# PROTODRIVE: SIMULATION OF ELECTRIC VEHICLE POWERTRAINS

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## ABSTRACT

Electric vehicles are a promising alternative to vehicles powered by fossil fuels due to their cleaner energy emission, but current limitations in battery technology are preventing electric vehicles from burgeoning in the mass consumer market.  Therefore, simulating and prototyping various power trains become paramount for finding different energy efficient models. A portable power train platform, known as Protodrive, is here to provide a stage in between pure software simulation and full-scale hardware simulation. This platform allows energy to transfer between the vehicle power train and the load power train through the use of regenerative braking. Protodrive is also able to accept a plethora of drive cycles and trajectories to help determine the forces acting on the vehicle. Through the use of mathematical models of these forces, the platform is capable of applying the proper load on the vehicle power train to determine the power consumption. Additionally, introduction of a super capacitor to the vehicle power train model allows for the analysis of various charging schemes to better manage the power consumption. The resulting simulated drive data can be viewed in real time through an intuitive web application that will allow users to enter drive cycles and define trajectories using Google Maps. The platform data can then be validated by comparing it with actual vehicle drive data.

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# 1. INTRODUCTION

On July 29, 2011, the Obama Administration announced a plan aimed to increase fuel economy, decrease oil dependence, and reduce pollution. Model year 2016 vehicles are to have an average fuel efficiency of 35.5 mpg, and model year 2025 vehicles are to have an average of 54.5 mpg, cutting greenhouse gas emissions by more than 6 billion metric tons [1]. To help fulfill the administration's goals, thirteen major automakers have agreed to actively pursue the research and development of electric vehicles [1].

Electric vehicles provide an alternative to vehicles powered by fossil fuels, leading to a dramatic decrease in dependence on gasoline. However, limitations such as low energy density, high costs, and long battery recharging time prevent mass consumer acceptance [2]. There are various ways to optimize the efficiency of electric vehicles. For example, the powertrain system and fuel control could be managed to reach an optimal range. The electric vehicle powertrain can be modeled using a battery, motor, motor controller, and gearbox.

The mLAB at the University of Pennsylvania has developed a small scale electric vehicle prototyping platform known as Protodrive [2]. The Protodrive provides a step in between software simulation and full-scale prototyping. The most important aspect is that the Protodrive is a physical hardware system that implements a small scale powertrain capable of fitting on a desktop. It will be able to simulate certain power optimization algorithms while capturing most hardware problems.

This paper will focus on the development of a method to accurately model vehicles on Protodrive, as well as the implementation of various charging schemes to better distribute power consumption among batteries and super capacitors.

# 2. BACKGROUND

## 2.1 Electric Vehicles Today

With regard to vehicles, the term ‘electric’ refers to the use of batteries to power either the motor, auxiliary devices, or both. Manufacturers have developed several different types of electric vehicles that are either purely battery powered or some sort of combination of battery power and gasoline power. There are several ways to charge these electric vehicles, through either charging stations or regenerative braking. They do, however, have a major disadvantage in that current battery technology has its own limitations.

### 2.1.1 Types of Electric Vehicles

With regard to vehicles, the term ‘electric’ refers to the use of batteries to power either the motor, auxiliary devices, or both. There are three main types of vehicles using electric vehicle technology (battery power) as a power source: electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEV) [3]. Electric vehicles use an electric motor powered by batteries to run both the motor and auxiliary devices. Hybrid electric vehicles implement both a gasoline engine and an electric motor. There are control schemes to maintain the proper use of the motor and engine so as to create a more efficient system. The plug-in hybrid electric vehicles also have a gasoline engine and electric motor; however, the main difference is the PHEVs having higher energy storage capabilities, i.e. more battery power [3]. These electric vehicles are paving the way to the reduction of fossil fuel emissions.

### 2.1.2 Consumer Acceptance

The main challenge electric vehicle manufacturers are facing is the energy storage requirements. High capacity battery packs are expensive; therefore, manufacturers are forced to use lower capacity batteries to make the vehicles more affordable. By limiting the capacity, manufacturers also limit the vehicle range, i.e. how far the vehicle can drive in one charge. For electric vehicles, batteries need to be designed to improve energy storage capacity. Batteries still need to be improved in many ways, such as durability, life-expectancy, energy density, power density, temperature sensitivity, reductions in charge time, and cost [3]. Without solutions to these problems, mass consumer acceptance is unrealistic.

### 2.1.3 Charging and Regenerative Braking

There are two ways to charge batteries within an electric vehicle. First, vehicles can visit charge stations to either swap battery packs, or stations to plug the vehicle in for charging. Second, the discovery of regenerative breaking has allowed for the recuperation of some of the energy lost during a drive. The regenerative braking process occurs when the vehicle is decelerating. A portion of the kinetic energy stored in the vehicle's translating mass is regained and can be stored in a battery or capacitor. This is generally done by allowing the traction motor to act as a generator, giving the proper braking torque to the wheels and recharging the traction batteries [4]. This recovered energy can then be used for either the motor or auxiliary devices.

### 1.1 Super capacitors in Electric Vehicles for Buffering

A driving cycle can place different types of strains on the vehicle. These strains include traffic, especially stop-and-go traffic, sudden acceleration due to driver behavior, and varying terrains. Because of these electric loads on the vehicle, the current surges traveling in and out of the battery tend to generate extensive heat inside the battery. This leads to increased battery internal resistance, which results in lower efficiency and eventually premature failure. This poses a problem when regenerative braking occurs because the process produces a sudden increase in the amount of current entering the batteries. These current spikes can lead to the degradation of the batteries [5]-[7]. A super capacitor, however, has a high power density, meaning it can rapidly charge and discharge. Therefore, it is effective ad a buffer for the batteries [8].

### 2.2 Overview of Protodrive

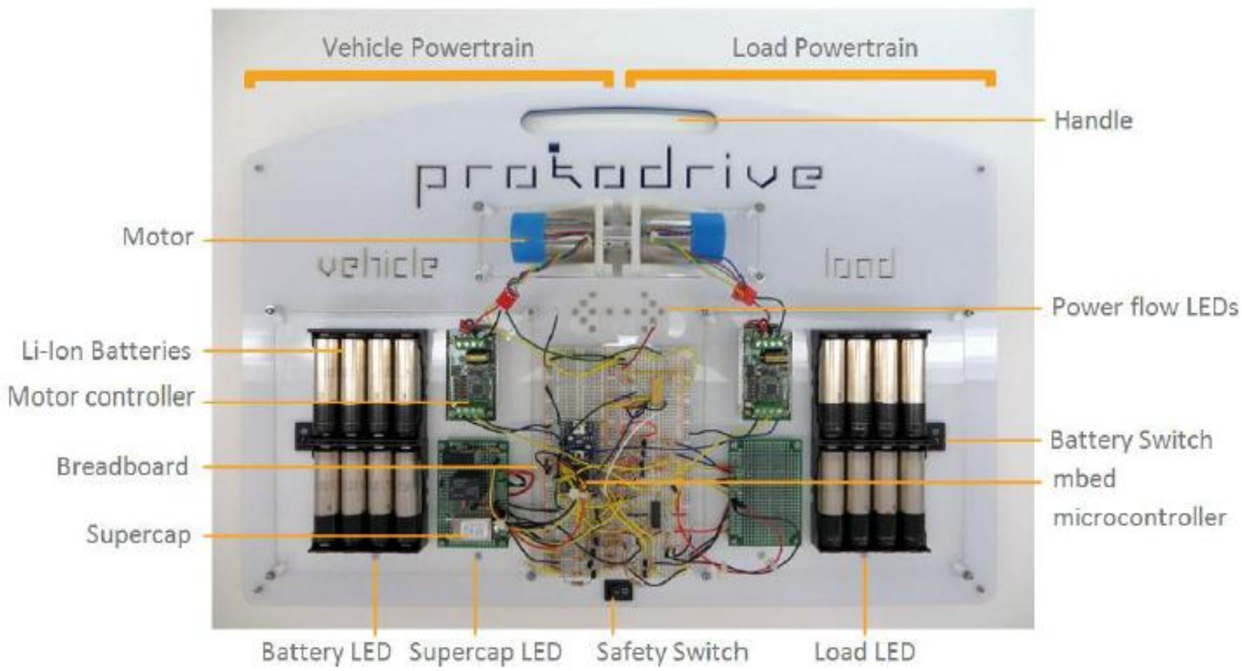


Fig. 1. [2] Protodrive platform

Protodrive was previously developed by University of Pennsylvania students William Price and Anthony Botelho [2]. Most powertrain simulations are currently done strictly on software and then created on a full-scale prototype vehicle [2]. This process can be quite costly and very time consuming since it requires putting together so many components. However, Protodrive is a small, portable, and easily modifiable. The platform consists of two models: the vehicle model, and load model. Both of these models are controlled by a microcontroller. The vehicle model is comprised of a brushed DC motor, motor controller with regenerative braking capabilities, lithium ion cells used in the Tesla Roadster, and a super capacitor. There is currently a relay to switch between the super capacitor and battery pack, giving the user control over when to charge and discharge the super capacitor. This model represents a vehicle's energy consumption [2].

The load model is also comprised of the same lithium ion cells, a brushed DC motor, and a motor controller with regenerative braking. The two motors (vehicle and load) are rigidly coupled together. This way, the load motor can act against the vehicle motor to simulate the proper load in a real-world situation [2]. There will be a more detailed explanation of how these loads are modeled and simulated in Section 3.

## 3. DRIVE CYCLES ON PROTODRIVE

The first step in being able to model the vehicle and the load acting upon it is finding a proper mathematical model for all the forces both driving the motor and acting against the motor. These models are then used in MATLAB to create the proper input voltage for each motor.

### 3.1 Understanding the Vehicle Model

The platform is comprised of the load and the vehicle model. They are rigidly coupled as shown in Fig. 2. According to W. Price and A. Botelho, the total force acting on the vehicle at any moment in time is split up into several different forces [2]:

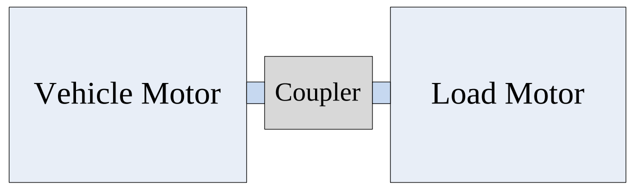


Fig. 2. Vehicle and load motor coupling

$$F_t = F_a + F_g + F_d + F_r$$

Where,

$F_t$ Total tractive force at the wheels
$F_a$ Force due to acceleration
$F_g$ Force due to gravity
$F_d$ Force due to aerodynamic drag
$F_r$ Force due to rolling resistance of the tires

These individual forces can be calculated by using vehicle specific parameters:

$$F_a = ma$$
$$F_g = m_v g sin(\theta)$$
$$F_d = \frac{1}{2} A_f C_d v^2$$
$$F_r = C_r m_v g cos(\theta)$$

Where,

$m$ Total mass acting on the wheels
$a$ Acceleration of the vehicle
$m_v$ Mass of the vehicle
$g$ Gravity
$\theta$ Angle of inclination of the vehicle
$A_f$ Frontal area of the vehicle
$C_d$ Coefficient of drag
$v$ Velocity of the vehicle
$C_r$ Coefficient of rolling resistance

The total mass of the vehicle $m$ represents the combination of the vehicle mass and the mass added due to the inertia of all the rotating components. In general, the moment of inertia can be converted into mass using:

$$T = J\acute{\omega} = rF$$

$$F = \frac{J\acute{\omega}}{r} = ma = mr\acute{\omega}$$

$$m = \frac{J}{r^2}$$

Where,

| | | | |
|---|---|---|---|
| $T$ | Torque | $F$ | Force |
| $J$ | Moment of inertia | $m$ | Mass |
| $\acute{\omega}$ | Angular acceleration | $a$ | Acceleration |
| $r$ | Wheel radius | | |

Using this equation it is possible to find the mass due to the moment of inertia:

$$m_j = m_{jw} + m_{jg} = \frac{1}{r^2}J_w + \frac{\gamma^2}{r^2}J_g$$

Where,

| | |
|---|---|
| $m_j$ | Mass due to moment of inertia |
| $m_{jw}$ | Mass due to moment of inertia of wheels |
| $m_{jg}$ | Mass due to moment of inertia of gearbox and motors |
| $r$ | Radius of wheels |
| $J_w$ | Moment of inertia of wheels |
| $\gamma$ | Gearbox ratio |
| $J_g$ | Moment of inertia of gearbox and motors |

The total mass of the vehicle can now be written as:

$$m = m_j + m_v$$

Using the total force, the voltages required for the vehicle and load motors can be calculated. Since these motors are rigidly coupled, the back EMF and shaft speed are identical for both motors. As described by W. Price and A. Botelho [2], the necessary voltages can be calculated through the analysis of equivalent circuit model of the motors:

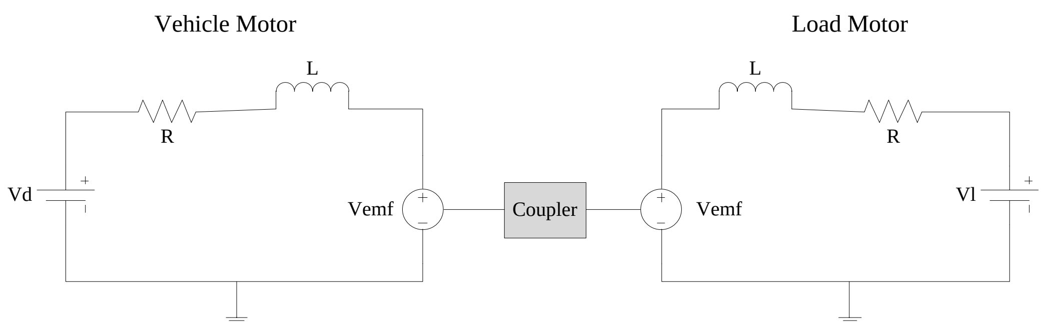


Fig. 3. [2] Equivalent Circuit Model

Through this model, the vehicle motor voltage and load motor voltage are described by:

$$V_D = RI_D + L\frac{dI_D}{dt} + V_{emf}$$
$$V_L = RI_L + L\frac{dI_L}{dt} + V_{emf}$$
$$V_{emf} = k_e\omega$$
$$T = k_tI$$

Where,

| | | | |
|---|---|---|---|
| $V_D$ | Vehicle motor voltage | $V_L$ | Load motor voltage |
| $R$ | Resistance | $I_L$ | Load motor current |
| $I_D$ | Vehicle motor current | $\omega$ | Angular velocity |
| $L$ | Inductance | $T$ | Torque |
| $V_{emf}$ | Back EMF | $I$ | Current |
| $k_e$ | Speed constant | $k_t$ | Torque constant |

Using the mechanical coupling equation, they described the torque as:

$$J\dot{\omega} = T_D + T_L + T_f \; where \; T_f < 0$$

Where,

| | |
|---|---|
| $J$ | Moment of inertia of both motors and a coupler |
| $T_D$ | Vehicle motor torque |
| $T_L$ | Load motor torque |
| $T_f$ | Torque to overcome friction |

The electrical and mechanical equations can be combined to calculate the proper motor voltages (the inductance has been set to zero to make it simpler):

$$V_D = \frac{RT_{ref}}{k_t} + k_e\omega_{ref}$$
$$V_L = \frac{R\left(J\dot{\omega}_{ref} - T_{ref} - T_f\right)}{k_t} + k_e\omega_{ref}$$
$$T_{ref} = \frac{F_tr}{\gamma T_{scaling}}$$
$$\omega_{ref} = \frac{\gamma v}{r}$$
$$\dot{\omega}_{ref} = \frac{\gamma a}{r}$$

Where,

| | |
|---|---|
| $T_{scaling}$ | Torque scaling between actual vehicle and Protodrive |
| $T_{ref}$ | Necessary torque |

| | |
|---|---|
| $\omega_{ref}$ | Necessary angular velocity |
| $\dot{\omega}_{ref}$ | Necessary angular acceleration |

These equations can now be used to run a simulation on the platform. They are used in MATLAB, which communicates with an mbed NXP LPC1768 microcontroller for PWM control. The function, calculate_Vd_Vl, outputs $V_D$and $V_L$using a set of vehicle and motor parameters, as well as the angle of inclination, velocity, and acceleration of the vehicle.

### 3.2 Using MATLAB for Drive Cycle Simulations

Vehicle drive cycles contain information about how quickly a vehicle is traveling along a path. This information provides the velocity and acceleration required for voltage calculations. Several drive cycles were used for testing the platform. The first set of drive cycles was created in MATLAB for testing various trajectories, as well as how the platform reacts to a certain range of velocities.

The second set of data was the federal drive cycle obtained from the U.S. Environmental Protection Agency as shown in Fig. 4.

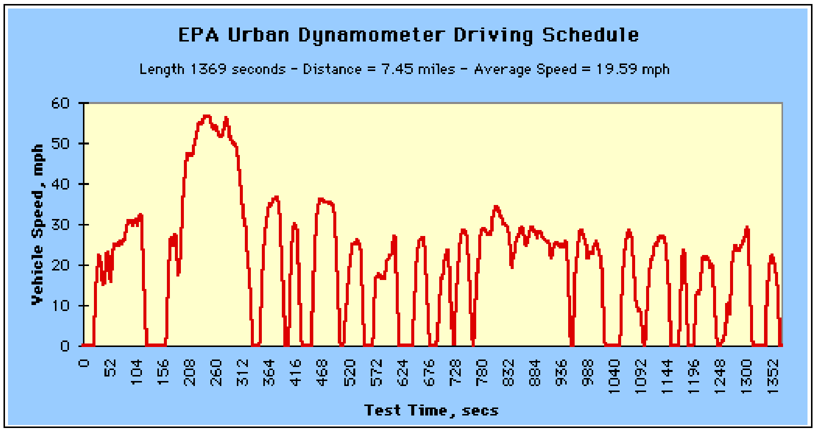


Fig. 4. [9] EPA Urban Dynamometer Driving Schedule

This drive cycle demonstrates a vehicle's stop-and-go characteristics as well as high speed characteristics. This is important because stop-and-go drive cycles exemplify a vehicle's ability to regenerate some of its energy through braking. However, there is no GPS data for obtaining a trajectory for the vehicle.

The third set of drive cycles was obtained from the Charge Car project at Carnegie Mellon University. There are numerous trips available with GPS and velocity data. This was used to simulate a drive cycle involving both the trajectory data, mainly used to calculate the angle of inclination, and the velocity data. This combination provides all the necessary data to run a full simulation that accounts for all the forces acting on the vehicle.

### 3.2.1 Initial MATLAB Setup

The initial MATLAB GUI contained two different trajectories with predefined duty cycles (voltages) for each motor. The first trajectory is a trapezoidal path showing how the motors would react to uphill, straight, and downhill paths. This was used mainly for debugging purposes since the current drawn for the vehicle motor can be easily predicted and then tested on this path. The second trajectory is a sinusoidal path showing how the motors would react to multiple hills. This is mainly used to demonstrate the regenerative capabilities of the system. However, it is necessary for the platform to demonstrate an array of diverse paths, as well as real-world routes.

### 3.2.2 Creating and Using Trajectories

The first set of trajectories was created using two dimensional paths for simplicity. Various trajectories could be created using piecewise linear equations; however, having a discontinuous path is nonrealistic since real driving paths have smooth transitions. Therefore, Bezier curve principles were used to provide continuous paths. The Bezier function created in MATLAB would accept an array of points for the path to follow, the total horizontal distance of the path, and the sampling rate with respect to the x-axis. With this, a set of fundamental paths was created: hill, multiple hills, straight, and steep downhill.

These trajectories were then passed through a second function called, response_to_path. This takes in the x and y coordinates of the path, as well as the length of the vehicle (l_v), and the drive cycle. The most important information necessary from the trajectory is the slope of the vehicle at each instant in time. Therefore, a series of steps need to be taken in order to extract this data successfully. First, the length of the path at each x-coordinate is calculated. This information is then used to calculate the slope between every l_v in order to find the angle of inclination of the vehicle with respect to the x-axis. Second, the vehicles acceleration and position are calculated with respect to time. This is done using the drive cycle entered as an input to the function. Third, the angle of inclination with respect to time is found using the position of the vehicle. All of this information is entered into the calculate_Vd_Vl function to obtain the required voltages at each time instant.

Since this was initially done using only two dimensional trajectories, the next objective was to create three dimensional trajectories and a way to analyze them for calculating the voltages. This was done easily by creating a Bezier function that would create three dimensional paths by accepting an array of yz-coordinates (z being in the upward direction) for the path to follow. The paths created with this function can then be analyzed by an improved response_to_path function. This function is different in that the calculations for the angle of inclination are done using vector calculus. With these functions, drive cycles on trajectories can be simulated on Protodrive.

### 3.2.3 Simulating Drive Cycles

The duty cycles obtained from the voltage calculations have to be sent to the microcontroller, which communicates these values to the motor controllers. This is done using the RPC interface library for MATLAB that is provided by mbed, the microcontroller manufacturer. MATLAB variables can be easily linked to variables used in the microcontroller code. The microcontroller then scales the duty cycles appropriately to stay within the operating range of the motors. However, high velocity drive cycles require high voltages for the motors. Since these voltages were out of range, it is necessary to scale the velocity down. This will then be accounted for when scaling back up to the energy consumption of an actual vehicle.

Speed and current data was retrieved from sensors for a drive cycle on a hill, as shown in Fig. 5. The velocity remained constant at 7 m/s to test whether the platform was responding to the hill.

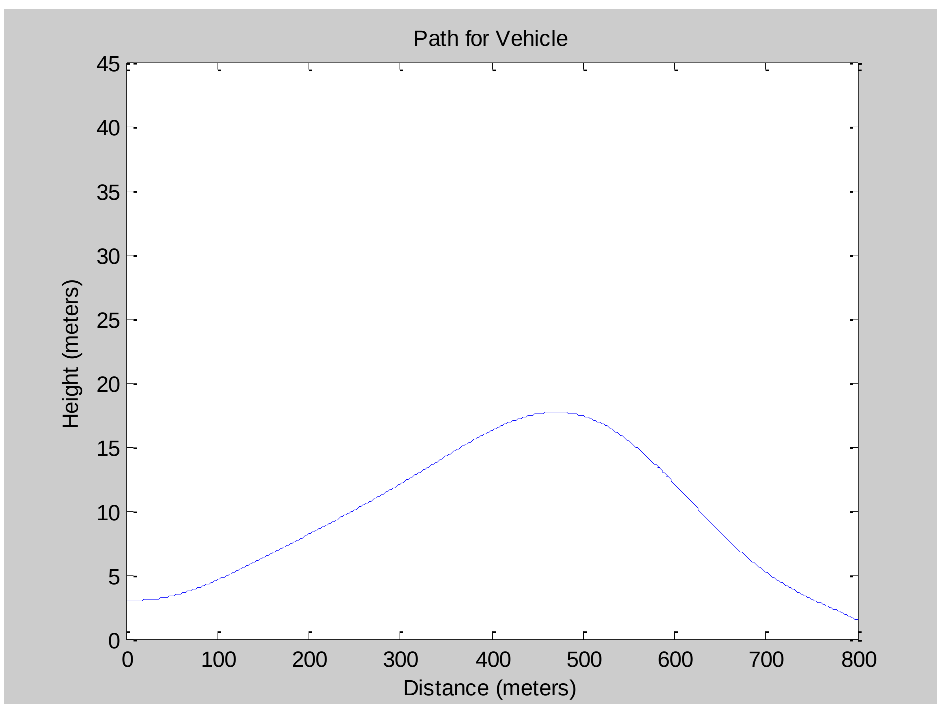


Fig. 5. Trajectory for the vehicle to follow

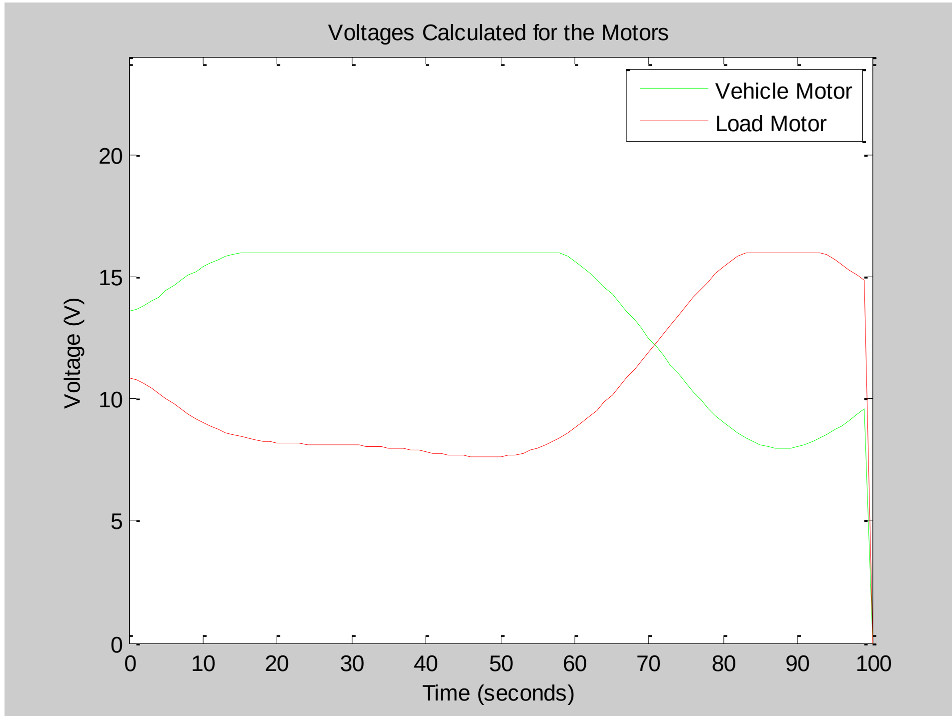


Fig. 6. Calculated voltages for each motor

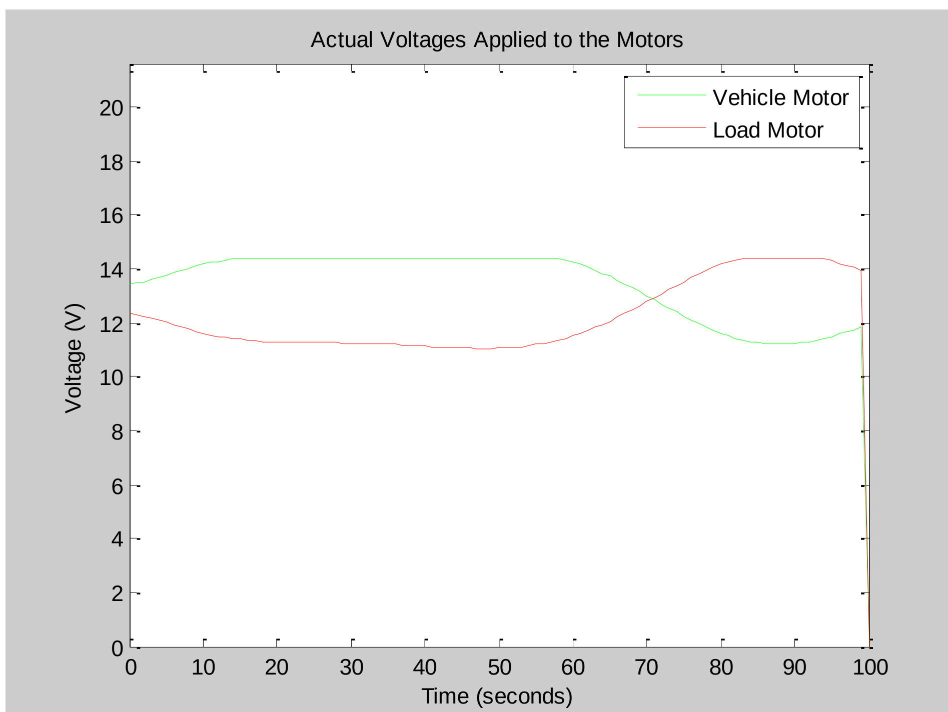


Fig. 7. Actual voltages applied to the motors after scaling

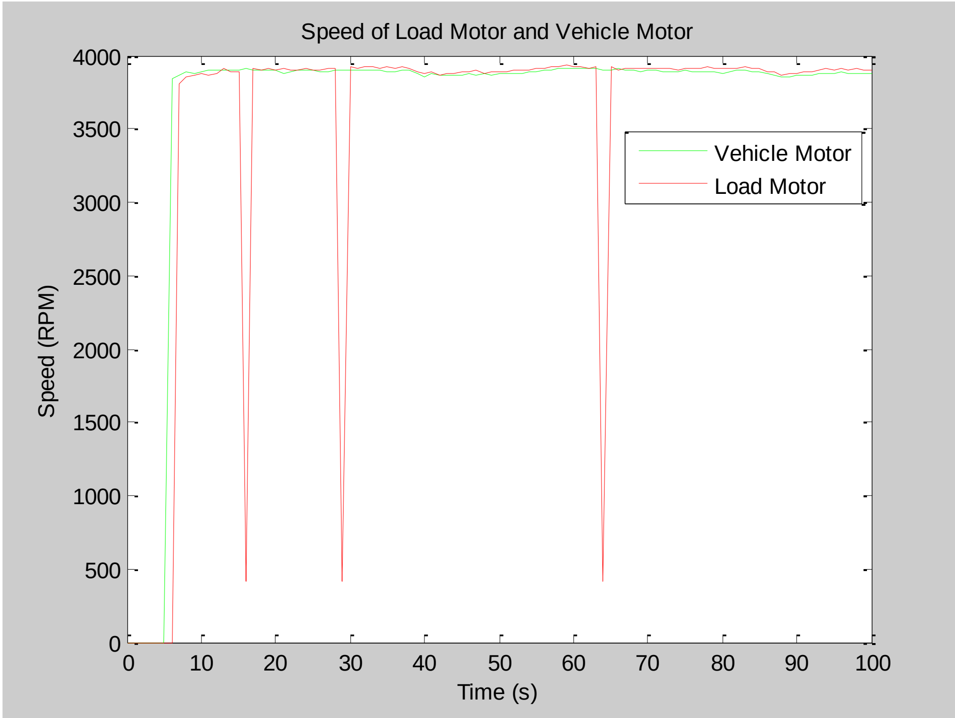


Fig. 8. Measured speed for both motors


Fig. 9. Measured current from both motors

As shown in Fig. 6, the voltage for the load motor exceeds the voltage for the vehicle motor as the vehicle drives downhill. This represents regeneration because the load motor will actually be spinning the vehicle motor, generating current on the vehicle side. Fig. 7 is a scaled version of the calculated voltages. This scaling was done to place the calculated voltages within the range of the motors' voltage requirements. Fig. 8 and Fig. 9 show the measured speed and current readings. The speed is fairly constant due to the constant velocity drive cycle entered. There are minor fluctuations due to the motor's direction changes. The current readings are directly correlated with the power consumption on each battery pack. The current readings demonstrate the vehicle is using more current as it goes uphill and less current as it travels downhill.

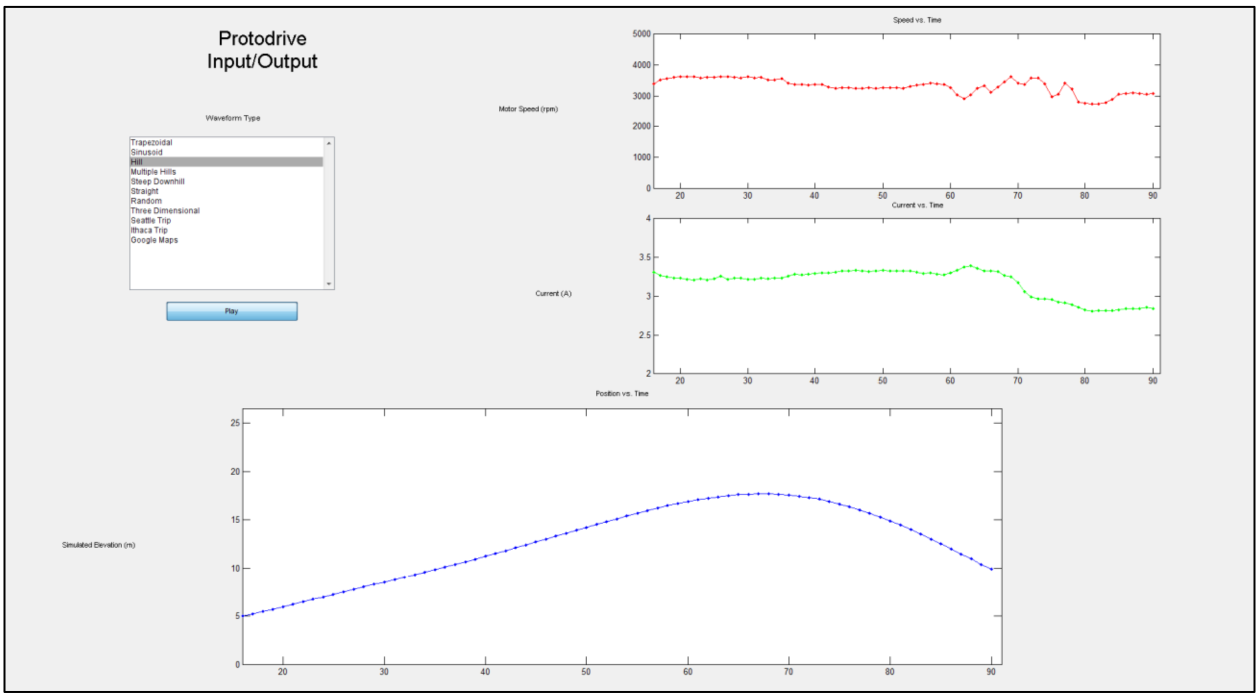


Fig. 10. MATLAB GUI simulating the hill trajectory

# 4. HARDWARE

## 4.1 Initial Hardware Setup

Protodrive consists of two brushed DC motors that are rigidly coupled so they put a load on each other. These motors are controlled by two SyRen 10A motor controllers that are capable of regenerative braking. The motor controllers are set in analog mode, where it accepts an analog signal for PWM control and accepts a signal for changing directions. These signals are controlled by the microcontroller. The two motors and motor controller are powered by 14.8V lithium ion batteries, the same ones used in the Tesla Roadster vehicles. The power on the vehicle motor can be supplied by either a super capacitor or the batteries. The switching is done by a relay controlled by the microcontroller.

## 4.2 Hardware Modifications

### 4.2.1 Motors and Power Supply

The battery packs had initially provided a total of 7.4V, limiting the speed of the motors to about 300 RPM. This became an issue since high velocity drive-cycles are impossible to simulate without any extreme velocity scaling. However, the motors are capable of reaching 6800 RPM. The power supply was then doubled to 14.8V for better simulations.

### 4.2.2 Current Sensing

Two changes have been made to the current sensing set up. First, the current sensor initially was not sensitive enough for the system. Current readings from an ammeter indicate current varying from about -0.4A to 2A. Therefore, a sensor with a smaller reading range replaced the original current sensor. Second, current sensing was initially done solely on the vehicle motor side, in between the vehicle battery pack and motor controller. However, it is necessary to analyze the current on the load motor as well. An additional current sensor has been placed in between the load battery pack and motor controller.

### 4.2.3 Current Flow

The platform must be able to use the batteries and super capacitor efficiently. Therefore, a method of controlling the current flow must be incorporated. The initial setup involved a relay that would switch between the battery pack and motor controller. However, this did not provide full control over the direction of current. The current needs to be able to travel in several directions:

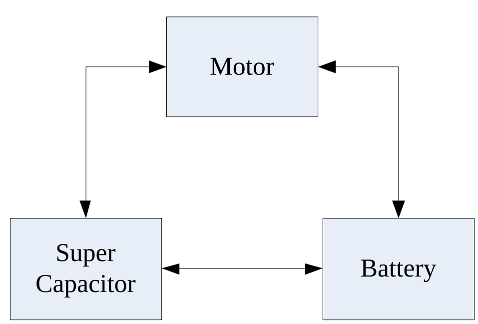


Fig. 11. Necessary current flow in vehicle power system

As seen in Fig. 10, there must be bidirectional current flow between each component in the vehicle power model. This application will allow various charging schemes to be implemented in the system. Therefore, a new circuit is being introduced to help control the current flow.

Several ideas were taken into consideration. The first idea was having two relays switching between the battery and super capacitor:

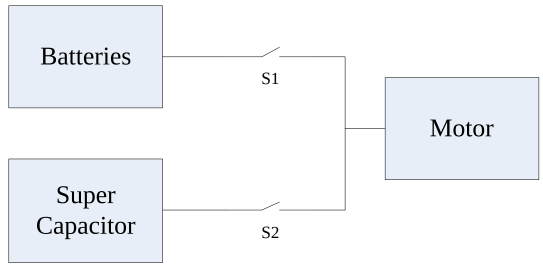


Fig. 12. Initial idea for how to control current flow

Although the configuration in Fig.11 does not allow users to have control over every direction of current, it does allow the super capacitor to be charged by the batteries. The one major problem the configuration is that it does not allow users to have control over how much the super capacitor should be charged. Another issue is that all three components must be rated at the same voltage. A suggested solution to that problem would be using buck-boost converters to apply proper voltages to each component; however, this converter does limit the current.

The final configuration involves using a chopper circuit, boosters, and switches:

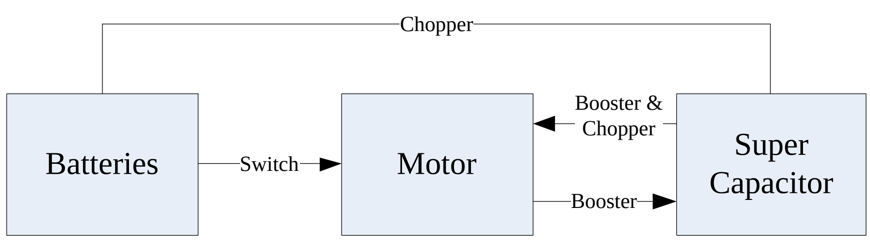


Fig. 13. Final idea for how to control current flow

The chopper circuits can control how much current is being passed through with respect to a reference. This allows users to control how much and how rapidly they want to charge the super capacitor. The battery switch will always be closed, unless the motors are being powered by the super capacitor. This setup was chosen because it gives users the ability to charge the super capacitor using both the batteries and the motor during regenerative braking.

# 5. CONTROLS

There are several control policies that need to be implemented on the platform. The controls aspect involves finding the most energy efficient charging scheme given the path and drive cycles. This is done by switching between the super capacitor and batteries for different conditions. For example, going uphill puts a strain on low power batteries, but is fine for a high power super capacitor. During these times, the super capacitor should be used to increase battery life.

## 5.1 Naïve Charging Scheme

The first charging scheme is simple but not the most energy efficient. The super capacitor is charged by regeneration from the motors whenever it occurs. This is good for the batteries because the sharp current intake can harm and degrade them. As soon as the capacitor is finished charging, the microcontroller checks whether the voltage is within the operating range of the motor. If the super capacitor has the proper voltage, the energy will be used to power the motors. Otherwise, the batteries will continue running the motors.  As seen in Fig. 13, about an 8% improvement can be seen in the battery current consumption. The problem with this charging scheme is that the energy in the super capacitor is not being used during crucial moments, for example going uphill. Therefore, it is known as the naïve charging scheme.

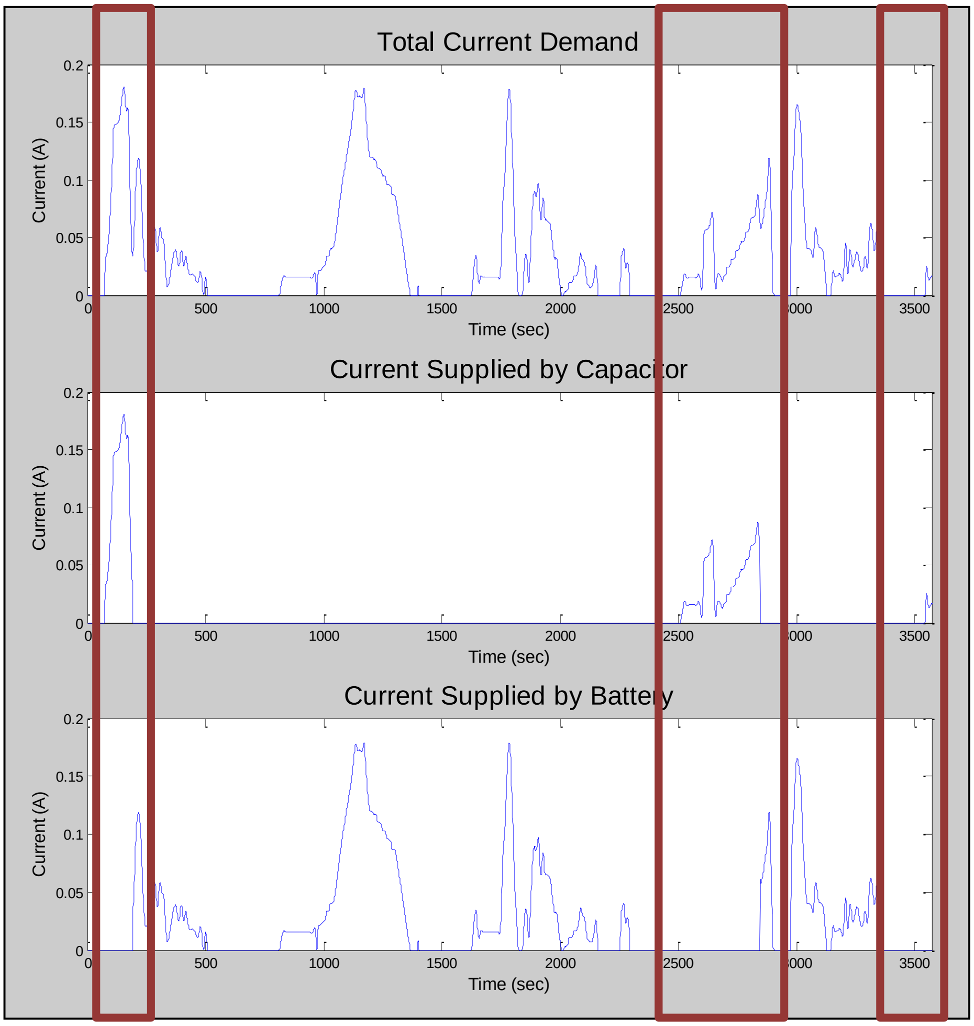


Fig. 14. Naïve charging scheme power consumption

## 5.2 Prescient Charging Scheme

The second charging scheme assumes every detail is known about the path and the drive cycle. The super capacitor will be charged up right before a big hill and the energy will be used when it is most needed. It will take into account small hills and big hills, knowing that it would be best to save the super capacitor energy for the big hill instead of a small hill. The same applies for regeneration. There could be steeper downhill paths that could regain more energy than other downhill paths. Therefore, it would be best to keep the super capacitor completely discharged before the steep downhill paths. This charging scheme does conserve more energy; however, it will not always be the case that the path details are known. The driver could make sudden stops that would cause a sudden current intake and the super capacitor would not be ready to take this current in. Therefore, it is known as the prescient charging scheme.

# 6. WEB APPLICATION

Users should be able to easily choose paths for simulations, as well as enter in a drive cycle and vehicle parameters. Although this can be done in MATLAB, not all users will have access to MATLAB. Therefore, a web application is being developed to provide a more intuitive user interface. The front end of the application is created using Javascript and HTML in conjunction with the Google Maps API. The MATLAB functions will all be deployed as an ASP.NET component to be stored onto a server. These functions will be accessed using ASP.NET and called in the application using Visual Basic C#.

## 6.1 Using the Google Maps API

The Google Maps Javacript API V3 was used mainly to retrieve map data including longitude, latitude, and elevation. The user will enter in an origin and a destination, and the application will display directions for the fastest route. This route will then be used as an input to for finding the longitude, latitude, and elevation along the path. The one disadvantage is that each request will only output 512 samples. For long routes, such as from New York, NY to Philadelphia, PA, this sample size is too small. Therefore, a quick solution would be to split the route up into n number of paths and send a request for each path. This will result in a total of 512*n samples. This data then can be used as inputs to the deployed MATLAB functions.

## 6.2 Future Goals

The web application will be interactive and allow users to put in any path and drive cycle. It will communicate with Protodrive and run these drive cycles in real-time, displaying a video feed of the platform in action. There will be multiple graphs updating the speed, current, and elevation data as the vehicle drives along the path.

### 6.2.1 Energy Efficient Routes

Once data has been collected for different drive cycles, there will be an option under directions for the most energy efficient path. This will route the vehicle through trajectories that will elongate the battery life of electric vehicles. For example, the routing algorithm will find paths without steep uphill paths. This will be done once Protodrive has energy consumption data along segments throughout a region.

## 7. DISCUSSION & CONCLUSION

The purpose of this project was to simulate various drive cycles and trajectories using different control policies. The drive cycles were communicated to the platform using an mbed microcontroller that translates the duty cycles calculated in MATLAB. The trajectories created in MATLAB started with simple paths involving hills. These were used for testing to see if the proposed voltages for the motors matched the theoretical values. As shown in Figs. 6-7, the voltages for each motor changed as expected for varying slopes. Some of these drive cycles were initially difficult to simulate due to having high velocities. However, once the power supply was doubled, the motors were able to run at higher speeds and were consuming more current as expected. There were some issues with sensing current since the current sensor already in place was for reading much higher current values. This was soon replaced with sensors that could read currents at around 0.5A to 1A with sufficient sensitivity. There is still future work that needs to be done to perfect Protodrive and have it efficiently run using many different control policies.

## 8. RECOMMENDATIONS

Protodrive could be linked with another project being worked on in the lab called Groovenet. Groovenet is a vehicle simulation program that includes map data. Instead of using the Google Maps API, the platform could be used in conjunction with Groovenet. Groovenet provides the user with more freedom when choosing drive cycles and trajectories. Traffic information such as stop signals and speed limits can be easily added to help with the energy efficient routing algorithm. This platform can also be validated for different vehicles. By collecting drive data from different electric vehicles, the platform data can be compared to see how well it is modeling the vehicle.

## 9. ACKNOWLEDGEMENTS

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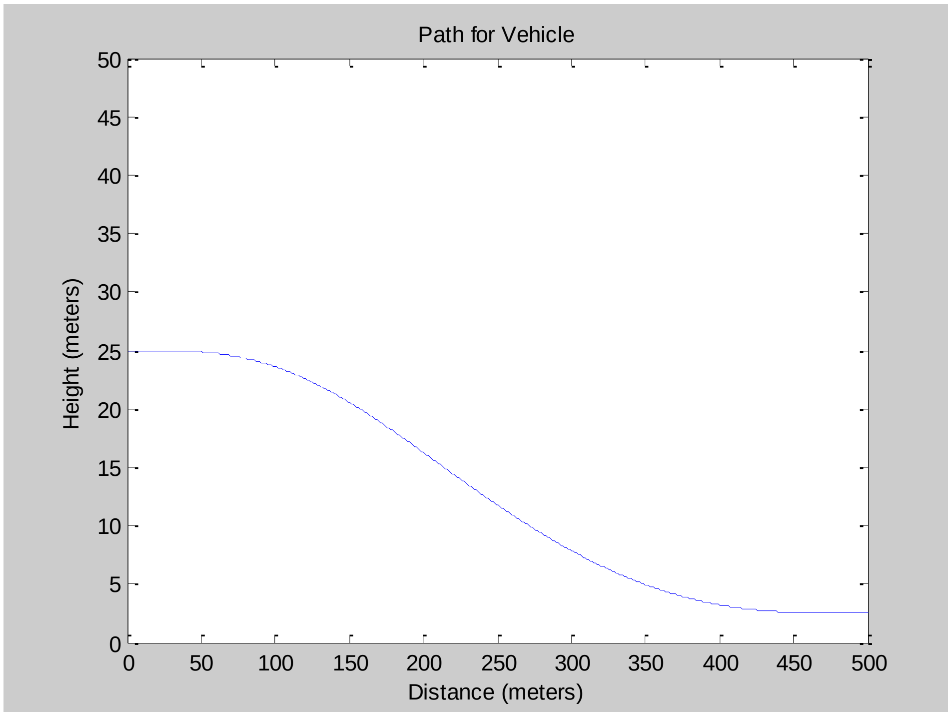
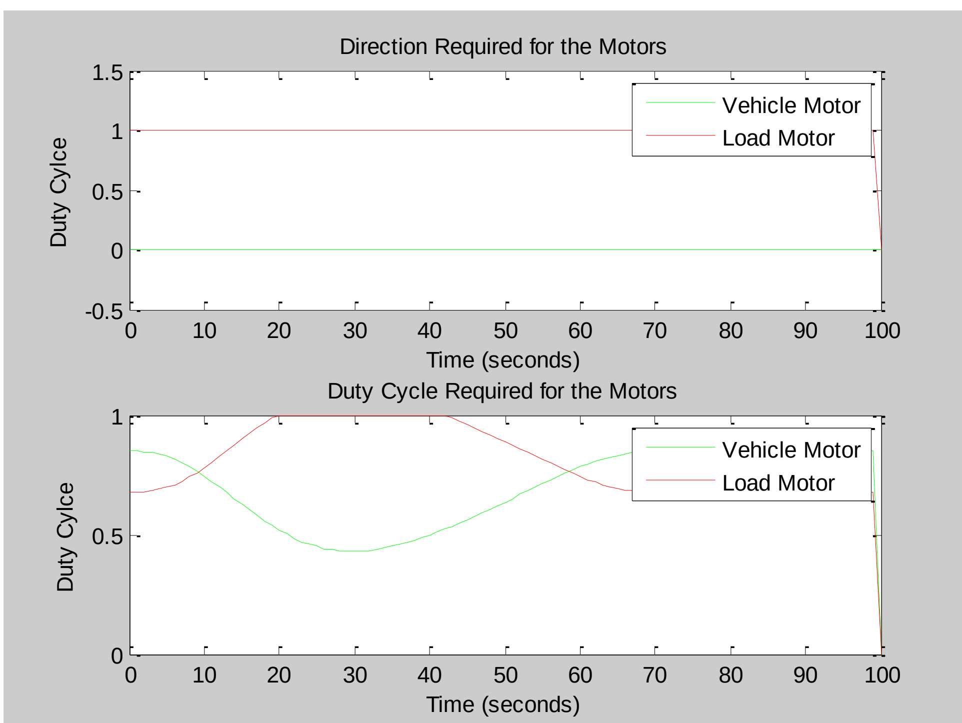
## 11. APPENDIX

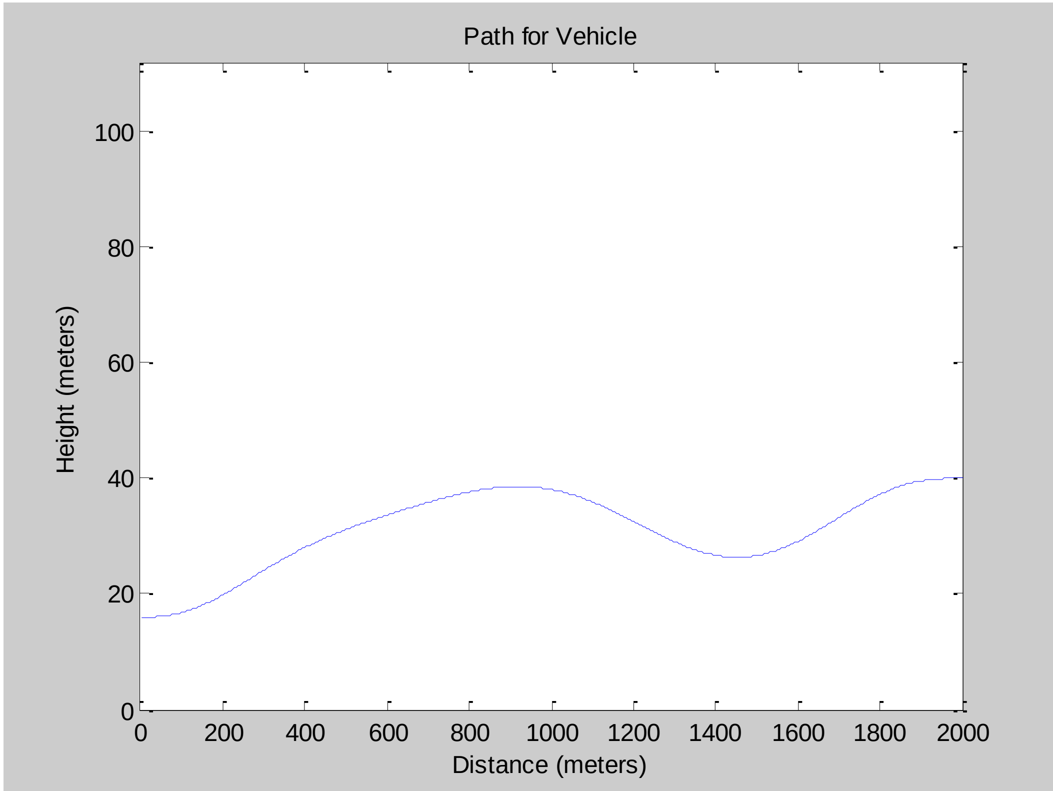
Trajectories and Drive Cycles:

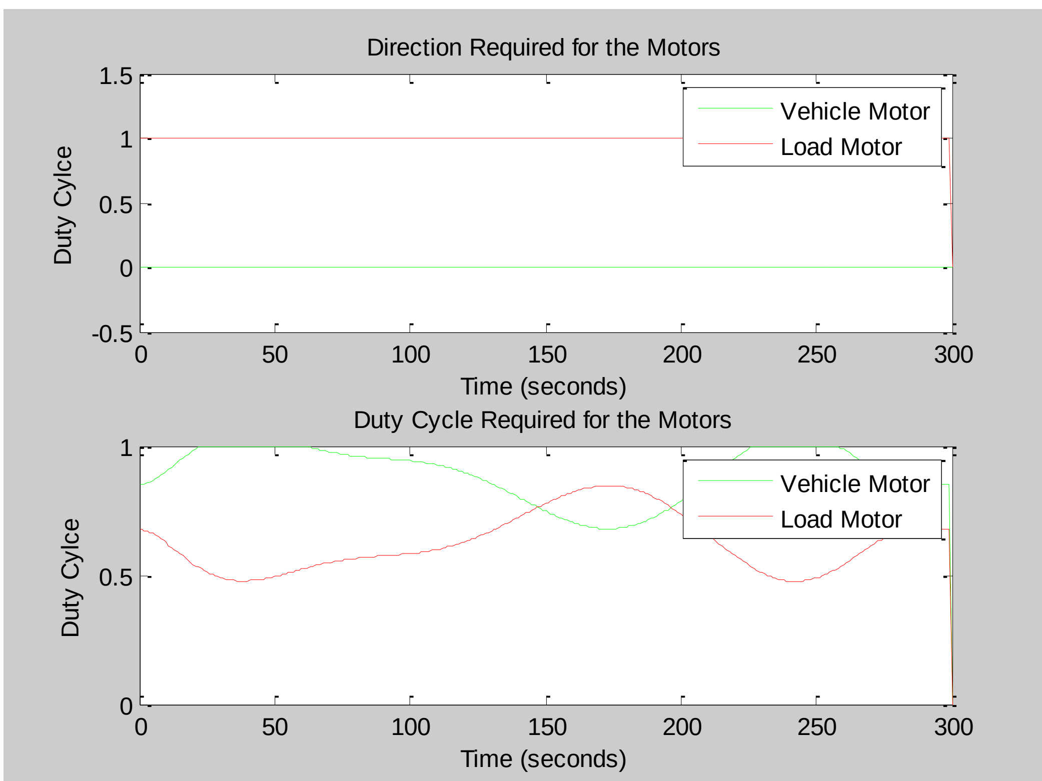
Steep Downhill with Constant Velocity:



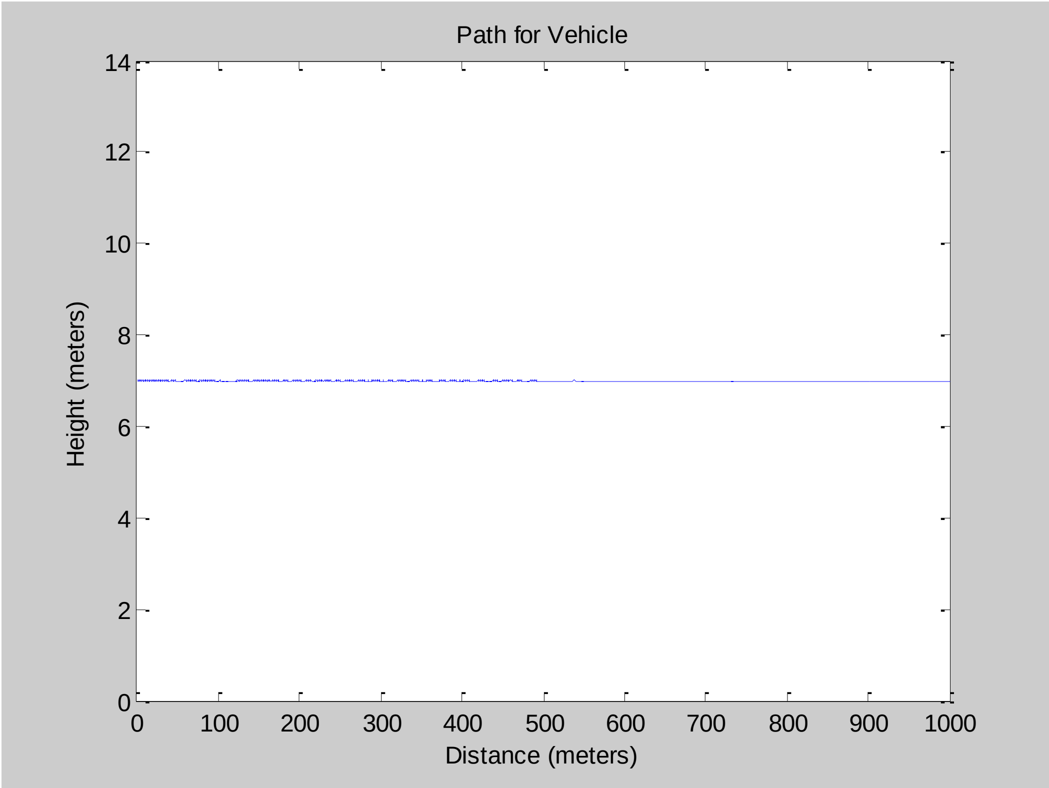



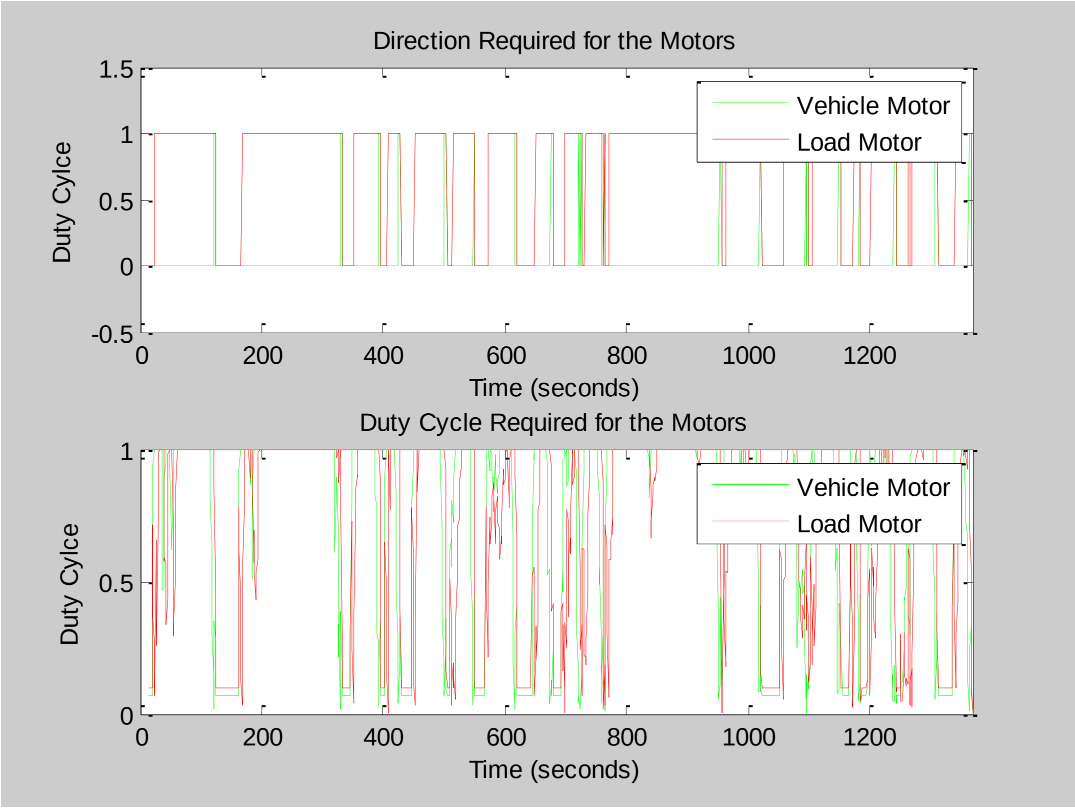
Multi-Hill with Constant Velocity:



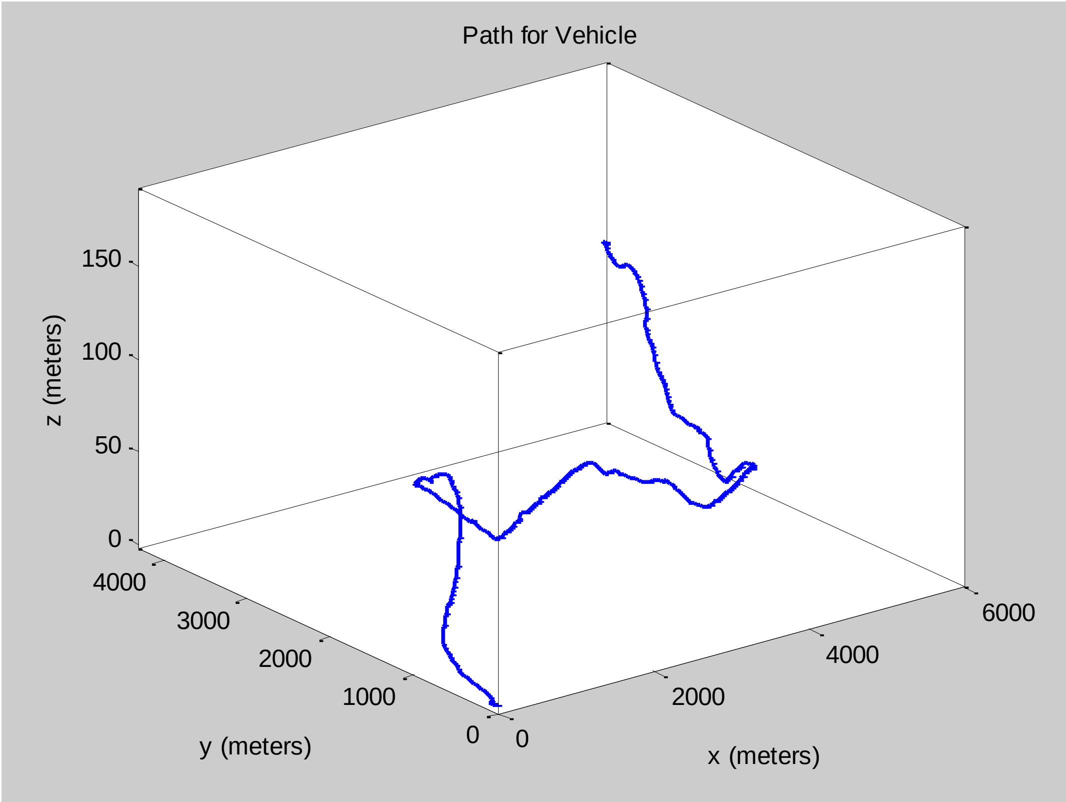



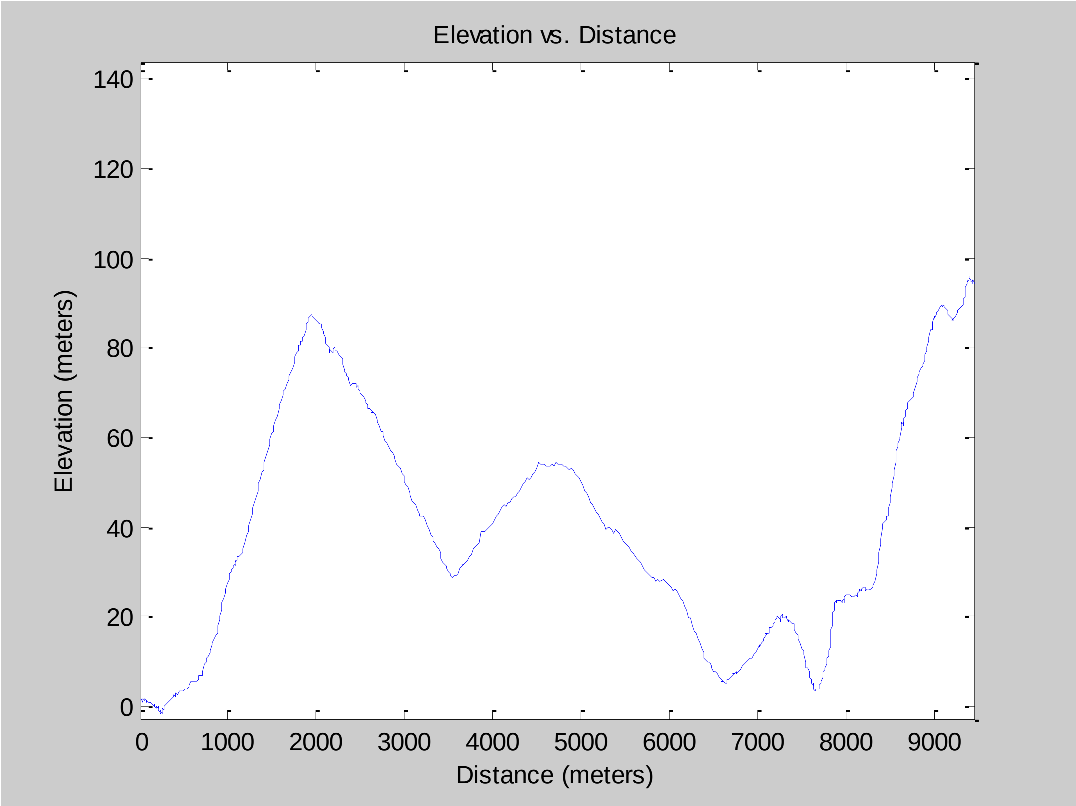
Straight Path with EPA Urban Dynamometer Driving Cycle:

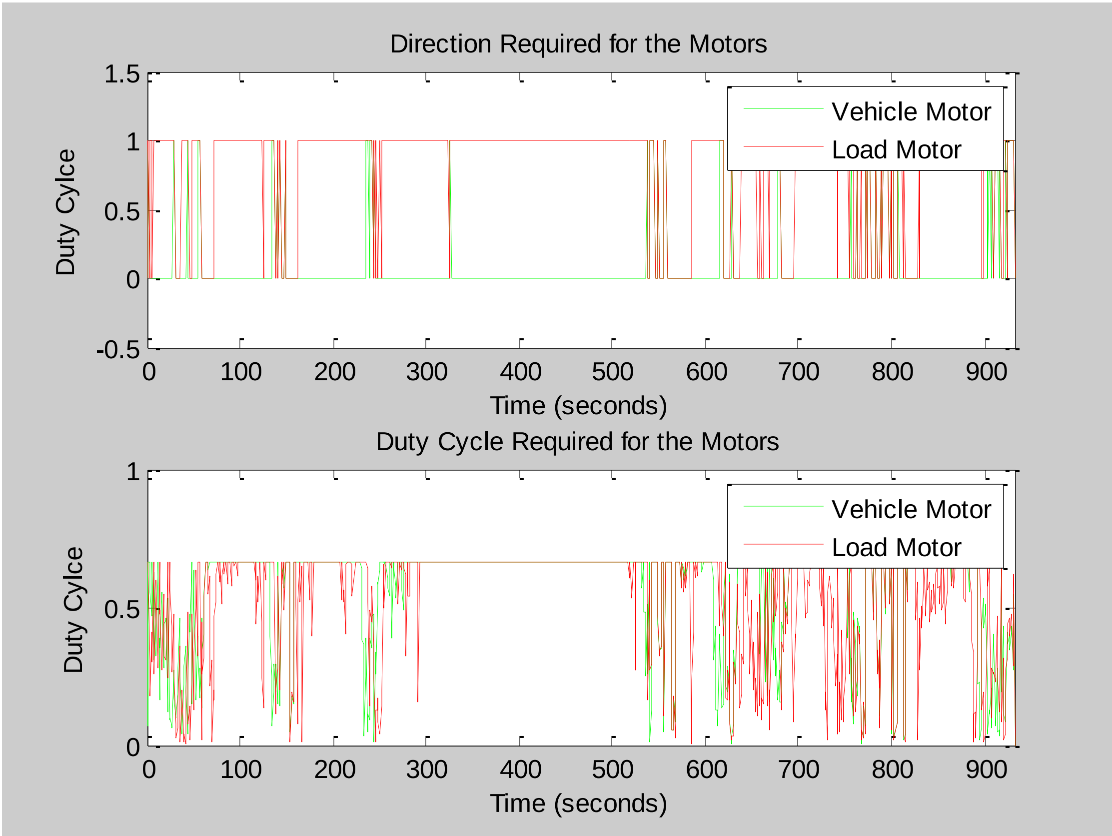


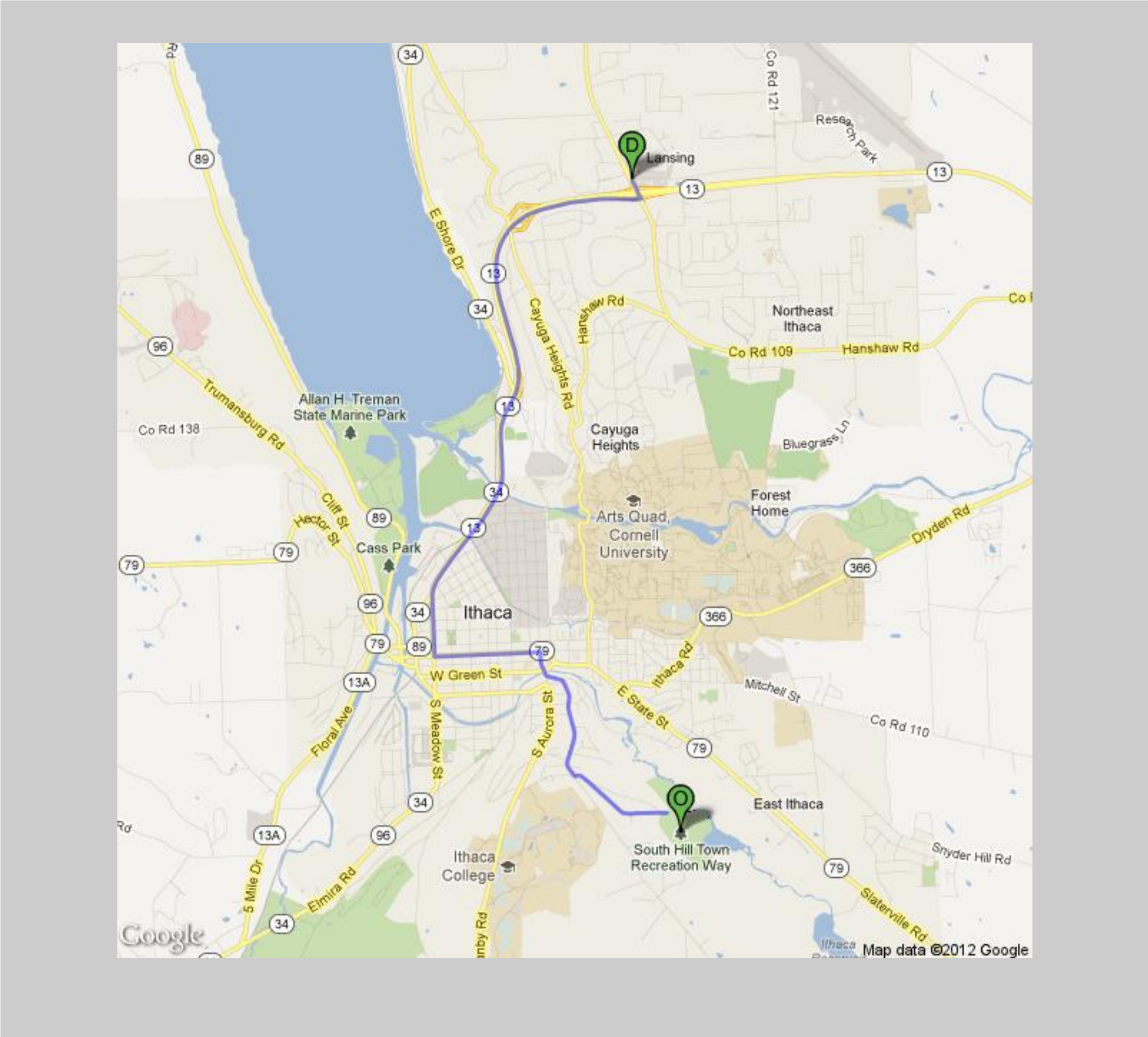
Seattle Trip using Charge Car Project GPS Data:

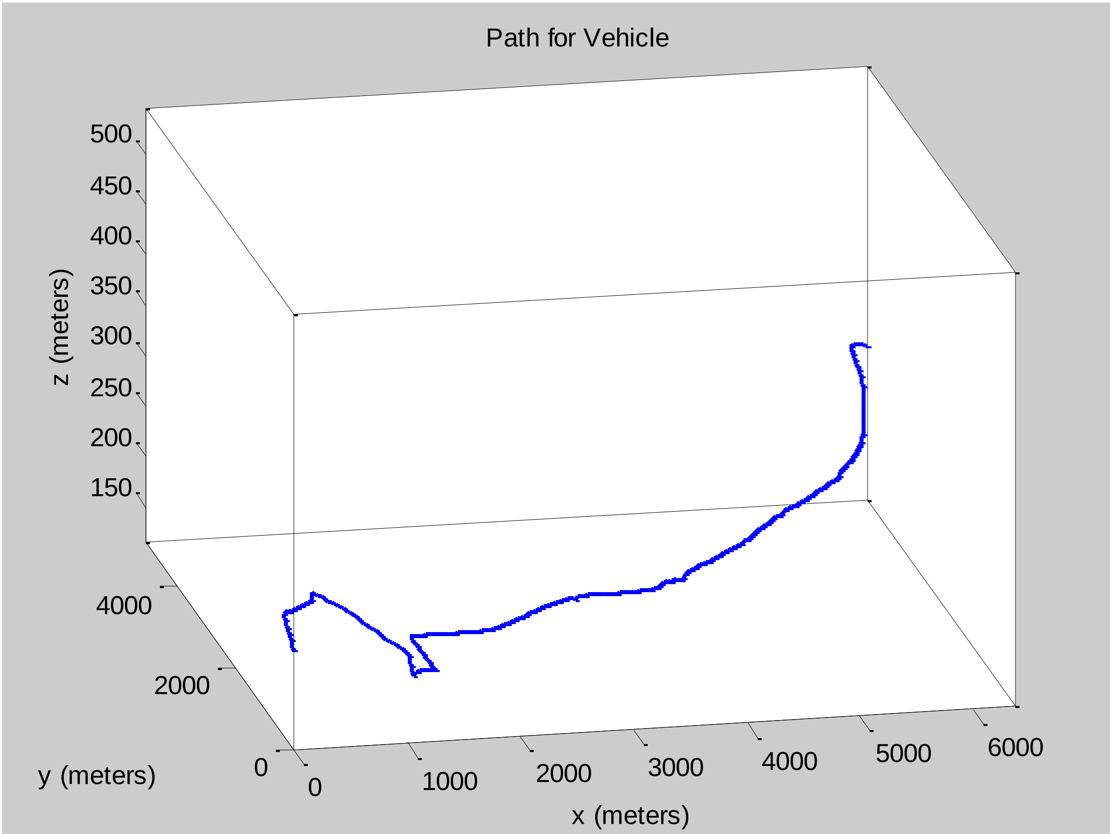


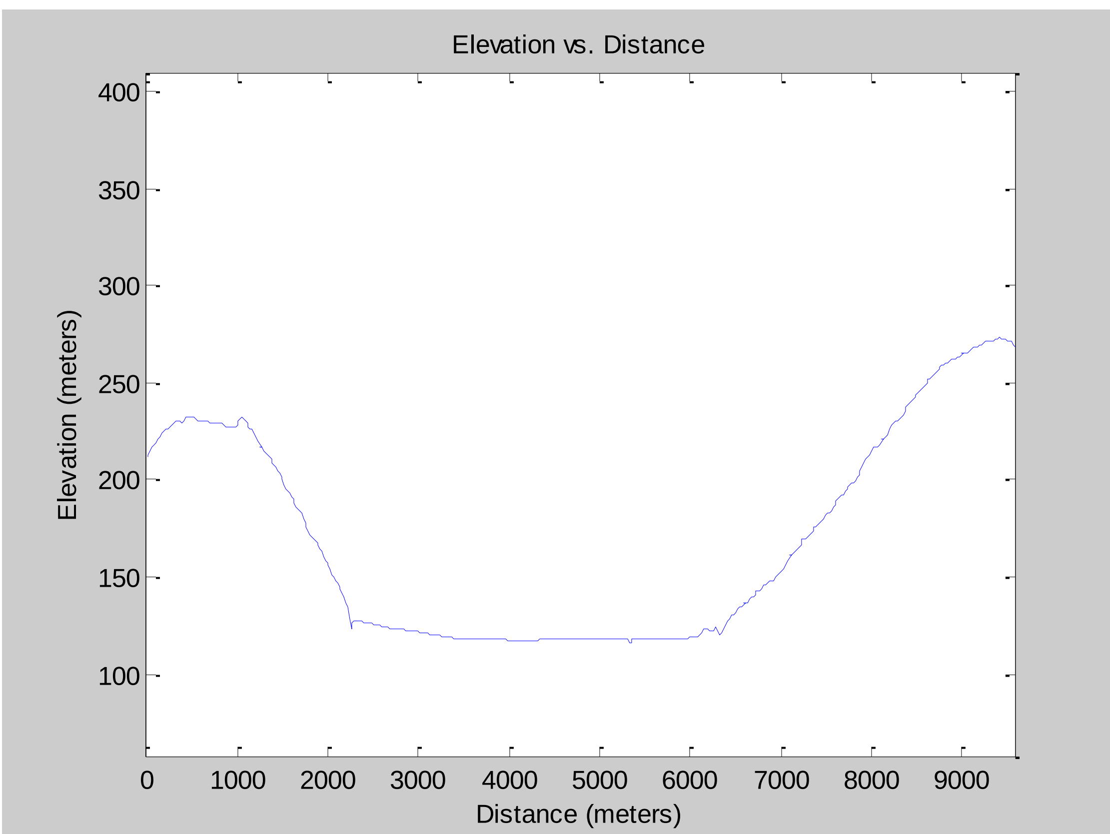



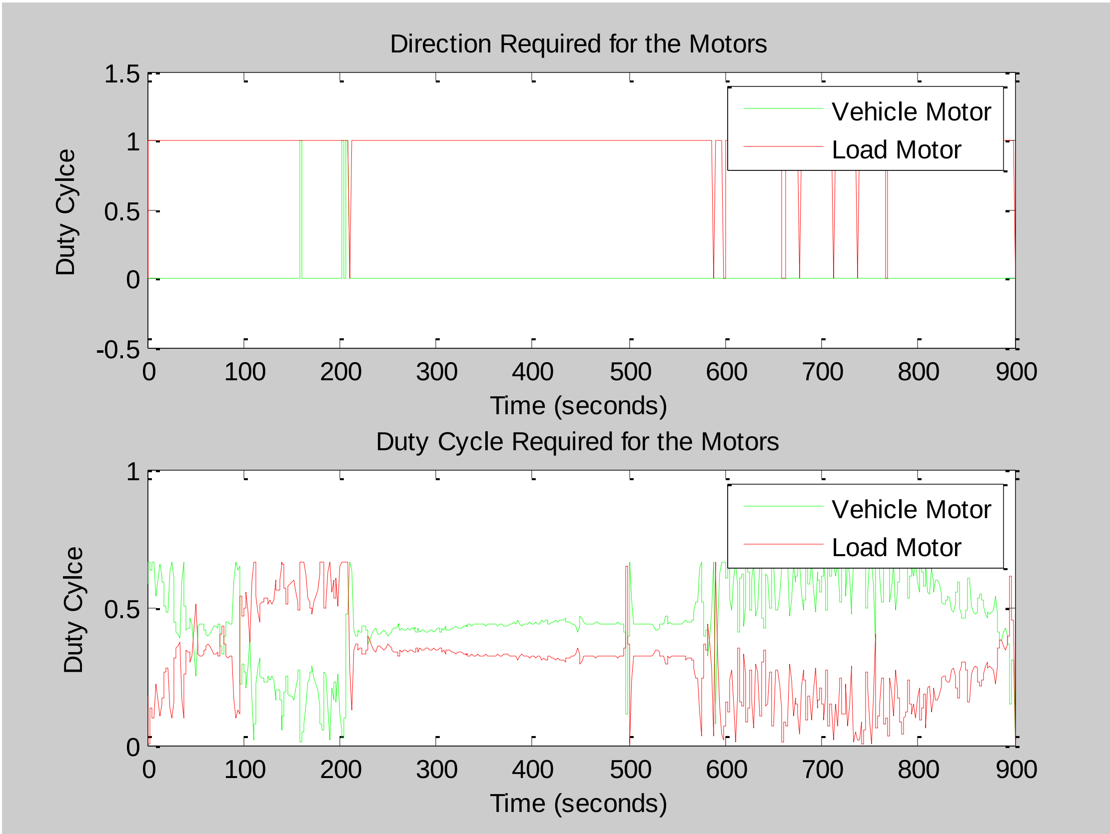

Direction Required for the Motors
Duty Cylce
Vehicle Motor
Load Motor
1.5
1
0.5
0
-0.5
0
100
200
300
400
500
600
700
800
900
Time (seconds)
Duty Cycle Required for the Motors
Duty Cylce
Vehicle Motor
Load Motor
1
0.5
0
0
100
200
300
400
500
600
700
800
900
Time (seconds)

Ithaca Trip with Constant Velocity:

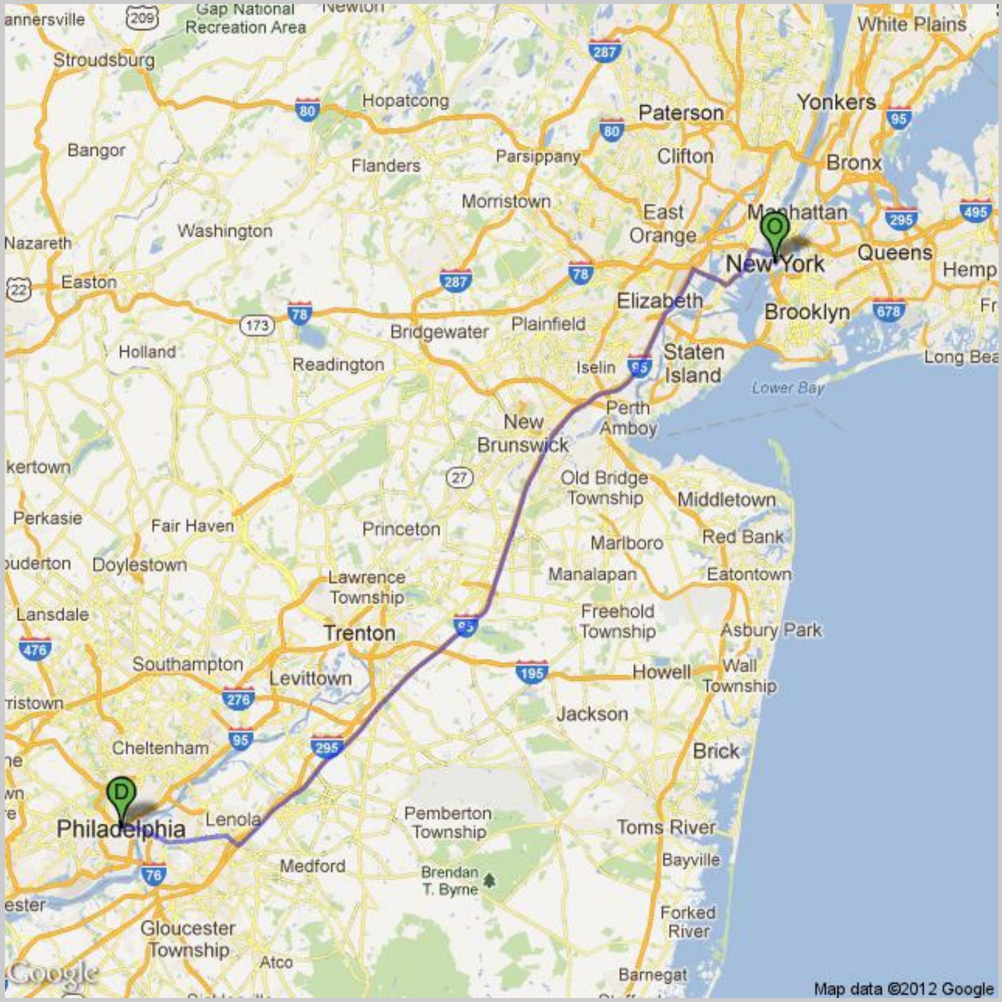


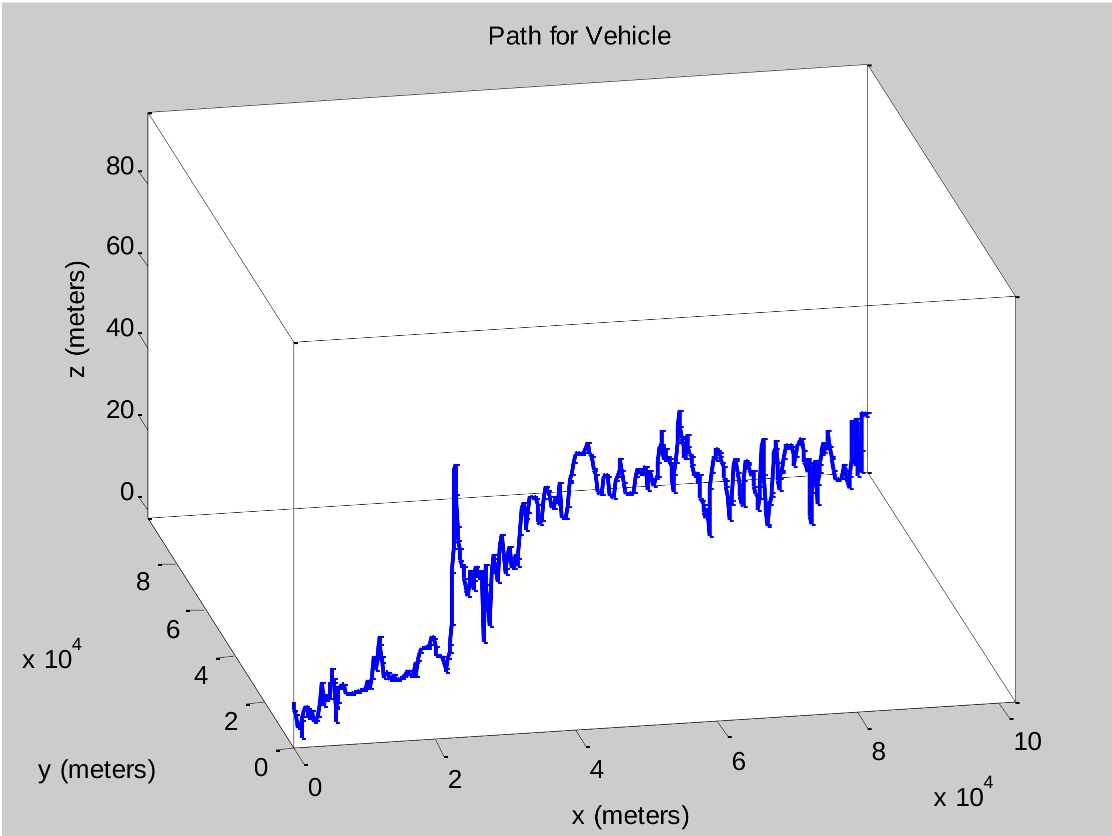

Path for Vehicle
z (meters)
500
450
400
350
300
250
200
150
4000
2000
0
y (meters)
0
1000
2000
3000
4000
5000
6000
x (meters)


Elevation vs. Distance
Elevation (meters)
400
350
300
250
200
150
100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Distance (meters)

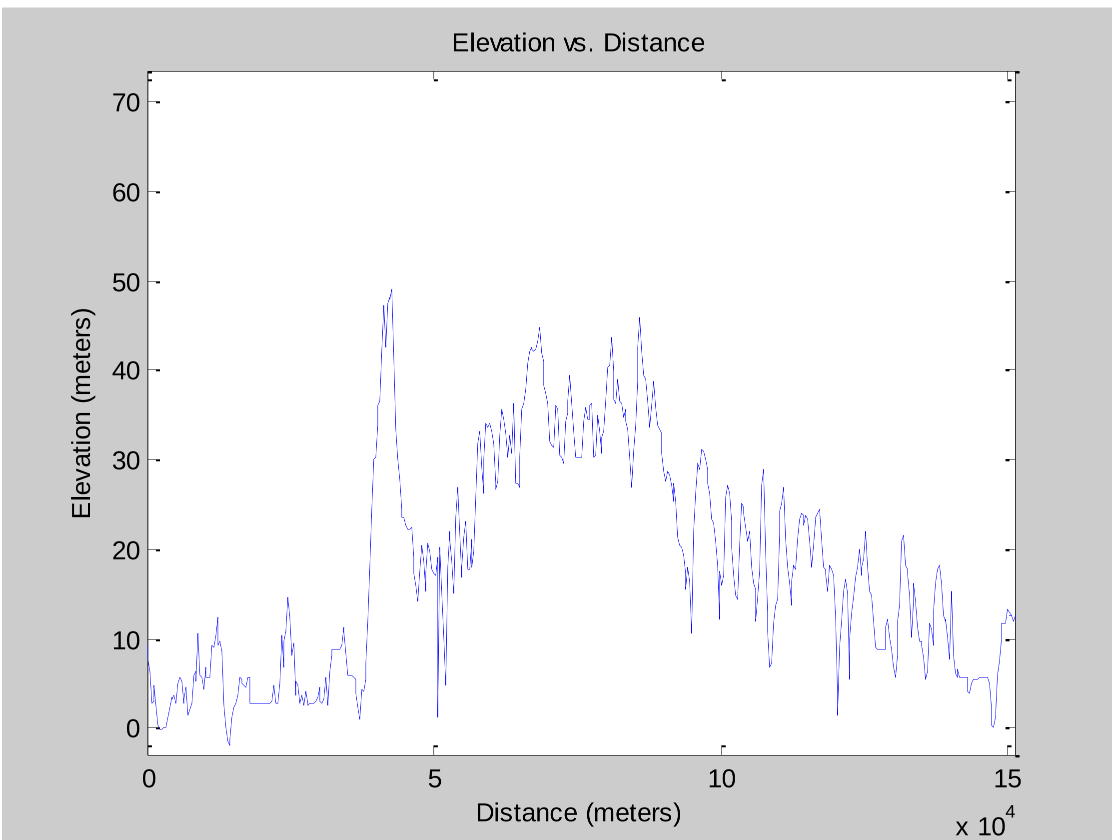

Direction Required for the Motors
Duty Cylce
Time (seconds)
Vehicle Motor
Load Motor
1.5
1
0.5
0
-0.5
0
100
200
300
400
500
600
700
800
900
Duty Cycle Required for the Motors
Duty Cylce
Time (seconds)
Vehicle Motor
Load Motor

New York, NY to Philadelphia, PA Trip with Constant Velocity:

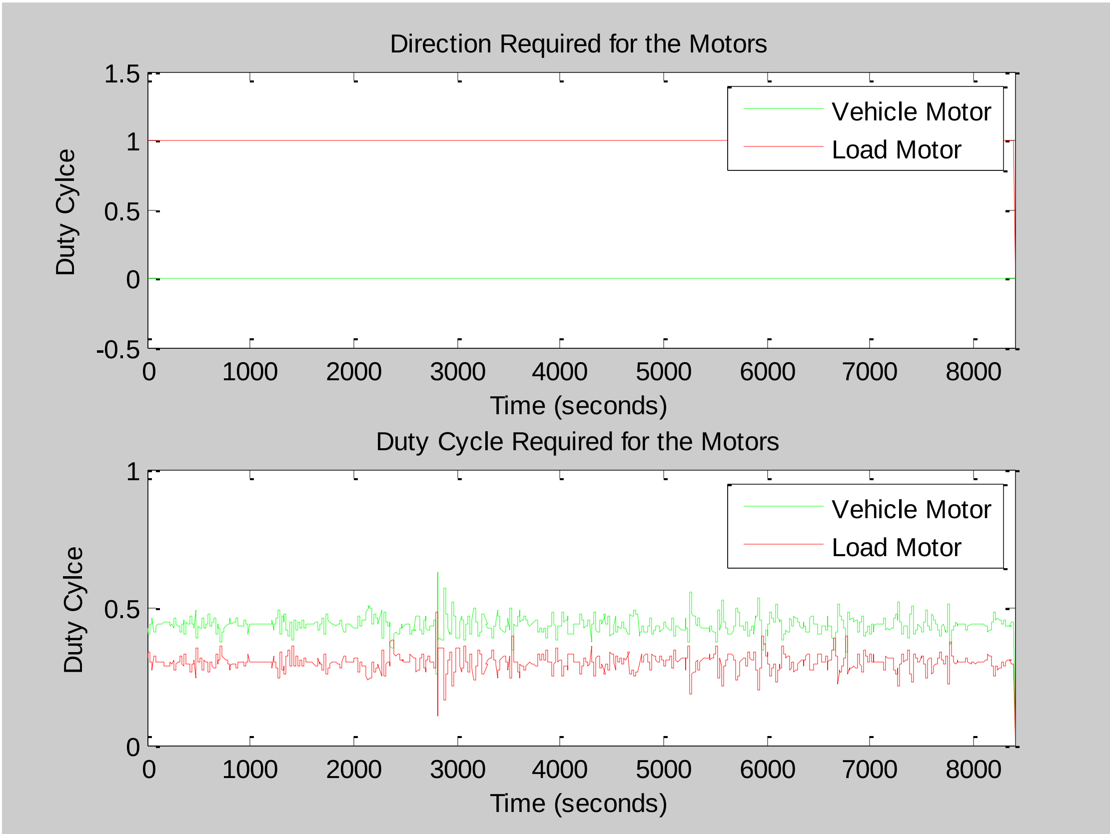




Path for Vehicle
z (meters)
80
60
40
20
0
8
6
x 10^4
4
2
y (meters)
0
0
2
4
6
8
10
x 10^4
x (meters)

Elevation vs. Distance
Elevation (meters)
70
60
50
40
30
20
10
0
0
5
10
15
Distance (meters)
x 10^4



Direction Required for the Motors
Vehicle Motor
Load Motor
Duty Cylce
1.5
1
0.5
0
-0.5
0
1000
2000
3000
4000
5000
6000
7000
8000
Time (seconds)
Duty Cycle Required for the Motors
Vehicle Motor
Load Motor
Duty Cylce
1
0.5
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Time (seconds)