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Optimal Energy Management for Forward-Looking Serial-Parallel Hybrid Electric Vehicle Using Rule-Based Control Strategy

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OPTIMAL ENERGY MANAGEMENT FOR FORWARD-LOOKING SERIAL-PARALLEL HYBRID ELECTRIC VEHICLE USING RULE-BASED CONTROL STRATEGY

by

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In today's sophisticated era of technology, resolving environmental problems is a matter of grave concern. Developing hybrid electric vehicles is a good step towards environmental preservation, since they use less fuel compared to conventional vehicles because of the combination of electric and mechanical energy. A hybrid electric vehicle reduces dependence on fossil fuels and hence lowers emissions. Specifically, a hybrid powertrain that includes a conventional gasoline engine and a brushless DC motor offers great potential to meet stringent CO_2 regulations and fuel economy requirements. This thesis focuses on the effects of initial state of charge (SOC) stored in Hybrid Electric Vehicle's battery that affects engine operation and fuel economy. The battery management system (BMS) that manages the electrical driving machine and generator machine based on vehicle speed and SOC plays a vital role. This thesis focuses on developing an optimal energy management strategy based upon logical operators for a serial-parallel HEV considering regenerative braking on flat and hilly terrain. This thesis also emphasizes optimizing engine operation without overrunning the generator machine. The results show that changes in initial SOC affect vehicle speed on hilly terrain; hence keeping SOC at an optimum level along with vehicle speed is necessary to maintain vehicle fuel economy and safety of electrical circuits.

TABLE OF CONTENTS

Table of Contents–Continued

LIST OF TABLES

LIST OF FIGURES

List of Figures—Continued

CHAPTER 1

INTRODUCTION

From the time automobile was introduced as mode of transportation, it has undergone changes because of more stringent emission laws and increasing fuel prices. According to an EPA, among the five major fuel consuming sectors, 33% of fuel consumption in the U.S. came from the transportation sector in 2009 [1]. Also, according to the US Energy Information Administration (EIA), the price of crude oil increased 500% from 1998 to 2011 [2]. Due to these changes, the automobile sector has emerged with cost-effective technologies like Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV), Electric Vehicles (EV), Fuel-Cell Hybrid Vehicles, and Autonomous Vehicles (AV) to meet stringent emission legislation and plummeting fuel prices.

Hybrid Electric Vehicles offer a great contribution to fuel-saving options because of transmission technology that combines the benefits of both engine and electrical machines to optimize system efficiency and improve vehicle performance. Toyota introduced the first generation Prius in late 1997 and laid the foundation of hybrid vehicles. This study focuses on discussing the Toyota Hybrid system (THS) and its power-split architecture.

HEVs can be categorized based on degree of hybridization and powertrain architecture. They can be categorized as full or mild hybrid based on degree of hybridization. If the motor is small, i.e., secondary power source is small, then neither the internal combustion engine nor the motor can run independently. Such Hybrids are termed mild hybrids. They can only be operated with slight engine assist and regenerative braking. When the motor is large, then the internal combustion engine and motors can run independently and also simultaneously. This type of hybrids is referred to as full hybrids. Full HEV’s can operate in electric mode, cruise mode, engine assist mode, ICE mode and battery charge mode. Hybrid electric vehicles can be classified as series HEV, parallel HEV and series-parallel HEV [6].

1.1 Series Hybrid Electric Vehicle

In series hybrid electric vehicles, the electric motor drives the vehicle and combustion is started only when needed. As seen in Figure 1 there is no direct connection between the combustion engine and the vehicle; the requested combustion engine power is transferred from mechanical to electric power via a generator, and the electric power is transferred to mechanical power via an electric motor. The advantage in this type of transmission is that the engine is able to operate in the optimal region around the "sweet spot": the region of maximum engine efficiency. The electric motor operates as a generator and provides regenerative braking energy during deceleration. The major disadvantage in this type of transmission is the power loss occurring during conversion from mechanical to electrical or electrical to mechanical power. Also, because electrical machines are solely responsible for transmission, the size of these machines is large and the cost is also relatively high.

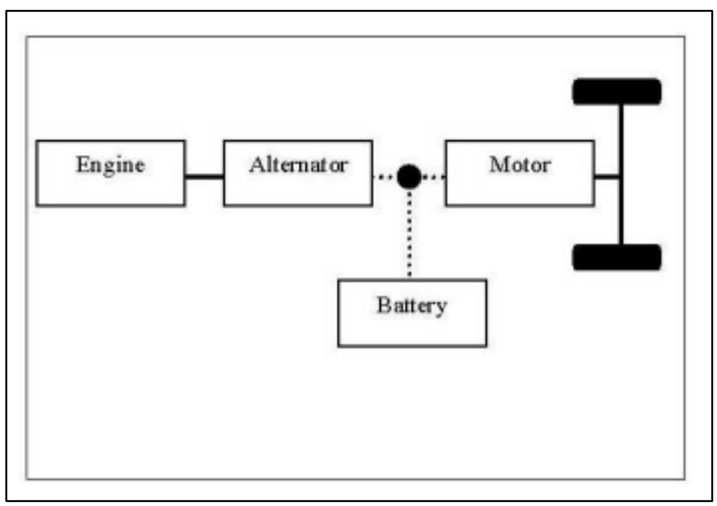


Figure 1. Series hybrid electric vehicle architecture layout [8]

1.2 Parallel Hybrid Electric Vehicle

In parallel hybrid electric vehicles, the electric machine is placed in parallel to the engine to wheel transmission. The major advantage of this type of powertrain is its high efficiency because there is no power conversion involved in the transmission process but the direct connection between engine and wheels limits the ability of engine to operate in its optimal operating region, which is a major disadvantage in parallel hybrid electric vehicle. The similarity between series hybrid and parallel hybrid is the regenerative braking provided by the electric motor (MG). The energy supplied by the motor during regeneration is stored in the battery.

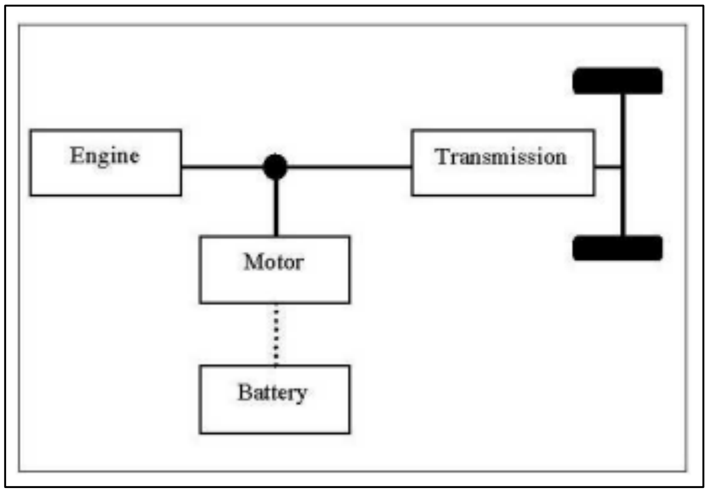


Figure 2. Parallel hybrid electric vehicle architecture layout [8]

1.3 Series-Parallel Hybrid Electric Vehicle

Serial-parallel hybrid electric vehicles combine the benefit of both series hybrids and parallel hybrids. The reason it is called power-split transmission is because the combustion engine power is split, where one part is transferred to the wheels via a mechanical branch and the other part flows to wheels via an electric branch. The generator machine does the job of controlling the engine in its sweet spot so the efficiency of series-parallel HEV is high and the motor provides power assist and regenerative braking. Excess engine power is transferred to the generator via the electric branch; any remaining energy is transferred to the wheels via the mechanical branch. In figure 3 ‘S’ is sun gear, ‘C’ is carrier gear and ‘R’ is the ring gear.

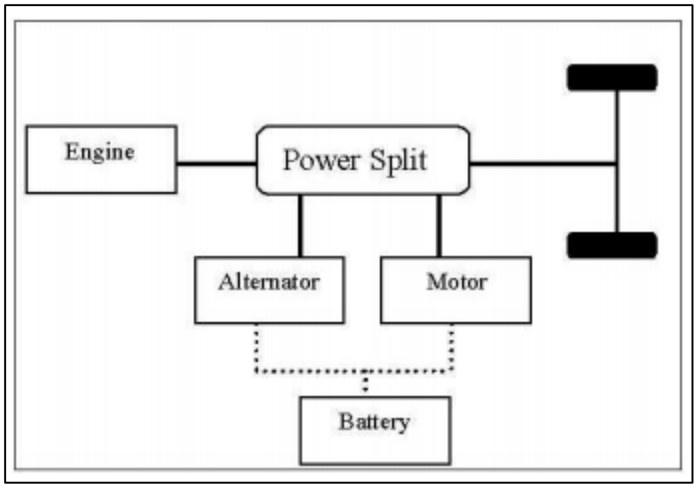


Figure 3. Series-parallel hybrid electric vehicle architecture layout [8]

The major concern in HEV is its performance and hybrid control. The combination of ICE, brushless DC motor, Ni-MH Battery, planetary gear set, and transmission have an impact on vehicle tractive propulsion, efficiency of vehicle, SOC of battery, and fuel economy. This study focuses on developing a velocity-driven forward-looking model and tries to minimize fuel consumption by detailed analysis of these parameters.

The battery plays a key role in managing electrical energy, hence maintaining SOC of the battery at a reasonable level becomes important. This study focuses on the battery management system because it has a significant impact on vehicle propulsion and fuel economy. Another contribution of this study is the simulation tests performed on the HEV model under level and hilly terrain to study optimal levels of SOC in these conditions. A study on the effect of SOC under flat and hilly terrain for a forward-looking serial-parallel HEV has not previously been conducted. This thesis offers contributions to battery management strategies for these applications.

1.4 Literature Review

Proper modeling leads to accurate results and lays the foundation for variety of research. The model developed in this study is based on work performed by Gökce et al. at Istanbul university [3]. This model is a velocity-driven model where the controller takes into account the difference in velocity between the target velocity and the actual velocity, and feeds the difference to the driver model, where the position of the pedal is evaluated and the resistances acting on vehicle are determined [4].

There are various approaches in building a HEV model in standard computational modeling software, such at MATLAB/Simulink. A power based Toyota Hybrid system was modelled and simulated in [5]. A similar approach was proposed in [6] but on a parallel HEV. Another such research based on Toyota Hybrid System was presented using a torque-based approach 7]. A dynamic model considering vehicle speed and desired torque was presented in [8]. The mathematical modelling of a power-split device with steady-state performance is well documented by the researchers at Michigan Technological University [9]. This thesis builds upon prior research on the engine-CVT Optimum Operating line (OOL) and a novel ratio scheduling technique for CVT transmissions using a backward-looking cycle-driven model [10].

There are few prior studies that illustrate the importance of operating the engine without overrunning the generator. One detailed study on this topic is presented by Gökce, where he provides the operating speed of engine without overrunning generator [11]. The battery provides energy to the driving machine and stores energy supplied by the generator machine. Relevant literature for battery modelling and control algorithm development for the battery is described in [12].

HEV energy management is a major area of research, including both global optimization and local optimization solutions. Dynamic programming [13] and Pontryagin's Minimum Principle [14] are global optimization solution techniques, with Equivalent Consumption Minimization Strategy (ECMS) [6] being a great example for local optimization technique. Neural Networks have revolutionized control algorithm development given the amount of data that can be stored and utilized [15]. Another technique in control algorithm development that is emerging in recent times is recognizing driving patterns in advance and organizing control algorithms based on Machine Learning. This approach has been shown to reduce lag in the powertrain and increase fuel economy [16].

Reference [17] shows that about 30% of a vehicle's energy is lost in braking. Reducing this loss and diverting this supply of energy to the battery can significantly improve fuel economy. Managing the battery's SOC becomes crucial because this energy management ultimately affects vehicle performance and fuel economy [18]. Similar investigations were performed by Argonne National Laboratory on the Toyota Prius HEV [19], wherein they have studied the effect of battery charge for EPA, US06 and UDDS cycles.

A simulated arc terrain was developed [20] and the effects of change in initial SOC on vehicle fuel economy over this terrain was studied. The investigations presented in this work provide details of vehicle performance with changes in initial SOC under different terrains and illustrate the importance of reasonable SOC levels.

1.5 Assumptions

Steady state operating conditions were considered for this study. Thermal effects were not considered. The benchmarked data for engine modelling, Motor and generator maps remained consistent from [3]. Control algorithm development strategies developed were determined using the study presented in [3]. The engine operation based on generator machine speed and vehicle remained consistent from [10]. The benchmark data for battery modelling and battery control strategy remains consistent from [12]. The parameters for resistances acting on the wheels and the equations required to evaluate total resistances were obtained from [4]. Simulated arc terrain benchmark data determined and used in this study was assumed to simulate hilly region conditions.

CHAPTER 2

SERIES-PARALLEL HYBRID ELECTRIC VEHICLE MODELLING

The model developed in this study is a forward-looking, velocity-driven, serial-parallel HEV. The inputs to this model are the US06 drive test cycle and the environmental resistances acting on the vehicle. The controller evaluates whether the vehicle is accelerating or decelerating and then determines the pedal position to enact the energy management strategy. Based on the pedal position, the speed function block in the engine model determines operating parameters for the engine. This is fed to the planetary gear model, where motor RPM and generator RPM are determined and the operating parameters for the motor (M/G 1) and generator (M/G 2) are determined based on the planetary results and the SOC of the battery. The transmission and wheels model determines the vehicle actual speed. Figure 4 shows a block diagram of overall model functionality. The model components are described in greater detail in Sections 2.1 – 2.6.

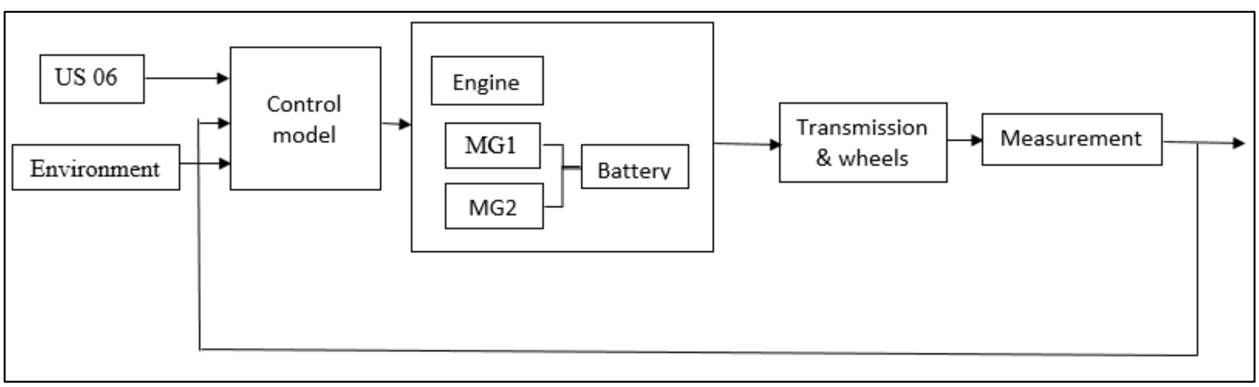


Figure 4. Forward-looking serial-parallel HEV model overview

2.1 Engine Model

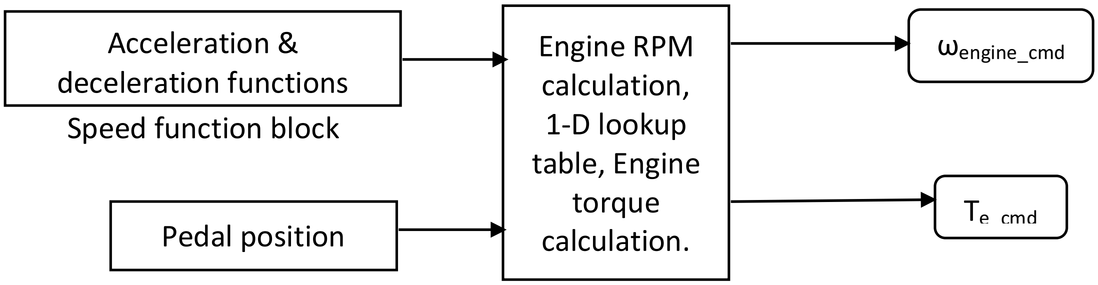


Figure 5. Engine model overview

The 2005 Toyota Prius engine model determines engine RPM and engine Torque based on the pedal position pressed by the driver. The pedal position determines engine RPM from the speed function block based upon whether the vehicle is accelerating or decelerating. This speed function block sets engine output within the working boundaries of the Motor/Generator 2 because it is connected to the output of a power split device. Engine torque is evaluated from engine RPM using a 1-D lookup table based on the Optimum Operating Line (OOL). OOL is the line of least specific fuel consumption across the range of engine speed and engine torque. In figure 6 the red line is OOL. The values for engine torque and engine RPM lie at the intersection between OOL and power contours.

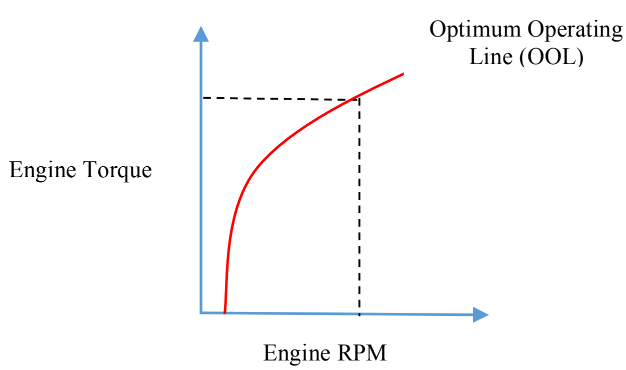


Figure 6. Engine RPM vs Engine Torque 1-D lookup table

2.2 Motor/Generator 1 Model

A 35 kW brushless DC motor is taken into consideration as a driving electrical machine. It operates on low speed and assists the engine during high power demand. Motor/generator 1 functions as a motor in vehicle accelerating conditions and as a generator in vehicle decelerating conditions. It supplies the regenerative braking energy of the vehicle to the battery and maintains SOC level. The input to the motor/generator 1 model is obtained from the planetary model where motor RPM is evaluated from vehicle actual speed. The motor model determines motor torque and motor power using a 1-D lookup table [3] optimized from motor efficiency maps.

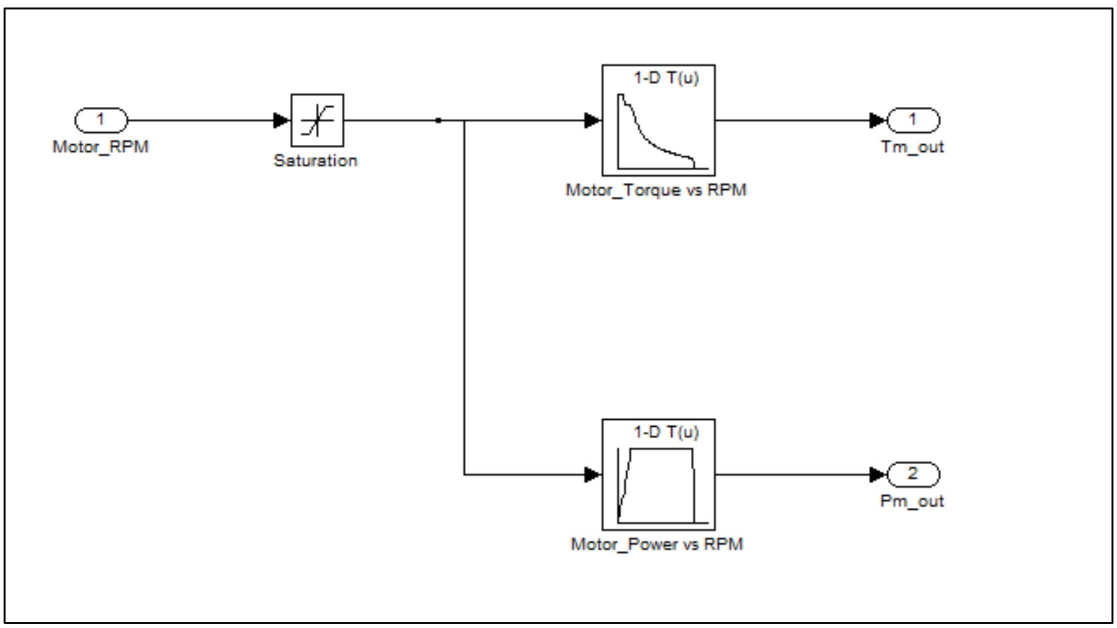


Figure 7. Motor/Generator 1 model

2.3 Motor/Generator 2 Model

A 15 kW motor/generator 2 does the job of maintaining gear ratio and helps motor/ generator 1 when the vehicle runs in full throttle condition by assisting the motor in driving the vehicle. When the vehicle runs in normal driving mode, excess engine power is utilized to keep the generator running, which helps charge the battery. This ultimately keeps the engine operating at its most efficient operating region and helps save fuel. The input to this model is the generator RPM which is evaluated in the planetary gear set equation Eq. [7] Generator torque and generator power are the outputs from this model, which are calculated from the generator RPM using a OOL [3].

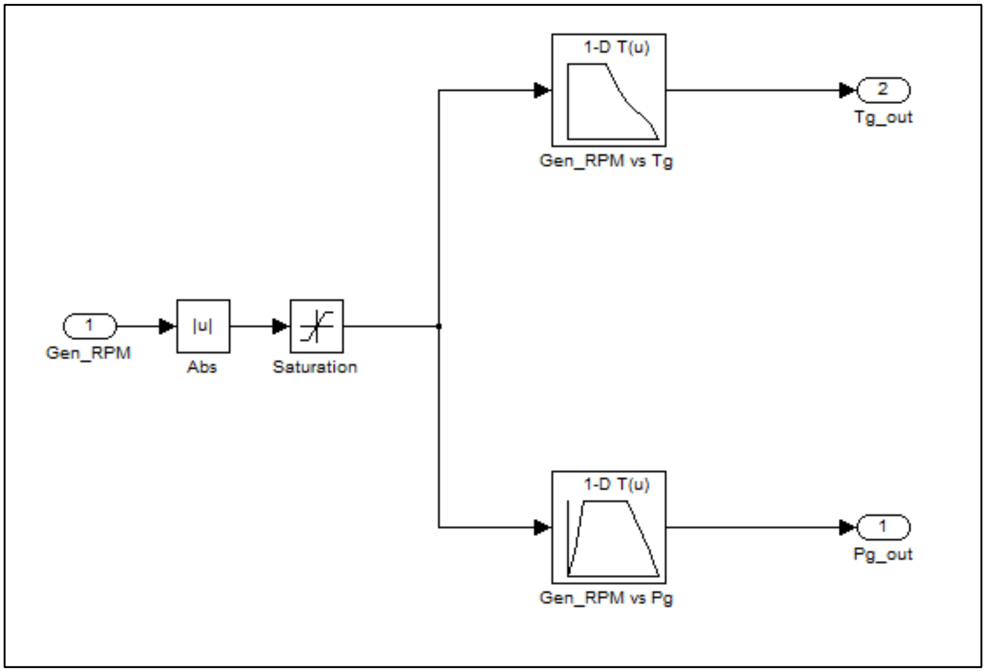


Figure 8. Motor/Generator 2 Model

2.4 Battery Model

The 480V NiMh battery supplies electrical energy to motor/generator 1 for driving the vehicle during electric propulsion mode and motor assist mode. It stores energy supplied by Motor/Generator 2 during deceleration i.e., regenerative braking energy. Engine excess power is also supplied to the battery via Motor/generator 2 in normal driving mode. This energy is either supplied to the motor for vehicle propulsion or stored to maintain SOC levels. The battery model presented in this study consists of an EMF calculation model, an internal resistance (R_w) calculation model, and a SOC calculation model. The EMF i.e., EMF1 in below figure of the battery depends on the SOC of the battery and is estimated using a lookup table. Internal resistance also depends upon the SOC of the battery, but the deciding factor between charging and discharging resistance is the power of the battery. The details on the lookup tables mentioned in this section is already discussed in assumptions. In the SOC calculation model, depending upon charging and discharging condition, the SOC is estimated along with battery current Eq. [1] and output voltage Eq. [2].

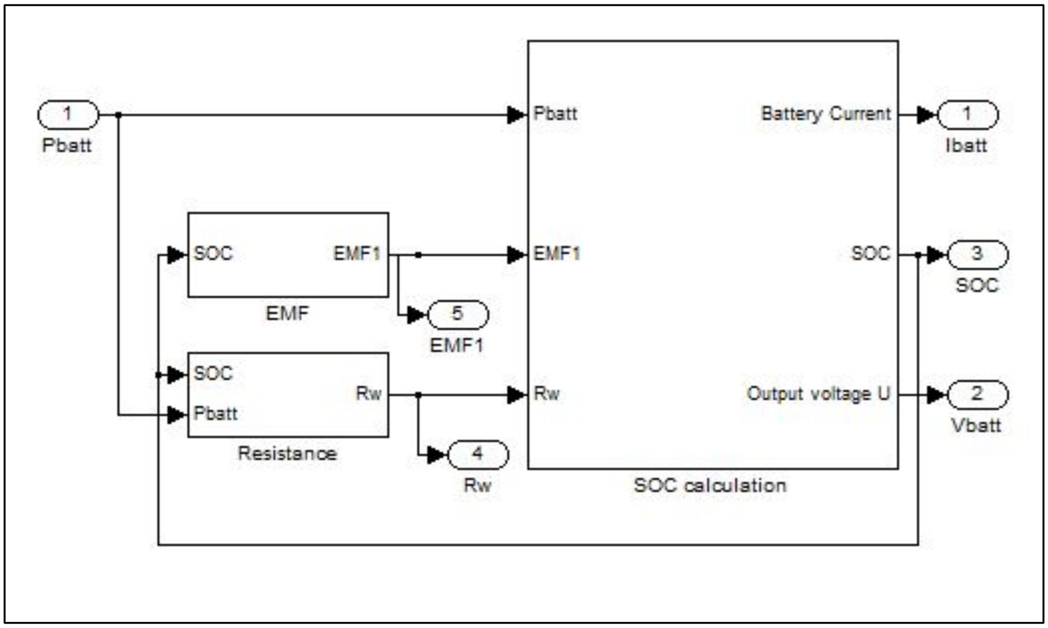


Figure 9. Battery model overview

$$I = \frac{(EMF1 - \sqrt{(EMF1^2 - 4\,P_{batt}\,R_w)}\,)}{2R_w} \quad \text{Eq. [1]}$$

$$U = EMF1 - IR_w \quad \text{Eq. [2]}$$

2.5 Driver Model

The driver model consists of environmental resistances, power requirement calculations, and wheel load calculations. The environmental resistances acting on the wheel include aerodynamic resistance, rolling resistance, and grade resistance mentioned in Eq. [3] – Eq. [6]. The power required to overcome these resistances and meet the velocity demand is evaluated. Load on the wheels is the output from this model that is calculated from torque required to overcome the resistances and the braking torque.

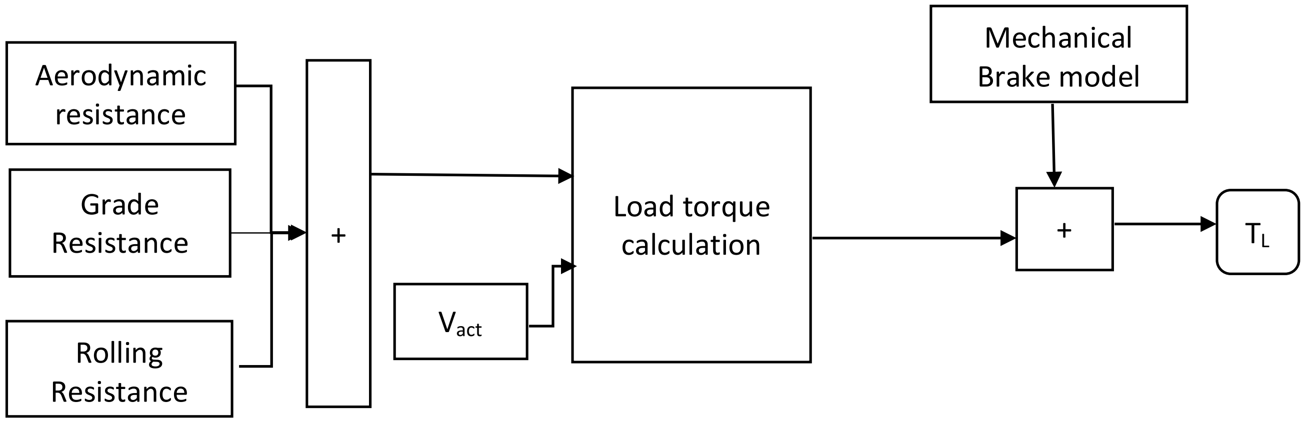


Figure 10. Driver model overview

$$R_{rolling} = 0.02mg\cos\theta \qquad \text{[Eq.3]}$$

$$R_{air} = 0.5\rho_{air}C_{d}Av_{act}^{2} \qquad \text{[Eq. 4]}$$

$$R_{grade} = mg\sin\theta \qquad \text{[Eq.5]}$$

$$F_{r} = R_{rolling} + R_{air} + R_{grade} \qquad \text{[Eq.6]}$$

Where,

Table 1. Driver model constants

Abbreviation	Definition	Units
$Rrolling$	Rolling resistance	N
$Rair$	Aerodynamic resistance	N
$Rgrade$	Grade resistance	N
F_r	Total resistances acting on vehicle	N
m	Mass of the vehicle	1300 kg
g	Gravitational constant	9.81 m/s^2
ρair	Density of air	1.17 kg/m^2
Cd	Drag coefficient	0.3
A	Vehicle frontal area	1.746 m^2
v_{act}	Actual vehicle speed	m/s
θ	Slope of the road	radians

2.6 Transmission and Wheels Model

The transmission and wheels model consists of the power split device and the vehicle model. The power split device is the heart of HEV, which maintains the planetary gear set ratio. The inputs to the power split device are engine RPM and actual vehicle speed. Motor RPM is evaluated from the actual vehicle speed and using the power split equation in Eq. [7], generator

RPM is evaluated. The outputs of the power split device model are motor RPM, generator RPM, and the coefficients of torque transferred by the ICE and generator to the driving shaft. Total torque acting on the vehicle is calculated in the vehicle model from the ICE torque, motor torque, generator torque, coefficients of torque transferred by ICE and generator to the driving shaft and the load torque acting on wheels. The values of coefficients for Eq. [7] – Eq. [9] remain consistent from [4]. Actual vehicle speed is obtained by integrating the actual speed function block.

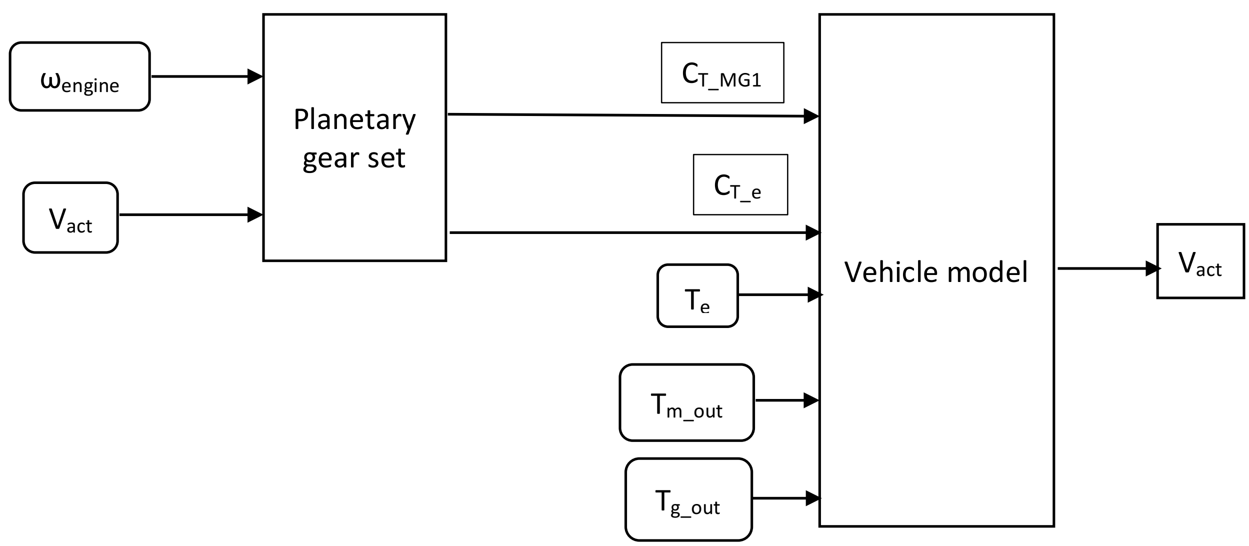


Figure 11. Transmission and Wheels Model overview [4]

The equations for the planetary gear set are:

$$\omega_{engine} = \frac{(\omega_{generator} + 2.6\omega_{motor})}{3.6} \quad \text{[Eq. 7]}$$

$$\text{Coefficient of torque\_MG1} = \frac{(9.36\omega_{engine}) - (6.76\omega_{motor})}{(3.6\omega_{engine}) - \omega_{generator}} \quad \text{[Eq. 8]}$$

$$\text{Coefficient of torque\_ICE} = \frac{(3.6\omega_{engine})}{0.722\ ((\omega_{generator} + (2.6\omega_{motor}))} \quad \text{[Eq. 9]}$$

CHAPTER 3

RULE-BASED LOGICAL OPERATOR CONTROL METHODOLOGY

The HEV modeled in this thesis operates on 5 modes of operation. The control strategy is built around these five modes of operation considering fuel economy, SOC, and the propulsion capacity of the vehicle.

3.1 Modes of Operation

The five modes of operation are vehicle start up and low-speed range, cruising mode, sudden acceleration, regenerative braking, and battery charge at rest.

3.1.1 Vehicle start up and low speeds

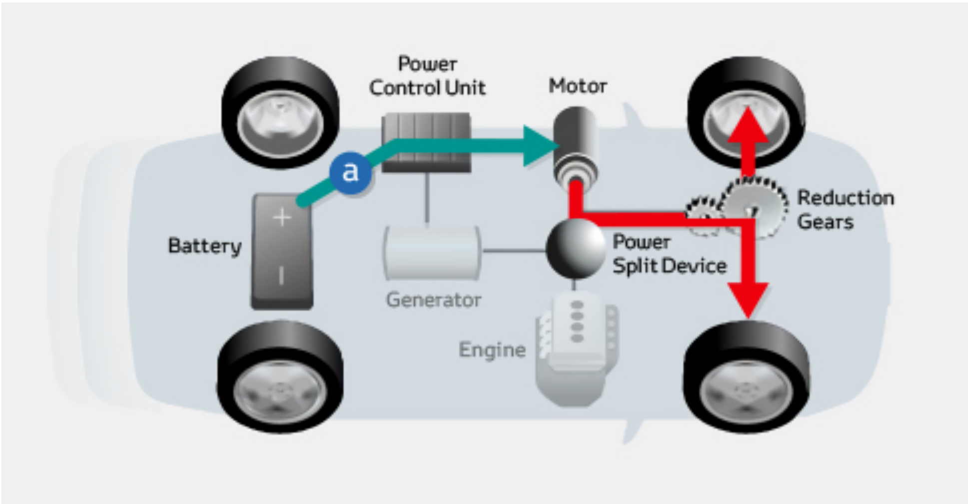


Figure 12. Vehicle start up and low speed overview [21]

In low speeds from vehicle start up to mid-speed range, the internal combustion engine of the vehicle is less efficient so it remains off in this period and the vehicle is propelled by the motor alone.

3.1.2 Cruising mode

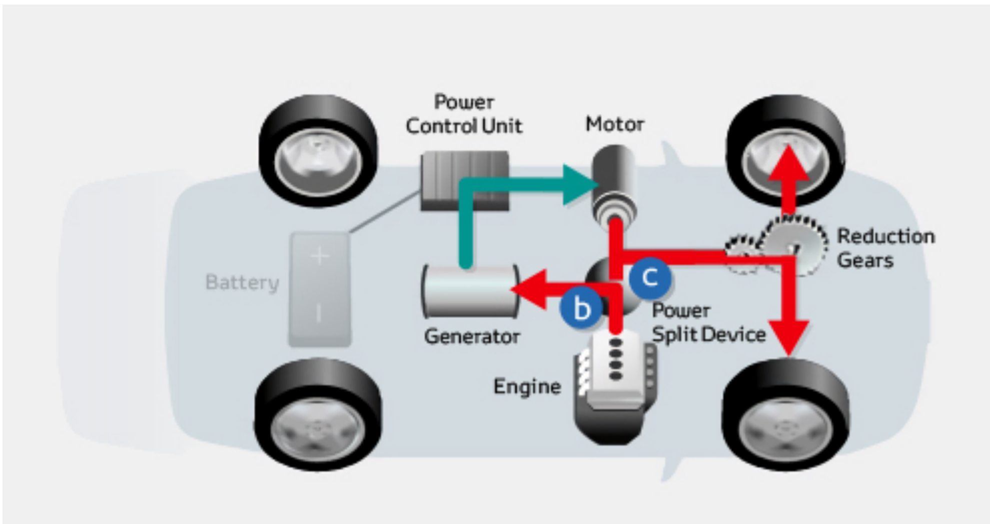


Figure 13. Vehicle cruising mode overview [21]

In this mode, the engine is the main power source and the power is split by the power split device. One part charges the batteries via the generator and the other is directed to the wheels. The engine is operated in the most efficient range and the rest of the power is supplied by the motor during normal driving.

3.1.3 Sudden acceleration

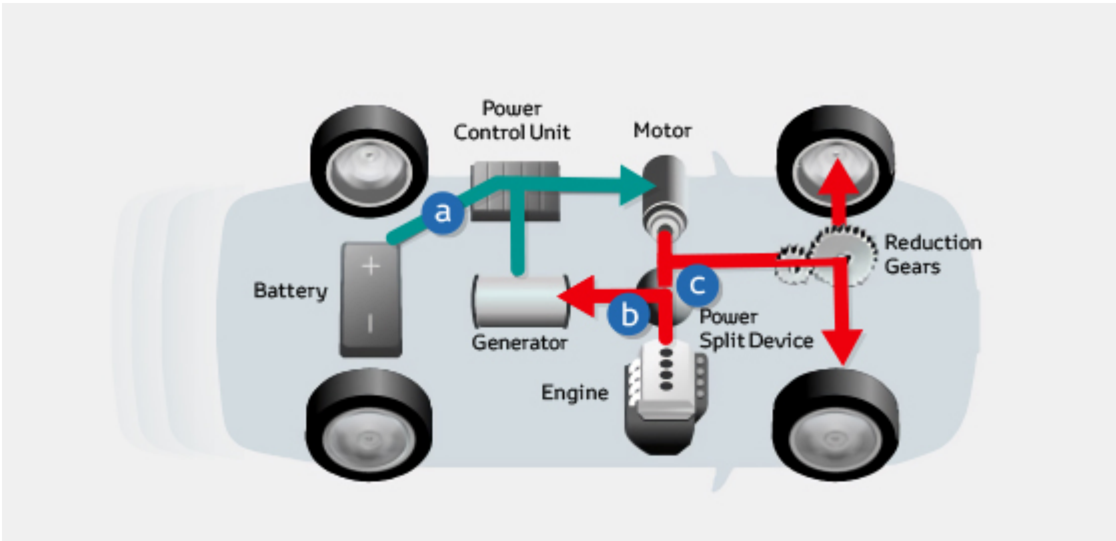


Figure 14. Vehicle sudden acceleration overview [21]

During rapid acceleration, the vehicle operates at full throttle, so with some help from the generator, the driving machine runs in full performance. In this mode of operation, both the internal combustion engine and the motor drive at full performance to meet the power demand of the vehicle.

3.1.4 Regenerative braking

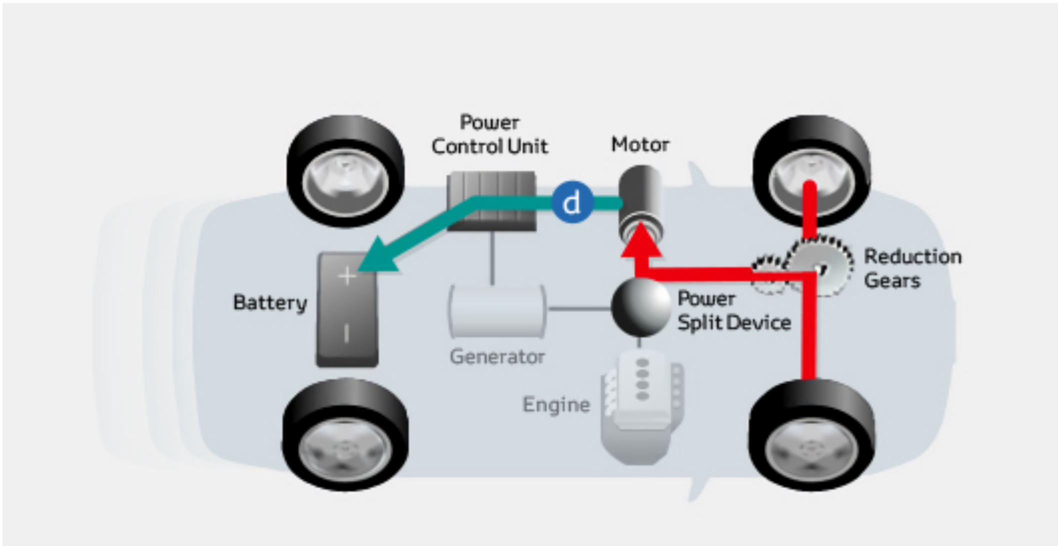


Figure 15. Vehicle regenerative braking overview [21]

During deceleration and braking, the wheels drive the motor, i.e., the kinetic energy generated by vehicle is used to charge the battery. In this mode of operation, the motor operates as a generator and stores the energy in the battery.

3.1.5 Battery recharge at rest

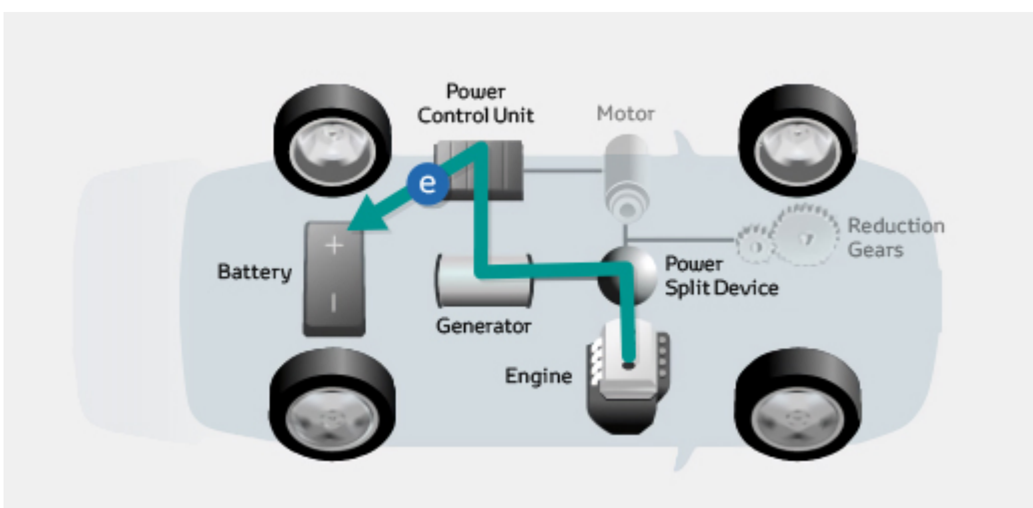


Figure 16. Vehicle operation at rest overview [21]

When the vehicle is at rest and if the battery SOC is below a specific level, the internal combustion engine operates in its most efficient range and runs the generator, which charges the battery.

3.2 Control Methodology

Control logic is developed based on the vehicle actual speed V_{act}, vehicle target speed V_{tgt} (drive cycle input) and SOC of the battery. SOC is considered adequate between 0.4 to 0.6. The vehicle runs in silent mode below 40 km/hr., i.e., on electric drive mode. If the vehicle is above 40 km/hr., then the ICE runs in its optimum region and stores excess energy in the battery. Between 0.6 to 0.9 SOC, only regenerative braking is available. Excess engine power is transferred to generator and used for driving the motor. Above 0.9 SOC, there is no regenerative braking and generation. Below 0.4 and above 0.1 SOC, silent mode is cancelled. Below 0.1 SOC, electric assist is cancelled and energy in battery is recovered by excess engine power. This control methodology is developed using conditions derived from logical operators [3].

Table 2. Rule-based control strategy using logical operators

Control logic	Control logic definition
CL_0 : $V_{act} = 0$ & $V_{tgt} = 0$	Vehicle stopped.
CL_1 : $V_{act} \leq 40$Km/hr. & $SOC \geq 0.4$	The control logic defines vehicle is running in silent mode.
CL_2 : $V_{tgt} \geq V_{act} + 20$	The control logic defines vehicle is running in full throttle condition.
CL_3 : Pedal_Pos = 1	The control logic defines vehicle is accelerating.
CL_4 : $V_{act} = 0$ & $SOC < 0.4$	The control logic defines vehicle is idling.
CL_5 : $SOC > 0.6$	The control logic defines upper adequate SOC limit.
CL_6 : Pedal_Pos = 0	The control logic defines vehicle is decelerating.
CL_7 : $SOC < 0.4$	The control logic defines lower adequate SOC limit.
CL_8 : $SOC > 0.9$	The control logic defines overcharge level.
CL_9 : $\omega_{engine} \geq 1000$	The control logic defines minimum engine speed for operation.
CL_10 : $V_{act} \leq 5$ & $V_{tgt} > 0$	The control logic defines vehicle is reaching low speed condition.
CL_11 : $SOC < 0.9$	The control logic defines regenerative braking condition limit.
CL_12 : $V_{act} = 0$ & $V_{tgt} > 0$	The control logic defines vehicle is starting up.

Based on the control logic in Table 1, the control model was developed. The control logic was used to define engine on-off conditions, motor acceleration, deceleration logic, and generator on-off conditions.

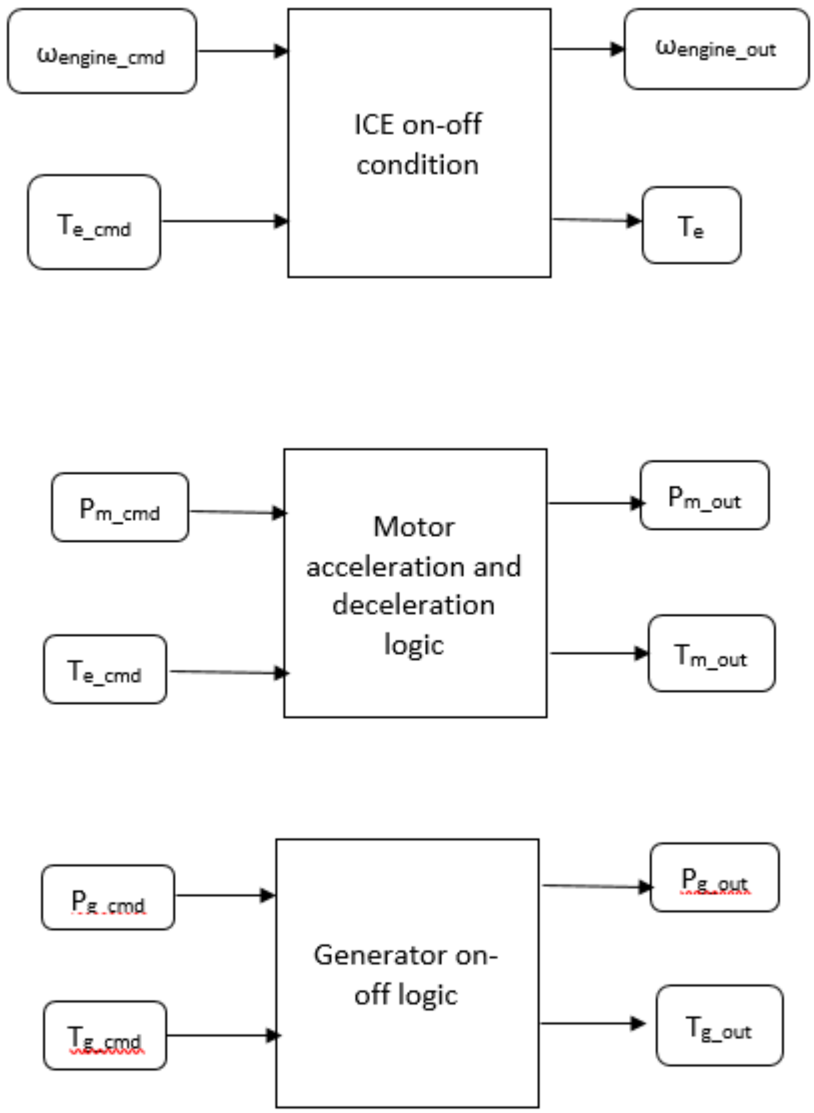
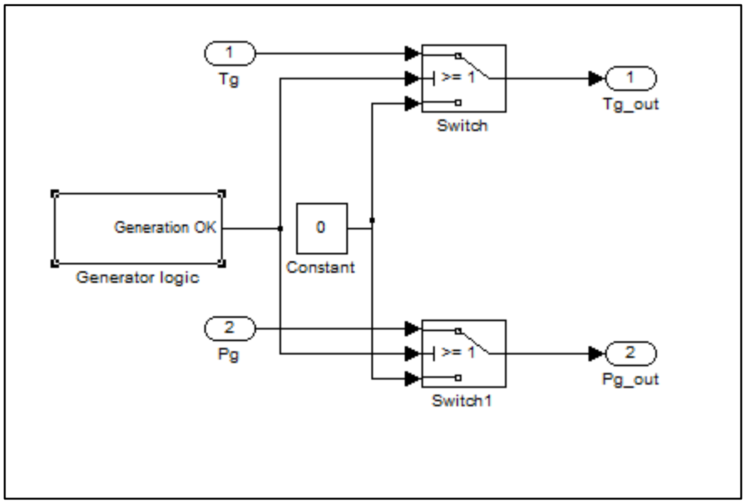


Figure 17. HEV control model overview

The above model can be illustrated using generator on-off logic in figure 18. The generator is on when CL_2, CL_3, CL_4, CL_7 are all working or one of them is working. The figure 18 below sums up all these logics together.



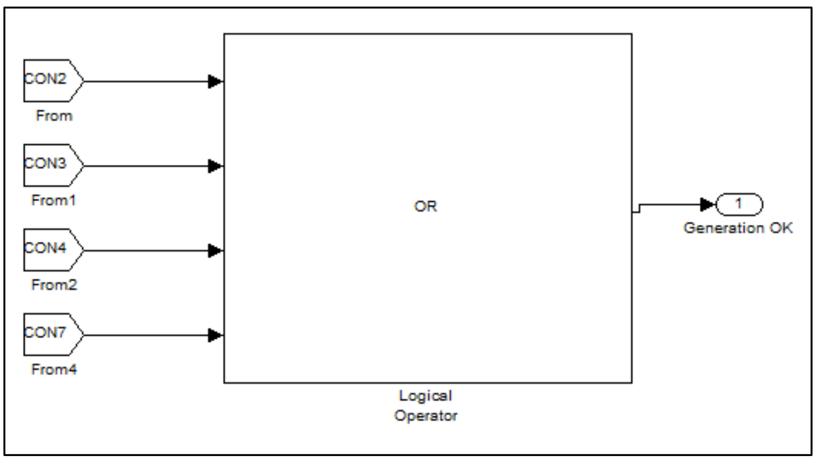


Figure 18. Generator control logic

CHAPTER 4

SIMULATION

The US06 highway cycle, shown in Figure 19, is used as the drive cycle input for the proposed MATLAB/Simulink simulation.

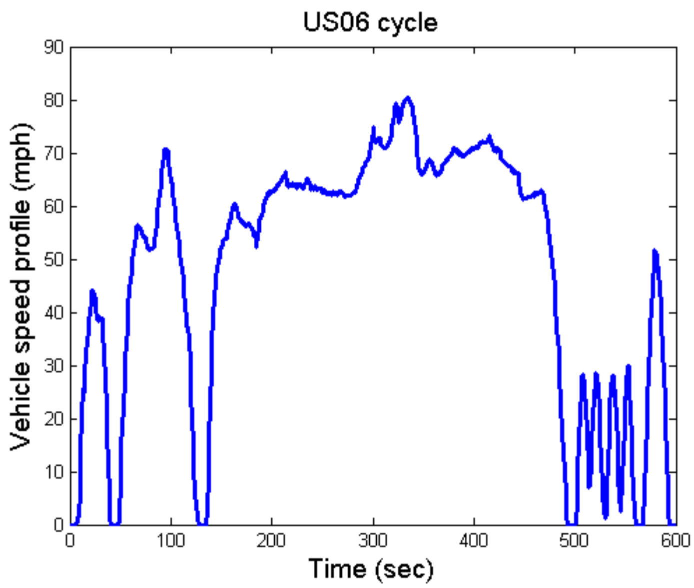


Figure 19. US06 Drive cycle

4.1 $SOC_{initial} = 0.6$

With $SOC_{initial} = 0.6$ the simulation results show that the vehicle travelled 12.6 km and recovered about 1.673 KW-hr of regenerative braking energy in this period. It consumed 1.22 KW-hr of energy during this cycle with a fuel economy of 60 MPG. In figure 20 it is evident that actual velocity tracks target velocity at all points. The root mean square between actual and target velocity in figure 20 is 3.02 km/hr. The SOC profile in figure 21 shows that vehicle operates near optimum battery level.

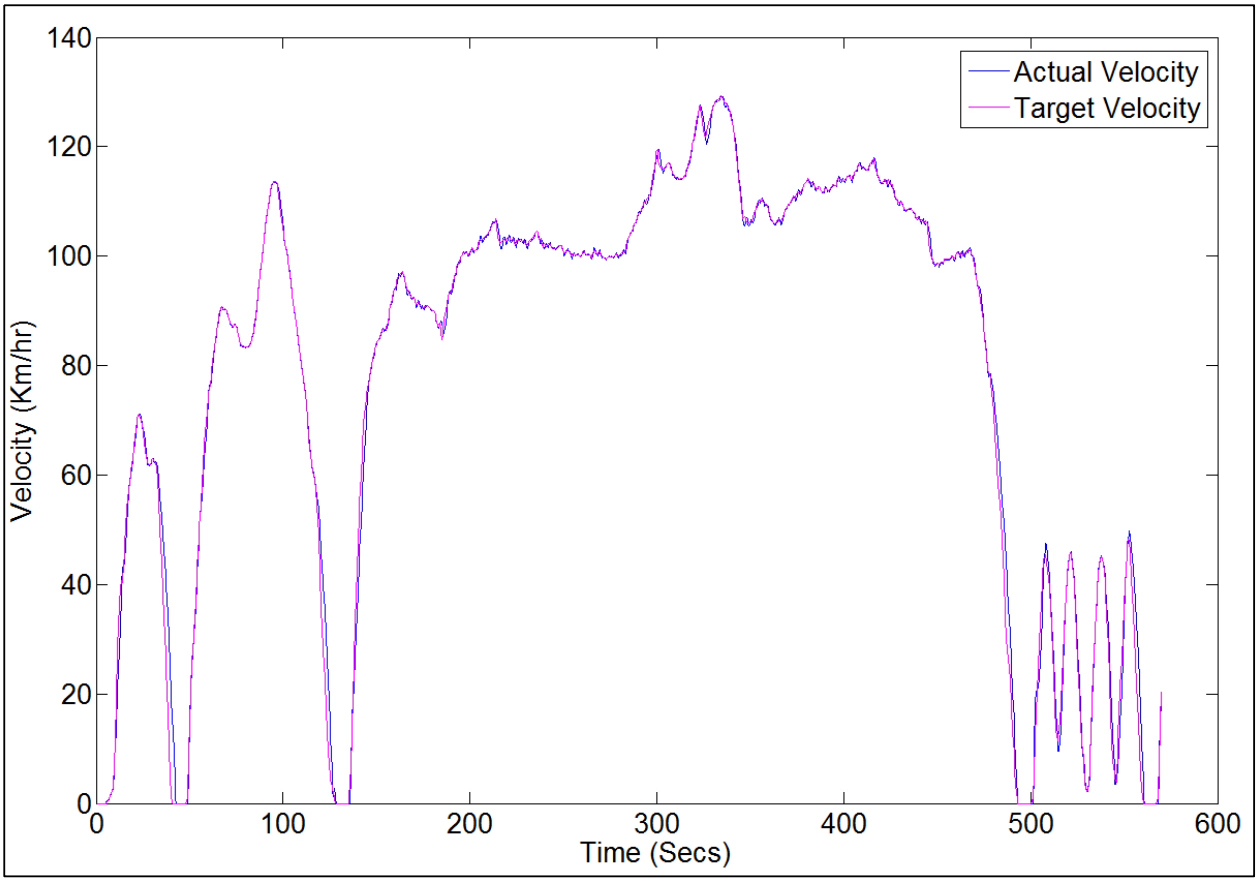


Figure 20. Velocity profile for $SOC_{initial} = 0.6$

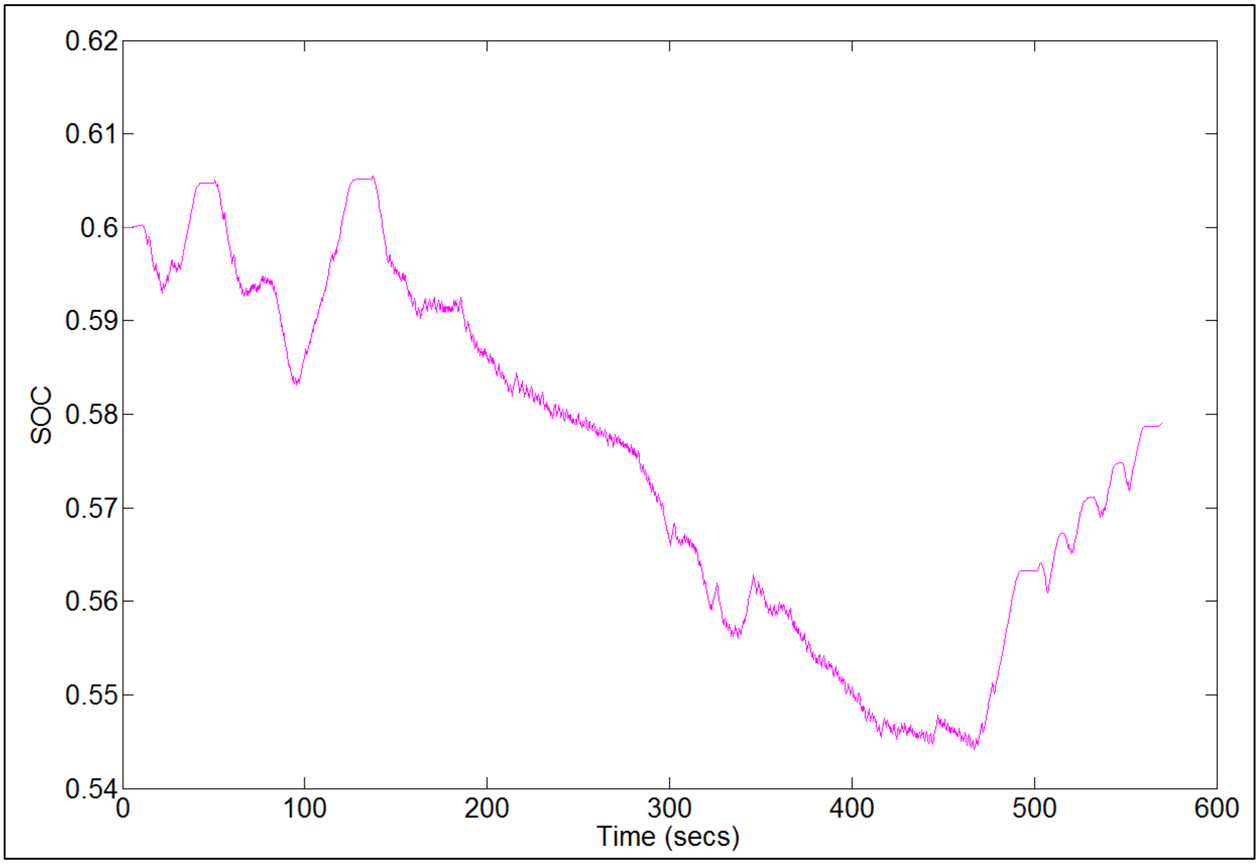


Figure 21. SOC profile for $SOC_{initial} = 0.6$

4.2 $SOC_{initial} = 0.95$

When initial SOC of the battery is set at 0.95 to endure battery discharge, the investigations show that the simulated vehicle is not able to accurately track the target velocity at some time steps during deceleration for the current set of control logics as seen in figure 22. The root mean square between actual and target velocity in figure 22 is 3.30 km/hr. This is because the control algorithm tries to gain proper SOC level as seen in figure 23 by shutting down the engine using CL_8 (SOC > 0.9 overcharge level) to avoid battery flattening and damage to electrical circuits. Hence, the ability of actual velocity to reach target velocity decreases during deceleration as the generator does not operate in this period. In this case, the distance travelled by the vehicle is 13.47 Km with fuel economy of 72 mpg. Although fuel economy is great for short cycle but as seen from figure 23 the vehicle operates near 0.9 SOC. For longer driving cycles the control logic tries to bring SOC level near 0.6 optimum level so energy required to recover from 0.6 to 0.9 will be huge which means loss in fuel economy. There is also possibility of battery heating up while operating near 0.9 SOC.

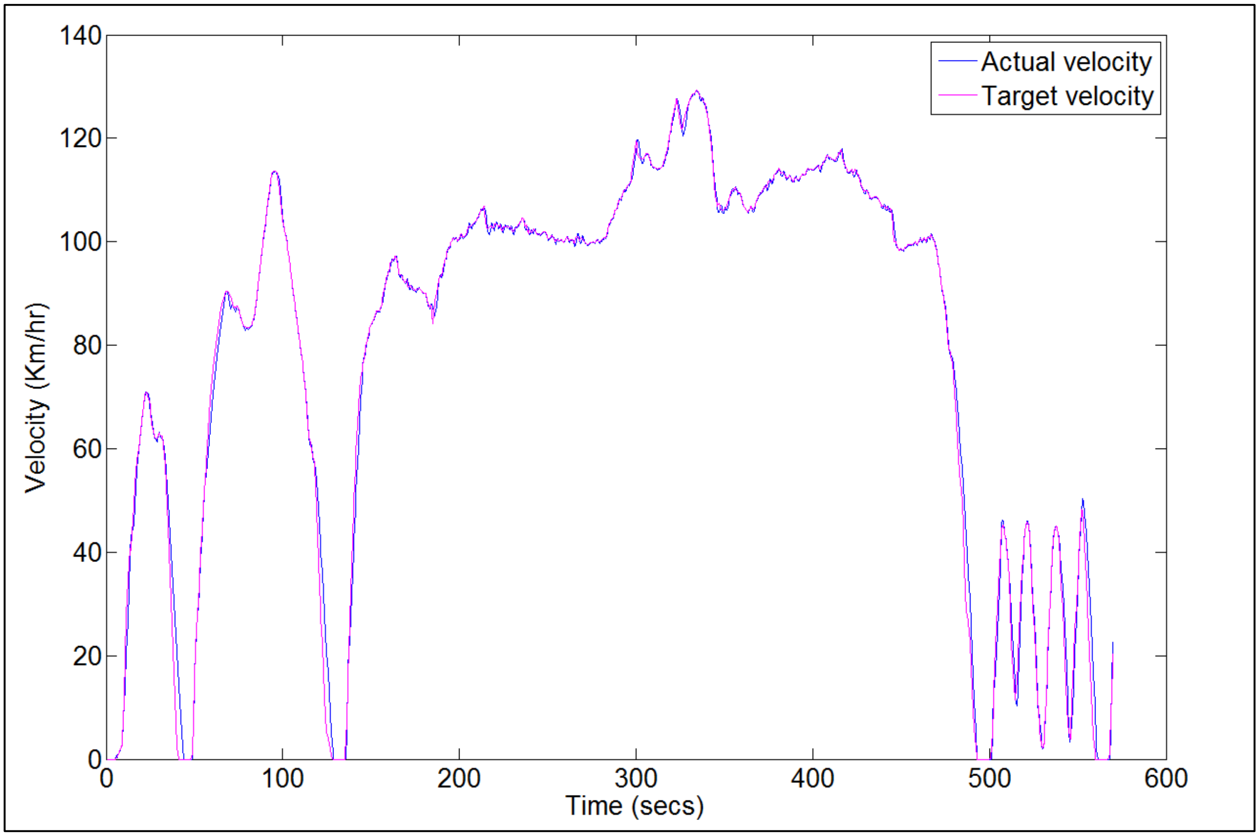


Figure 22. Velocity profile for $SOC_{initial} = 0.95$

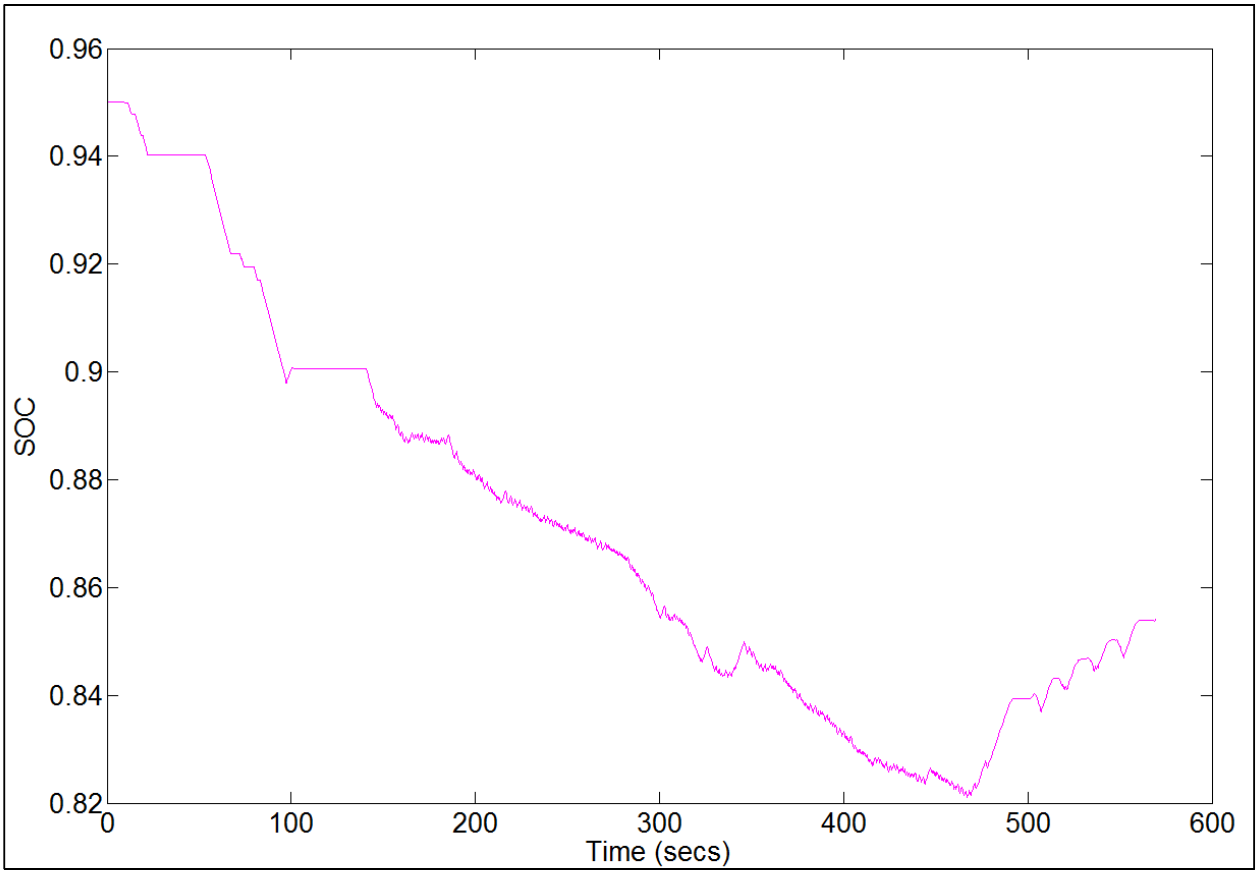


Figure 23. SOC profile for $SOC_{initial} = 0.95$

4.3 $SOC_{initial} = 0.6$ and generation above SOC > 0.6

For the current rule-based control, when $SOC_{initial} = 0.6$ and generator machine operation is considered above upper adequate SOC level i.e., considering CL_5 from table 1 in generator on-off logic model mentioned in figure 17, the distance travelled by vehicle is 13.19 Km and fuel economy is 75 mpg. Although fuel economy is high compared to the previous results, the SOC profile in figure 25 shows that the battery charge is increasing gradually and may cause damage to electrical circuits if overcharged, since the charge will always be added with generator on after 0.6 SOC. The velocity profile in figure 24 tracks the target profile at most times of vehicle operation except during deceleration. The root mean square between actual and target velocity in figure 24 is 5.03 km/hr.

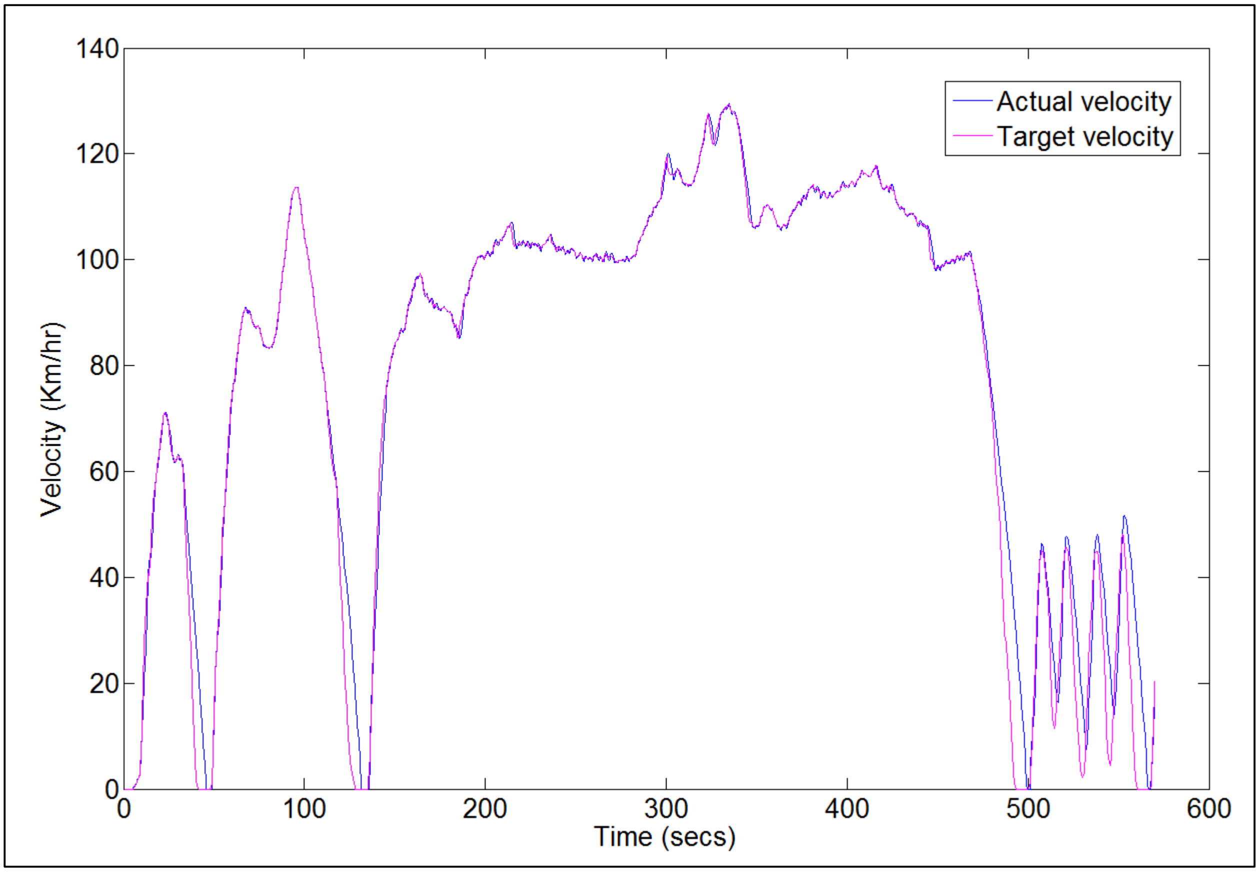


Figure 24. Velocity profile for $SOC_{initial} = 0.6$ and generation above SOC > 0.6

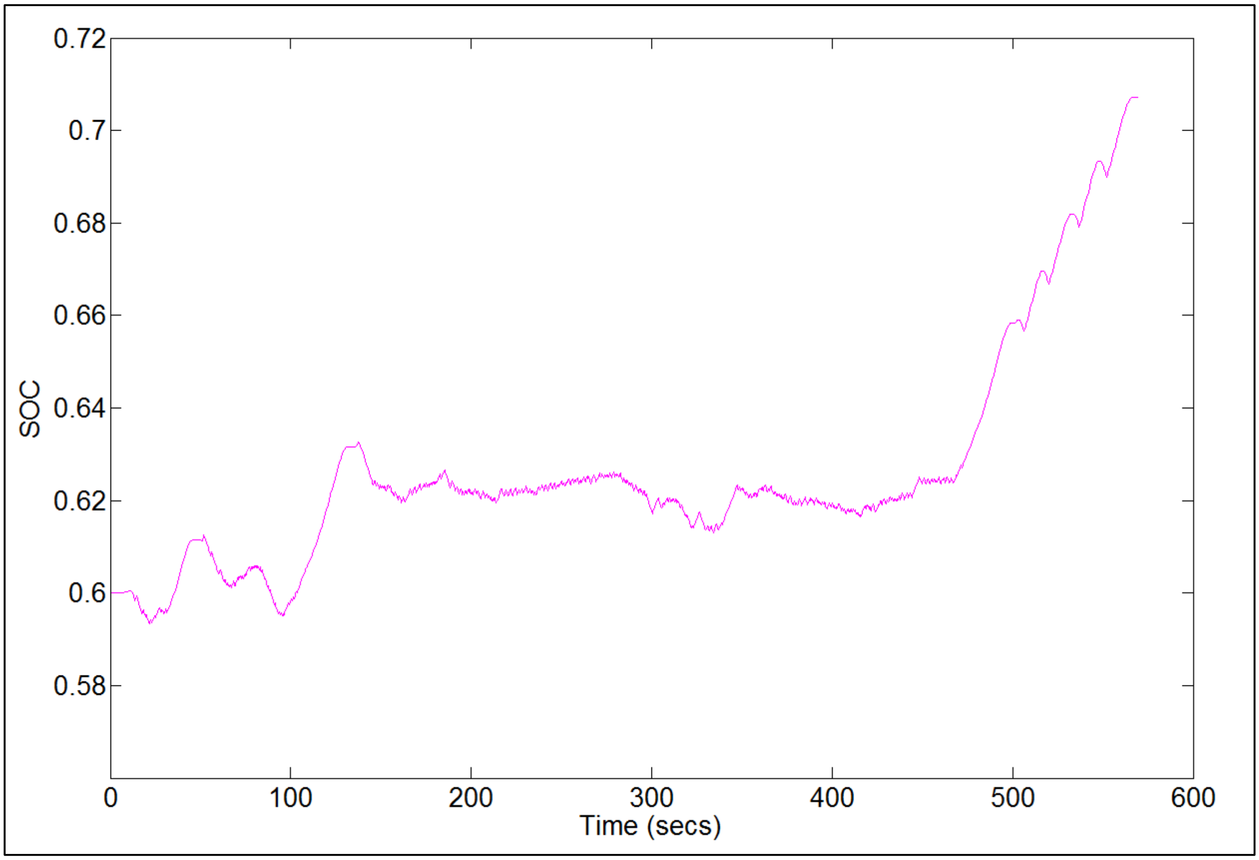


Figure 25. SOC profile for $SOC_{initial} = 0.6$ and generation above SOC > 0.6

4.4 Hilly Terrain

In hilly terrain there is increased power demand and this brings less fuel economy and fluctuations in the battery. Maintaining a stable SOC level becomes vital because SOC and vehicle velocity determine fuel economy and propulsion capacity. The road grade is estimated using following expression.

$$i = \tan(\arcsin\frac{E2-E1}{L}) * 100\% \qquad \text{[Eq. 10]}$$

This road grade information is used to calculate resistances acting on the wheels from Eq. [1] – Eq. [4] in hilly regions. Given the length of uphill road and difference in altitude between two points it is possible to estimate road grade as illustrated in following figure.

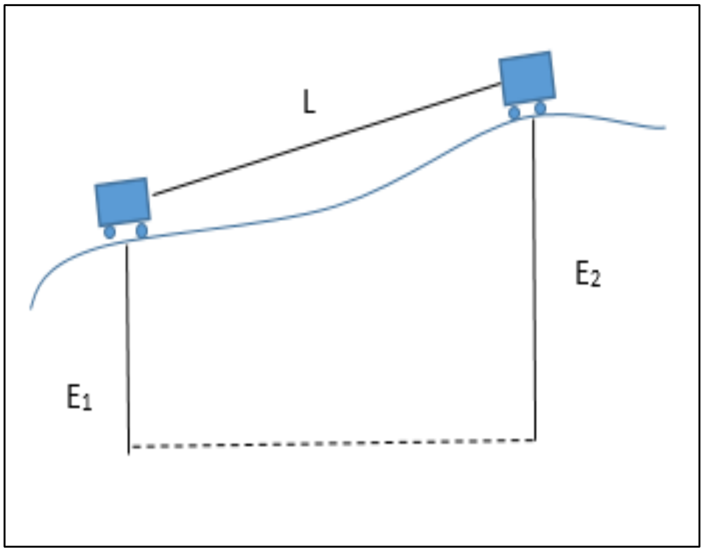


Figure 26. Road grade estimation

To study the effect of hilly regions, an arc terrain was simulated with the nature shown in Figure 27. Investigation were performed at cruise speeds of 30 mph, 45 mph and 60 mph and with initial SOC at 0.6 and 0.7.

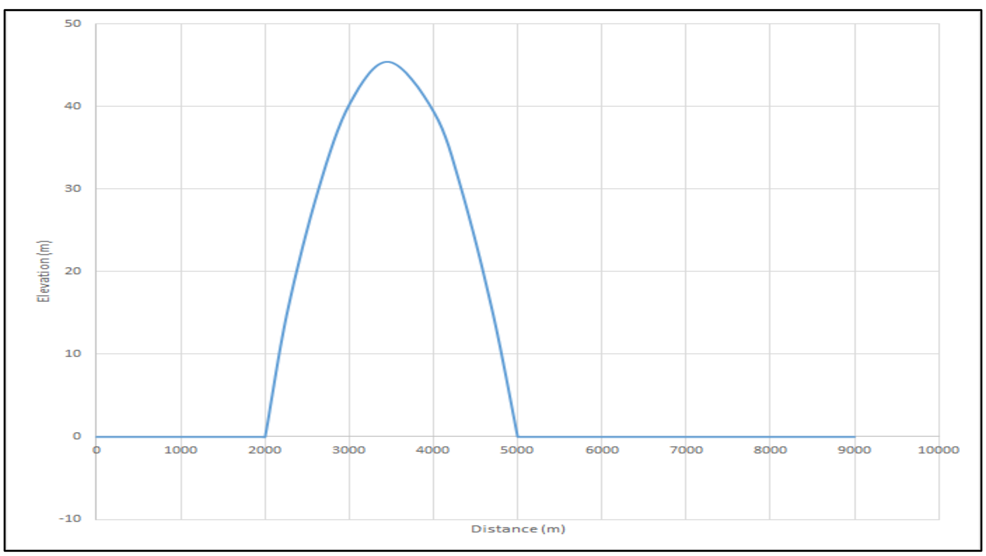


Figure 27. Simulated arc terrain

At cruise speed of 30 mph and initial SOC = 0.6, the vehicle travelled 6.3 km and fuel economy of the vehicle was 26.4 mpg. When the control strategy was implemented at initial SOC = 0.7, the vehicle travelled 6.3 km and the fuel economy of the vehicle was 26.37 mpg. The distance travelled by the vehicle remained the same but $SOC_{initial}$ = 0.6 showed better fuel economy compared to vehicle operation at $SOC_{initial}$ = 0.7.

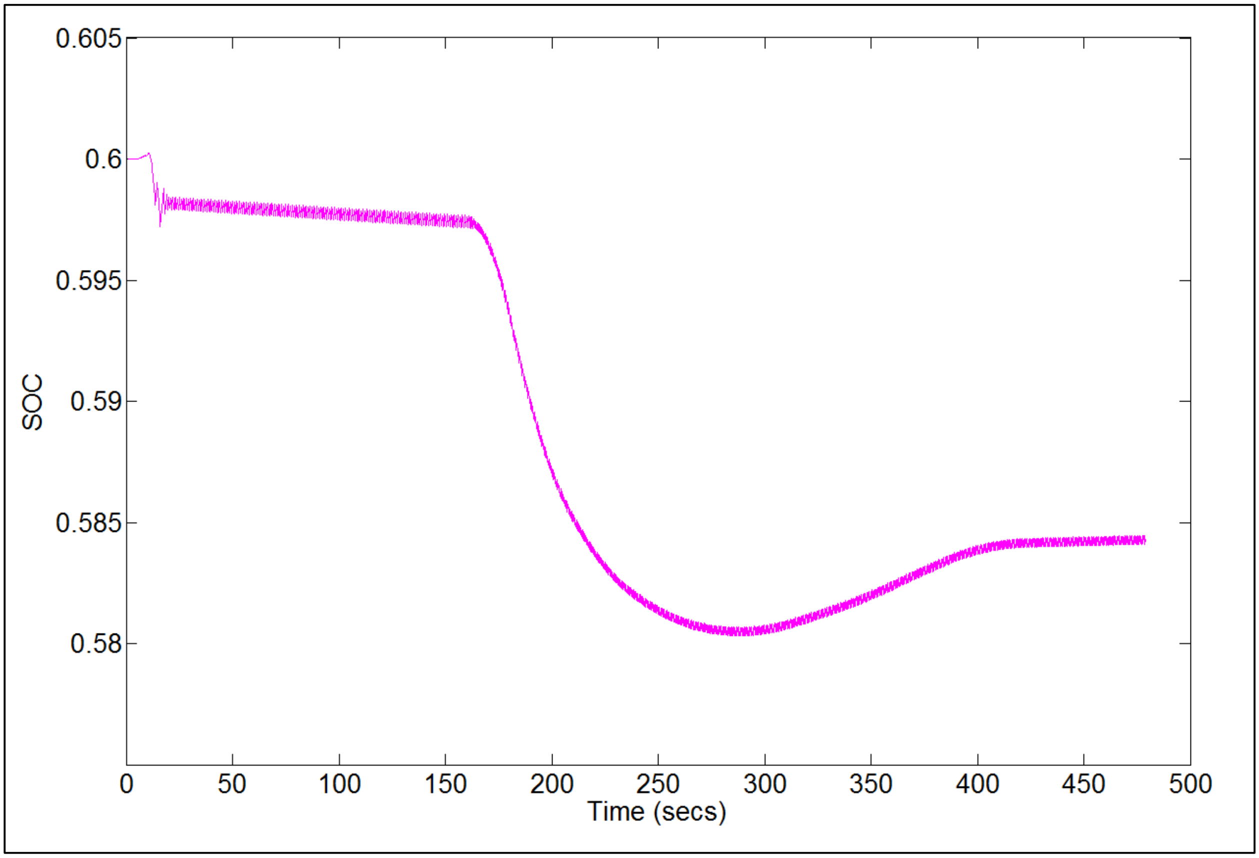


Figure 28. SOC graph for cruise speed of 30 mph and $SOC_{initial}$ = 0.6

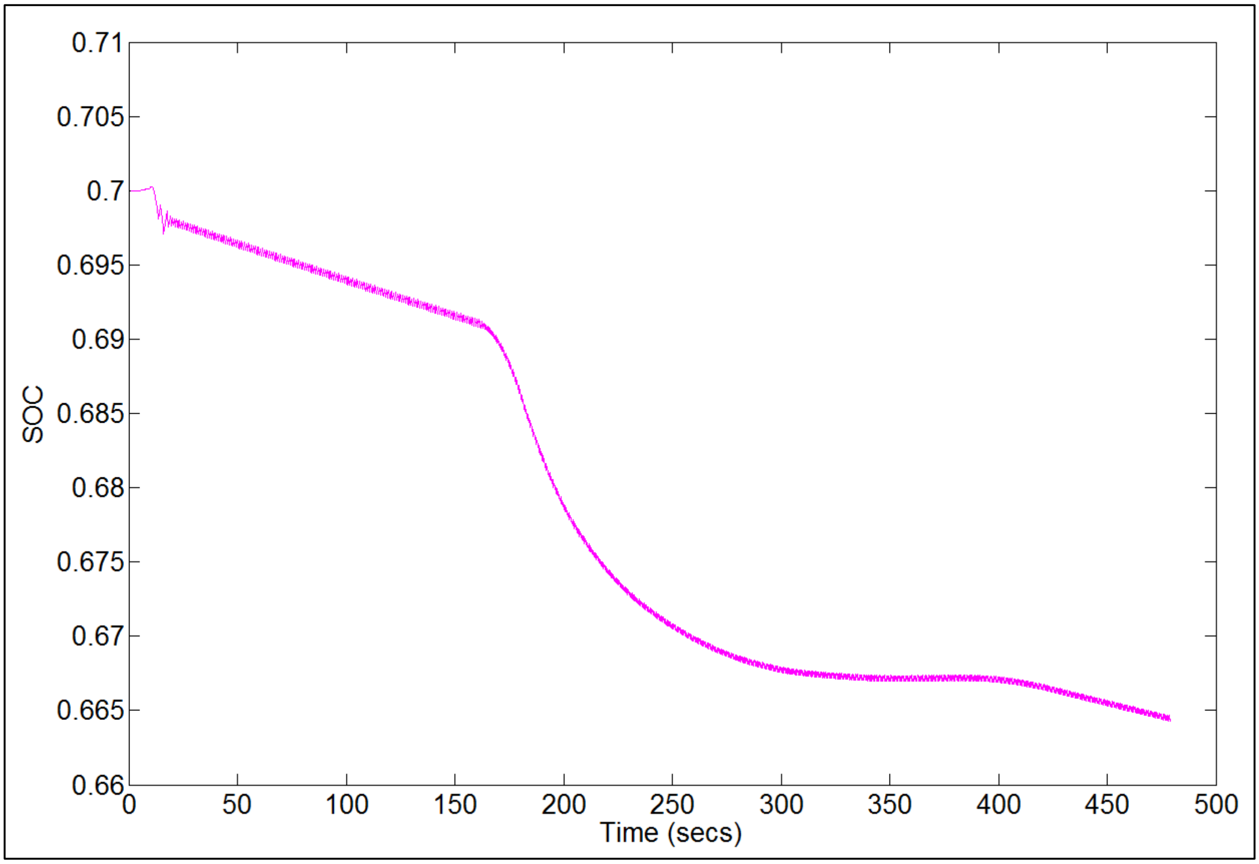


Figure 29. SOC graph for cruise speed of 30 mph and $SOC_{initial} = 0.7$

Table 3. Fuel economy comparison between $SOC_{initial} = 0.6$ and $SOC_{initial} = 0.7$ at 30 mph.

FE at $SOC_{initial} = 0.6$ and cruise speed =30 mph	FE at $SOC_{initial} = 0.7$ and cruise speed =30 mph	FE improvement
26.4 mpg	26.37 mpg	-0.11%

At cruise speed of 45 mph and initial SOC = 0.6 the vehicle travelled 9.36 KM and fuel economy of the vehicle was 36.5 mpg. Investigation were further performed considering SOCinitial = 0.7 at 45 mph and results show that vehicle travelled 9.34 Km which shows that there is not much difference in the propulsion capacity of the vehicle compared to $SOC_{initial} = 0.6$ at same cruise speed. However, $SOC_{initial} = 0.7$ shows better fuel economy of 37.1 mpg compared to $SOC_{initial} = 0.6$.

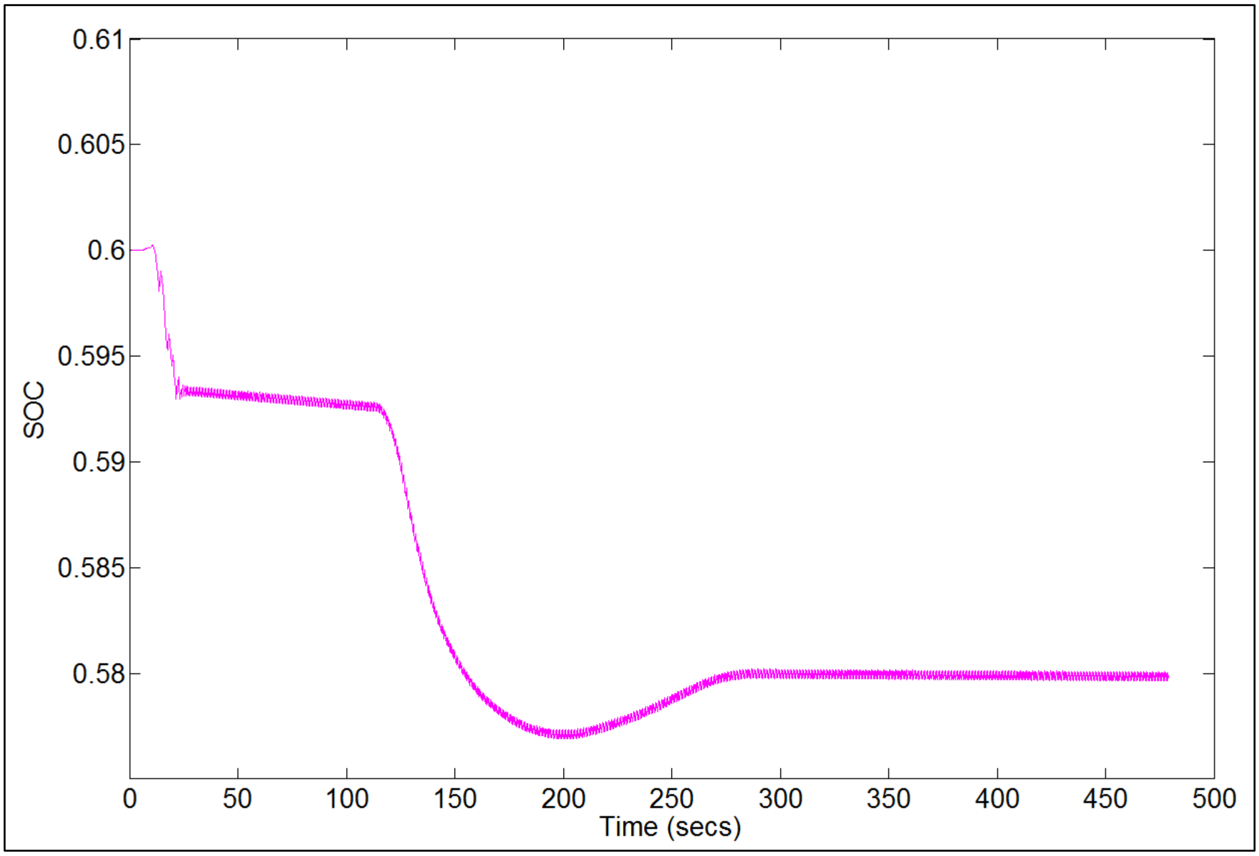


Figure 30. SOC graph for cruise speed of 45 mph and $SOC_{initial} = 0.6$

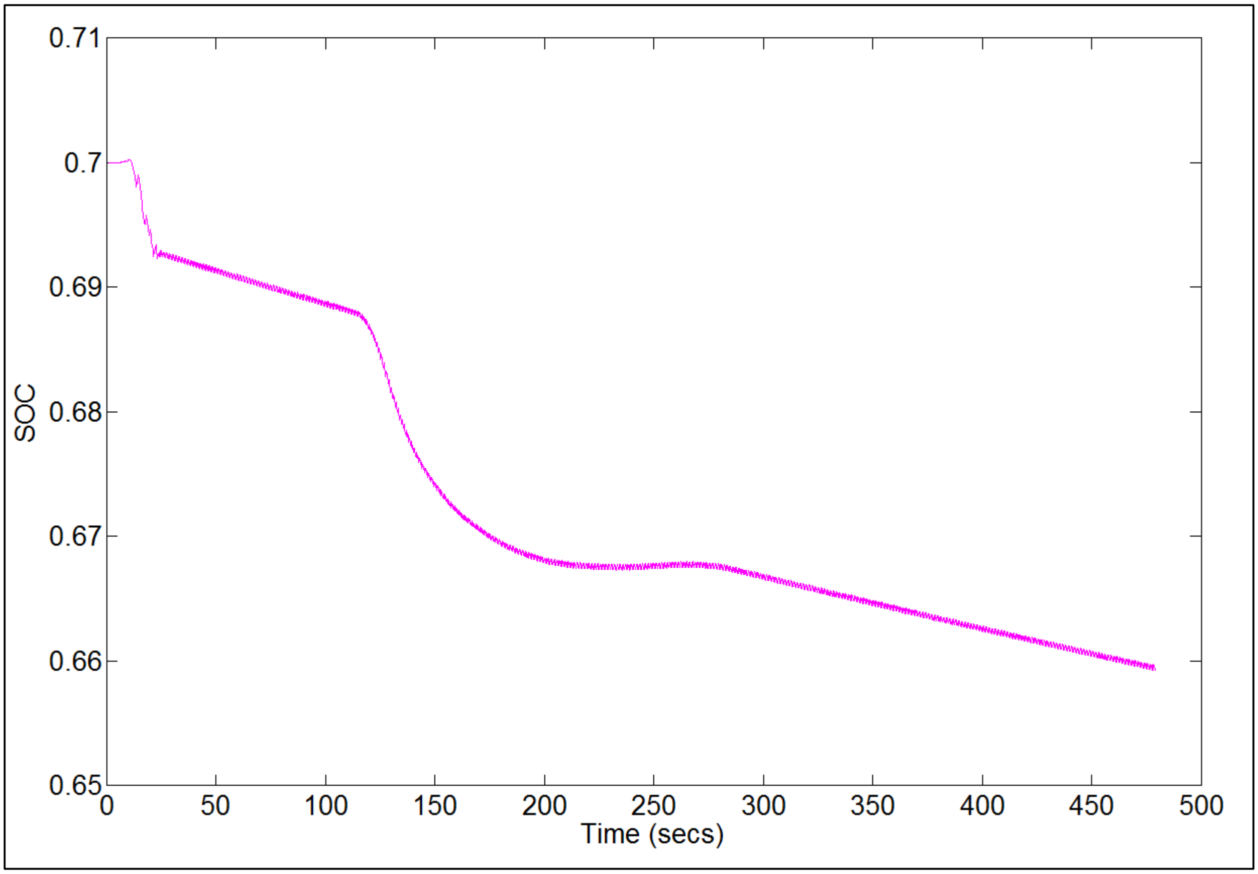


Figure 31. SOC graph for cruise speed of 45 mph and $SOC_{initial}$ = 0.7

Table 4. Fuel economy comparison between $SOC_{initial}$ = 0.6 and $SOC_{initial}$ = 0.7 at 45 mph.

FE at $SOC_{initial}$ = 0.6 and cruise speed =45 mph	FE at $SOC_{initial}$ = 0.7 and cruise speed =45 mph	FE improvement
36.5 mpg	37.1 mpg	1.64%

At cruise speed of 60 mph and initial SOC = 0.6 the vehicle travelled about 11.6 KM and fuel economy of the vehicle was 42.376 mpg. When the control strategy was implemented at initial SOC = 0.7 the vehicle travelled 11.75 km. and the fuel economy of the vehicle was 43.07 mpg. The fuel economy was better for $SOC_{initial}$ = 0.7 compared to vehicle operation at $SOC_{initial}$ = 0.6. As the vehicle runs in its optimal speed range between 30 – 60 mph, the fuel economy is better for 60 mph compared to 30 mph and 45 mph. After 60 mph the fuel economy drops significantly because of more aerodynamic resistance. The study presented in [22] based on [23] and [24] proves the relation between fuel economy and vehicle speed.

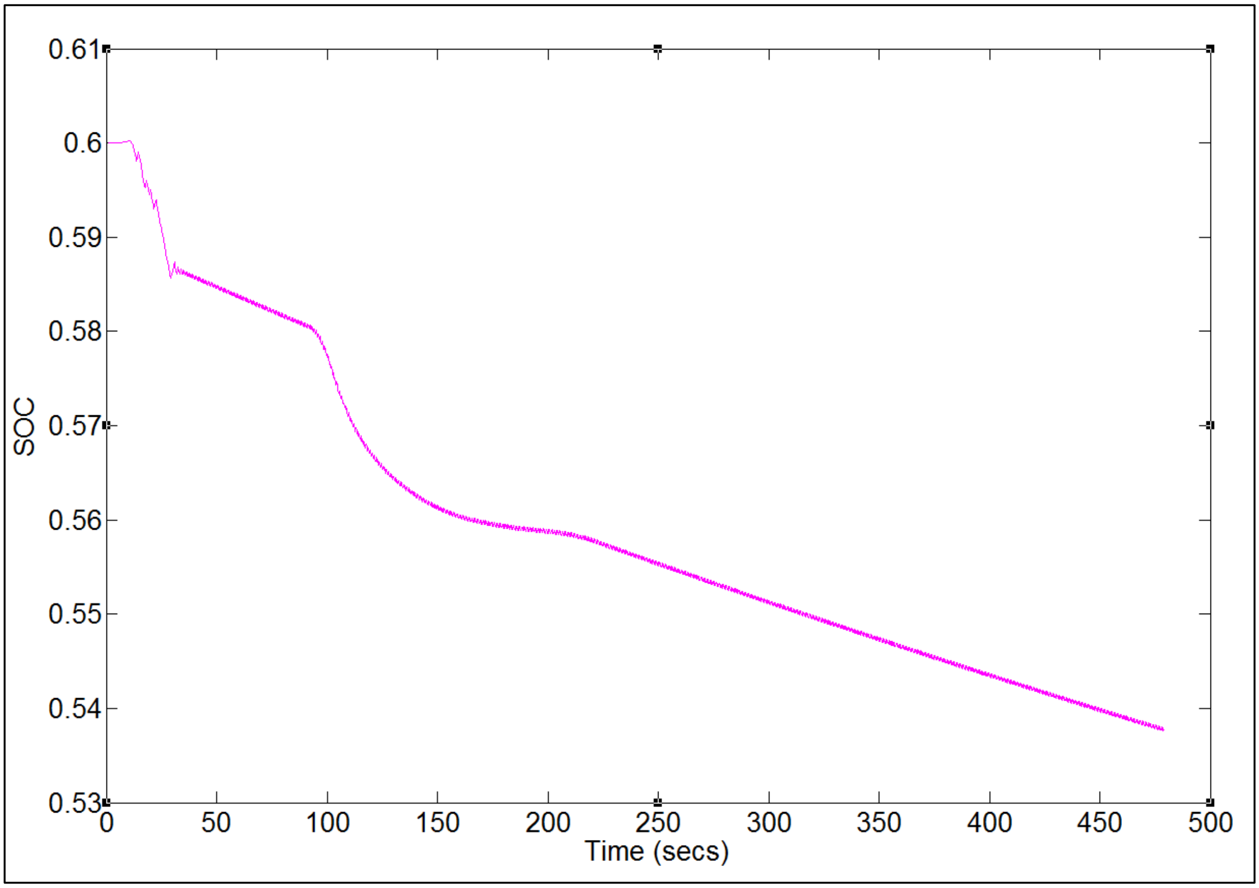


Figure 32. SOC graph for cruise speed of 60 mph and $SOC_{initial}$ = 0.6

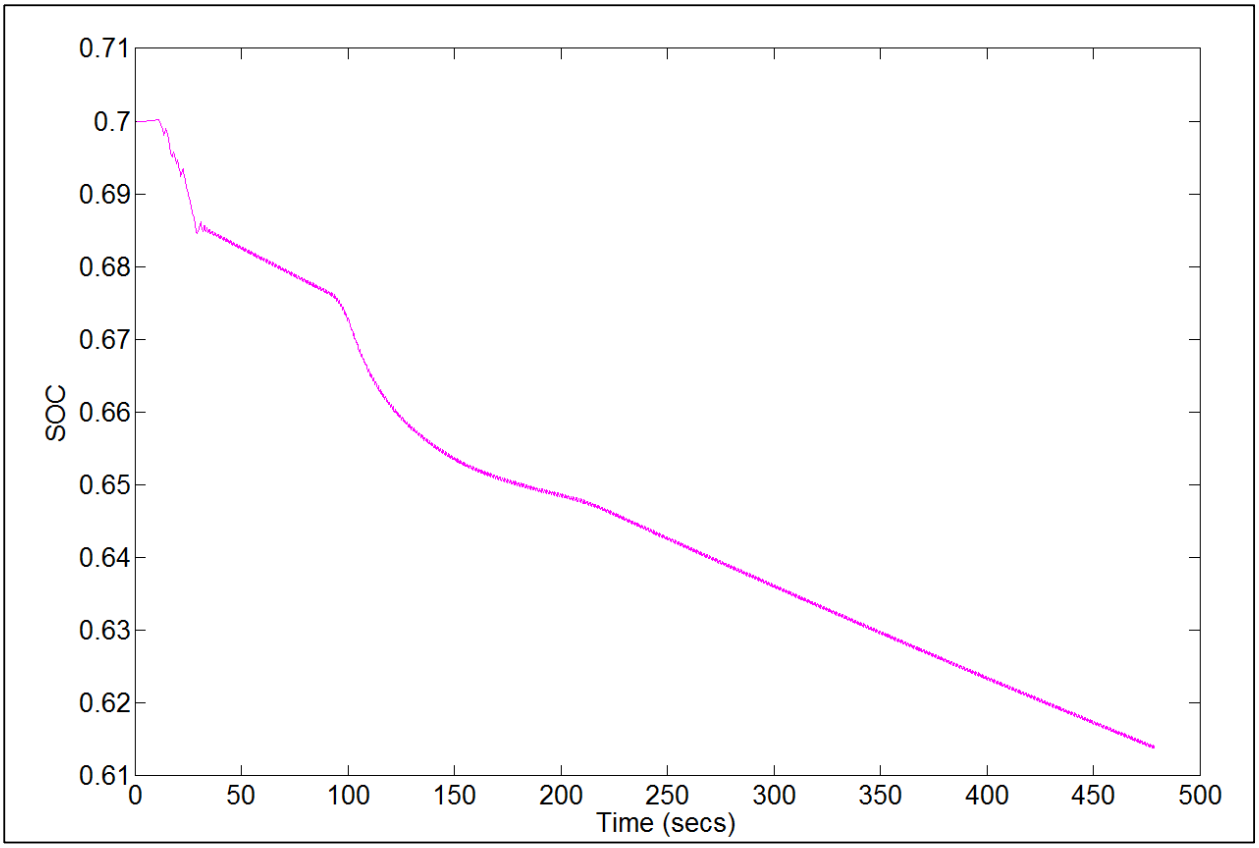


Figure 33. SOC graph for cruise speed of 60 mph and $SOC_{initial}$ = 0.7

Table 5. Fuel economy comparison between $SOC_{initial}$ = 0.6 and $SOC_{initial}$ = 0.7 at 60 mph.

FE at $SOC_{initial}$ = 0.6 and cruise speed =60 mph	FE at $SOC_{initial}$ = 0.7 and cruise speed =60 mph	FE improvement
42.376 mpg	43.07 mpg	1.63%

Although the fuel economy improves for $SOC_{initial}$ = 0.7 compared to $SOC_{initial}$ = 0.6 as the speed increases but SOC graph shows stability in the case of $SOC_{initial}$ = 0.6 compared to $SOC_{initial}$ = 0.7 since it operates near SOC level of 0.5. The fuel economy improvement between $SOC_{initial}$ = 0.6 and $SOC_{initial}$ = 0.7 in all three cases i.e., at 30 mph, 45 mph and 60 mph is not huge and considering SOC stability it can be concluded that keeping SOC at adequate level between 0.4 and 0.6 seems reasonable in both hilly and flat terrains.

CHAPTER 5

CONCLUSION

In this study, a forward-looking, velocity-driven, serial-parallel, hybrid electric vehicle is modeled and the vehicle performance is investigated on flat and hilly terrains. The propulsion characteristics of the vehicle for flat terrain are investigated over the US 06 drive cycle while an arc terrain was simulated to study the effects of initial battery SOC on vehicle performance. Modelling and simulation of the proposed hybrid electric vehicle model was carried out in MATLAB and Simulink. The proposed control strategy is a stepping stone in the direction of real-time control algorithm development, as it investigates vehicle behavior in flat and hilly terrain.

Simulation results show that the vehicle has improved fuel economy and stable battery results in adequate SOC levels between 0.4 and 0.6. Although fuel economy is greatest for cases in flat terrain with greater regenerative effect, this can also bring possible damage to electrical circuits. In hilly regions, as speed increases, fuel economy improves for initial SOC of 0.7 compared to results obtained by using initial SOC of 0.6. But because the SOC graph for 0.6 initial SOC shows stability compared to 0.7 initial SOC, operating the vehicle at 0.6 initial SOC seems more reasonable. This study underscores the value of initial SOC of the battery for both flat and hilly region using real-time control strategy for hybrid electric vehicle. With the inputs from GPS and GIS it is possible to determine driving pattern and road grade estimation. The proposed study facilitates use of this information in organizing control algorithm beforehand which will help improve fuel economy furthermore.

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