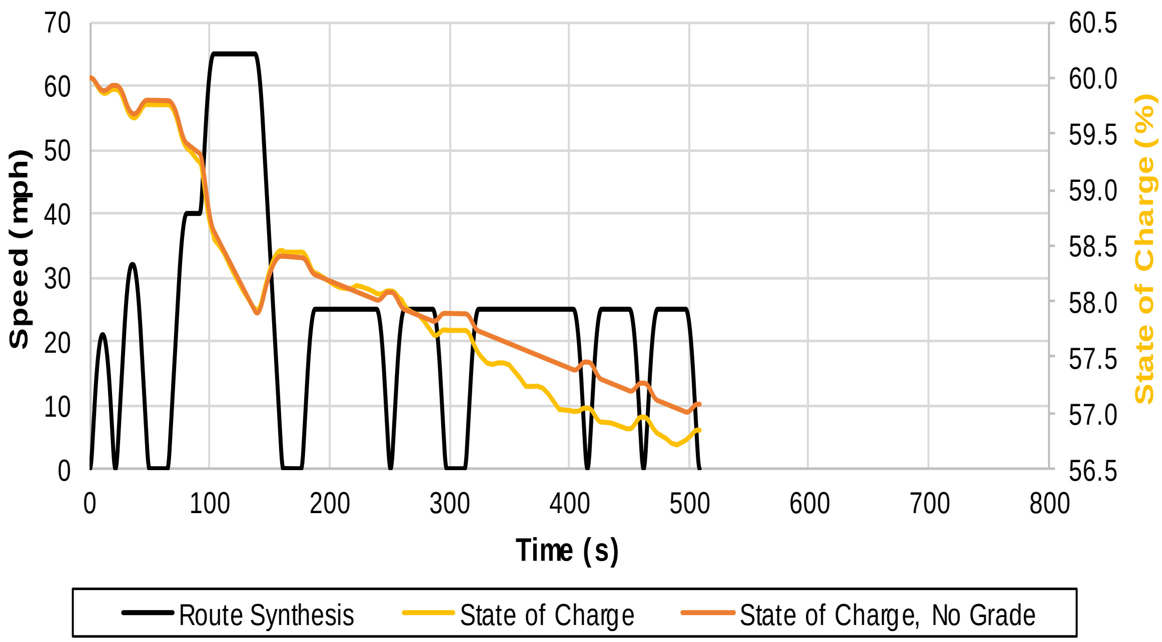

Figure 4-7: Route 3 synthesis with all conditional stops applied.

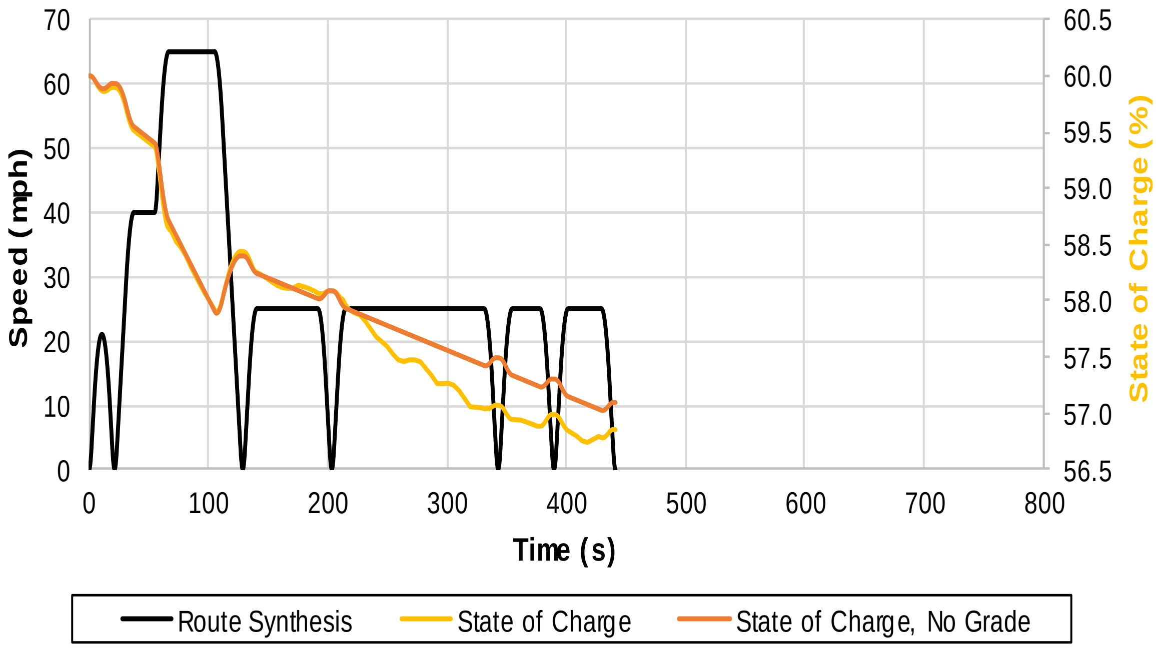

Figure 4-8: Route 3 synthesis with no conditional stops applied.

Finally, the energy consumption results must be understood in context. Route 3 represents the shortest-time route when no conditional stops and all conditional stops are considered, while Route 1 and 2 experience large time penalties. For instance, although Route 1 is the eco-route when grade is considered, a driver may still prefer Route 3 due to the time increase caused by stoplights.

When all conditional stops are applied, Route 1 represents a 23% reduction in battery terminal energy consumption at the expense of a 54% increase in total travel time compared to Route 3 with all conditional stops also applied. Several existing studies demonstrate similar findings – the EcoRoute is rarely the shortest in time.

We thus conclude this study by saying that although Route 1 gives us the optimal solution for minimizing energy, it fails to give us an optimal solution for travel time and hence, Route 3 is chosen as the EcoRoute as it gives us an optimal solution in terms of travel time as well as fuel economy when we consider the effect of conditional stops. The results obtained from this study have been submitted as a student research paper to the SAE International Journal.

4.2) Case Study: San Francisco

A similar study is shown in the city of San Francisco, California and the EcoRouting analysis is presented in this thesis. The road network that we have considered in San Francisco consists of three routes that originate along State Road 1 and end at Sloat Boulevard, San Francisco. The routes are presented below in Figure 4-9.

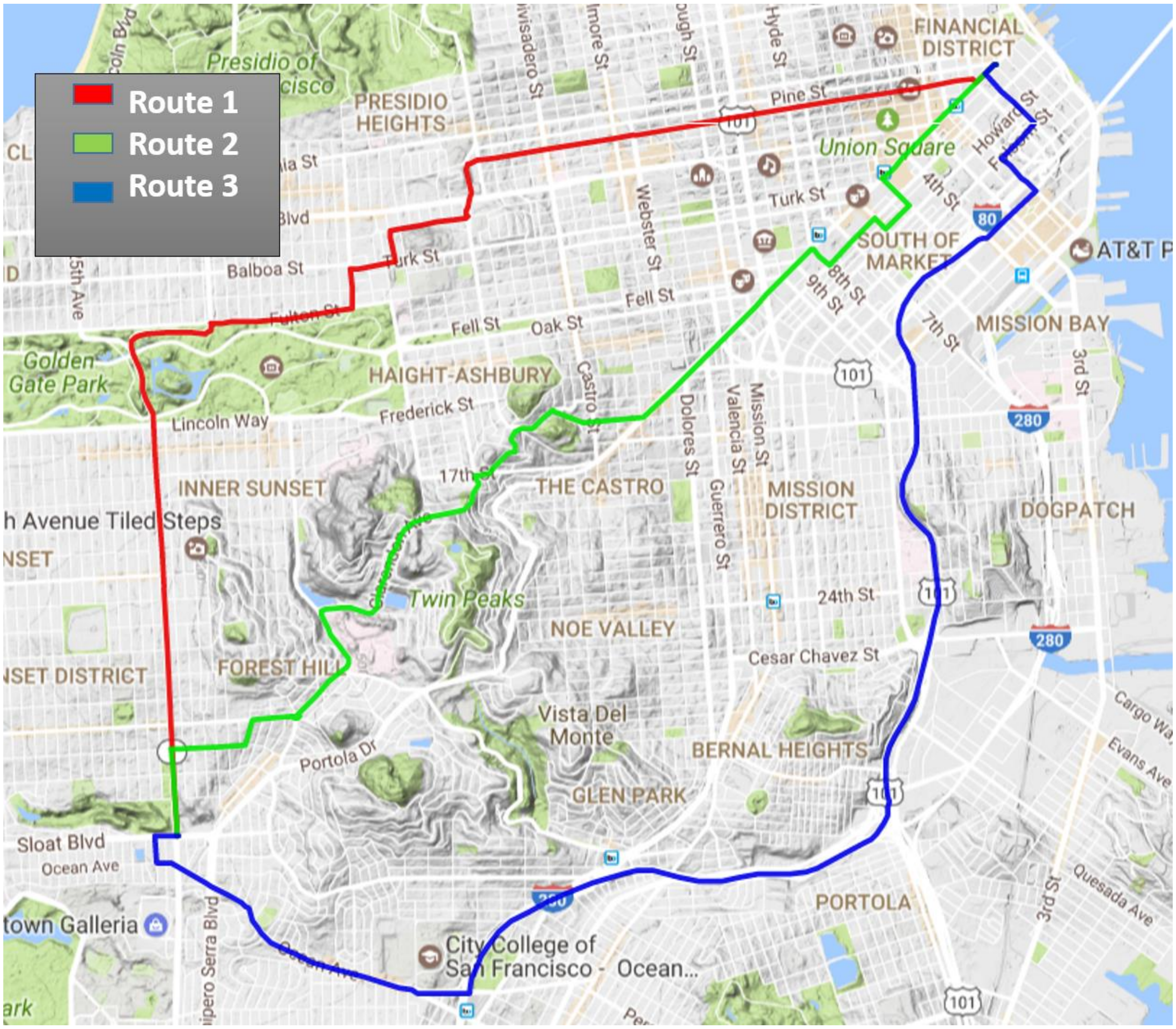

Figure 4-9: San Francisco Routes

The route network in San Francisco is similar to the route network in Blacksburg as it consists of a mixture of urban and highways driving routes. Route 1 used in the San Francisco case study is a perfect example of a route having both urban as well as a freeway driving characteristics. Route 1 originates in the city and after travelling for a few miles in an urban driving condition, it merges onto a freeway. Route 1 has 15 conditional stops and has a maximum grade of only 1.93% making it a relatively flat route as compared to the other two routes.

Route 2 is a predominantly urban driving route. It consists of many conditional stops and the speed limit on Route 2 is also significantly lower as compared to the other two routes. This route passes through the Market Street in San Francisco, and thus makes a great candidate to judge the impact of grade on our EcoRouting analysis. Route 2 has a maximum grade of 3.38% and has the most number of conditional stops: 17. The maximum speed limit on Route 2 is 30 mph making it the slowest route to drive on. However, Route 2 is also the shortest route from among the 3 routes and is also the route that requires the least travel time from the source to the destination.

Route 3 is a highway route and has a speed limit significantly greater than the other two routes. Since it is a highway route, Route 3 is also the longest route from amongst the three routes taken into consideration. However, the conditional stops for Route 3 are only 13, the lowest from all the 3 routes. This makes route 3 a great candidate to study the effect of EcoRouting while considering the idle time spent at conditional stops.

Table 4-3: San Francisco Route Characteristics

Route	Length (km)	Max speed (mph)	No. of Stops	Idle Time (seconds)	Max Grade (%)
1	12.8	55	15	375	1.93
2	11.1	30	17	425	3.38
3	15.0	65	13	325	2.03

The EcoRouting analysis for these routes is done and the results are presented below. The same set of output parameters used for the Blacksburg study are used in the San Francisco study as well. A detailed analysis of the results is also given below with respect to the effect of choosing the EcoRoute by considering the total travel time taken to reach the destination.

4.2.1) Results obtained from San Francisco Case Study

The 2013 Nissan Leaf vehicle model is again used to find the terminal energy for the given set of routes. This model also returns the value of the State of Charge (SOC) as well as the total travel time required to reach the destination. The inputs of distance, velocity, grade, and idle time spent at conditional stops are provided to this model to get the required output.

Table 4-4: Terminal energy results for San Francisco routes

Route	Energy expended without grade considered			Energy expended with grade considered		
	No Cond. Stops (kJ)	All Cond. Stops (kJ)	Energy Diff. (kJ)	No Cond Stops (kJ)	All Cond. Stops (kJ)	Energy Diff. (kJ)
1	8149	8163	14	8232	8241	9
2	**6563**	**6950**	387	**6862**	**7228**	366
3	11741	11878	137	11726	11843	117

Table 4-4 shows the results obtained for the three routes in San Francisco. The results show a predictable trend as seen from the Blacksburg study. Route 2 is the most energy efficient route for the four cases that are considered for this study. Since Route 2 is an urban driving route consisting of lower speed limits and shortest distance to reach the destination, the results for the energy consumption of the vehicle are concomitant with the powertrain model that is used for the EcoRouting analysis. Route 2 is a route having the highest grade among the three routes. This reflects in the energy consumption results when the effect of grade is considered in our analysis. The number of conditional stops along Route 2 is also the highest among the three routes and therefore, the difference in energy consumption of the vehicle when we consider the effect of conditional stops is substantial. The impact of conditional stops along the route plays an important role in determining the travel time taken by the vehicle to reach the destination.

Route 1 is a mixture of city and highway routes and therefore the difference in energy consumption of the vehicle for the four cases is marginal owing to the higher speed limits on this route and lesser number of conditional stops. The maximum road grade for route 1 is also the lowest among the three routes and therefore the effect of grade on this route is minimal as compared to the other two routes. The difference in energy consumption between Route 1 and Route 2 is approximately 25% for all the four cases and therefore, Route 2 will not be considered as the EcoRoute if we consider only the energy consumption of the car along the two routes.

The energy consumption of the vehicle along Route 3 is the highest amongst the three routes. The length of the route, higher speed limits and the effect of road grade along Route 3 make this route the most unfavorable route to drive along in terms of energy consumption. The difference in energy consumption of the vehicle between Route 2 and Route 3 is nearly 80% for all the four cases that are considered in this study.

A similar study was done on the same set of routes by Pramit Baul [17] and the energy consumption was determined for a 2016 Camaro hybrid electric vehicle. The energy consumption along the routes was calculated by assuming a random number of stops. The case for calculating energy consumption for the charge depleting mode is the most comparable to the methodology used in this thesis. The results obtained in this thesis are qualitatively similar and exhibit the same trends obtained by Baul. Route 2 is the route that contains the least energy and Route 3 is the route that has the largest energy consumption. However, the results for energy consumption differ because of the different number of conditional stops that are considered in the analysis and the different vehicle powertrains used to calculate energy consumption.

4.2.2) Analysis of Travel Time for San Francisco Study

Travel time plays an important factor in determining the EcoRoute for a network of routes. A route that takes more time to reach the destination will be less preferred by drivers even if it provides a better fuel economy. The analysis of travel times for the network of routes in San Francisco is shown in Figure 4-10. The impact of conditional stops is considered both in terms of deceleration and travel time to determine the EcoRoute.

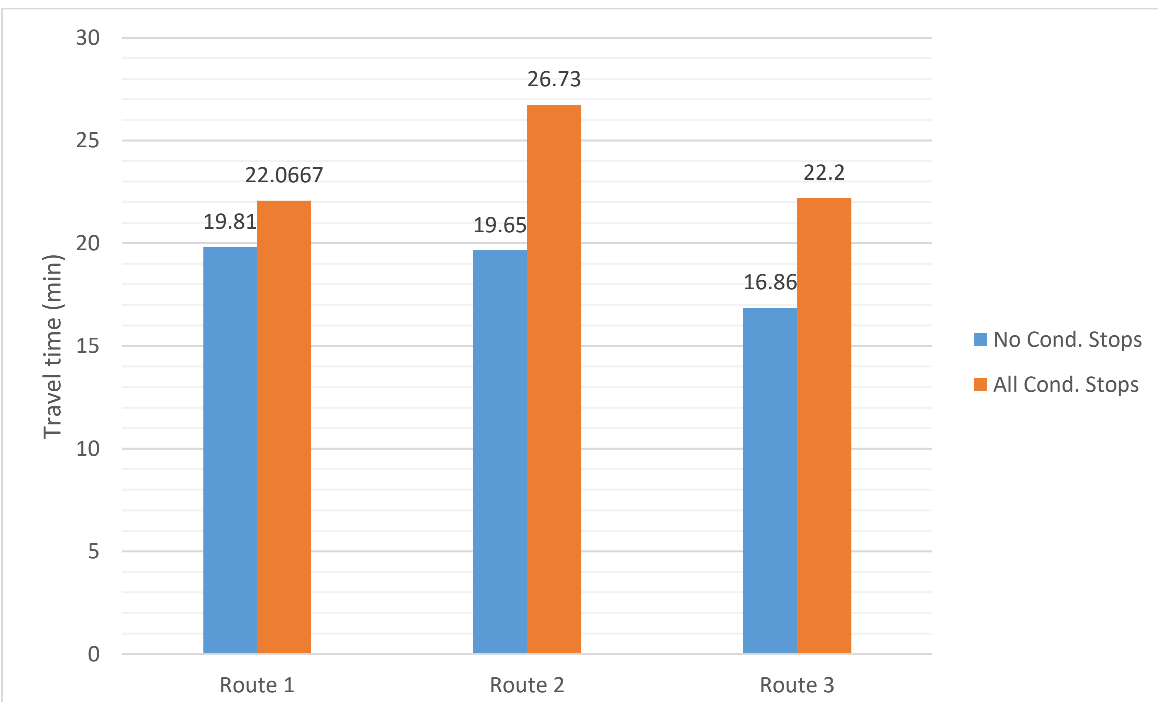

Figure 4-10: Analysis of Travel Time for San Francisco study.

The difference in travel times for Route 1 when conditional stops are considered and not considered is 11.3%. Similarly, for Route 2 and Route 3 the difference is 36% and 31.6% respectively. If no conditional stops are considered, Route 3 becomes the most efficient route to travel on with respect to travel time. The difference in Route 2 and Route 1 to reach the destination without considering the impact of conditional stops is only 14 seconds. However, when all the conditional stops are taken in to consideration, the travel increases by almost 8 minutes and 6 minutes for Route 2 and Route 3 respectively. In that case, Route 1 becomes the route with the shortest travel time.

This analysis shows that if we consider the effect of conditional stops on the three routes, Route 2 and Route 3 show a larger variance in time to reach the destination. The variance in travel time to reach the destination is the lowest for Route 1 and hence, Route 1 will be the most preferred route to reach the destination followed by Route 3 and Route 2.

For the case with no conditional stops, t_{min} = 16.86 minutes.

Therefore, Maximum Permissible Travel Time= 16.86 + (16.86) * (20%) = 20.23 minutes.

Route 2 is the route that has the minimum energy consumption and has a travel time less than the MPTT. Therefore, Route 2 is the EcoRoute in the case when no conditional stops are considered.

For the case with all conditional stops, t_{min}= 22.06 minutes.

Therefore, Maximum Permissible Travel Time= 22.06 + (22.06) * (15%) = 25.37 minutes.

Route 1 is the route that has the minimum energy consumption and has a travel time less than the MPTT for the case with all conditional stops. Therefore, Route 1 is the EcoRoute in the case when all conditional stops are considered.

We finally conclude this study and say that although Route 2 gives us a better solution in terms of energy consumption it is, in fact, Route 1 that gives us a better solution in terms of both energy consumption and travel time. Therefore, Route 1 will be chosen as the EcoRoute in most of the cases. Route 2 will be chosen as the EcoRoute when the impact of conditional stops is minimal along Route 2 and maximum along the other two routes.

4.3) Comparative Study

A similar analysis of EcoRouting was carried by De Nunzio et al. [37] in the city of Turin. The authors use the Bellman- Ford algorithm to calculate the optimal energy path to reach to the destination. In this paper, the authors have used a Fiat 500e battery electric vehicle model in conjunction with HereMaps [38] to calculate the most energy efficient route. The results that are obtained by De Nunzio et al. are compared against the powertrain used in this thesis to test the reasonableness of our EcoRouting algorithm.

4.3.1) Route Parameters

For the EcoRouting Analysis, the authors have considered 3 routes from the source to the destination. The origin and the destination of the paths is given below.

Origin: 393, Corso Moncalieri, Turin, Italy

Destination: Variante del Dojrone, Rivalta di Torino, Turin, Italy

Of the 3 paths, Route 1 is the shortest distance path but takes the most amount of time to reach the destination. Route 1 is a city based path and consists of a significant number of stops along with one mandatory toll booth.

Route 3 is the shortest time path to reach the destination but it is also the longest-distance path with a total length of 21.8 km. Route 3 is a highway based path and the speed limit on this path is 130 km/ hour (81mph). Route 2 is a combination of city and highway driving and has a speed limit of 130km/hr in some parts and 70 km/hr in others.

The route parameters for these three routes is given below.

Table 4-5: Turin Route Characteristics

Route	Length (km)	Max speed (mph)	No. of Stops	Idle Time (seconds)	Max Grade (%)
1	15.6	43.5 (70 kmph)	15	375	3.32
2	16.1	81 (130 kmph)	9	225	1.38
3	21.8	81 (130 kmph)	6	150	2.15

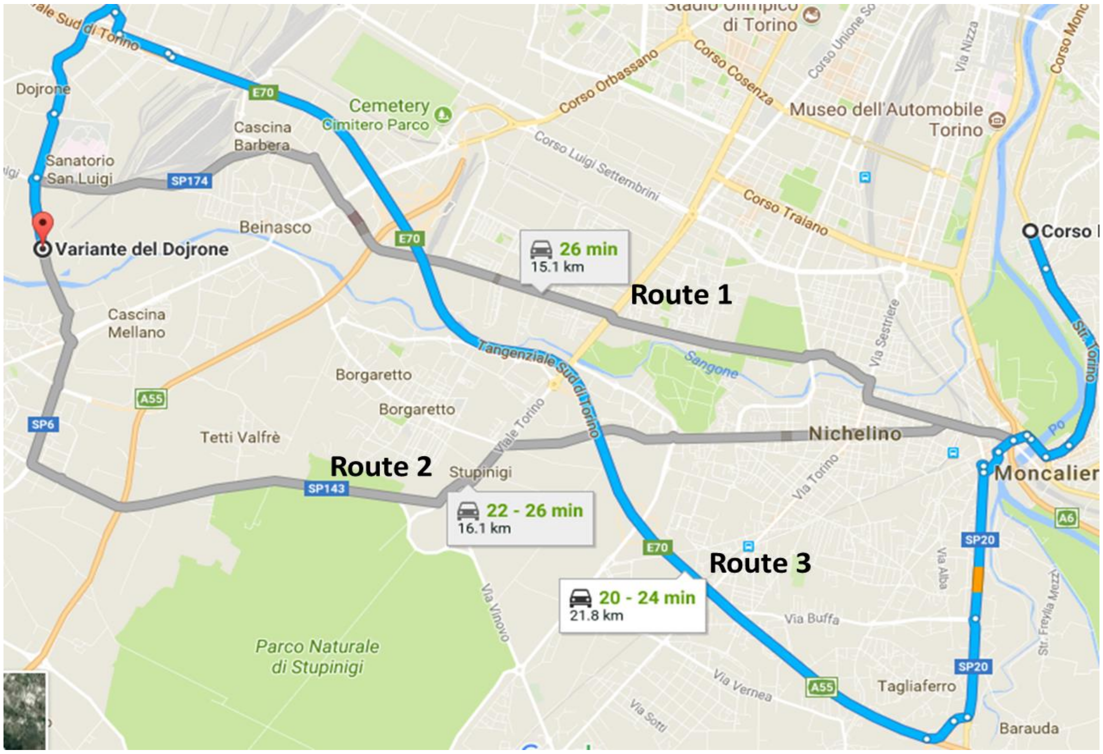

Figure 4-11: Routes considered for EcoRouting Analysis

4.3.2) Results obtained from Turin study

De Nunzio et al. have obtained the energy consumption of the vehicle by measuring the initial and final State of Charge (SOC) readings on the Controller Area Network (CAN) bus. The authors have compared their predicted readings for energy consumption with that of the energy consumption readings obtained from the vehicle. In the present work, a 2013 Nissan Leaf model is used to calculate the energy consumption along the 3 routes to find the EcoRoute. The results are compared against the results obtained by De Nunzio et al.

Table 4-6: Comparison of Energy Consumption Results

Route	**Results obtained by De Nunzio et al. for Fiat 500e battery electric vehicle**			**Results obtained by Warpe for 2013 Nissan Leaf BEV (with grade)**			**Energy Difference Range**
	Predicted energy consumption (Wh)	Energy consumption on CAN (Wh)	Energy Diff. (Wh)	All Cond Stops (Wh)	No Cond. Stops (Wh)	Energy Diff. (Wh)	CAN vs No and All conditional stops (%)
1	2000.00	1980.00	20	2069.55	**2018.31**	51.24	1.93-4.52%
2	**1900.00**	**1860.00**	40	**2053.66**	2029.84	23.82	9.13-10.41%
3	2440.00	2110.00	330	2344.70	2328.35	16.35	10.34-11.12%

The results obtained by De Nunzio et al. show that route 2 is the EcoRoute. The travel time analysis is carried out to calculate the EcoRoute through the methodology used in this thesis.

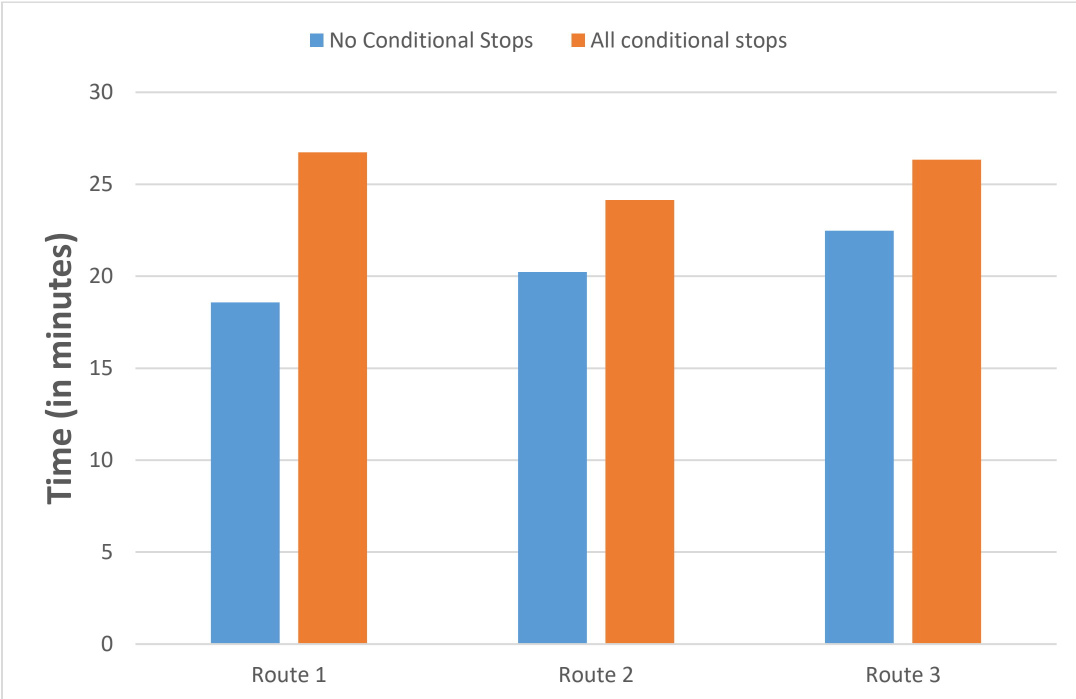

Figure 4-12: Analysis of travel Time for Turin Study

For the case with no conditional stops the t_{min} is 18.57 minutes. Route 1 is the route with minimum travel time and minimum energy consumption. Thus, Route 1 is the EcoRoute in this case.

For the case with all conditional stops, the t_{min} is 24.15 minutes. The maximum permissible travel time (MPTT) for this case is calculated by the method introduced in section [insert section]:

MPTT= 24.15 + (24.15) *(15%) = 27.77 minutes

Route 2 is the route that has the minimum energy consumption and has a travel time less than the MPTT. Therefore, Route 2 is the EcoRoute in the case when all conditional stops are considered.

4.3.3) Conclusions of Turin Study

The energy consumption obtained along the three routes is compared with the energy consumption obtained by De Nunzio et al. The energy difference between the measured data of the Fiat 500e battery electric vehicle and the readings obtained by the Nissan Leaf powertrain model, is found to vary from 1.3 % to 11.1%. The EcoRoute is close but slightly different when the cases with no conditional stops and all conditional stops are considered. The EcoRoute obtained by the 2013 Nissan Leaf model is the same as that obtained by De Nunzio et al. when the effect of all the conditional stops is taken into consideration.

4.4) Sensitivity Study

A sensitivity study is performed to analyze the change in energy consumption with changes in road grade and acceleration. For this study 4 routes of equal length but unequal grades are constructed. Out of the four routes, two routes are initially uphill routes with road grades 1.5% and 3.5% followed by a downhill portion with road grades of -1.5% and -3.5% respectively. The other two routes are initially downhill routes with grades -1.5% and -3.5% followed by an uphill portion with road grades of 1.5% and 3.5% respectively. The length of all the four routes is 0.25 miles (402 meters). The energy consumption is calculated on all these four routes by considering acceleration of the vehicle as 1.5 m/s^2 and 3.5 m/s^2 and a deceleration of -1.5 m/s^2 and -3.5m/s^2. The cruise velocity on all the four routes is same and is equal to 40 mph. The energy consumption on these routes is compared against a route with 0% grade to study the effect of road grade on net energy consumption.

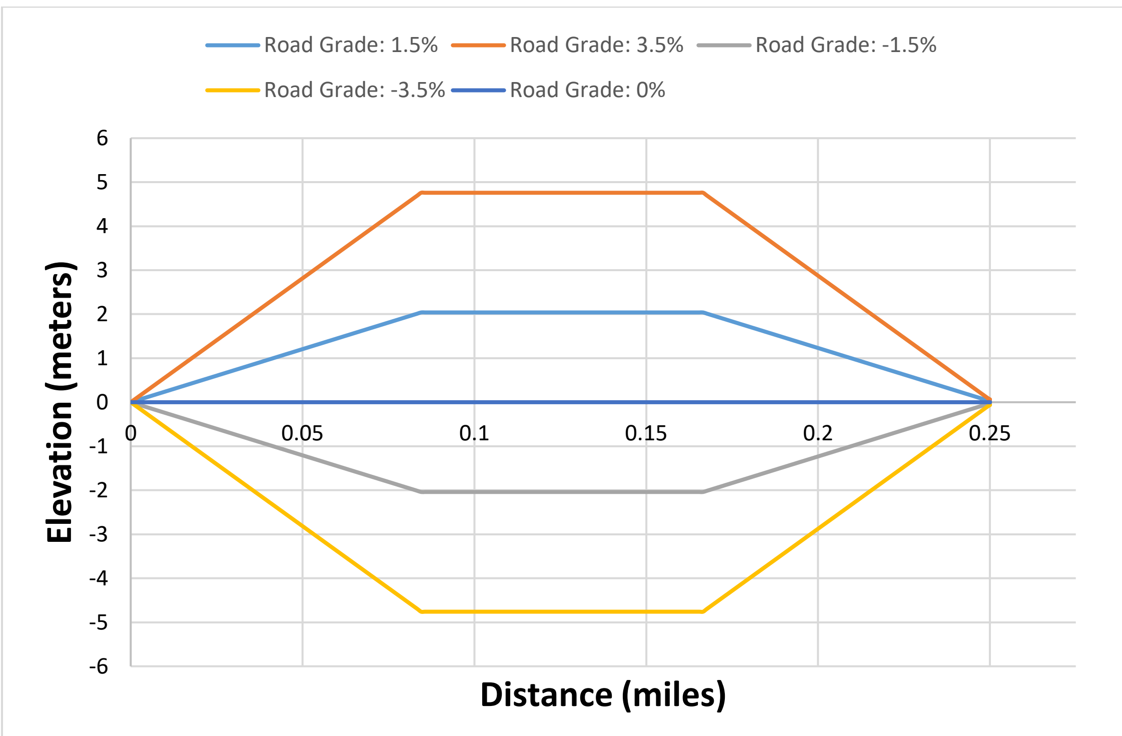

Figure 4-13: Routes simulated for sensitivity study

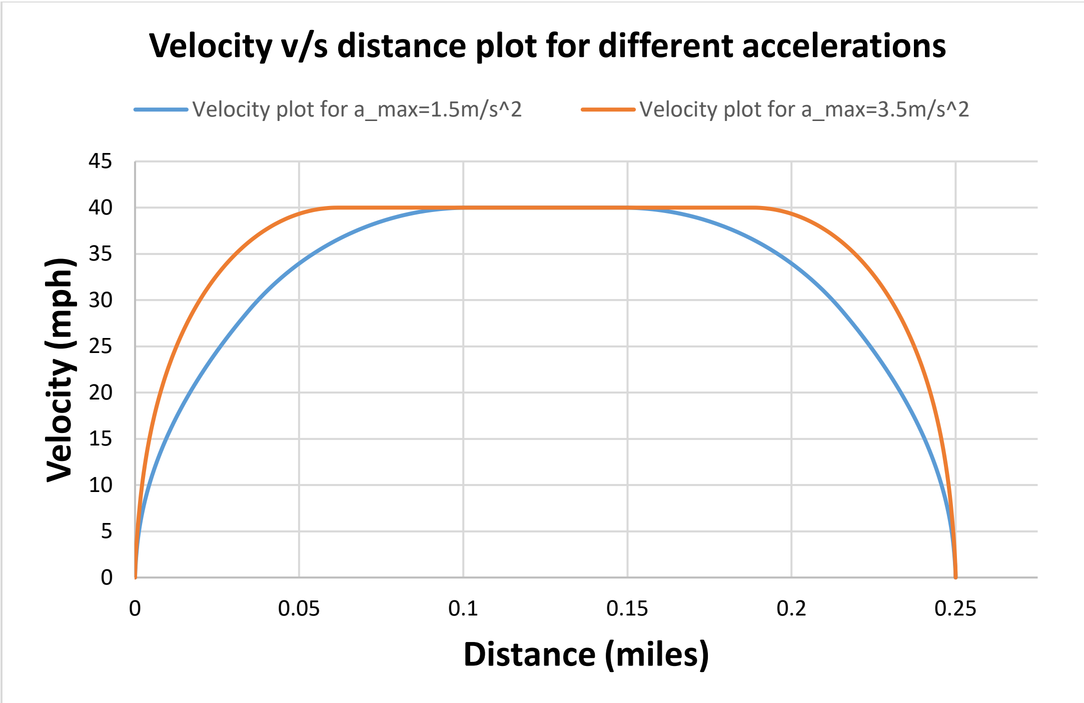

Figure 4-14: Velocity v/s distance plot for different accelerations

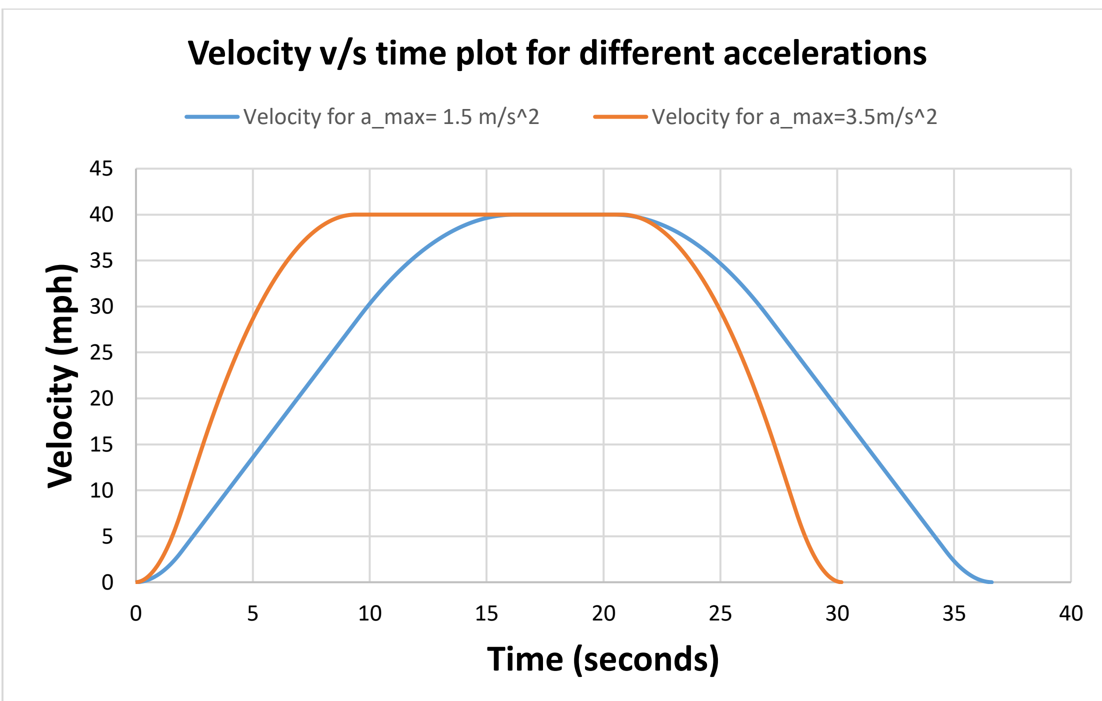

Figure 4-15: Velocity v/s time plot for different accelerations

The cruise velocity of 40 mph is achieved faster with acceleration of $3.5 m/s^2$. Consequently, a higher deceleration rate also causes the vehicle to reach zero velocity in a shorter amount of time. The time taken to reach the destination is higher by 6.51 seconds in the case where the acceleration is $1.5 m/s^2$.

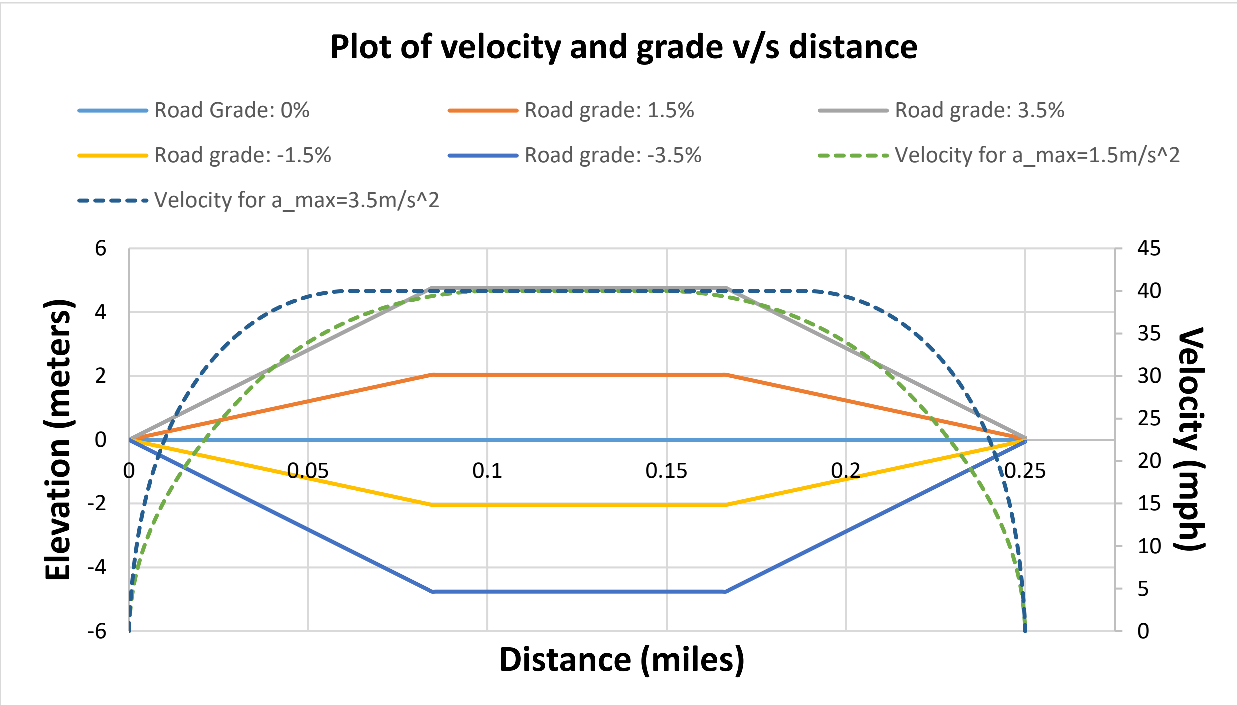

Figure 4-16: Plot of velocity and grade v/s distance

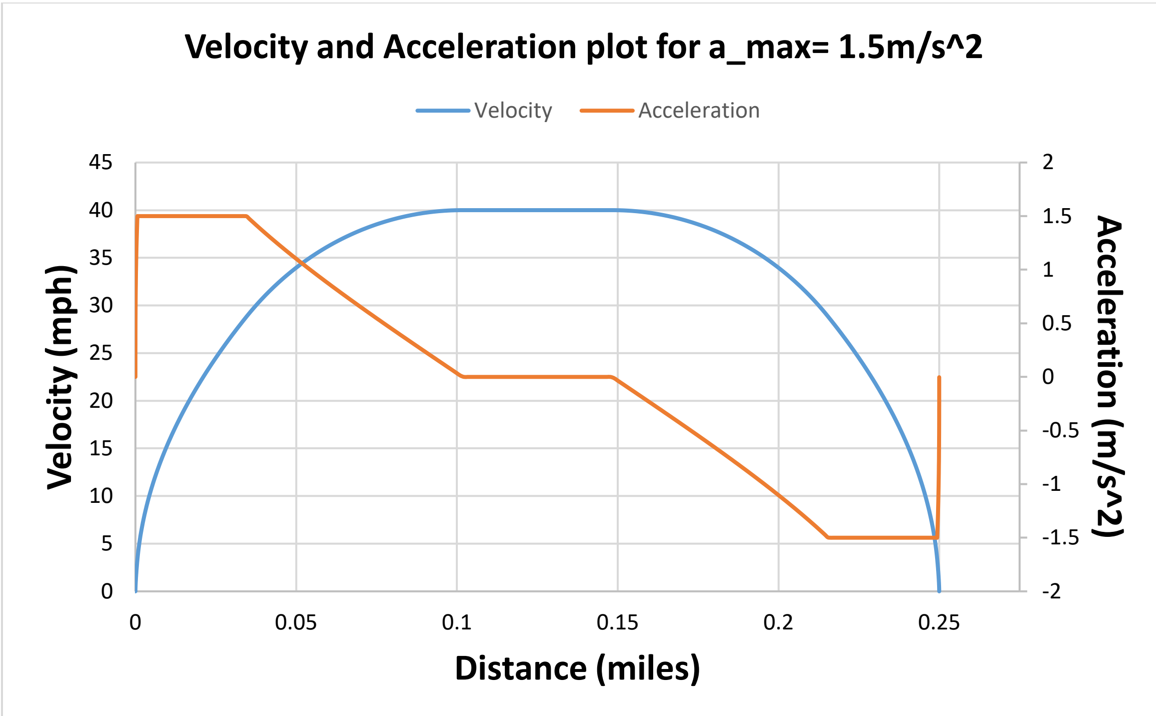

Figure 4-17: Velocity and acceleration plot for a_max= 1.5m/s^2

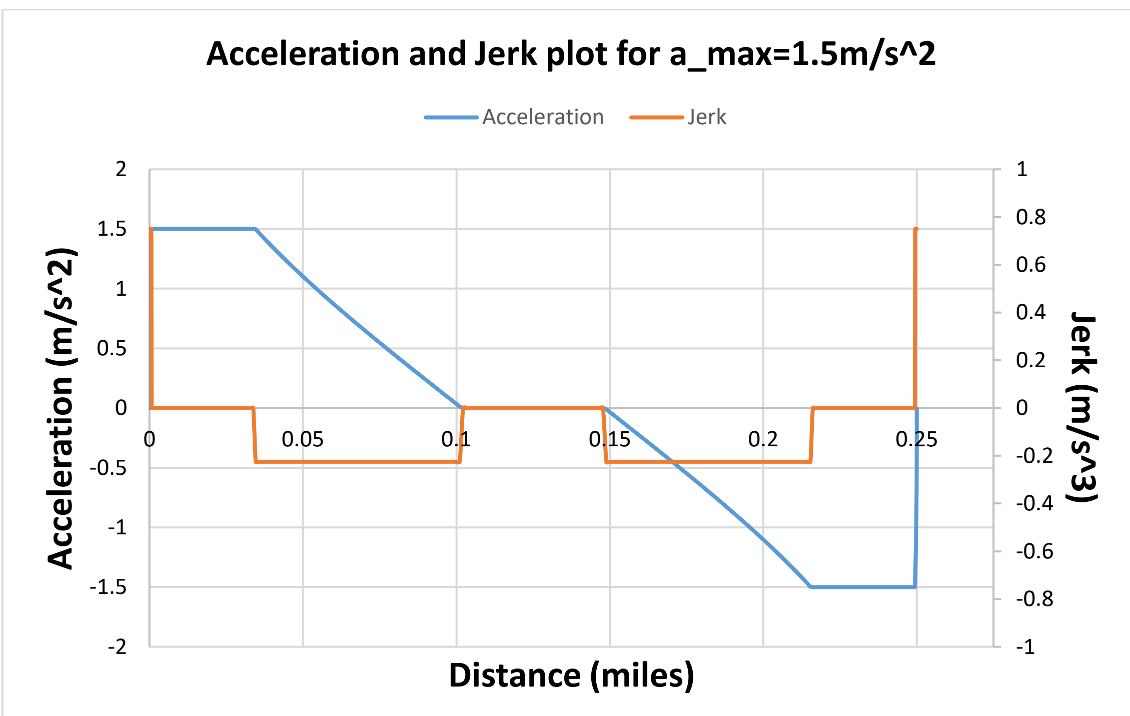

Figure 4-18: Acceleration and jerk plot for a_max= 1.5m/s^2

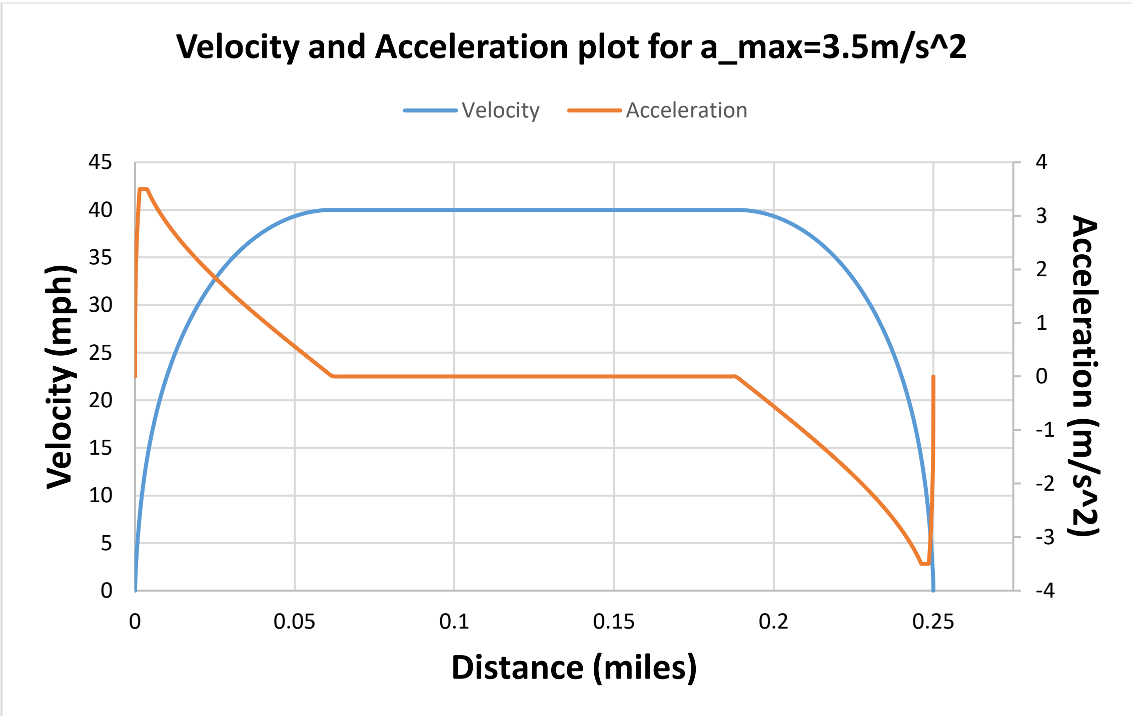

Figure 4-19: Velocity and acceleration plot for a_max=3.5m/s^2

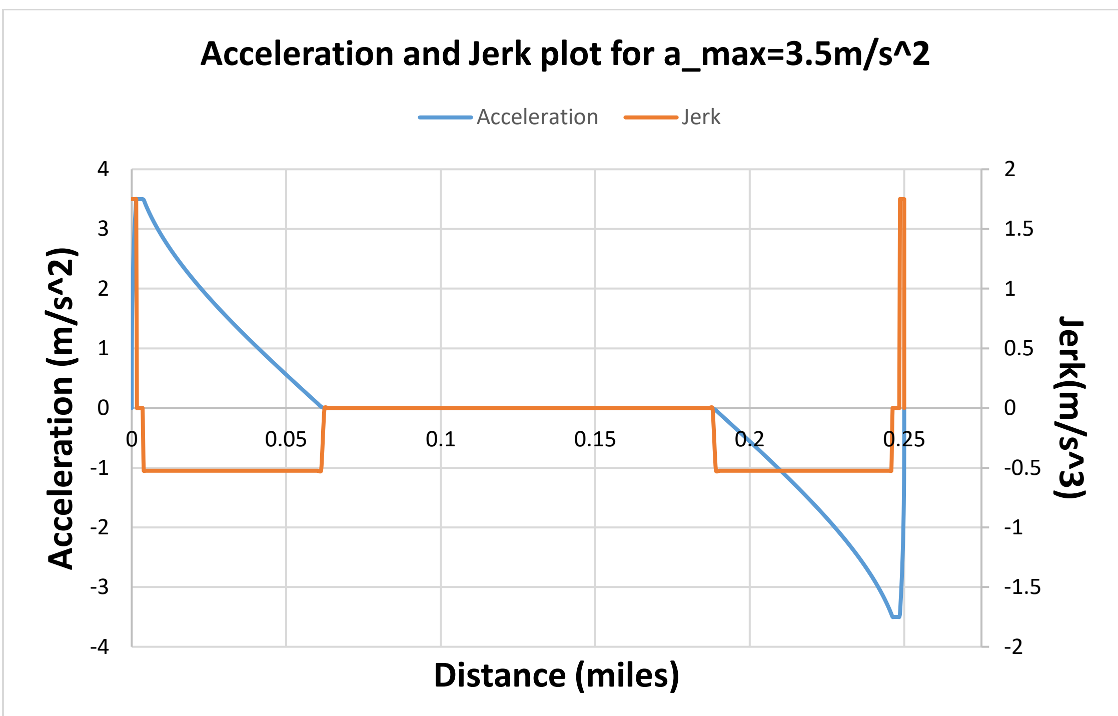

Figure 4-20: Acceleration and jerk plot for a_max=3.5m/s^2

The energy consumption for the different cases of acceleration and grades is shown below. A case with 0% road grade for the same distance is also studied and the energy consumption for this case is calculated. The results for the sensitivity analysis are bifurcated in two categories: Initially uphill and Initially downhill.

4.4.1) Sensitivity analysis for an uphill driving scenario

The sensitivity analysis is performed to measure the change in energy consumption of the vehicle due to the change in the road grade and acceleration of the vehicle. The net energy consumption of the vehicle along the entire route and the effect of net elevation on the energy consumption is studied. For an initially uphill route, the energy consumption is calculated till the vehicle reaches uphill and is compared against a route with 0% grade to observe the effect of grade on energy consumption of the vehicle. The effect of different accelerations along the same path on energy consumption of the vehicle is also observed. The effect of negative grade and deceleration while driving downhill to reach the destination is also studied. The route with 0% grade is the reference against which the results for energy consumption are compared against. The results for the energy consumption for routes with different grades are presented below.

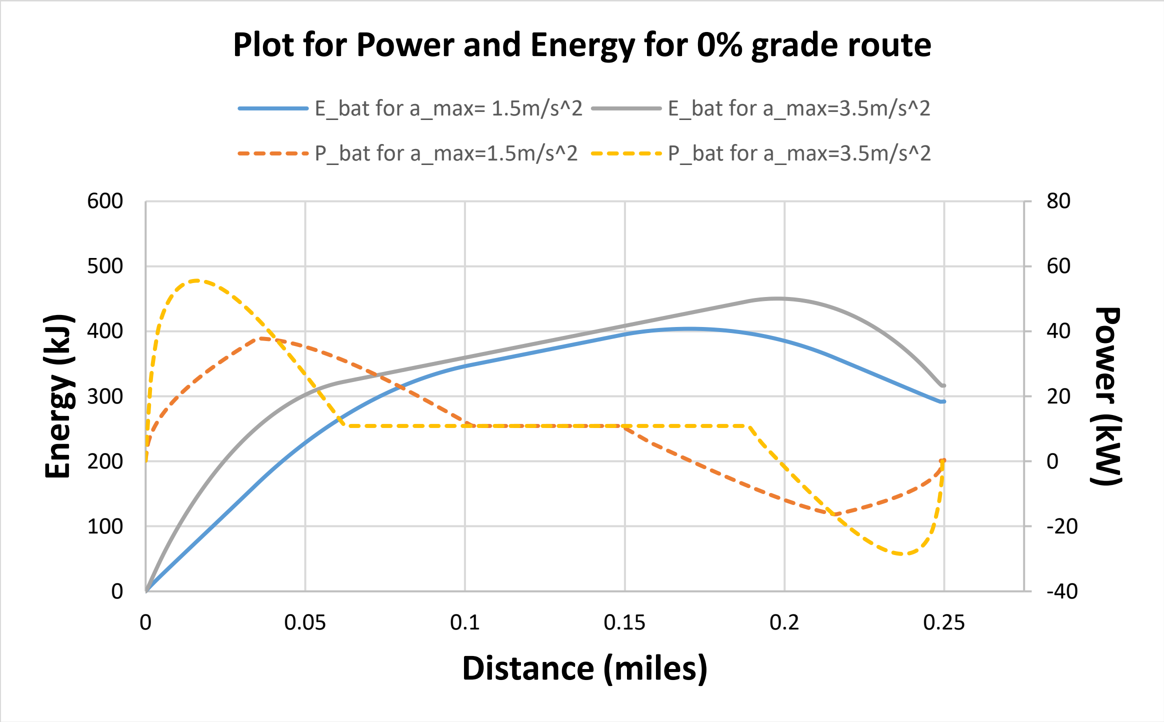

Figure 4-21: Plot for power and energy for 0% grade route

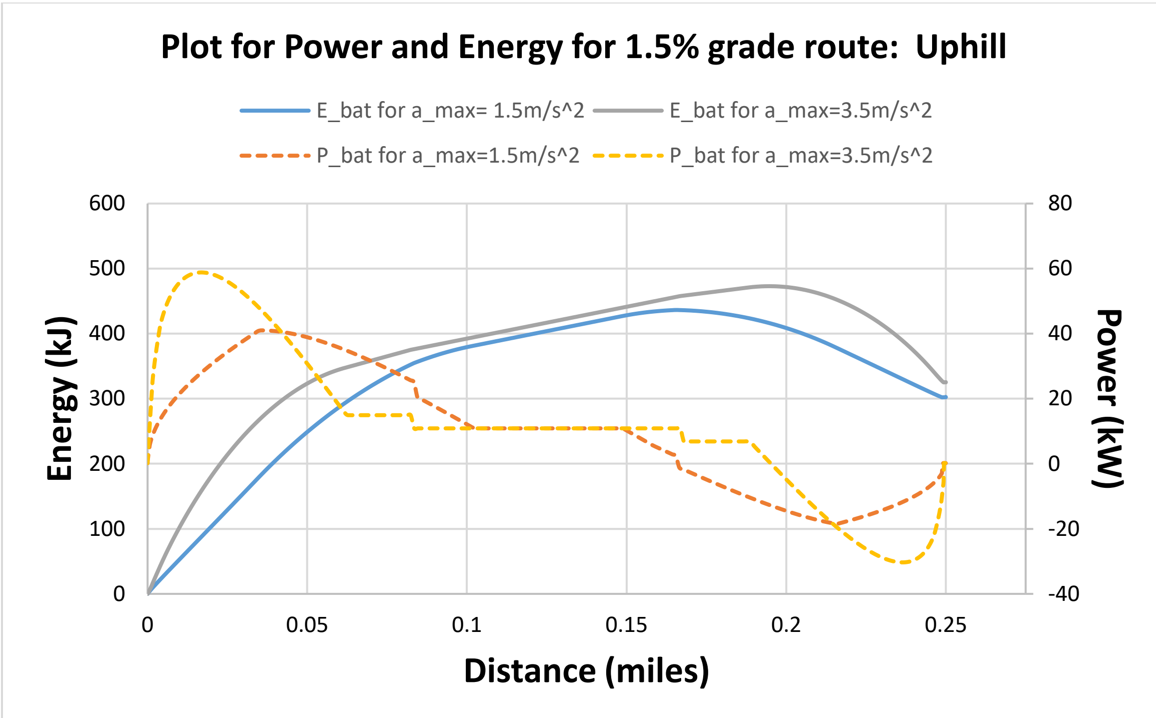

Figure 4-22: Plot for Power and Energy for 1.5% road grade route: Uphill

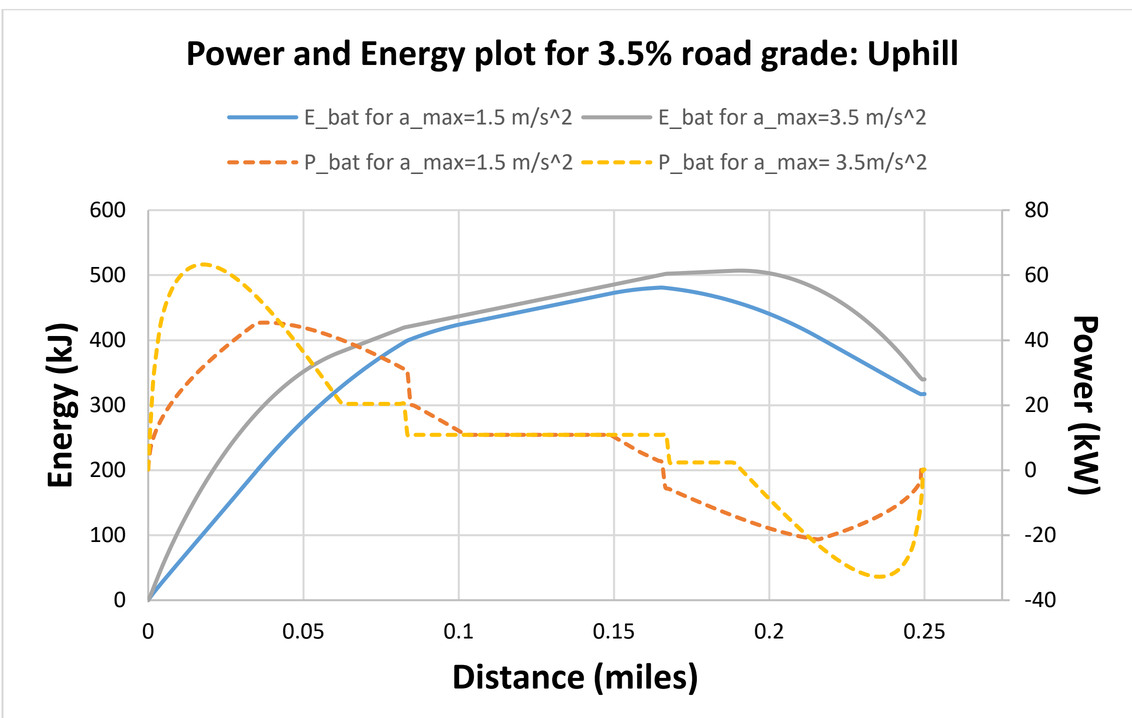

Figure 4-23: Plot for Power and Energy for 3.5% road grade: Uphill

The plots for power and energy show that the energy consumption and power of the vehicle is lower for lower accelerations. The energy consumption of the vehicle is the highest for the case with acceleration of 3.5m/s^2. This indicates that the power losses in the vehicle are less when the vehicle is driven at lower acceleration. However, a smaller power loss may not always imply a higher efficiency.

Table 4-7: Sensitivity analysis for acceleration along entire route of 0.25 miles- Uphill driving

Grade (%)	Energy consumed with acceleration= 1.5 m/s^2 (kJ)	Energy consumed with acceleration= 3.5 m/s^2 (kJ)	Net Elevation Change (meters)	Change in Energy consumption (kJ)
0%	292.16	316.62	0	24.46(8.37%)
1.5%	302.61	325.44	0	22.83(7.54%)
3.5%	317.39	339.84	0	22.45(7.07%)

The energy consumption of the vehicle along the entire route is calculated and studied. These readings for energy consumption are calculated for a net change of 0 meters in elevation. It is observed that the energy consumption increases by more than 7% for a net increase of 2m/s^2 in acceleration.

Table 4-8 and Table 4-9 below show the effect of road grade on energy consumption. The energy consumption of the vehicle is found to increase with an increase in road grade.

Table 4-8: Sensitivity analysis for grade of 1.5% along entire route of 0.25 miles- Uphill

Acceleration (m/s^2)	Energy consumed with grade=0% (kJ)	Energy consumed with grade= 1.5% (kJ)	Net Change in elevation (meters)	Change in Energy Consumption (kJ)
1.5	292.16	302.61	0	10.45(3.57%)
3.5	316.62	325.44	0	8.82(2.78%)

Table 4-9: Sensitivity analysis for grade of 3.5% along entire route of 0.25 miles- Uphill

Acceleration (m/s^2)	Energy consumed with grade=0% (kJ)	Energy consumed with grade= 3.5% (kJ)	Net Change in elevation (meters)	Change in Energy Consumption (kJ)
1.5	292.16	317.39	0	25.23(8.63%)
3.5	316.62	339.84	0	23.22(7.33%)

Figure 4-24 below shows the effect of accelerations on power and energy of the vehicle with respect to time. The peak power of the vehicle with higher acceleration occurs before the peak power of the vehicle with a lower acceleration.

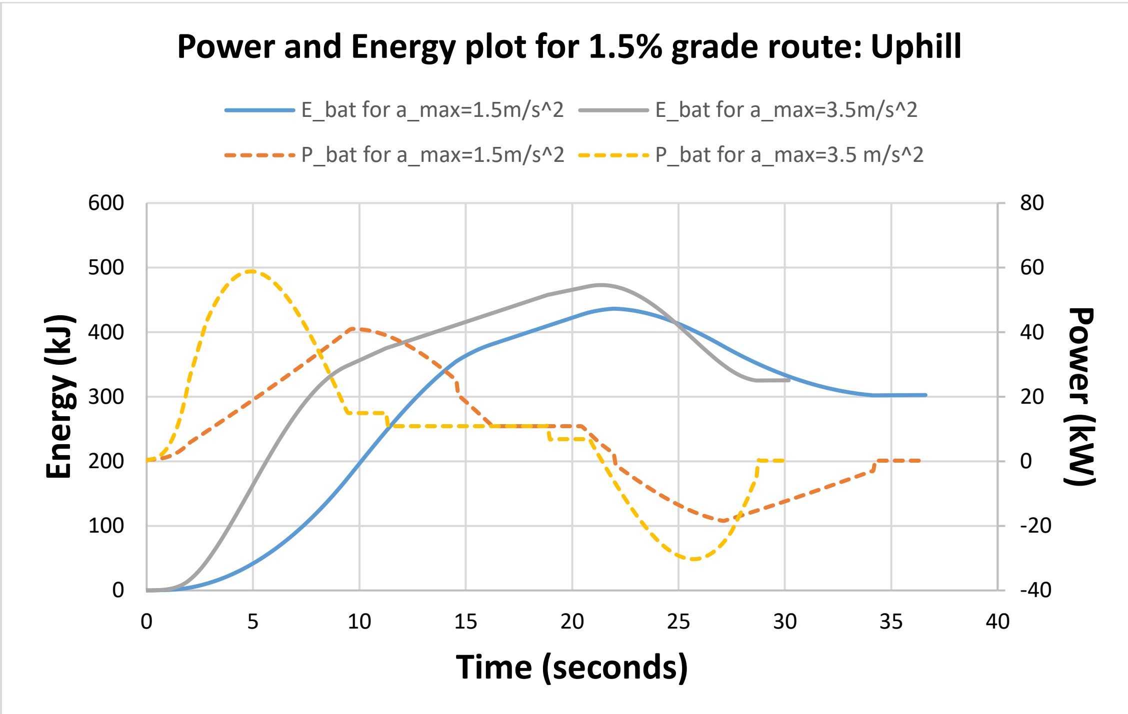

Figure 4-24: Power and Energy plot v/s time: 1.5% road grade uphill

For an initially uphill route, the energy consumption is calculated till the vehicle reaches uphill and is compared against a route with 0% grade to observe the effect of elevation on energy consumption of the vehicle. The energy consumption of the vehicle is calculated when it attains maximum net elevation on a route. The effect of different accelerations along the same path on energy consumption of the vehicle is also observed.

Table 4-10: Sensitivity analysis for acceleration- Initially Uphill driving

Grade (%)	Energy consumed with acceleration= 1.5 m/s^2 (kJ)	Energy consumed with acceleration= 3.5 m/s^2 (kJ)	Net change in elevation (meters)	Change in Energy consumption (kJ)
0%	323.80	344.41	0.00	20.61(6.3%)
1.5%	354.74	375.11	2.00	20.37(5.7%)
3.5%	399.27	419.46	4.78	20.19(5.05%)

From the above results, it is observed that the energy consumption increases with an increase in acceleration along an uphill route having the same grade. An increase of more than 5% in energy consumption is observed along every route for a net increase of $2m/s^2$ in acceleration. More energy is expended in going uphill along the route with 3.5% road grade while the least energy is expended along the path with a 0% grade. Gravitational force plays a major role in the energy consumption of the vehicle along an inclined path. The gravitational force opposes the motion of a vehicle along an inclined path, and this results in more torque being expended by the electric motor to propel the vehicle to move forward.

Table 4-11: Sensitivity analysis for grade- Initially Uphill driving with 1.5% grade

Acceleration (m/s^2)	**Energy consumed with grade=0% (kJ)**	**Energy consumed with grade= 1.5% (kJ)**	**Net Change in elevation (meters)**	**Change in Energy Consumption (kJ)**
1.5	323.80	354.74	2.00	30.94(9.55%)
3.5	344.41	375.11	2.00	30.70(8.91%)

Table 4-12: Sensitivity analysis for grade- Initially Uphill driving with 3.5% grade

Acceleration (m/s^2)	**Energy consumed with grade=0% (kJ)**	**Energy consumed with grade= 3.5% (kJ)**	**Net Change in elevation (meters)**	**Change in Energy Consumption (kJ)**
1.5	323.80	399.27	4.78	75.47(23.30%)
3.5	344.41	419.46	4.78	75.05(21.79%)

For an uphill driving scenario, a 1.5% change in road grade with a net change in elevation of 2 meters causes a change of more than 8.5% in energy consumption along a route if the acceleration of the vehicle is the same. However, for a change of 3.5% in road grade and a net change in elevation of 5 meters, the increase in energy consumption is more than 21%. The energy consumption of the vehicle is not as sensitive to change in acceleration as it is for change in road grade.

Along with gravitation, regenerative braking plays a major role in determining the energy consumption of a vehicle during deceleration downhill. For a downhill path, the effects of regenerative braking are observed while decelerating the vehicle. Briefly, a regenerative brake is an energy recovery mechanism that slows a vehicle by converting its kinetic energy into a form that can be stored until needed. The electric motor functions as a generator while decelerating, to convert the kinetic or potential energy into electric energy. This results in more energy being stored in the battery and less energy being expended by the battery. From the above table, we can see that more deceleration leads to less energy being stored into the battery. However, there is a limit on the amount of energy that can be utilized for regen braking, called as the regen limit. The results that show the impact of road grade and deceleration on the energy consumption of a vehicle for the case of downhill deceleration are presented below.

Table 4-13: Sensitivity analysis for acceleration - Downhill driving after initial uphill driving

Grade (%)	Net Energy with acceleration= -1.5 m/s^2 (kJ)	Net Energy with acceleration= -3.5 m/s^2 (kJ)	Net change in elevation (meters)	Change in Energy consumption (kJ)
0%	-110.98	-106.12	0.00	4.86 (4.33%)
-1.5%	-133.66	-133.03	-2.00	0.63(0.47%)
-3.5%	-163.00	-162.53	-4.78	0.47(0.28%)

The net change in energy consumption of the vehicle does not change by a significant amount with a change in the deceleration for a downhill route. The change in energy consumption due to a change in deceleration reduces with an increase in the downhill grade. However, road grade significantly affects the energy consumption for downhill driving. The results are presented in Table 4-14 and Table 4-15 below.

Table 4-14: Sensitivity analysis for grade - Downhill -1.5% grade after initial uphill driving

Acceleration (m/s^2)	Energy consumed with grade=0% (kJ)	Energy consumed with grade= -1.5% (kJ)	Net Change in elevation (m)	Change in Energy Consumption (kJ)
-1.5	-110.98	-133.66	-2.00	-22.68(-20.43%)
-3.5	-106.12	-133.03	-2.00	-26.91(-25.35%)

Table 4-15: Sensitivity analysis for grade - Downhill -3.5 % grade after initial uphill driving

Acceleration (m/s^2)	Energy consumed with grade=0% (kJ)	Energy consumed with grade= -3.5% (kJ)	Net Change in elevation (m)	Change in Energy Consumption (kJ)
-1.5	-110.98	-163.00	-4.78	-52.02(-46.87%)
-3.5	-106.12	-162.53	-4.78	-56.41(-53.15%)

A change of more than 20% and 45% in energy consumption is observed for a downhill driving scenario with decelerations of -1.5 m/s^2 and -3.5m/s^2 respectively. Thus, a change in road grade is more significant than a change in acceleration rate to determine the energy consumption of a vehicle.

4.4.2) Sensitivity analysis for a downhill driving scenario

For an initially downhill route, the energy consumption is calculated till the vehicle reaches downhill and is compared against a route with 0% grade to observe the effect of grade on energy consumption of the vehicle. The same analysis that was done for uphill driving is done for downhill driving. The effect of different accelerations along the same path on energy consumption of the vehicle is also observed. The effect of positive grade and deceleration while driving uphill to reach the destination is also studied. The route with 0% grade is the reference against which the results for energy consumption are compared against. The results for the energy consumption for routes with different grades are presented below.

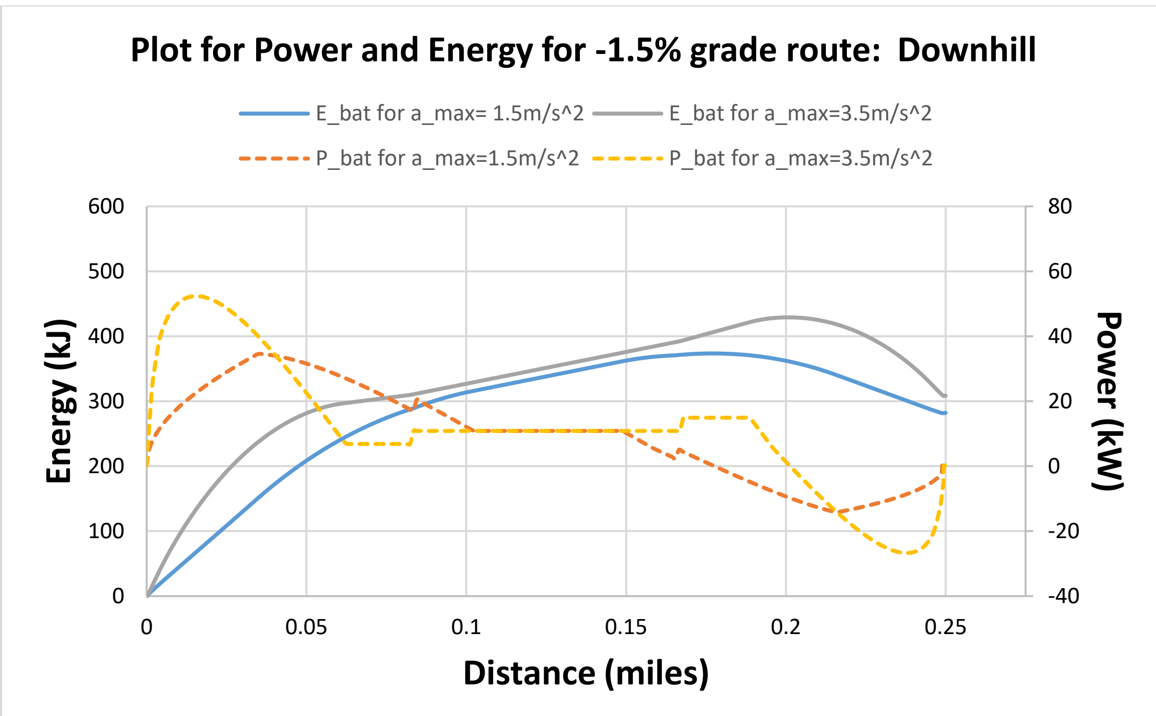

Figure 4-25: Plot for power and energy for -1.5% road grade: Downhill

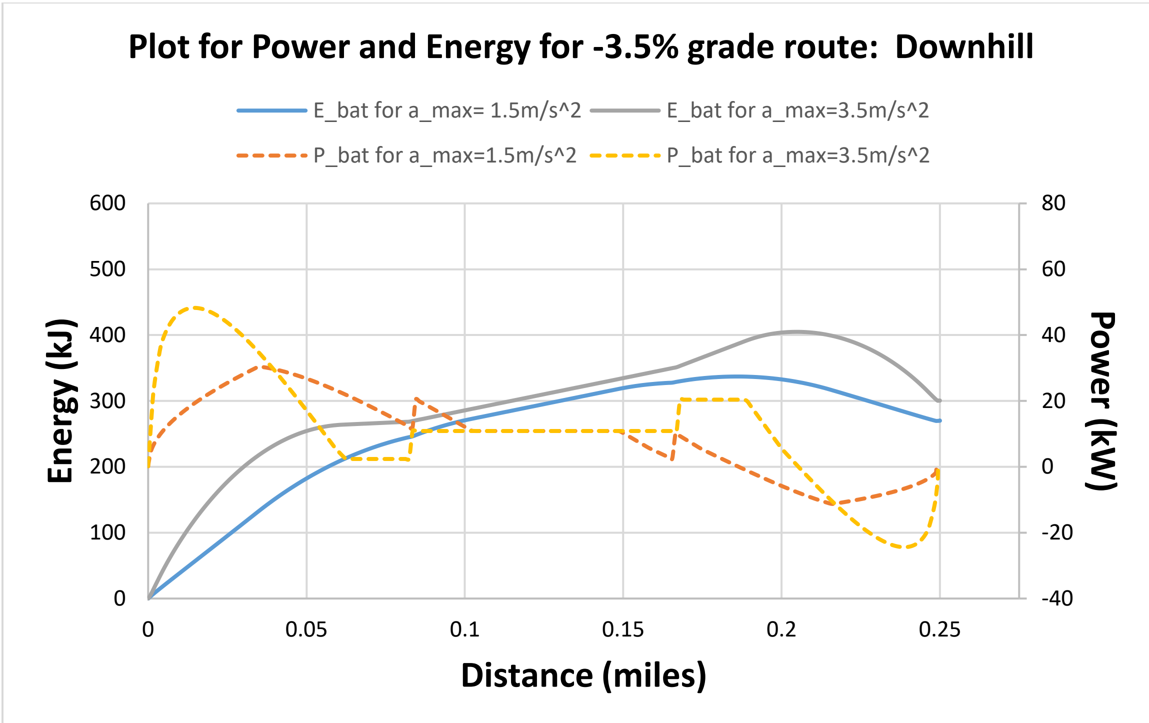

Figure 4-26: Plot for power and energy for -3.5% road grade: Downhill

The plots for power and energy show that the energy consumption and power of the vehicle is lower for lower accelerations. The energy consumption of the vehicle is the highest for the case with acceleration of 3.5m/s^2. However, the energy consumption of the vehicle is significantly lower than when the vehicle was driven initially uphill.

Table 4-16: Sensitivity analysis for acceleration along entire route- Downhill driving

Grade (%)	Energy consumed with acceleration= 1.5 m/s^2 (kJ)	Energy consumed with acceleration= 3.5 m/s^2 (kJ)	Net change in elevation (meters)	Change in Energy consumption (kJ)
0%	292.16	316.62	0	24.46(8.3%)
-1.5%	282.28	308.60	0	26.32(9.3%)
-3.5%	270.31	300.71	0	30.40(11.23%)

The energy consumption of the vehicle along the entire route is calculated and studied. These readings for energy consumption are calculated for a net change of 0 meters in elevation. It is observed that the energy consumption increases by more than 8% for a net increase of 2m/s^2 in acceleration.

The tables below show the effect of road grade on energy consumption. The energy consumption of the vehicle is found to decrease with a decrease in road grade. The effect of gravitational force helps the vehicle to move forward when it is driven downhill. This results into less energy consumption of the vehicle to propel forward.

Table 4-17: Sensitivity analysis for -1.5% grade- Initially Downhill driving

Acceleration (m/s^2)	Energy consumed with grade=0% (kJ)	Energy consumed with grade= -1.5% (kJ)	Net Change in elevation (meters)	Change in Energy Consumption (kJ)
1.5	292.16	282.28	0	-9.88(-3.38%)
3.5	316.62	308.60	0	-8.02(-2.53%)

Table 4-18: Sensitivity analysis for -3.5% grade- Initially Downhill driving

Acceleration (m/s^2)	Energy consumed with grade=0% (kJ)	Energy consumed with grade= -3.5% (kJ)	Net Change in elevation (meters)	Change in Energy Consumption (kJ)
1.5	292.16	270.31	0	-21.85(-7.47%)
3.5	316.62	300.71	0	-15.91(-5.02%)

For an initially downhill route, the energy consumption is calculated till the vehicle reaches downhill and is compared against a route with 0% grade to observe the effect of elevation on energy consumption of the vehicle. The energy consumption of the vehicle is calculated when it attains minimum net elevation on a route. The effect of different accelerations along the same path on energy consumption of the vehicle is also observed.

Table 4-19: Sensitivity analysis for acceleration- Initially downhill driving

Grade (%)	Energy consumed with acceleration= 1.5 m/s^2 (kJ)	Energy consumed with acceleration= 3.5 m/s^2 (kJ)	Net change in elevation (meters)	Change in Energy consumption (kJ)
0%	323.80	344.41	0.00	20.61(6.36%)
-1.5%	291.15	309.72	-2.00	18.57(6.37%)
-3.5%	248.15	268.52	-4.78	20.37(8.2%)

From the above results, it is observed that the energy consumption increases with an increase in acceleration along a downhill route having the same grade. An increase of more than 6% in energy consumption is observed along every route for a net increase of 2m/s^2 in acceleration. Least energy is expended in going downhill along the route with -3.5% road grade while more energy is expended along the path with a 0% grade.

Table 4-20: Sensitivity analysis for grade- Initially downhill driving with 1.5% grade

Acceleration (m/s^2)	**Energy consumed with grade=0% (kJ)**	**Energy consumed with grade= -1.5% (kJ)**	**Net Change in elevation (meters)**	**Change in Energy Consumption (kJ)**
1.5	323.80	291.15	-2.00	-32.65(-10.08%)
3.5	344.41	309.72	-2.00	-34.69(-10.07%)

Table 4-21: Sensitivity analysis for grade- Initially downhill driving with 3.5% grade

Acceleration (m/s^2)	**Energy consumed with grade=0% (kJ)**	**Energy consumed with grade= -3.5% (kJ)**	**Net Change in elevation (meters)**	**Change in Energy Consumption (kJ)**
1.5	323.80	248.15	-4.78	-75.65(-23.36%)
3.5	344.41	268.52	-4.78	-75.89(-22.03%)

For a downhill driving scenario, a -1.5% change in road grade with a net change of 2 meters in elevation causes a change of more than 10% in energy consumption along a route if the acceleration of the vehicle is the same. However, for a change of -3.5% in road grade and a net change in elevation of 5 meters, the increase in energy consumption is more than 22%. The energy consumption of the vehicle is not as sensitive to change in acceleration as it is for change in road grade.

For an uphill path, the effects of regenerative braking are observed while decelerating the vehicle. A higher deceleration leads to less energy being expended by the battery. The results for decelerating uphill are presented below.

Table 4-22: Sensitivity analysis for acceleration- Uphill driving after initial downhill driving

Grade (%)	Energy consumed with acceleration= -1.5 m/s^2 (kJ)	Energy consumed with acceleration= -3.5 m/s^2 (kJ)	Net change in elevation (meters)	Change in Energy consumption (kJ)
0%	-110.98	-106.12	0.00	4.86(4.37%)
1.5%	-88.97	-85.28	2.00	3.69(4.14%)
3.5%	-58.46	-52.52	4.78	5.94(10.16%)

Table 4-23: Sensitivity analysis for grade- Uphill 1.5% grade after initial downhill driving

Acceleration (m/s^2)	Energy consumed with grade=0% (kJ)	Energy consumed with grade= 1.5% (kJ)	Net Change in elevation (meters)	Change in Energy Consumption (kJ)
-1.5	-110.98	-85.28	2.00	25.7(23.15%)
-3.5	-106.12	-88.97	2.00	17.15(16.16%)

Table 4-24: Sensitivity analysis for grade- Uphill 3.5% grade after initial downhill driving

Acceleration (m/s^2)	Energy consumed with grade=0% (kJ)	Energy consumed with grade= 3.5% (kJ)	Net Change in elevation (meters)	Change in Energy Consumption (kJ)
-1.5	-110.98	-58.46	4.95	52.52(47.32%)
-3.5	-106.12	-52.52	4.95	53.60(50.50%)

For an uphill driving scenario, a -1.5% change in road grade with a change in elevation of 2 meters causes a change of more than 16% in energy consumption along a route if the deceleration of the vehicle is the same. For a change of -3.5% in road grade and a change in elevation of 5 meters, the increase in energy consumption is more than 50%. Extra energy is expended by the electric motor to propel the vehicle forward as the gravitational force opposes the motion of the vehicle. Therefore, more energy is spent for an uphill route. The energy consumption of the vehicle is not as sensitive to change in road grade as it is for change in acceleration.

4.4.3) Conclusions for Sensitive Study

A sensitive study showing the effect of road grade and acceleration on energy consumption is performed on 3 routes with road grades of 0%, 1.5% and 3.5%. For an uphill route, it is observed that a vehicle consumes more energy for higher grades and higher accelerations, however road grade plays a bigger part than acceleration in determining the energy consumption along a route. For an uphill route, a net elevation of 2 meters causes a change of more than 8% in energy consumption of a vehicle, while a change of 4.75 meters causes a change of more than 21% in energy consumption. These results were measured against the energy consumption along a route which consisted of 0% grade.

For a downhill route, a net elevation of 2 meters causes a change of more than -20% in energy consumption, while a change of 4.75 meters causes a change of more than -46% in energy consumption of a vehicle. While going downhill, less energy is expended by the vehicle since gravitational forces help in propelling the vehicle forward. The impact of regenerative braking on energy consumption was also observed and it was found that regenerative braking saves more energy if the downhill slope is steeper. The results for only initially uphill and only initially downhill cases are summarized in the table below.

Table 4-25: Summary of sensitivity analysis for grade

	Energy consumption for different values of road grade (kJ)				
Acceleration (m/s)	**-3.5 % (4.8m)**	**-1.5% (2m)**	**0%**	**1.5% (2m)**	**3.5% (4.8m)**
1.5	248.15	291.15	323.80	354.74	399.27
3.5	268.52	309.72	344.41	375.11	419.46

The net elevation between the origin and the destination plays an important role to determine the energy consumption. This analysis can also be extended to cases where the horizontal distance between the origin and the destination is longer. A high change in net elevation along longer routes will significantly impact the energy consumption of the vehicle.

The energy consumption of the vehicle along the five individual routes with different grades is presented in Table 4-26. The net change in grade along each of these five routes is 0%. The effect of the change in acceleration on energy consumption of the vehicle along an entire route of 0.25 miles is presented below.

Table 4-26: Summary for sensitivity analysis for acceleration along entire route of 0.25 miles

Grade (%)	Energy consumed with acceleration= 1.5 m/s^2 (kJ)	Energy consumed with acceleration= 3.5 m/s^2 (kJ)	Net change in elevation (meters)	Change in Energy consumption (kJ)
-3.5%	270.31	300.71	0	30.40(11.23%)
-1.5%	282.28	308.60	0	26.32(9.3%)
0%	292.16	316.62	0	24.46(8.37%)
1.5%	302.61	325.44	0	22.83(7.54%)
3.5%	317.39	339.84	0	22.45(7.07%)

The net energy consumption of the vehicle for the cases with different accelerations is observed to not change much with a change in acceleration rate. It is also observed that the vehicle consumes more energy while travelling uphill with a higher acceleration and less energy while travelling downhill. However, from the power and energy consumption results obtained in Figure 4-21, Figure 4-22, and Figure 4-23, the peak power occurs at different times for the same route depending on the acceleration rate of the vehicle. The power loss is less for downhill routes and higher for uphill routes but a low power loss does not imply a high efficiency. The net change in energy consumption of the vehicle for the routes is observed to decrease with an increase in the maximum elevation of the entire route. However, the difference in energy consumption due to variable acceleration rates is not significant. This study shows that the road grade plays a bigger role than acceleration to determine the net energy consumption of the vehicle along an entire route.

5) Chapter Five- Conclusion

The analysis of energy consumption along a given network of routes constitutes most of the work in this thesis. The effect of road grades, mandatory stops and conditional stops is studied and the results are presented.

5.1) Route import

The methodology to import route characteristics such as road grades, conditional stops, and speed limits of routes is presented in this thesis. The method to parse these parameters in each network of nodes and segments is also presented. The algorithms and code to conduct the directed graph analysis are provided in the Appendix. The parameters obtained as a result of the code are then used to construct the route parameters and are fed through a variable acceleration based velocity profile model to simulate driver behavior.

5.2) Energy consumption of battery electric vehicle

The extensive analysis of the energy consumption of a vehicle on routes is done by considering the cases with maximum and minimum number conditional stops. A similar analysis is done on energy consumption of vehicles by considering the impact of having no road grade. It is found that the most energy efficient path may not always be the most time efficient path to reach the destination. It is also observed that routes which contain a mixture of city and highway driving perform relatively better than only city- based driving or highway-based driving routes for electric vehicles.

A comparative study is done on 3 routes of Blacksburg, Virginia, San Francisco, California, and Turin, Italy using the variable acceleration rate synthesis methodology to find the most energy efficient route in a geographical region. The effect of road grade and stops is studied to see how these parameters impact the energy consumption of a vehicle and how a route is selected based on the data available through the model synthesis. The parameter of Maximum Permissible Travel Time (MPTT) is introduced to quantify the effect of travel time. The travel time analysis also shows that more often than not, a route having a mixture of mild and hard accelerations is always a better candidate for the EcoRouting analysis as it saves more time and energy consumption.

5.3) Simulation of velocity profile

While a constant acceleration produces a linear profile between the initial and the final speed limit, the jerked nature of the variable acceleration creates a more natural velocity profile and gives a more accurate representation of how a driver drives a vehicle. The distance of the route, velocity along the route, the grade along the route and the idle time along a route are fed as inputs to a backward facing vehicle model that helps to calculate the total energy along one route.

5.4) Effect of external parameters

The effect of stops in determining the acceleration of the vehicle and the idle time plays a dominant role in deciding whether the shortest route is always the most energy efficient route or not. The results obtained show that road grade information and conditional stops play an important part in determining the EcoRoute in a geographical area. The other factors that have an impact on determining the EcoRoute are speed limits and the number of mandatory stops.

The net elevation between the origin and the destination plays an important role to determine the energy consumption. The results obtained from the sensitivity analysis show that a large difference in net elevation along longer routes will significantly impact the energy consumption of the vehicle. The results of the sensitivity study show that the road grade plays a bigger role than acceleration to determine the net energy consumption of the vehicle.

The methodology implemented in this thesis can be used with any type of vehicle powertrain architecture and thus can be extended to any vehicle. The data available on government organizations such as Argonne National Labs (ANL) can be used to model the vehicle powertrain and calculate total energy consumption of a vehicle.

6) Future Work

The EcoRouting analysis was conducted on one battery electric vehicle. Further research and testing of the EcoRouting algorithm needs to be done for a wide variety of cars. The EcoRouting algorithm also needs to be tested for plug-in hybrid electric vehicles to judge the impact on a blended strategy and optimize the fuel consumption as well as the electric power consumption to get more savings.

The data obtained from driving can be provided to the driver as feedback to improve his/ her driving behavior and encourage more people to adopt energy efficient driving practices that will help them to save more money in the future.

The effect of traffic in real time would provide more data about how stops and idle time are affected due to traffic patterns at different times of the day. Further, an extensive study over different urban vs highway driving test cases needs to be conducted to test the efficacy of the EcoRouting algorithm.

It has been seen that the number of conditional stops greatly increases the travel. For an efficient algorithm, more study needs to be done in choosing a route that contains medium or a slightly lower number of conditional stops to reduce latency caused due to stops and increase energy savings.

Machine learning algorithms can also be implemented in this methodology to predict the energy consumption by considering previously available traffic data. The traffic flow and idle times can be predicted from an exhaustive dataset of past information for a given route. A few studies show the use of Artificial Neural Networks (ANN) for predicting the traffic and idle times from past data. Machine learning algorithms using Support Vector Machines (SVM's) can also be implemented to study the effects on energy consumption while choosing the EcoRoute. The investigation into using the right architecture or kernel needs to be done to accurately predict the effect of machine learning on energy consumption for a vehicle.

The EcoRouting module can also be used with any level of autonomy and thus can be used as an efficient tool for any vehicle. The effect of V2V (Vehicle to Vehicle) communication can also be studied so vehicles can assist each other to save energy. The V2V module can enable vehicles to communicate with one another and formulate an optimized solution as a group rather than an individual entity.

The V2X (Vehicle to Infrastructure) module can also be used by cars so that a centralized server can streamline the traffic and make a fuel as well as time efficient choice for the vehicles along a given route. With the advent of new communication protocols and with the emergence of 5G technology many automobile companies are also looking at the possibility of making vehicles communicate with one another to reduce accidents and help in navigating other vehicles along a given route.

The effect of other external factors like weather and humidity (cabin climate control energy use), altitude, and type of road also needs to be studied to make the EcoRouting algorithm as accurate as possible to account for the changes caused by the external factors. External factors like traffic flow (commonly expressed as vehicles per hour) can be estimated from past data to determine the average velocity along a given path and the time taken to travel from the source to the destination.

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A) Appendix

A.1) Implementation code of all path between two nodes

```
% It takes a connectivity matrix of a road network and generates
% All possible paths between two nodes.
child_handles = allchild(0);
names = get(child_handles,'Name');
k = find(strncmp('Biograph Viewer', names, 15));
close(child_handles(k))
set(0,'DefaultFigureWindowStyle','docked')
DG = sparse(connectivity_matrix)
g1 = view(biograph(DG))
from4 = graphtraverse(DG,886); % Traversals from origin
DG_from=DG(from4,from4);
g2 = view(biograph(DG_from,cellstr(num2str(from4'))))
to1 = graphtraverse(DG',305);
DG_to=DG(to1,to1); % Traversals to destination
g3 = view(biograph(DG_to,cellstr(num2str(to1'))))
h = intersect(from4,to1)
DG2 = DG(h,h);
g4 = view(biograph(DG2,cellstr(num2str(h'))))
[Dist, Path]=graphkshortestpaths(DG,886,305,5)
DG3=DG(Path{1},Path{1})
g5 = view(biograph(DG3,cellstr(num2str(Path{1}'))))
```

A.2) Calculation of road grades

```
clc

clear

% Find the cumulative distance value of a route

route=gpxread('D:\HEVT2\Innovation\OakManor_Kroger\Route3\Route3_Part2_Modified_With_Elevation.gpx');

lat=deg2rad(route.Latitude); %Lattitude is the y coordinate;

lon=deg2rad(route.Longitude); %Longitude is the x coordinate;

ele=route.Elevation;

%earth=wgs84Ellipsoid;

%co_ord=lla2ecef([lat(1),lon(1),ele(1);lat(2) lon(2),ele(2)],'WGS84');

%dist_m=sqrt(diff(co_ord(:,1)).^2+diff(co_ord(:,2)).^2+diff(co_ord(:,3)).^2);

%dist_m=[0 10]; %If we want resolution of 10 metres, then dist_m=[0 10];

%cum_dist=cumsum(dist_m);

dist= input('Enter the distance in metres: ');

resolution = (dist/size(ele,2));

%dist_miles=cum_dist*(0.000621371);

% Convert Elevation to grade

for i=1:size(ele,2)

    if (i==size(ele,2))

        del_z(i)=0;

    else

del_z(i)=(ele(:,i+1)-ele(:,i))/resolution;

end

end

grade=zeros(1,length(del_z));

grade=del_z*100;

grade=grade';
```

A.3) Velocity profile simulation code

```
clc
clear all
%read document ('distance, Grades, Speed Limits, Stop Signs)

a_max= 1.5;%input('Enter the value of a_max: ');
a_min=-1.5;%input('Enter the value of a_min: ');
j_max=0.5*a_max;%input('Enter the value of j_max: ');
j_min= -0.3 *j_max;%input('Enter the value of j_min: ');
x=804.672;%  metres  input('Enter total distance in meters: ');
vel_0=15; %%%%REMEMBER TO CHANGE!!
vel_f=15; %%%%REMEMBER TO CHANGE!!
vel_c=22.352; %%%% m/s   REMEMBER TO CHANGE!!

del_t1= (a_max/j_max);
del_t3= ((-1*a_max)/j_min);
del_t5= (a_min/j_min);
del_t7= ((-1*a_min)/j_max);

del_v1= j_max*(((del_t1)^2)/2);
del_v3= (j_min*(((del_t3)^2)/2))+ (a_max*del_t3);
del_v5= j_min*(((del_t5)^2)/2);
del_v7= (j_max*(((del_t7)^2)/2))+ (a_min*del_t7);

del_t2= ((vel_c-del_v1-del_v3-vel_0)/a_max);
del_t6= ((vel_f-del_v5-del_v7-vel_c)/a_min);
```

```
del_x1=((j_max* (del_t1^3))/6)+ (vel_0*del_t1); %del_v1*del_t1;
v_1=((j_max*(del_t1)^2)/2) + vel_0;
v_2= (a_max*del_t2)+ v_1;
del_x3= ((j_min* (del_t1^3))/6)+ (a_max*(del_t3^2)/2)+ (v_2*del_t3);            %del_v3*del_t3;
%v_1=((j_max*(del_t1)^2)/2) + vel_0;
del_x2= (a_max*((del_t2)^2)/2)+ v_1*del_t2;
del_x5= ((j_min* (del_t5^3))/6)+ (vel_c*del_t5);
v_5= ((j_min*(del_t5)^2)/2) + vel_c;
v_6= (a_min*del_t6)+ v_5;
del_x7= ((j_max* (del_t7^3))/6)+ (a_min*(del_t7^2)/2)+ (v_6*del_t7);
%v_5= ((j_min*(del_t5)^2)/2) + vel_c;
del_x6= (a_min*((del_t6)^2)/2)+ v_5*del_t6;

del_x4= x- (del_x1+ del_x2+del_x3+del_x5+del_x6+del_x7);
del_t4= del_x4/vel_c;

%v_2= (a_max*del_t2)+ v_1;
v_3= ((j_min*(del_t3^2)/2)+ (a_max*del_t3) + v_2);
v_4=vel_c;
%v_6= (a_min*del_t6)+ v_5;
v_7= ((j_max*(del_t7^2)/2)+ (a_min*del_t7) + v_6);

% %for t= 0.001:0.01:(del_t1+del_t2+del_t3+del_t4+del_t5+del_t6+del_t7);
%
t=0:0.1:del_t1;
%if(t>0 & t<= del_t1)
    vel1= (((j_max*(t.^2))/2) + vel_0);
    plot (t,vel1);
```

```
    hold on
  dist1=0:((del_x1)/(10*del_t1)):del_x1;
%end

t2=del_t1:(del_t2/15):(del_t1+ del_t2) ;
%if( t2>=(del_t1) & t2<=(del_t1+del_t2))
    vel2= (a_max*(t2-del_t1))+ v_1;
    plot (t2,vel2)
    hold on
    dist2=del_x1:(del_x2/15):(del_x1+del_x2);
%end

  t3=(del_t1+del_t2):(del_t3/20):del_t1+del_t2+del_t3;
 % if( t>=(del_t1+del_t2)& t<=(del_t1+del_t2+del_t3))
      vel3= ((j_min*((t3-(del_t1+del_t2)).^2)/2)+ (a_max*(t3-(del_t1+del_t2)))...
          + v_2);
      plot (t3,vel3)
    hold on
    dist3=(del_x1+del_x2):(del_x3/20):(del_x1+del_x2+del_x3);
%end
%
  t4=del_t1+del_t2+del_t3:(del_t4/100):del_t1+del_t2+del_t3+del_t4;
    %  if( t>=(del_t1+del_t2+del_t3) & t<=(del_t1+del_t2+del_t3+del_t4))
          test = ones(1,length(t4));
          vel4= vel_c*test;
          plot (t4,vel4)
    hold on
    dist4=del_x1+del_x2+del_x3:(del_x4/100):del_x1+del_x2+del_x3+del_x4;
```

```
%end
  t5=del_t1+del_t2+del_t3+del_t4:(del_t5/20):del_t1+del_t2+del_t3+del_t4+del_t5;
%           if( t>=(del_t1+del_t2+del_t3+del_t4) & t<=(del_t1+del_t2+del_t3+del_t4+del_t5));
          vel5= (j_min*((t5-(del_t1+del_t2+del_t3+del_t4)).^2)/2) + vel_c;
            plot (t5,vel5)
    hold on
    dist5=del_x1+del_x2+del_x3+del_x4:(del_x5/20):del_x1+del_x2+del_x3+del_x4+del_x5;
% end
% %

t6=del_t1+del_t2+del_t3+del_t4+del_t5:(del_t6/100):del_t1+del_t2+del_t3+del_t4+del_t5+del_t6;
%                           if(t>=(del_t1+del_t2+del_t3+del_t4+del_t5)                          & t<=(del_t1+del_t2+del_t3+del_t4+del_t5+del_t6))
                vel6= (a_min*(t6-(del_t1+del_t2+del_t3+del_t4+del_t5)))+ v_5;
                plot (t6,vel6)
    hold on

dist6=del_x1+del_x2+del_x3+del_x4+del_x5:(del_x6/100):del_x1+del_x2+del_x3+del_x4+del_x5+del_x6;
% end

t7=del_t1+del_t2+del_t3+del_t4+del_t5+del_t6:(del_t7/10):del_t1+del_t2+del_t3+del_t4+del_t5+del_t6+del_t7;
%if(t>=(del_t1+del_t2+del_t3+del_t4+del_t5+del_t6)                          & t<=(del_t1+del_t2+del_t3+del_t4+del_t5+del_t6+del_t7))
                vel7=((j_max*((t7-(del_t1+del_t2+del_t3+del_t4+del_t5+del_t6)).^2)/2)+ (a_min*(t7-(del_t1+del_t2+del_t3+del_t4+del_t5+del_t6))) + v_6);
                plot (t7,vel7)
    hold on
```

```
dist7=del_x1+del_x2+del_x3+del_x4+del_x5+del_x6:(del_x7/10):del_x1+del_x2+del_x3+del_x4+del_x5+del_x6+del_x7;

% end

  hold off;

% %  end

%


vel1_1=vel1(1:size(vel1,2)-1);

dist1_1= dist1(1:size(dist1,2)-1);

vel2_1=vel2(1:size(vel2,2)-1);

dist2_1= dist2(1:size(dist2,2)-1);

vel3_1=vel3(1:size(vel3,2)-1);

dist3_1= dist3(1:size(dist3,2)-1);

vel4_1=vel4(1:size(vel4,2)-1);

dist4_1= dist4(1:size(dist4,2)-1);

vel5_1=vel5(1:size(vel5,2)-1);

dist5_1= dist5(1:size(dist5,2)-1);

vel6_1=vel6(1:size(vel6,2)-1);

dist6_1= dist6(1:size(dist6,2)-1);

%vel7_1=vel1(1:size(vel7,2)-1);


velocity=horzcat(vel1_1,vel2_1,vel3_1,vel4_1,vel5_1,vel6_1,vel7);

velocity=velocity';

distance= horzcat(dist1_1,dist2_1,dist3_1,dist4_1,dist5_1,dist6_1,dist7);

distance=distance';
```

A.4) Code to calculate RMSE error

```
clc
load 'xTr.mat';
load 'yTr.mat';
tic
error = loocvreg_slow(xTr, yTr);%You can also use loocvreg_fast
toc
%%%%%%%%
function [rmse] = loocvreg_slow(xTr, yTr)
xTr=xTr';
yTr=yTr';

loocv_error=zeros(size(xTr,1),1);
for i=1:size(xTr,1)
x_left=xTr(i,:);
y_left=yTr(i,:);
for ii=1:size(xTr,1)-1
    if(i==1)
        x_new(ii,:)=xTr(ii+1,:);
        y_new(ii,:)= yTr(ii+1,:);
    else if(ii~=i)
        x_new(ii,:)=xTr(ii,:);
        y_new(ii,:)=yTr(ii,:);
        else
        end
    end
end
       w=(pinv(x_new)*y_new);
```

```
    y_hat_loocv= w'*x_left';
    loocv_error(i)= (yTr(i)-y_hat_loocv)^2;
end
loocv_error=sum(loocv_error)/size(xTr,1);
rmse=sqrt(loocv_error);
end
%%%%%%%%%%
function [rmse] = loocvreg_fast(xTr, yTr)
xTr=xTr';
yTr=yTr';
H=(xTr*pinv(xTr));
y_hat= H*yTr;
for i=1:size(xTr,1)
loocv(i)= ((yTr(i)-y_hat(i))^2)/(1-H(i,i));
end
loocv=sum(loocv)/size(xTr,1);
rmse=sqrt(loocv);
end
```

A.5) Code to calculate cumulative distance

```
clc

clear

% *Find the cumulative distance value of a route*

route=gpxread('Detroit_Route2_4_Elevation');

lat=deg2rad(route.Latitude); %Lattitude is the y coordinate;

lon=deg2rad(route.Longitude); %Longitude is the x coordinate;

ele=route.Elevation;

earth=wgs84Ellipsoid;

[x,y,z]=lla2ecef(lat,lon,ele);

dist_m=sqrt(diff(x).^2+diff(y).^2+diff(z).^2);

dist_m=[0 dist_m];

cum_dist=cumsum(dist_m);

dist_miles=cum_dist*(0.000621371);

dist_miles=dist_miles';
```

A.6) Code for WGS84 to ECEF conversion

```
% LLA2ECEF - convert latitude, longitude, and altitude to
% earth-centered, earth-fixed (ECEF) cartesian
%
% USAGE:
% [x,y,z] = lla2ecef(lat,lon,alt)
%
% x = ECEF X-coordinate (m)
f
% y = ECEF Y-coordinate (m)
% z = ECEF Z-coordinate (m)
% lat = geodetic latitude (radians)
% lon = longitude (radians)
% alt = height above WGS84 ellipsoid (m)
%
% Notes: This function assumes the WGS84 model.
% Latitude is customary geodetic (not geocentric).
%
% Source: "Department of Defense World Geodetic System 1984"
% Page 4-4
% National Imagery and Mapping Agency
% Last updated June, 2004
% NIMA TR8350.2
%
% Michael Kleder, July 2005
function [x,y,z]=lla2ecef(lat,lon,alt)
% WGS84 ellipsoid constants:
a = 6378137;
```

```
e = 8.1819190842622e-2;
% intermediate calculation
% (prime vertical radius of curvature)
N = a ./ sqrt(1 - e^2 .* sin(lat).^2);
% results:
x = (N+alt) .* cos(lat) .* cos(lon);
y = (N+alt) .* cos(lat) .* sin(lon);
z = ((1-e^2) .* N + alt) .* sin(lat);
return
```