Development of a Model for Hybrid Electric Vehicle Powertrain

M.Tech. Thesis

By

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A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

of

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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Development of a Model for Hybrid Electric Vehicle Powertrain** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted to the **Department of CEVITS, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from August 2023 to May 2024 under the supervision of **Dr. Devendra Deshmukh, Professor, Department of Mechanical Engineering, Indian Institute of Technology Indore.**

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Hrishikesh
28-05-2024

Signature of the student
(Hrishikesh Meshram)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

28/05/2024

Signature of the Supervisor
(Dr. Devendra Deshmukh)

Hrishikesh Meshram has successfully given his M.Tech. Oral Examination held on **27th May 2024**

Signature(s) of Supervisor(s) of M.Tech. thesis
Date: **28/05/2024**

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With Regards,

Hrishikesh Meshram

Dedicated

to

My beloved

Parents

ABSTRACT

Hybrid Electric Vehicles (HEVs) having power-split architectures have come up with a promising solution to address environmental concerns and energy efficiency in the automotive industry. This project focuses on the development of a comprehensive Simulink model for a power split HEV powertrain, aiming to provide a versatile platform for analysis and optimization.

The Simulink model incorporates essential components such as internal combustion engine (ICE), electric motor(s), power electronics, energy storage systems (ESS), and transmission mechanisms, capturing the complex interactions among these elements. Detailed sub-models are developed to simulate the dynamic behavior of individual components and their integration within the powertrain system.

Key objectives include accurate representation of power flows, energy management strategies, and control algorithms to optimize fuel consumption and vehicle performance. Model validation is conducted through fuel consumption comparison against existing HEV systems i.e. Toyota Prius 4^{th} Generation system.

The developed Simulink model serves as a valuable tool for HEV powertrain design, allowing engineers to explore various configurations, assess the impact of component specifications, and evaluate control strategies in a virtual environment. Additionally, it facilitates research and development efforts toward advancing HEV technology, contributing to the realization of more sustainable and efficient transportation solutions.

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NOMENCLATURE

r	Ring Gear
s	Sun Gear
p	Planet Gear
T	Total Gear Teeth
G. R	Gear Ratio
m	Module
$\mathbf{mg_1}$	Generator
$\mathbf{mg_2}$	Motor
$\boldsymbol{\omega}$	Angular Velocity in rad/sec
$\boldsymbol{\omega_r}$	Angular Velocity of the ring gear in rad/sec
$\boldsymbol{\omega_c}$	Angular Velocity of the crank in rad/sec
$\boldsymbol{\omega_s}$	Angular Velocity of sun gear in rad/sec
$\boldsymbol{\omega_w}$	Angular Velocity of wheel gear in rad/sec
$\boldsymbol{\omega_p}$	Angular Velocity of planet gear in rad/sec
$\mathbf{T_r}$	Teeth of the ring gear
$\mathbf{T_s}$	Teeth of the sun gear
$\mathbf{T_p}$	Teeth of the Planet gear
$\mathbf{T_{a1}}$	Axle gear teeth connected to mg_2.
$\mathbf{T_{a2}}$	Axle gear teeth connected to the wheel gear.

ACRONYMS

EV Electric Vehicle

HEV Hybrid Electric Vehicle

IC Internal Combustion

PGT Planetary Gear Transmission

CVT Continuous Variable Transmission

MG1 Generator

MG2 Motor

K_P Proportional Gain

K_I Integral Gain

BSFC Brake Specific Fuel Consumption

Chapter 1

1 Introduction

The invention of the engine was a significant achievement of the early century, but greater advancements came with their integration into automobiles, marking notable accomplishments of modern technology. The automotive industry plays a pivotal role in modern society by facilitating easy mobility. Over time, rapid development in this industry has transformed society from a rudimentary to a highly developed one. However, the increasing number of automobiles has led to environmental and human issues, including air pollution, global warming, and depletion of fossil fuel resources, posing major concerns for the industry [1].

The associated costs of addressing these issues are substantial, involving financial and human aspects. While alternative resources are being explored, they remain costly and limited in availability. Fuel consumption continues to rise, especially in developing countries, with projections indicating depletion of oil reserves shortly. The automobile industry is a significant contributor to air pollution and fossil fuel consumption, particularly in urban environments where vehicles often operate at low speeds, resulting in fuel consumption and pollution. Electric vehicles offer a promising solution for urban transportation, but the challenge remains ineffectively storing energy at a low cost, whether through batteries or alternative methods. Hybrid electric vehicles are anticipated to emerge as a viable solution [2]. Over the last few years, Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) have experienced significant growth due to increased awareness of climate change and resource depletion [3].

In this section, we'll explore the concise background of hybrid vehicles, delve into the principles behind HEV drivetrains including their various types and structures, and underscore the importance and driving force behind the advancement of affordable hybrid propulsion systems.

1.1 History of HEVs

The concept of Hybrid Electric Vehicles (HEVs) dates back almost as far as automobiles themselves. Initially, they were designed to assist the engine during startup to enhance the driving experience. However, in modern times, the primary focus of HEVs has shifted towards fuel efficiency while driving. Some important dates in the evolution of HEVs are discussed as follows [1][2][3]:

- In 1899: At the Paris Salon, the first hybrid vehicles were exhibited, showcasing a pioneering approach to address the limitations of early Internal Combustion (IC) engines and Electric Vehicles (EVs). These vehicles, developed by Pieper establishments of Liège, Belgium, and the Vedovelli and Priestly Electric Carriage Company of France, represented a significant step in the evolution of automotive technology.
- In 1902-1903: Camille Jenatzy presented a groundbreaking parallel hybrid vehicle at the Paris Salon, integrating a gasoline engine and an electric motor to provide versatile power delivery options.
- Concurrently, H. Krieger unveiled the second reported series hybrid vehicle, employing two independent DC motors to drive the front wheels and a combination of lead-acid cells and an alcohol spark-ignited engine for power generation and storage.
- In 1967: Dr. Ernest H. Wakefield revitalized the series hybrid design, introducing innovations in powertrain architecture aimed at enhancing efficiency and performance while minimizing environmental impact.
- In 1975: Dr. Victor Wouk and his team pioneered the development of a parallel hybrid version of the Buick Skylark, leveraging advancements in engine and electric motor technology to achieve notable improvements in fuel economy and emissions.
- In 1997: Toyota's introduction of the Prius sedan in Japan marked a watershed moment in the commercialization of hybrid vehicles, demonstrating the viability of hybrid technology in mainstream automotive markets. Honda followed suit with its Insight and Civic Hybrid models, further solidifying the position of hybrid vehicles in the automotive landscape.

- At Present: Toyota's Prius and Honda's Insight vehicles have become synonymous with hybrid technology, embodying decades of innovation and refinement. These models continue to set the standard for fuel efficiency and environmental sustainability, driving further advancements in hybrid propulsion systems and shaping the future of automotive transportation.

1.2 Concept of Drivetrain

In the context of vehicle powertrains, several key requirements must be met [1]:

(1) Sufficient power generation to meet performance needs,
(2) Adequate onboard energy storage for the driving range,
(3) Peak Effectiveness, and
(4) Minimal environmental impact.

Typically, vehicles today are designed with a range of powertrain configurations, which essentially dictate how they generate and utilize energy. These configurations include traditional options like gasoline or diesel engines, as well as more innovative technologies like hydrogen fuel cells and chemical batteries.

Hybrid vehicles are a notable category within this spectrum. They integrate multiple power sources, which can include a combination of internal combustion engines and electric motors. When electric powertrains are part of this mix, the vehicles are specifically termed Hybrid Electric Vehicles (HEVs).

The drivetrain, on the other hand, is the collective term for all the components involved in transferring power from the engine or motor to the wheels, including the transmission, differential, and drive shafts. It essentially encompasses the mechanical system responsible for propelling the vehicle forward or backward.

A typical hybrid vehicle drivetrain usually consists of no more than two powertrains, as incorporating additional units can lead to increased complexity. To capture and reuse braking energy dissipated as heat in conventional Internal Combustion (IC) engine vehicles, hybrid drivetrains often feature bidirectional energy flow in one powertrain, while the other may be bidirectional or unidirectional. Various power flow routes are illustrated in **Figure 1.1**, demonstrating the concept of a hybrid drivetrain and potential energy flow configurations.

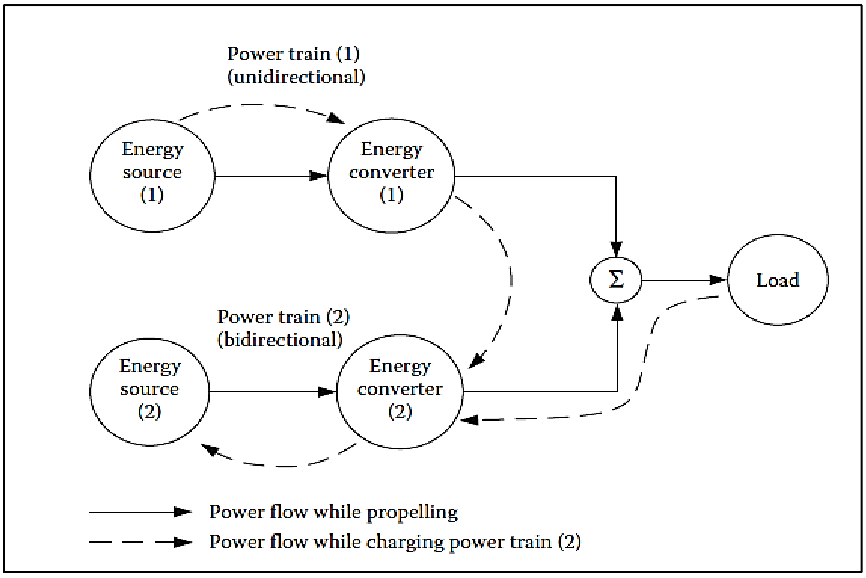

Figure 1.1 Conceptual illustration of HEV Drivetrain [1]

In a hybrid drivetrain, power can be delivered to the load through different power trains. There are various ways to operate two power trains to meet the load needs [1]:

- Only Power Train 1 supplies power to the load.
- Only Power Train 2 supplies power to the load.
- Both Power Train 1 and Power Train 2 supply power to the load at the same time.
- Power Train 2 gets power from the load (during regenerative braking).
- Power Train 2 gets power from Power Train 1.
- Power Train 2 gets power from both Power Train 1 and the load together.
- Power Train 1 sends power to both the load and Power Train 2 at the same time.
- Power Train 1 sends its power to Power Train 2, and then Power Train 2 sends its power to the load.
- Power Train 1 sends its power to the load, and then the load sends the power to Power Train 2.

1.3 Types of Hybridization

Hybrid vehicles can be categorized by how much they rely on electricity versus the traditional engine. This is called hybridization. We can divide them into different types [2]:

Full Hybrid

In this kind of hybrid car, both the engine and the electric motor are powerful enough to move the vehicle by themselves. The big challenge is smartly using both power sources, depending on how the car is being driven. Some helpful features, like a start-stop system and regenerative braking, save energy. Cars like the Toyota Camry, Toyota Prius, and Chevy Volt are examples of full hybrids. Lots of other car companies are also creating full hybrid cars.

Mild Hybrid

In this kind of hybrid, there's a little DC motor linked to the main engine. This motor gives a boost to the engine when it's necessary. It works on a battery charged up by regenerative braking. Also, it has a start-stop system. But this DC motor can't drive the car all by itself. In India, you can find several mild hybrids like Maruti Suzuki Ciaz and Ertiga. Internationally, cars like the Honda Insight with integrated motor assist and Chevrolet models with e-assist are good examples of mild hybrids.

Micro Hybrid

Microhybrids aren't completely hybrid cars because they only use an IC engine. But they do have some hybrid-style features like a start-stop system and regenerative braking. In these cars, the engine switches off when the car is stopped, and the accessories run on battery power. The engine starts again when the car moves or when the battery is low. Many cars in India, such as Mercedes Benz ML250 and Mahindra Scorpio, have mild hybrid features.

1.4 HEV Architecture

Full hybrid electric cars can also be sorted by how their drivetrain is made. These groups are as follows [1][2]:

Series Hybrid

In a series architecture, the IC engine runs a generator that charges up the batteries. These batteries then drive the electric motor, propelling the vehicle, akin to diesel-electric locomotives. Because the engine doesn't directly drive the wheels, it can operate at its most efficient state, optimizing fuel efficiency and emissions. The electric motor manages the vehicle's speed. Depending on battery capacity, the vehicle can travel solely on electric power for a distance, with the IC engine running when the batteries are depleted.

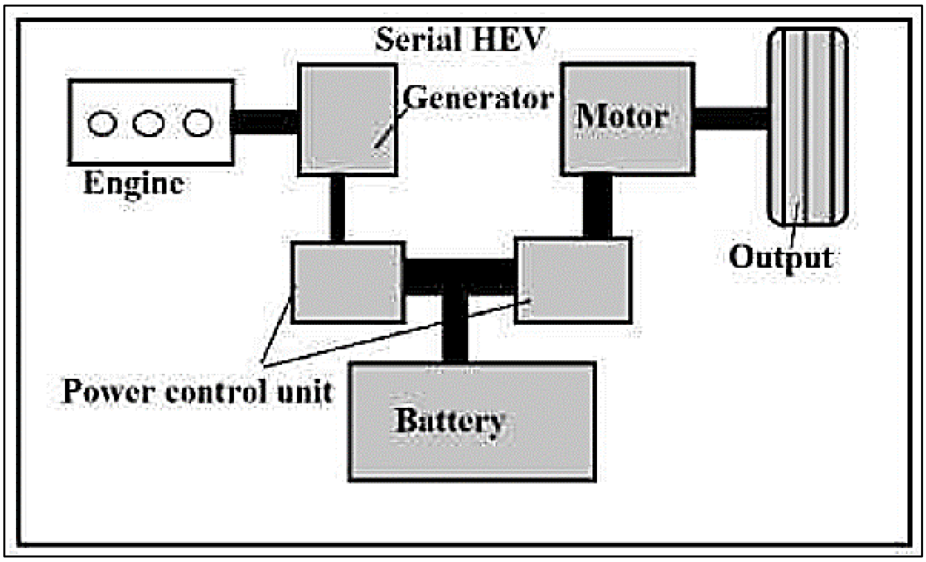

Figure 1.2 Series Hybrid Architecture [2]

The series hybrid excels in city driving with frequent stops and starts due to its efficient operation during such conditions. Moreover, the IC engine can be swapped with a fuel cell, to convert it to a pure electric vehicle. However, the series hybrid's main drawback is its complex architecture, necessitating all components to meet peak power demands, leading to increased costs.

Parallel Hybrid

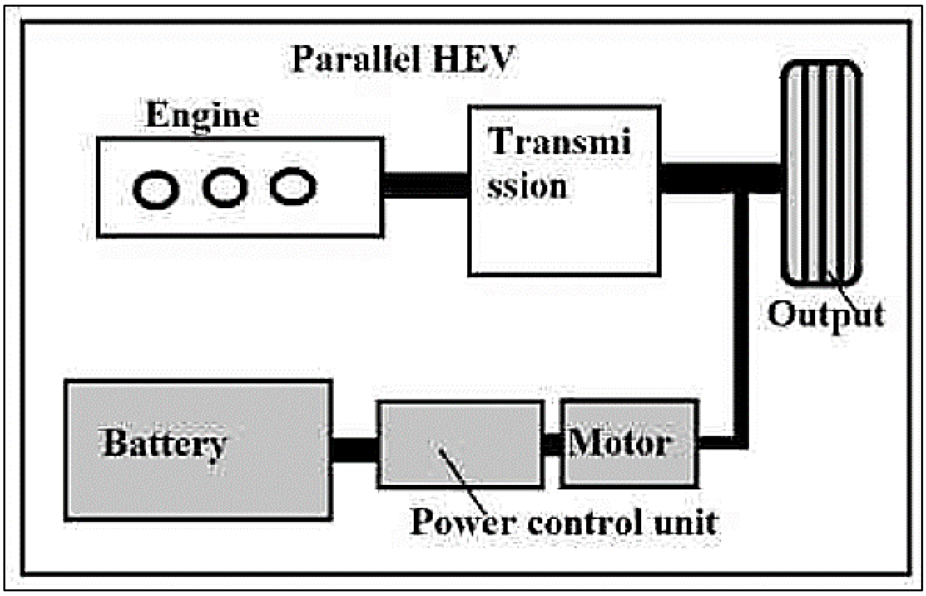

Figure 1.3 Parallel Hybrid Architecture [2]

In a parallel hybrid, power can come from the batteries, the IC engine, or both, moving the wheels together. An electronic controller adjusts power distribution based on wheel speed and load. In urban driving, where peak power needs are rare, the vehicle can primarily run on batteries, reducing emissions, and improving fuel efficiency. Only, when necessary, does the IC engine kick in. Unlike in series hybrids, individual components in parallel hybrids don't need to meet peak power requirements, potentially lowering costs.

Additionally, parallel hybrids offer higher efficiency on highways, where consistent speeds make direct IC engine power more efficient. They can also use electric power for city driving while the IC engine recharges the depleted battery, boosting overall efficiency. However, designing powertrains for power addition and using complex electronic controllers adds complexity.

Series-Parallel (Power-split) Hybrid

In this type of architecture, a planetary gear set transfers power from the engine to the wheel axles. This helps disconnect the engine speed from the vehicle speed to some degree. With the PGT, engine power can go directly to the wheels, or it can go to an electric generator, producing electricity that powers the motor to move the wheels. Sometimes, there are batteries between the generator and the wheel, providing extra power for shorter periods, like in the Toyota Prius. Another option is to use a CVT. Overall, this power split system combines features of both parallel and series engine operations to some extent.

1.5 Couplings for HEVs

In hybrid electric vehicles (HEVs), the utilization of multiple power sources necessitates precise coupling to optimize performance. Generally, two types of coupling are employed [1]:

- **Electrical Coupling:** This occurs in series architectures, where the IC engine charges the battery, and the motor propels the vehicle using stored battery power. However, this method incurs more energy losses due to multiple conversions from chemical to mechanical than to electrical, and back to mechanical.

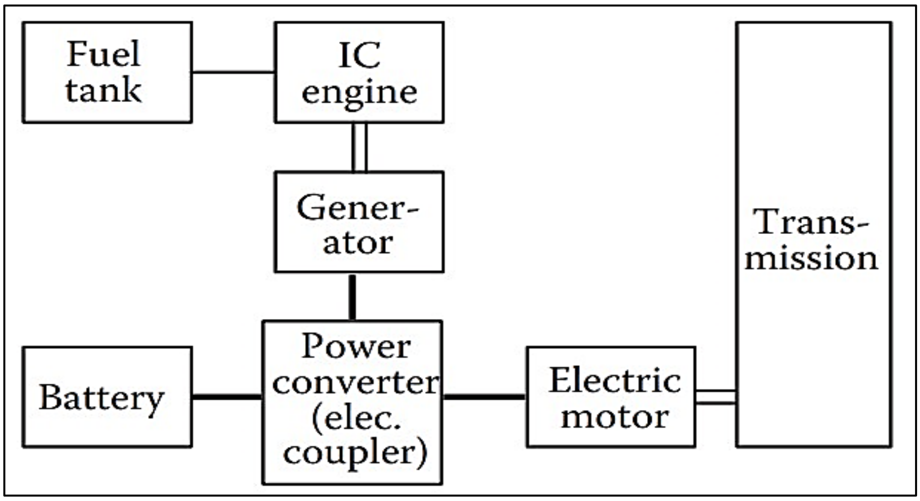

Figure 1.4 Electrical Coupling [1]

- **Mechanical Coupling:** Found in parallel and series-parallel architectures, this method directly links the powers of the engine and electric motor. Within this coupling, there are several subtypes:
    - **Torque Coupling:** Allows independent torque control but links engine, motor, and vehicle speeds in a fixed relationship.

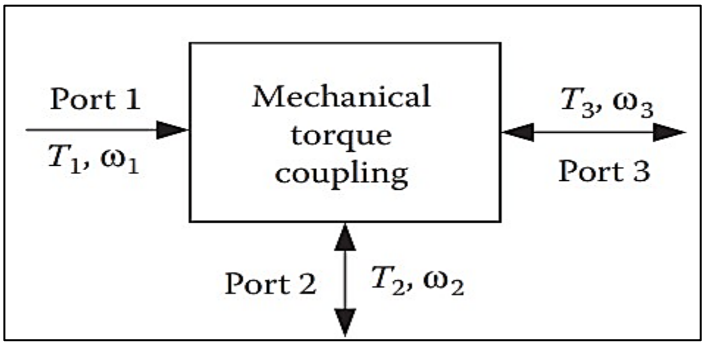

Figure 1.5 Torque Coupling Device [1]

- **Speed Coupling:** Combines engine and motor speeds and interlinks all torques.

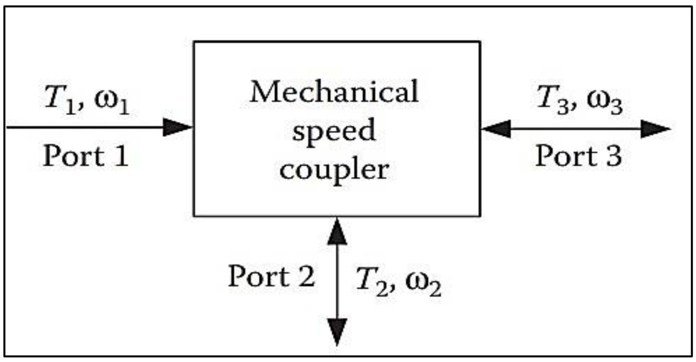

Figure 1.6 Speed Coupling Device [1]

- **Integrated Speed and Torque Coupling:** Enables the engine to operate within specific speed and torque ranges, delivering mechanical power directly to the wheels. The Toyota Prius, developed by Toyota Motor Company, exemplifies this coupling approach.

Understanding these coupling mechanisms is crucial for optimizing HEV drivetrains, and balancing flexibility, control, and energy efficiency. In Chapter 3 we will discuss the Toyota Prius Integrated Speed and Torque coupling system.

1.6 Organization of the Thesis

The transition towards sustainable transportation has led to the increasing prominence of Hybrid Electric Vehicles (HEVs). This thesis embarks on the development of a comprehensive MATLAB model for HEV powertrains using Simulink and Simscape libraries, focusing on all operation modes of full hybrid vehicles. The primary aim is to optimize the powertrain by selecting appropriate components with precise specifications for maximum efficiency. This includes enhancing the internal combustion engine's performance through advanced algorithms designed to optimize fuel consumption. Additionally, the work involves detailed simulations to ensure that the electric motor complements the engine for improved overall performance.

By evaluating performance metrics such as acceleration, range, and fuel efficiency under various driving conditions, the model provides insights into the most efficient powertrain configurations. Moreover, the incorporation of regenerative braking strategies aims to maximize energy recovery, resulting in a smaller battery size and further enhancing vehicle efficiency. This thesis contributes to the development of efficient and environmentally friendly hybrid electric vehicles, supporting the broader goal of sustainable transportation.

Here is the Overview of the chapters as follows:

Chapter 2: Literature Review

This chapter provides an in-depth exploration of existing literature, examining the evolution of hybrid vehicle technology, key components of HEV powertrains, and relevant methodologies employed in HEV modeling and simulation.

Chapter 3: Analysis of Toyota Prius HEV Transaxle

Focusing on the Toyota Prius HEV as a case study, this chapter delves into the analysis of its transaxle system, detailing its configuration, specifications, and gear ratio calculations to gain insights into its operational characteristics.

Chapter 4: Modeling of a Power-split HEV

Building upon the insights from the previous chapters, this section presents a meticulous modeling approach for a power-split HEV, encompassing mechanical, electrical, and battery systems, alongside longitudinal driver dynamics and MATLAB-based simulation.

Chapter 5: Results and Discussion/Analysis

The culmination of the modeling efforts, this chapter presents results and discusses various output parameters including torque demand, vehicle speed, shaft angular speed, torque delivery, battery performance, and fuel consumption, providing valuable insights into the performance of the developed HEV model.

Chapter 6: Conclusions and Future Scope

This chapter consolidates the findings from the study, highlighting key observations, implications, and limitations. Additionally, it outlines potential avenues for future research and development in the field of HEV powertrain modeling and optimization.

Chapter 2

2 Literature Review

In the realm of electric, hybrid electric, and fuel cell vehicles, significant advancements have been made in recent years, as documented by Ehsani et al. (2019). This comprehensive work covers various aspects of modern vehicle technologies, providing valuable insights into their design, operation, and performance.

Das (2021) contributes to the field by presenting modeling approaches specifically tailored for hybrid and electric vehicles using Simscape. This work is crucial for understanding the intricate dynamics and behaviors of such vehicles, essential for their efficient design and optimization.

Chanumolu (2016) introduces hybrid vehicle architecture, offering insights into modeling, simulation, and experimental validation. Such research efforts are pivotal for pushing the boundaries of hybrid vehicle design and performance.

Zeng and Wang (2017) delve into the analysis and design of power-split devices for hybrid systems, addressing fundamental components that play a crucial role in hybrid vehicle powertrains. Their work lays the groundwork for optimizing power distribution and efficiency in hybrid vehicles.

Matsumura et al. (2018) focus on the development of a new hybrid transaxle tailored for mid-size vehicles. This research contributes to enhancing the performance and drivability of hybrid vehicles, catering to a broader range of vehicle sizes and applications.

The evaluation of the Toyota Prius Hybrid Synergy Drive System by V. Technologies (2011) sheds light on real-world performance and efficiency metrics of a popular hybrid vehicle. Such evaluations are essential for benchmarking and improving existing hybrid technologies.

Gao and Ehsani (2006) explore a torque and speed coupling hybrid drivetrain, offering innovative solutions to enhance the efficiency and dynamic performance of hybrid vehicles. Their work contributes to advancing the state-of-the-art hybrid drivetrain design.

The Toyota P610 Continuously Variable Transmission (CVT), as described by Code (Year), represents a significant technological advancement in hybrid vehicle transmissions. This transmission technology plays a crucial role in optimizing power delivery and efficiency in hybrid vehicles.

Tuan (2018) presents a modeling and simulation study of a series-parallel hybrid electric vehicle using MATLAB/Simulink, offering a valuable understanding of the dynamic behavior and performance of such vehicles under various operating conditions.

Shubham and Ganguly (2021) contribute to the field by presenting a detailed model and simulation of a series-parallel hybrid electric vehicle, facilitating a deeper understanding and analysis of hybrid vehicle dynamics and control strategies.

Patil and Johri (2013) focus on the design and control aspects of series-parallel hybrid electric vehicles, addressing key challenges in integrating multiple power sources and optimizing their coordination for improved vehicle performance and efficiency.

Pandit, Rajankar, and Kulkarni (2017) present a design and simulation study of a split parallel hybrid electric vehicle, offering insights into alternative hybrid architectures and their potential advantages in specific applications or vehicle segments.

Zhang (2015) explores the design of power-split hybrid powertrains with multiple planetary gears and clutches, introducing innovative transmission architectures to enhance the efficiency and versatility of hybrid vehicles.

MoRTH (Year) provides regulatory insights into hybrid vehicle standards and certification processes, highlighting the importance of adhering to safety and environmental regulations in hybrid vehicle development and deployment.

The press kit accompanying the European launch of the fourth generation Toyota Prius in February 2016, as documented by "T. H. E. New and T. Prius" (2016), offers valuable historical context and insights into the evolution of hybrid vehicle technologies over time.

This literature review synthesizes the contributions of various studies and provides an overview of key advancements, challenges, and trends in the field of electric, hybrid electric, and fuel cell vehicles, as documented in the referenced works.

2.1 Objectives

Based on the literature review, I have identified the following objectives to address key limitations in the development of a hybrid electric vehicle powertrain model.

1) Develop a Power split HEV using MATLAB Simulink and Simscape Library to optimize the hybrid powertrain by selecting optimal configurations for the engine, motor, and other power-electronics components.
2) Develop and validate a model that optimizes the energy management strategy of the hybrid electric vehicle (HEV) powertrain to maximize the utilization of available battery energy.
3) Develop a high-fidelity simulation model of the HEV powertrain using advanced modeling techniques and high-quality data. Validate the model against real-world performance data.
4) Design an integrated HEV powertrain model that seamlessly combines electrical, mechanical, and control subsystems. Ensure compatibility and coherence among subsystems through comprehensive integration testing.
5) Implement a robust validation framework for the HEV powertrain model that includes extensive testing under various driving conditions.
6) Develop and implement advanced control algorithms that simplify the management of power flow between the internal combustion engine, electric motor, and battery. Focus on optimizing control strategies for various operating scenarios.

Chapter 3

3 Analysis of Toyota Prius HEV Transaxle

3.1 Introduction

The world's first mass-produced hybrid system was developed and installed in the 1st generation Prius and successfully held a patent in 1997 [4], increased environmental awareness has led to heightened demands for vehicles to possess superior fuel efficiency and cleaner exhaust gases.

As eco-friendly cars become more popular, customers now seek various performances beyond fuel efficiency, such as driving dynamics and styling. Automakers face the challenge of integrating these diverse performances at a high level. TOYOTA has responded by implementing the new development strategy, TNGA, for the new generation Prius [5]. This chapter describes the working of the newly developed hybrid transaxle P610 for hybrid vehicles, including its gear ratio analysis.

3.2 Objective of P610 Transaxle

The primary objectives for enhancing P610 entail (1) minimizing the transaxle's footprint to align with the dimensions of the novel platform, (2) diminishing mass and optimizing mechanical efficiency to bolster fuel efficiency, and (3) elevating NV (Noise and Vibration) characteristics to uphold a tranquil vehicle environment [5].

3.2.1 Configuration of P610 Transaxle

In the design called P610, there's a structure with four axles. Each of these axles has different parts attached to it. These parts include things like a torsional damper (which absorbs vibrations and shocks), an input shaft (which carries power into the system), and planetary gears (which are special gears used for distributing power) [5] as shown in the **Figure 3.1**.

The planetary gears are important here. They do a specific job: they take the power coming from the engine and split it into two parts. One part is used to make the vehicle move, and the other part goes to a generator, which is like a power station on wheels. This setup is clever because it allows the engine to do two jobs at once: moving the vehicle and generating electricity.

Here's where it gets interesting: the motor, which is like an electric engine, doesn't sit on the same axle as the main engine. Instead, it has its axle [5][6]. How does it still work together with the main engine? Well, there's another set of gears that connects them. This setup allows both the main engine and the motor to send their power to a part called the differential gear system, which helps in controlling how the wheels turn.

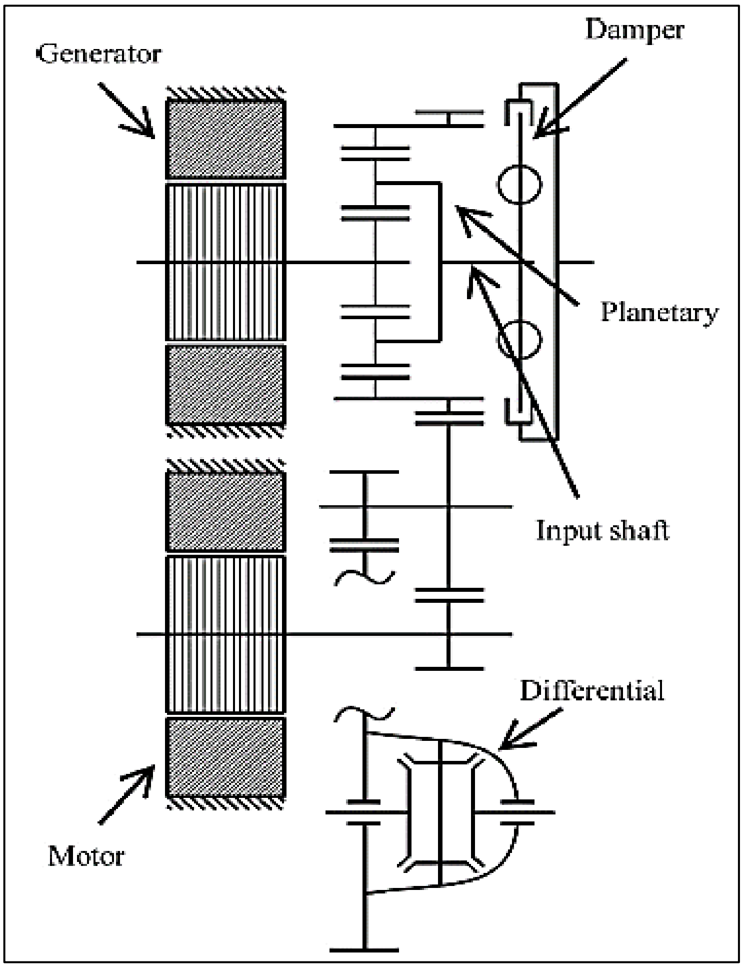

Figure 3.1 Schematic of hybrid Transaxle [5]

So, in simple terms, P610 is a smart setup that uses gears and axles to make the most out of the engine's power, making the vehicle move while also generating electricity, and efficiently combining the power from both the main engine and the motor to drive the wheels smoothly.

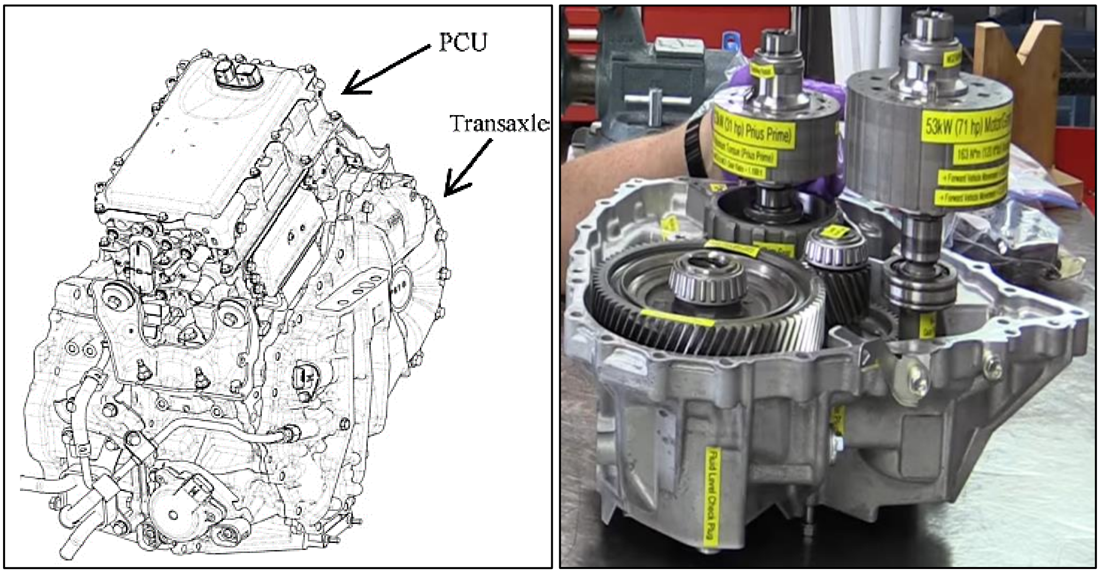

Figure 3.2 P610 Transaxle [5][A]

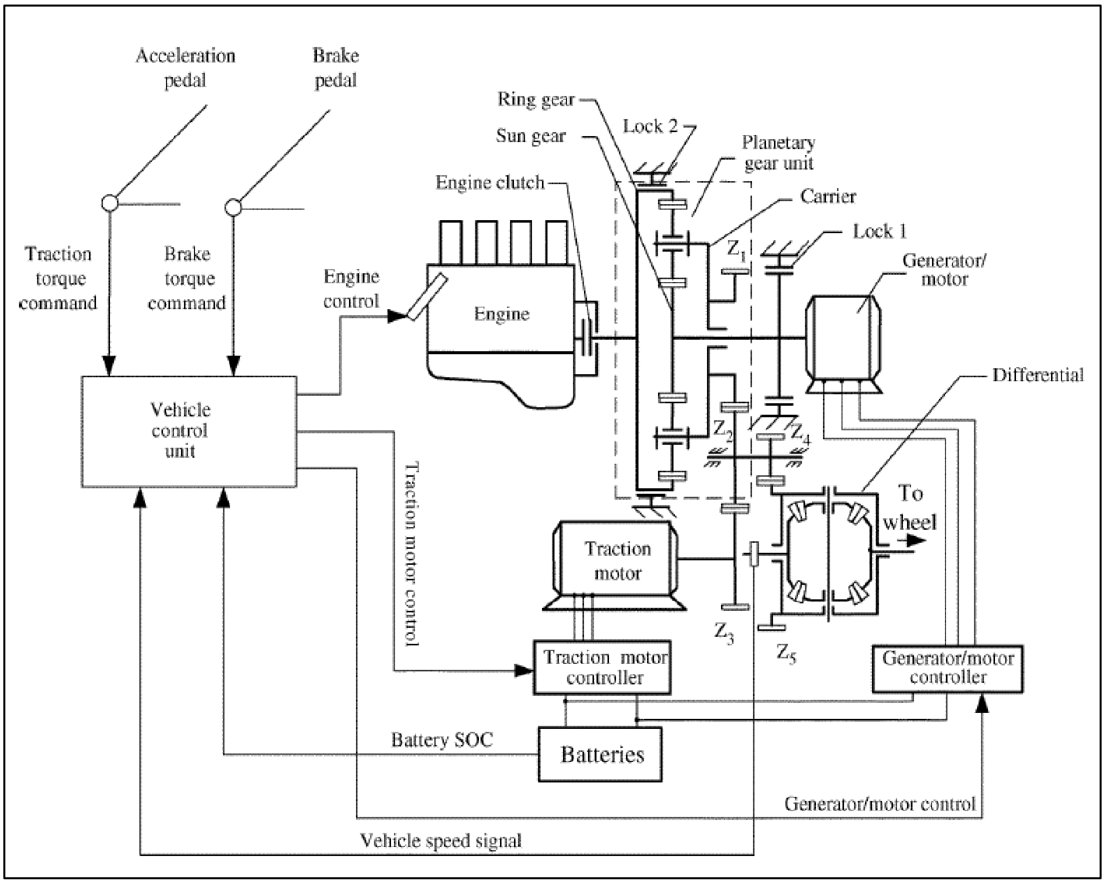

Figure 3.3 Configuration of Transaxle [7]

3.2.2 Transaxle Specifications

Table 3.1 Specification of Hybrid Transaxle [5][8]

Specification	Value
Engine: -	1.8 L
Max. output power	72 kW
Max. output Torque	142 Nm
MG1: -	
Max. output power	23 kW
Max. output Torque	40 Nm
MG2: -	
Max. output power	53 kW
Max. output Torque	163 Nm

Table 3.2 Specifications of Transaxle Gear System [A]

P610	**Value**
Ring Gear (T_r)	78
Sun Gear (T_s) (MG1 is connected)	30
Planet Gear (T_p) in 3 nos.	24
Ring gear outer (T_o)	65
Axle gear connected to MG2 (T_{a1})	53
Axle gear connected to Wheel gear (T_{a2})	21
MG 2 Gear Teeth (T_{mg2})	17
Wheel Gear (T_w)	73

3.3 Transaxle Gear Ratio Calculation

During vehicle operation on roadways, it is subjected to various loads including its weight, rolling resistance force, aerodynamic drag force, and hill-climbing force, all contingent upon the prevailing driving conditions. To propel the vehicle forward, a requisite torque is necessary. This torque demand is met through the utilization of a variable gear ratio mechanism positioned between the power source and the wheels. This arrangement enables the engine or motor to effectively cater to the torque requirements dictated by the prevailing driving conditions.

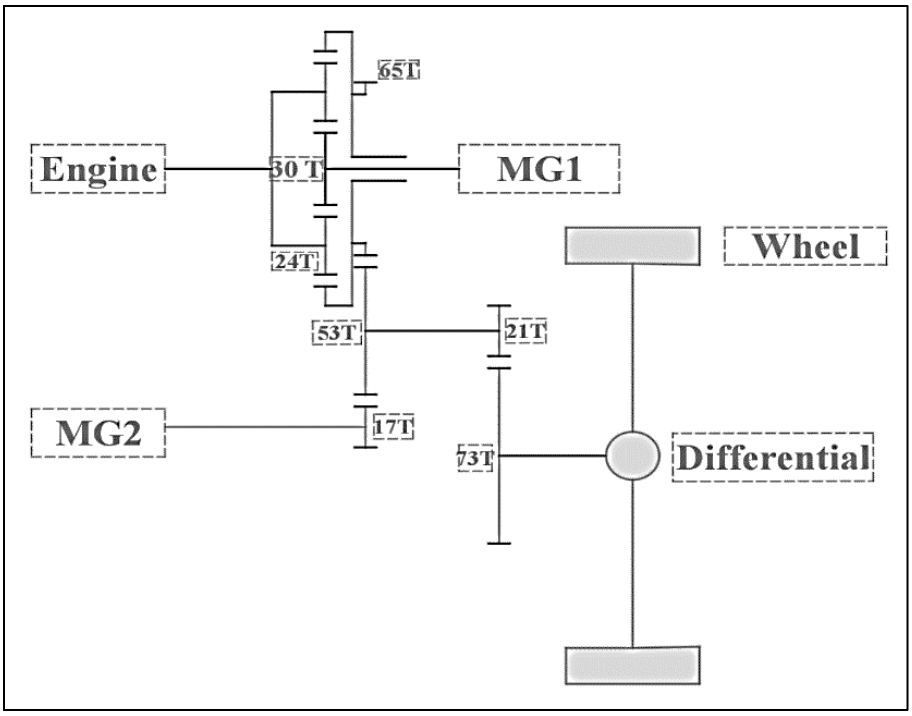

Figure 3.4 2D Schematic of P610 Transaxle

Calculation of Gear Ratio:

Willis Equation of planetary gear: $\boldsymbol{\omega_r T_r = \omega_c(T_r + T_s) - \omega_s T_s}$ [B]

Case 1: When Yoke is Fixed

a] <u>MG1 to Wheel gear:</u>

$\frac{\omega_s}{\omega_r}$ Fixed Carrier or stationary transmission ratio

- Planetary gear: $\mathrm{G.R\,1} = \frac{\omega_s}{\omega_r} = -\frac{T_r}{T_s} = \frac{-2.6}{1}$
- From Planetary gear to Axle gear of 53T: $\mathrm{G.R\,2} = \frac{T_{a1}}{T_o} = \frac{53}{65} = 0.815{:}\,1$
- From 21T Axle gear to 73T Wheel gear: $\mathrm{G.R\,3} = \frac{T_w}{T_{a2}} = \frac{73}{21} = 3.476{:}\,1$

- Total= $\frac{\omega_s}{\omega_w}$ = G.R1 x G.R2 x G.R3 = **7.3656:1**

b] MG2 gear to Wheel gear:

- MG2 to 53T Axle gear: $\text{G.R }1 = \frac{T_{a1}}{T_{mg2}} = \frac{53}{17} = 3.1176$
- From 21T Axle gear to 73T Wheel gear: $\text{G.R }2 = \frac{T_w}{T_{a2}} = \frac{73}{21} = 3.476{:}\,1$
- Total= $\frac{\omega_{mg2}}{\omega_w}$ = G.R1 x G.R2 = **10.8368:1**

c] MG2 gear to MG1 gear:

- MG2 to 53T Axle gear: $\text{G.R }1 = \frac{T_{a1}}{T_{mg2}} = \frac{53}{17} = 3.1176$
- Axle gear of 53T to Planetary gear: $\text{G.R }2 = \frac{T_o}{T_{a1}} = \frac{65}{53} = 1.226{:}\,1$
- From ring gear to sun gear: $\text{G.R }3 = \frac{T_s}{T_r} = \frac{30}{78} = 0.3846{:}\,1$
- Total= $\frac{\omega_{mg2}}{\omega_{mg1}}$ = G.R1 x G.R2 x G. R3=**1.4706:1**

Case 2: When Sun Gear is Fixed

a] Engine to Wheel gear:

- Planetary gear: $\text{G.R }1 = \frac{\omega_c}{\omega_r} = \frac{T_r}{T_r+T_s} = \frac{0.722}{1}$
- From Planetary gear to Axle gear of 53T: $\text{G.R }2 = \frac{T_{a1}}{T_o} = \frac{53}{65} = 0.815{:}\,1$
- From 21T Axle gear to 73T Wheel gear: $\text{G.R }3 = \frac{T_w}{T_{a2}} = \frac{73}{21} = 3.476{:}\,1$
- Total= $\frac{\omega_c}{\omega_w}$ = = G.R1 x G.R2 x G.R3 = **2.045:1**

b] MG2 gear to Wheel gear:

- MG2 to 53T Axle gear: $\text{G.R }1 = \frac{T_{a1}}{T_{mg2}} = \frac{53}{17} = 3.1176{:}\,1$
- From 21T Axle gear to 73T Wheel gear: $\text{G.R }2 = \frac{T_w}{T_{a2}} = \frac{73}{21} = 3.476{:}\,1$
- Total= $\frac{\omega_{mg2}}{\omega_w}$ = G.R1 x G.R2 = **10.8368:1**

c] Engine to MG2 gear:

- Planetary gear: $\text{G.R }1 = \frac{\omega_c}{\omega_r} = \frac{T_r}{T_r+T_s} = \frac{0.722}{1}$

- From Planetary 65T gear to Axle gear of 53T: $\mathrm{G.R}\,2 = \frac{T_{a1}}{T_o} = \frac{53}{65} = 0.815{:}\,1$
- From Planetary 53T gear to MG2: $\mathrm{G.R}\,2 = \frac{T_{mg2}}{T_{a1}} = \frac{17}{53} = 0.321{:}\,1$
- Total=$\frac{\omega_c}{\omega_{mg2}}$= G.R1 x G.R2 x G.R3 = **0.19:1**

Case 3: When Ring Gear is Fixed

a] Engine to MG1:

- Planetary gear: $\mathrm{G.R}\,1 = \frac{\omega_{mg1}}{\omega_c} = 1 + \frac{T_r}{T_s} = \frac{3.6}{1}$
- Total=$\frac{\omega_c}{\omega_{mg1}}$ = **0.277:1**

Based on the calculations, the gear ratio between MG2 and the Wheel stands at 10.8368:1, between the engine and the wheel gear is 2.045:1, and between the Engine and MG1, it is 0.277:1.

3.4 Summary

The analysis of the Toyota Prius P610 hybrid transaxle in Chapter 3 highlights its innovative design and efficient power management. The P610 transaxle was developed with the objectives of reducing size, decreasing weight, optimizing mechanical efficiency, and enhancing noise and vibration characteristics. The transaxle features a four-axle structure, incorporating components such as a torsional damper and planetary gears, which efficiently split engine power for propulsion and electricity generation. Gear ratio calculations reveal the transaxle's effectiveness in managing power distribution, contributing to the Prius's superior fuel efficiency and performance. This chapter underscores Toyota's advancements in hybrid technology to meet the growing demands for eco-friendly vehicles with dynamic performance.

Chapter 4

4 Modeling of Power-split HEV

4.1 Introduction

In the pursuit of sustainable transportation solutions, hybrid electric vehicles (HEVs) have emerged as a promising avenue. This project aims to develop the Simulink model of hybrid powertrains to optimize and enhance their performance. Inspired by recent research, we seek to contribute to the advancement of HEVs.

One influential study by Nguyen Khac Tuan, "Modeling and Simulation of Series Parallel HEV Using MATLAB/Simulink," explores the simulation of series-parallel HEVs using MATLAB/Simulink, offering insights into their behavior and potential enhancements [9]. Similarly, "Modelling and Simulation of Series-Parallel Hybrid Electric Vehicle" investigates series-parallel HEVs' performance through computer modeling, guiding our optimization efforts [10].

Furthermore, "Design and Control of Series-Parallel Hybrid Electric Vehicle" emphasizes effective design and control strategies crucial for series-parallel HEVs' smooth operation, serving as a cornerstone in our modeling endeavors [11]. Lastly, "Design and Simulation of Split Parallel Hybrid Electric Vehicle" sheds light on alternative hybrid architectures, enriching our understanding and informing our modeling approach [12].

By synthesizing insights from these studies and utilizing MATLAB/Simulink's capabilities, this chapter will discuss the modeling of HEVs with the primary objective of calculating fuel consumption based on various drive cycles. First, we will examine the forces acting on the vehicle body using its Simulink model. Then, we will delve into the Transaxle model, followed by the electrical subsystem with its input specifications. Finally, we will introduce the three main driving cycles on which the model is run. In the next chapter, we will discuss the results of the MATLAB model, comparing them with those of the Toyota Prius 4th Gen vehicle.

4.2 Mechanical Systems

In this section, we will explore all the mechanical blocks from the Simscape and Simulink libraries that are being used to model the HEV.

4.2.1 Vehicle Body

Before delving into our main objective of analyzing fuel consumption, it's important to acknowledge that a vehicle comprises thousands of components. We will first examine the forces exerted on the vehicle, calculate them using a Simulink diagram, and then model the vehicle body using the Simscape library in MATLAB.

Forces acting on vehicle body.

The mechanical energy obtained by burning fuel in an internal combustion engine is utilized for various purposes: accelerating the vehicle, overcoming road and aerodynamic resistance, and moving against gravity on inclines.

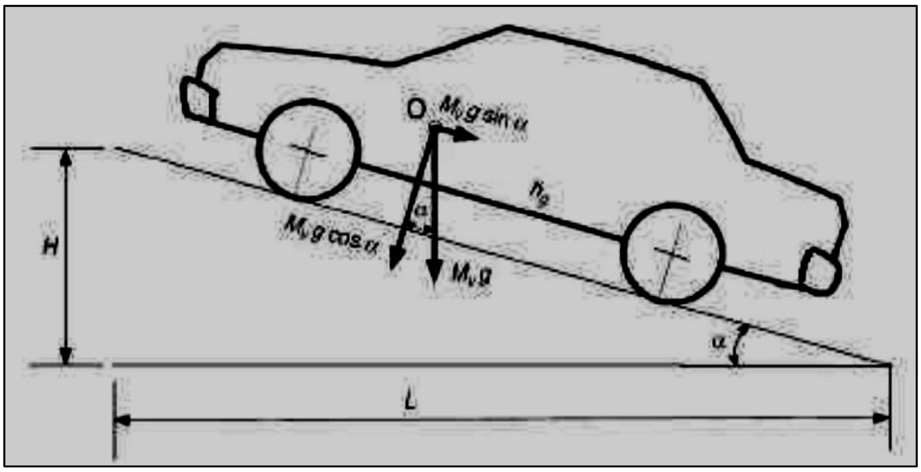

Figure 4.1 Forces Acting on Vehicle [2]

Assuming the vehicle to be a point mass, we can express this situation through the force equilibrium equation as follows:

$$\boxed{M_{vehicle}\frac{dV_{vehicle}}{dt} = F_{traction} - (F_{roll} + F_{aero} + F_{grade})}$$

Each term in the bracket is explained below one by one:

Rolling resistance

Rolling resistance, pivotal in automotive engineering, refers to the force opposing tire motion on surfaces. It significantly impacts vehicle efficiency and fuel consumption. Factors like tire design, pressure, and road conditions influence it. Understanding and minimizing rolling resistance are crucial for optimizing vehicle performance and sustainability in transportation and from **Figure 4.1** it is given by:

$$\boxed{F_{roll} = \mu * Mg\cos\alpha}$$

Aerodynamic resistance

Aerodynamic resistance is a critical aspect of vehicle design, impacting performance and efficiency. It refers to the force opposing the motion of a vehicle through the air. Minimizing aerodynamic drag through streamlined shapes and aerodynamic enhancements is essential for improving fuel economy and reducing emissions in automotive engineering and from **Figure 4.1** it is given by:

$$\boxed{F_{aero} = \frac{1}{2} * \rho ACDV^2}$$

Grade resistance.

Grade resistance is the force opposing vehicle motion on inclines or declines. It plays a significant role in vehicle performance and energy consumption, particularly in hilly terrain. Understanding and managing grade resistance is essential for optimizing vehicle efficiency and ensuring safe and reliable transportation systems and from **Figure 4.1** it is given by:

$$\boxed{F_{grade} = Mg\sin\alpha}$$

Using these concepts Simulink diagram is created as shown below,

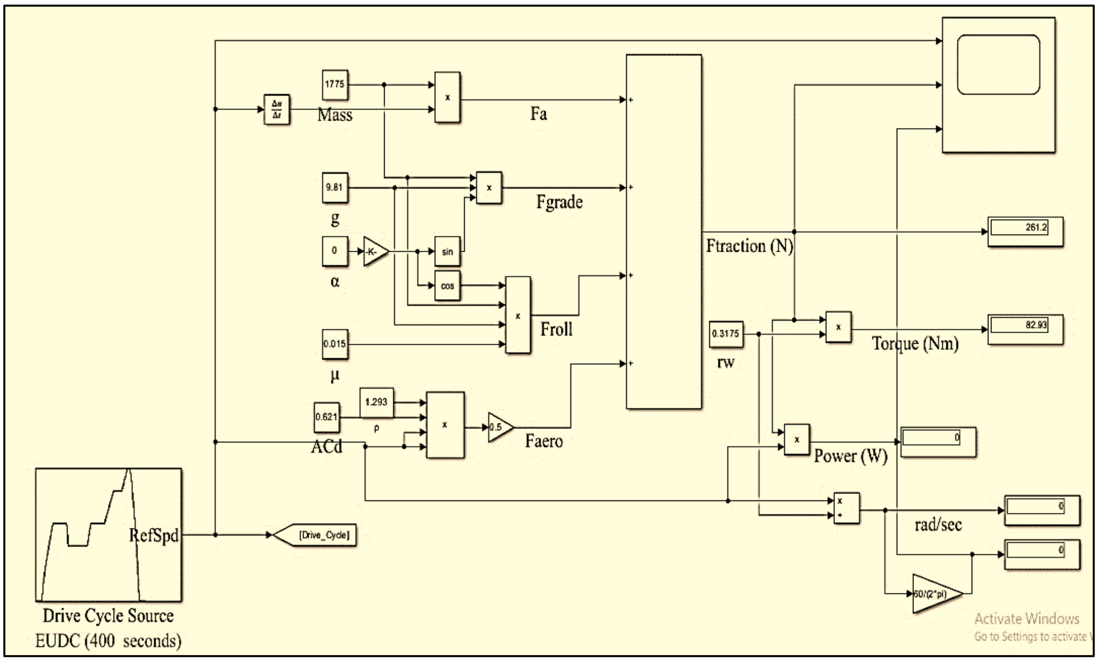

Figure 4.2 Simulink diagram for force calculation.

Considering the Simulink diagram of forces acting on the vehicle, the body is modeled using the MATLAB Simscape library, as depicted below:

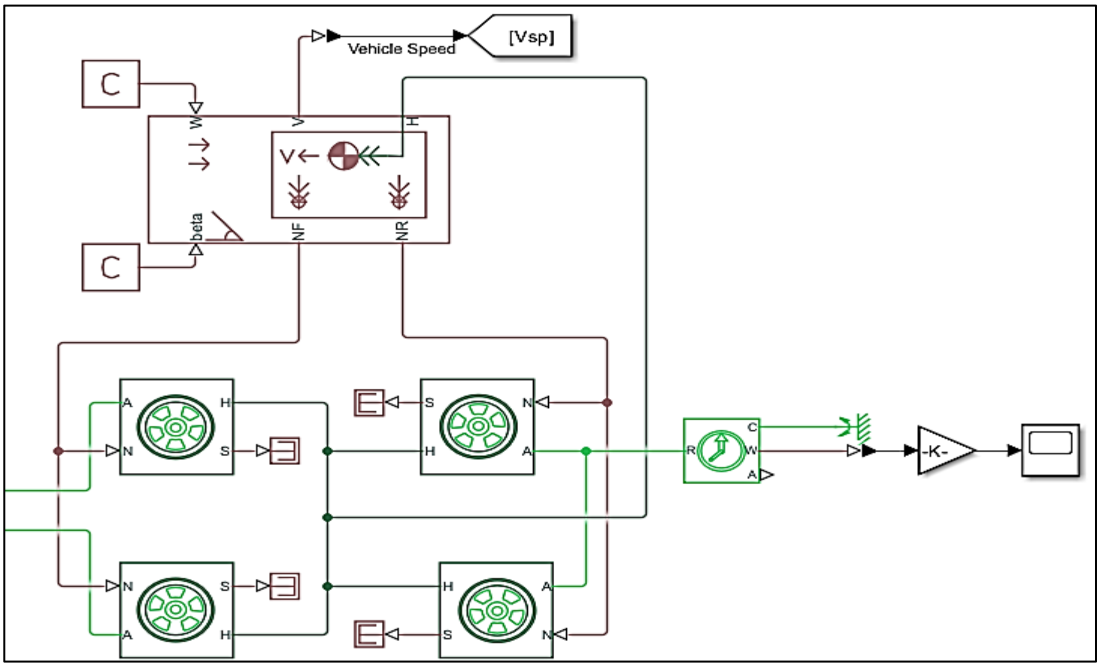

Figure 4.3 Vehicle Body

4.2.2 Transmission System

The transmission system is simulated using the Simscape library, incorporating a simple gear block from MATLAB Simscape library arranged in the sequence found in the Toyota Prius 4th generation vehicle (XW50). Gear ratios are determined based on discussions in Chapter 3 and these gear ratios are given as input to the simple gear block of the Simscape library.

Figure 4.4 illustrates the series-parallel transmission configuration where the engine and Traction motor are the two main power sources for the vehicle whereas the Motor/Generator will act as the alternator of the vehicle which will only charge the battery with the help of the engine. This approach enables a comprehensive understanding of the system's behavior and facilitates analysis of its performance characteristics.

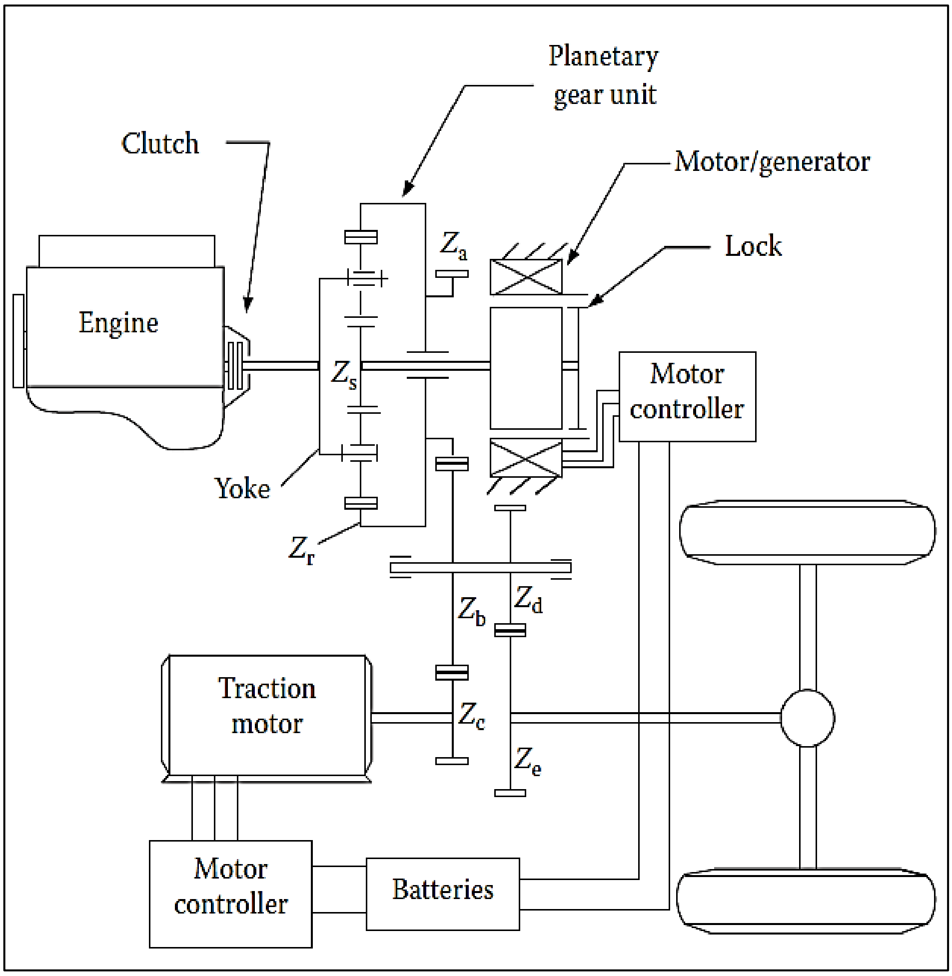

Figure 4.4 Series-Parallel Transmission system [1]

Based on the above figure, a basic block diagram is created to understand the power flow, and based on this diagram, a Simscape model is developed.

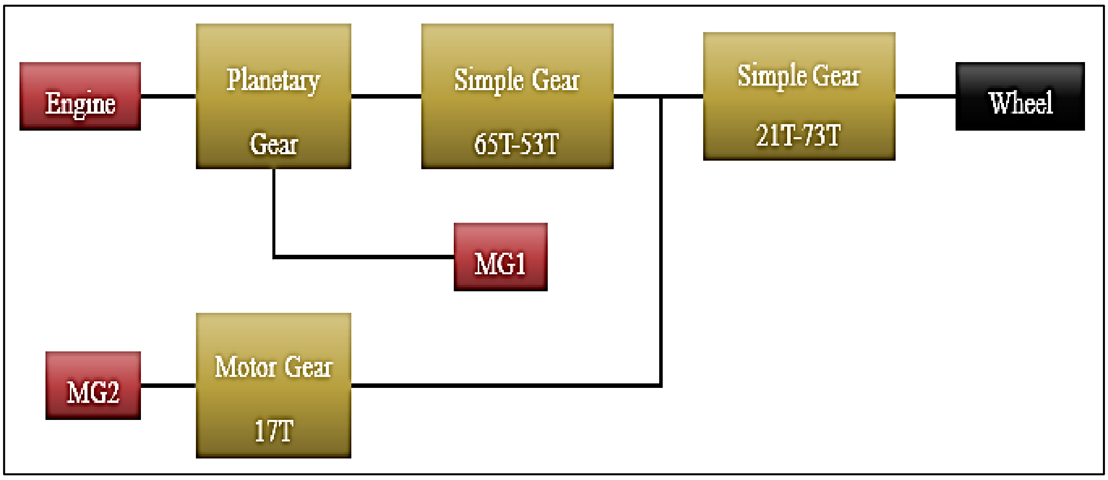

Figure 4.5 Block Diagram of Transmission System

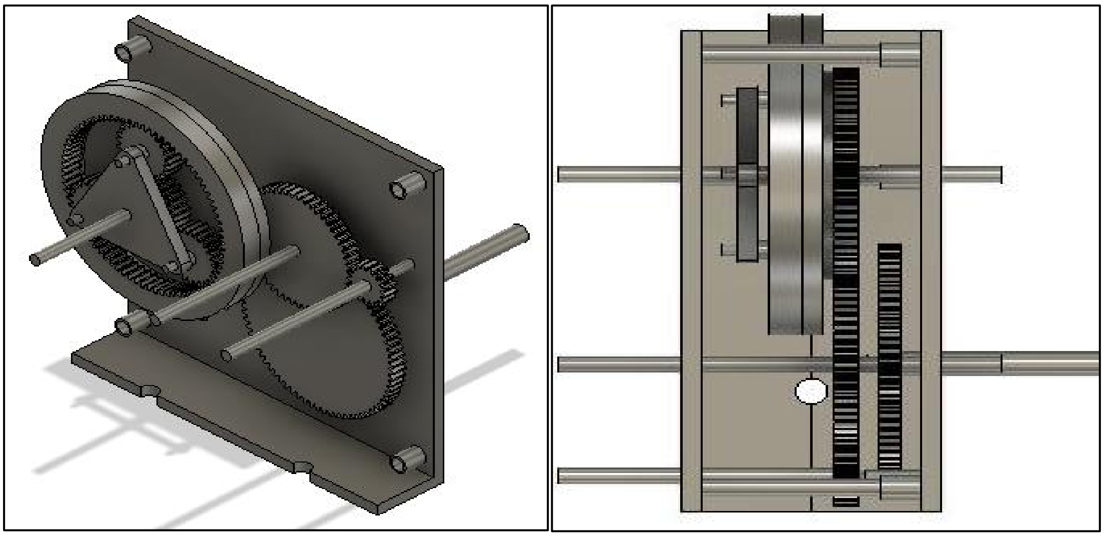

Figure 4.6 3D Model of Transmission System

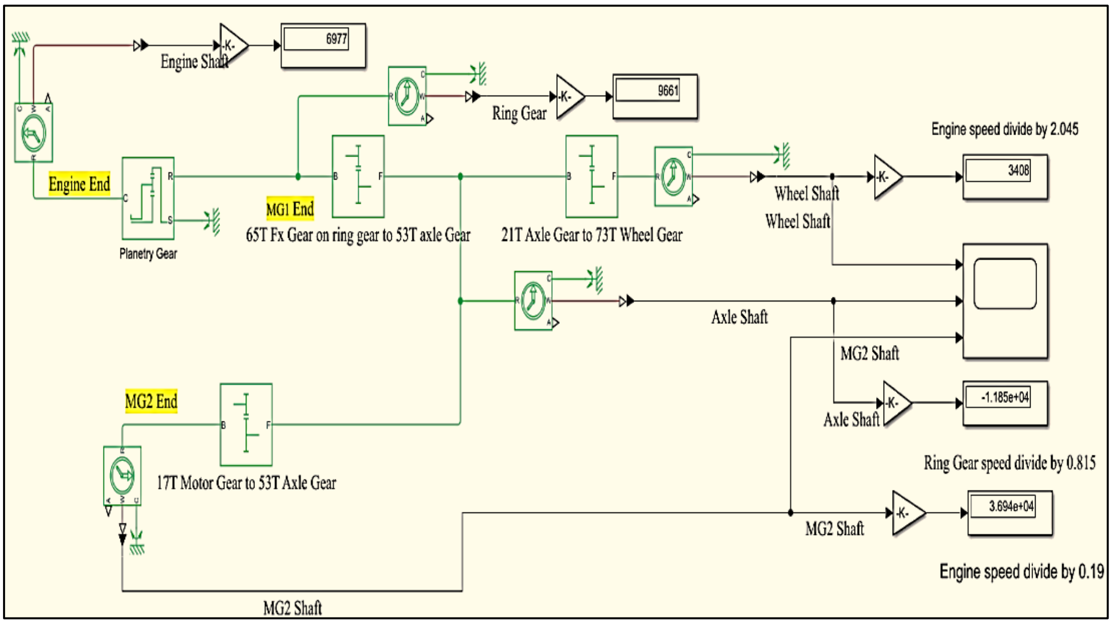

Figure 4.7 Simscape Diagram of Transmission System

4.2.3 Engine block

The engine block is directly sourced from the MATLAB Simscape library and provided with input data referencing the vehicle, specifically the Toyota Prius 4th generation. The vehicle's engine is a spark ignition engine, with input data as shown in **Figure 4.9**.

The engine block will take a throttle range of 0 to 1 as an input and can provide power produced in Watts, fuel Consumption in kg/sec, and the rotation of the shaft as an output. The Engine block B signifies the vehicle frame on which the engine is mounted this B signal is attached to the mechanical rotational reference which will be discussed further

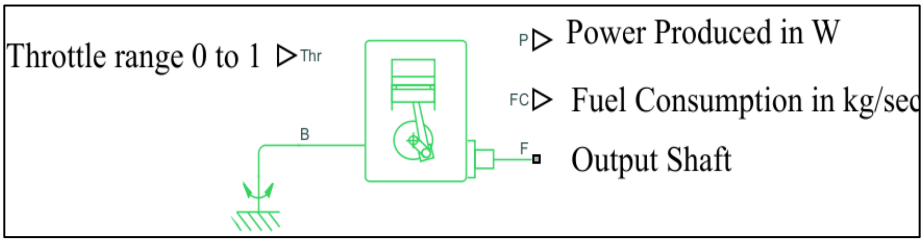

Figure 4.8 Engine Block

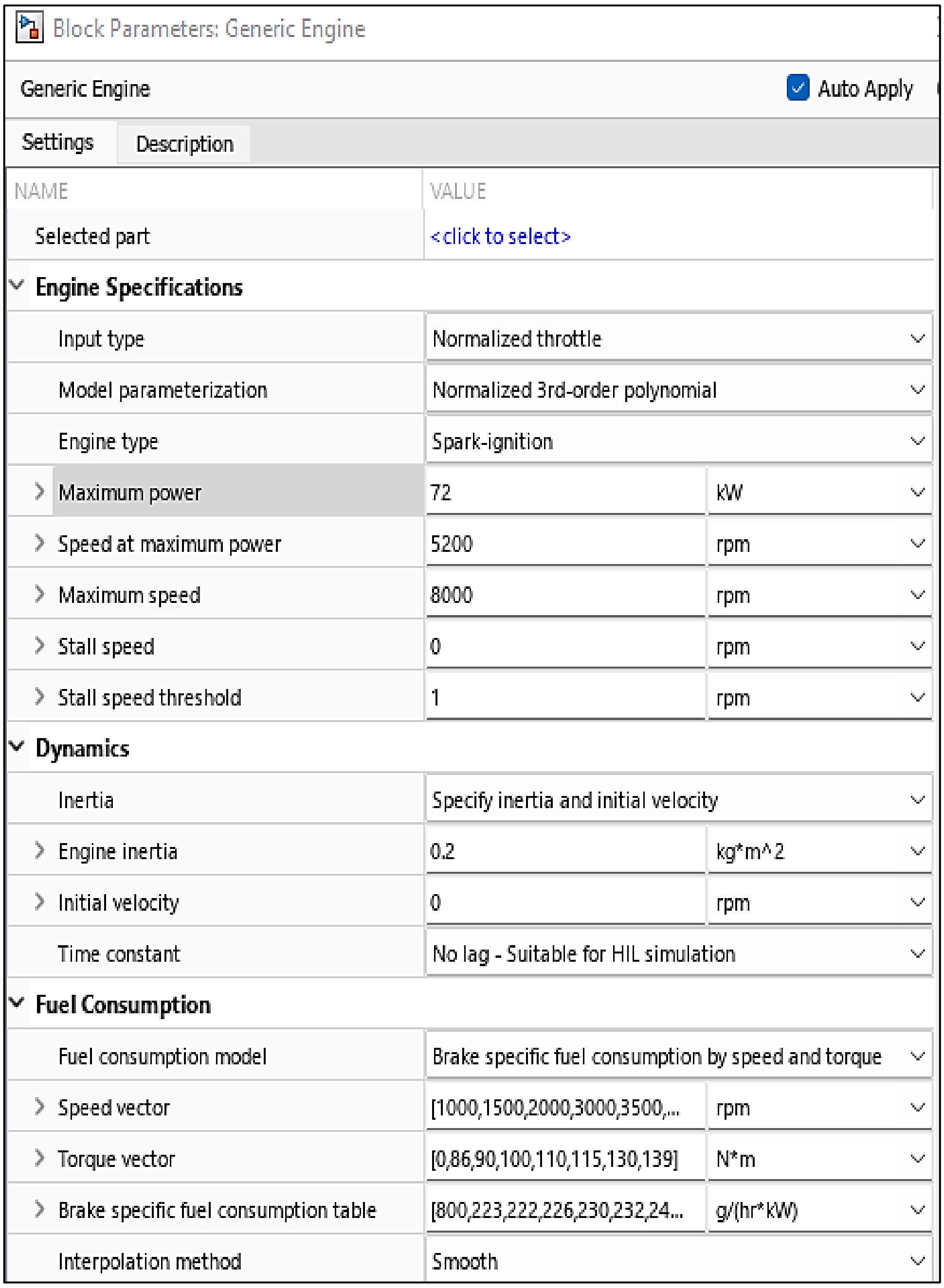

Figure 4.9 Engine Block Parameters

To operate the engine efficiently when the vehicle requires more torque, we provided the engine with torque vector, speed vector, and brake-specific fuel consumption data obtained from the actual engine speed and torque graph using the webplotdigitizer tool. The resulting matrix is depicted below.

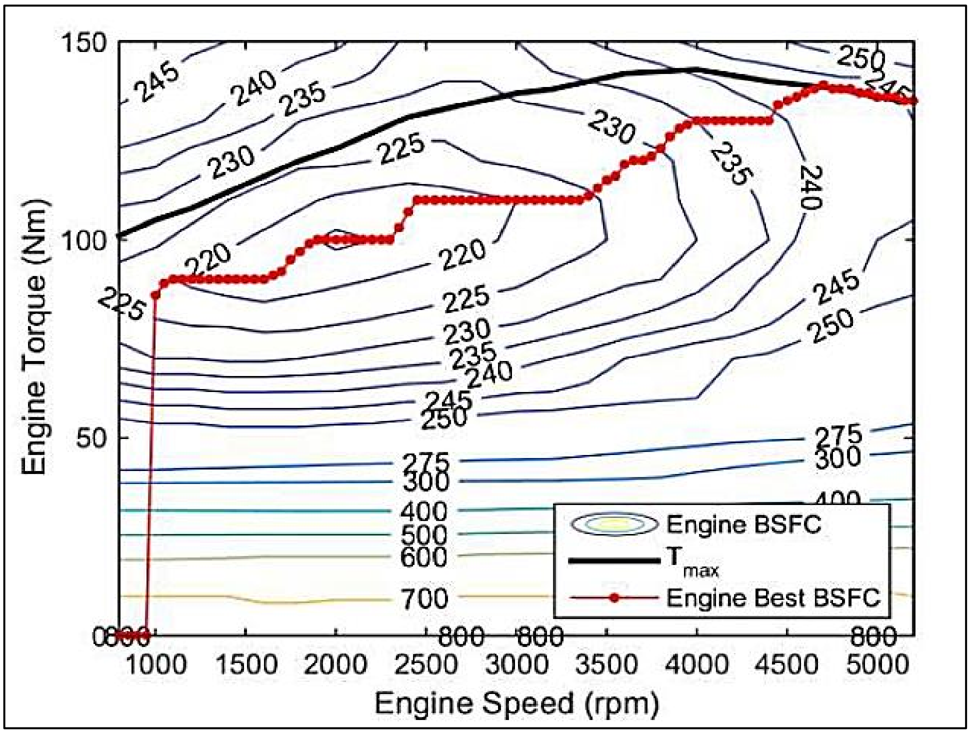

Figure 4.10 Engine BSFC map of Toyota 2ZR-FXE (Atkinson Cycle) [13]

Table 4.1 Torque Speed and BSFC data

Speed (rpm) \ Torque (Nm)	0	86	90	100	110	115	130	139
1000	800	223	222	226	230	232	241	245
1500	800	220	218	220	224	226	235	240
2000	800	221	219	214	220	223	228	235
3000	800	226	224	221	220	224	228	230
3500	800	231	228	225	226	226	230	234
4000	800	236	234	230	231	233	235	238
5000	800	250	247	245	243	243	244	245
	BSFC in g/kW*hr							

4.2.4 Mechanical Sensors

Sensor blocks have been used to measure the parameters directly when the vehicle is running. In the model, sensor blocks are mounted directly on the shaft whose parameter is to measure. The sensor blocks are as follows.

Mechanical Rotational Sensor

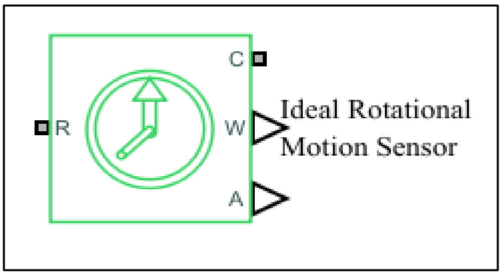

Figure 4.11 Ideal Rotational Motion Sensor Block

Within my model, this block serves to gauge angular velocity or angle within a mechanical rotational network. It operates ideally, disregarding factors like inertia, friction, delays, and energy consumption. The physical signal ports α, W, and A convey angular acceleration, velocity, and position, respectively, of port R relative to port C. A positive measured angular velocity indicates that the velocity at port R exceeds that at port C. Optionally, port C can be disabled, allowing measurement concerning ground.

Ideal Torque Sensor

In my model, this block embodies an ideal torque sensor, converting a variable passing through it into a control signal proportional to torque, governed by a specified coefficient of proportionality. It operates ideally, disregarding factors such as inertia, friction, delays, and energy consumption.

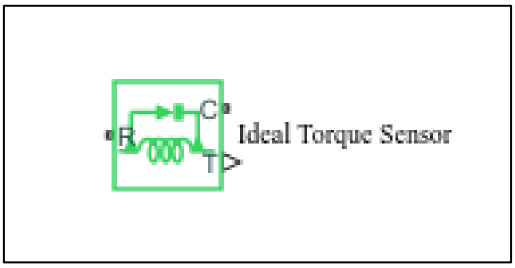

Figure 4.12 Ideal Torque Sensor Block

Connections R and C serve as mechanical rotational conserving ports linking the sensor to the line under torque monitoring. Connection T functions as a physical signal port, delivering the measurement outcome. Notably, the sensor's positive direction spans from port R to port C.

4.3 Electrical Systems

In this section, we will explore all the electrical blocks from the Simscape libraries that are being used to model the HEV.

4.3.1 MG2 Motor Circuit

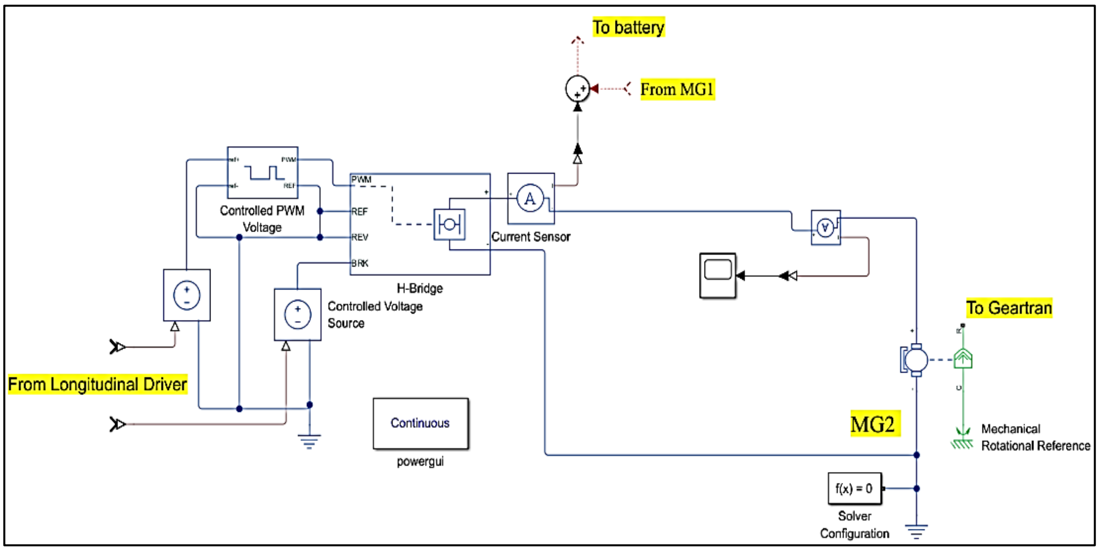

Figure 4.13 MG2 Motor Circuit

The Motor Generator 2 (MG2) serves as the primary traction motor in the vehicle, propelling it during startup when high torque is necessary, as well as during city driving conditions. MG2 is directly connected to the wheel gear axle means it can deliver power irrespective of the Engine. Moreover, MG2 functions as a generator during deceleration, enabling regeneration. Additionally, there are other components within the MG2 circuit, which will be discussed individually.

Control Voltage Source

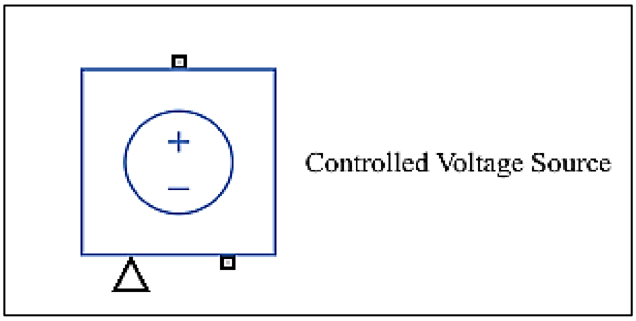

Figure 4.14 Control Voltage Source Block

The above-mentioned block in MATLAB Simscape is pivotal for maintaining a constant voltage across terminals, regardless of the current. It embodies an ideal voltage source, ensuring precise voltage regulation in simulations. The output voltage, V, equals the specified voltage value, Vs, provided at the physical signal port.

Control PWM Voltage

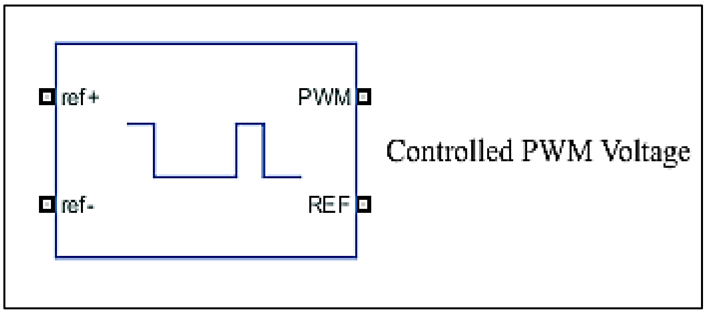

Figure 4.15 Controlled PWM Voltage

It is a fundamental component in modeling pulse-width modulated (PWM) voltage sources. It offers versatility in simulating electrical or physical signal input ports. By configuring the Modeling option parameter, users can either calculate the duty cycle based on reference voltages across ref+ and ref- ports or directly specify the value of the duty cycle using an input port of physical signal.

H Bridge Block

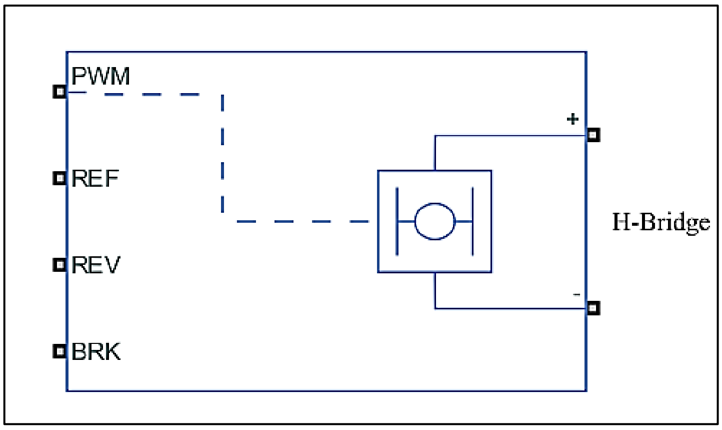

Figure 4.16 H-Bridge Block

The H-Bridge block in my thesis simulates an H-bridge motor driver, offering two Simulation mode options. In PWM mode, the block's output voltage is controlled by the input signal at the PWM port. If the input signal exceeds the Enable threshold voltage, the output is active, and its value equals the Output voltage amplitude. Otherwise, it maintains the load circuit through various Freewheeling mode options. The REV port signal determines output polarity. In Averaged mode, load current characteristics can be Smoothed or Unsmoothed.

Current Sensor

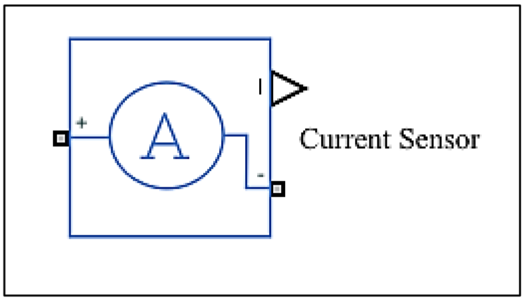

Figure 4.17 Current Sensor Block

The Current Sensor block serves as an ideal current sensor within my model, accurately converting electrical current within any branch into a proportional physical signal.

Solver Configuration and Powergui block

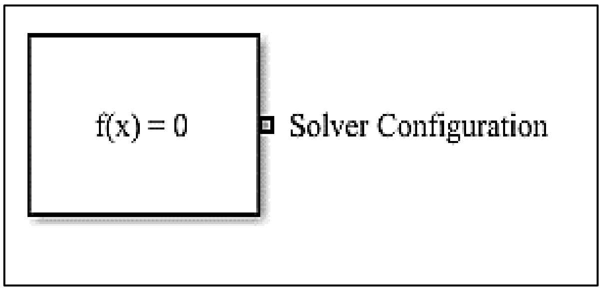

Figure 4.18 Solver Configuration Block

The Solver Configuration block delineates the required solver parameters for the model prior to simulation commencement. Notably, each topologically distinct Simscape block diagram mandates precisely one linked Solver Configuration block.

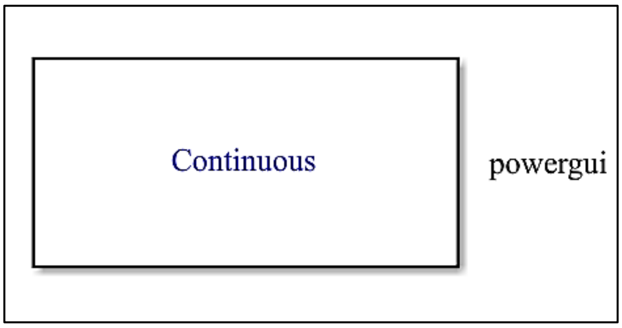

Figure 4.19 PowerGui Block

The powergui block provides flexibility in solving circuitry within my model, offering various methods:

1. The continuous method utilizes a variable-step solver from Simulink.

2. Discretization of the electrical system resolves solutions at fixed time intervals.

3. Continuous or discrete phasor solution for specialized analyses.

4.3.2 MG1 Generator Circuit

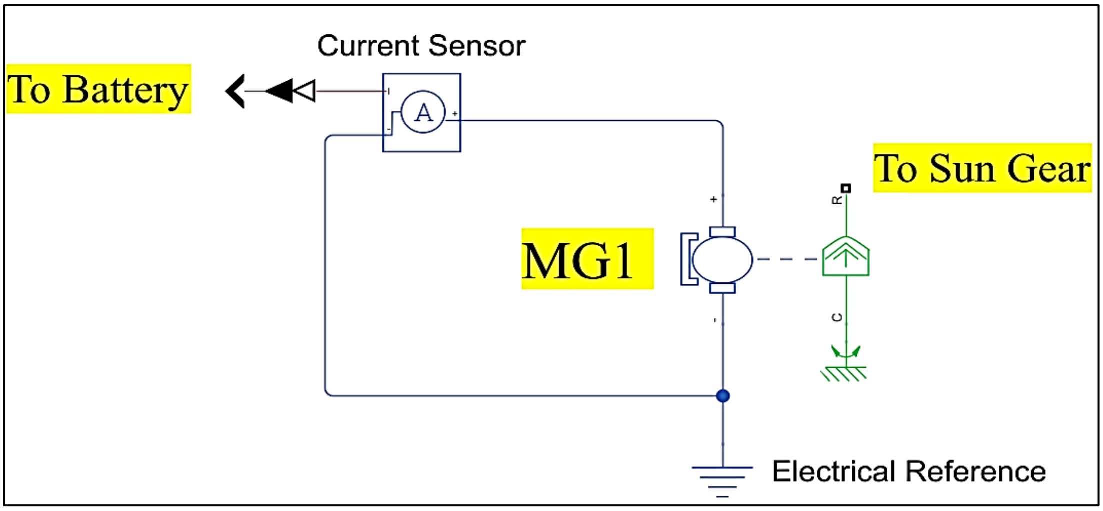

Figure 4.20 MG1 Generator Circuit

MG1 functions solely as a generator, activating only when the engine is turned on. Simultaneously, the engine assists the MG2 motor. Given MG1's connection to the sun gear, the engine transfers power to the MG1 motor, facilitating battery charging.

Generator Block

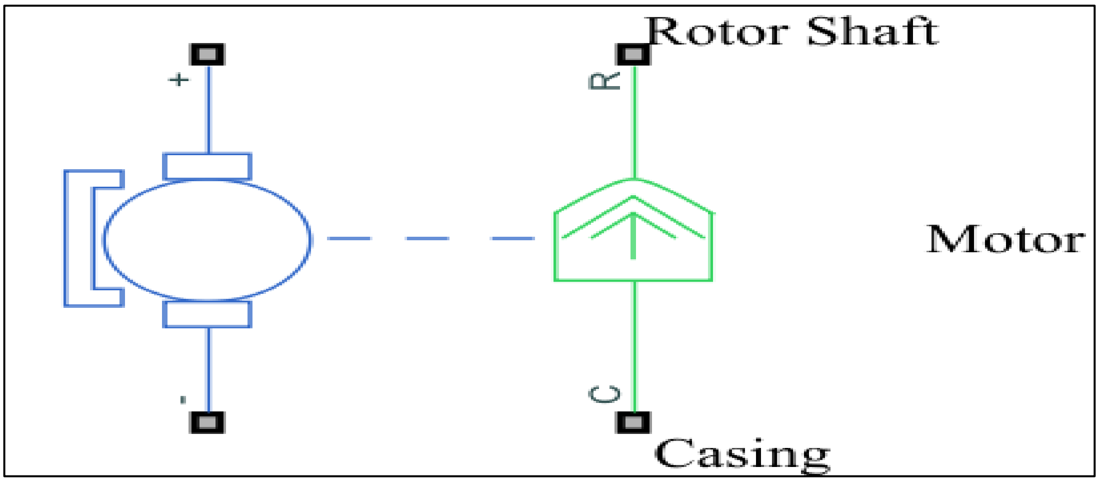

Figure 4.21 Generator or Motor Block

This block operates under the assumption of zero electromagnetic energy loss, resulting in back-emf and torque constants having identical numerical values in SI units. Motor parameters can be input directly or calculated from no-load speed and stall torque. In cases where armature inductance information is lacking, a small non-zero value can be assigned to this parameter.

When a positive current flows from the electrical + to - ports, it generates a positive torque from the mechanical C to R ports. Manipulating the sign of the back-emf or torque constants facilitates the alteration of motor torque direction.

Electrical Reference Block

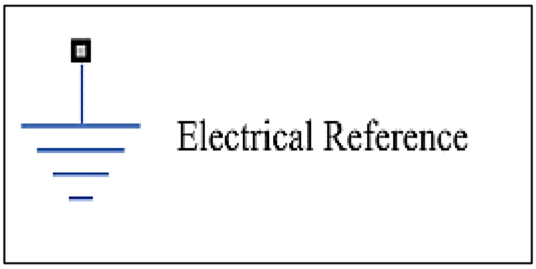

Figure 4.22 Electrical Reference Block

The Electrical Reference block symbolizes an electrical ground, a fundamental aspect of circuitry. All electrical conserving ports of blocks directly linked to ground necessitate connection to an Electrical Reference block. In models incorporating electrical components, the inclusion of at least one Electrical Reference block is imperative for accurate simulation.

4.3.3 Battery Circuits

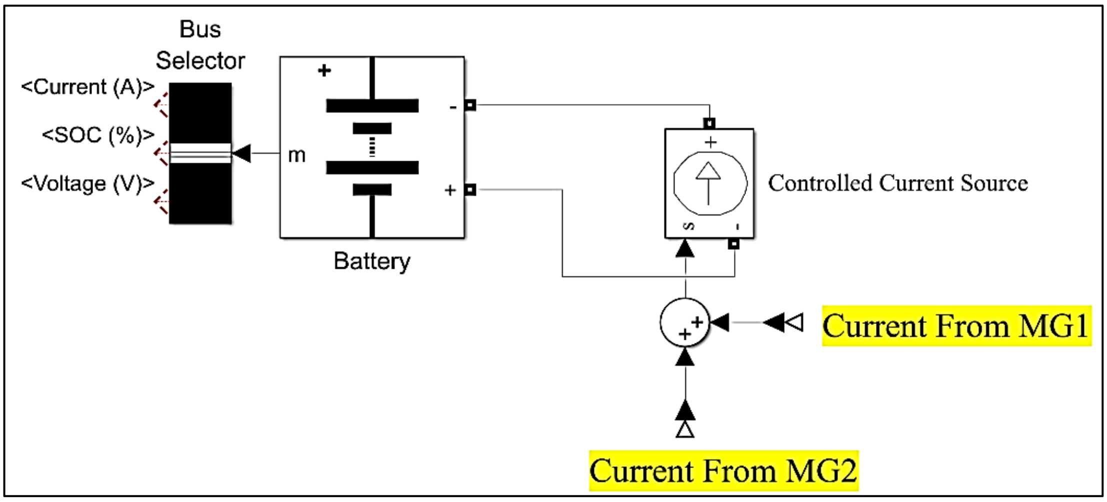

Figure 4.23 Battery Circuits

Within the thesis model, the battery exclusively powers the MG2 motor and receives charge from MG1 when the engine is activated. Additionally, it replenishes its charge from MG2 during regenerative mode operations. The charge from MG2 and MG1 is added with the help of the sum block as shown in **Figure 4.23.**

Controlled Current Sensor

The Controlled Current Source block facilitates the conversion of the Simulink input signal into a corresponding current source. This generated current mirrors the input signal supplied to the block, with the positive current direction depicted by the arrow in the block icon.

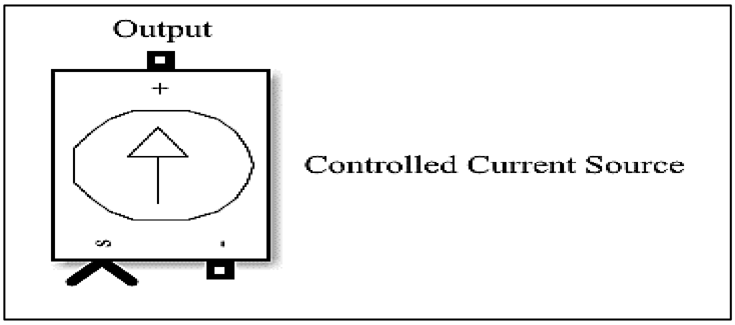

Figure 4.24 Controlled Current Source

Initialization options within the Controlled Current Source block permit the specification of AC or DC. To ensure simulations commence in a steady state, it's advisable to connect the block input to a signal that begins as either a sinusoidal or DC waveform, matching the intended initial values.

Battery Block

The Battery block incorporates a comprehensive dynamic model, encompassing various widely used rechargeable battery types.

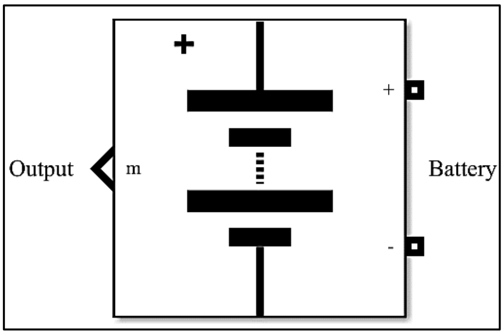

Figure 4.25 Battery Block

This figure shows the equivalent circuit that the block models.

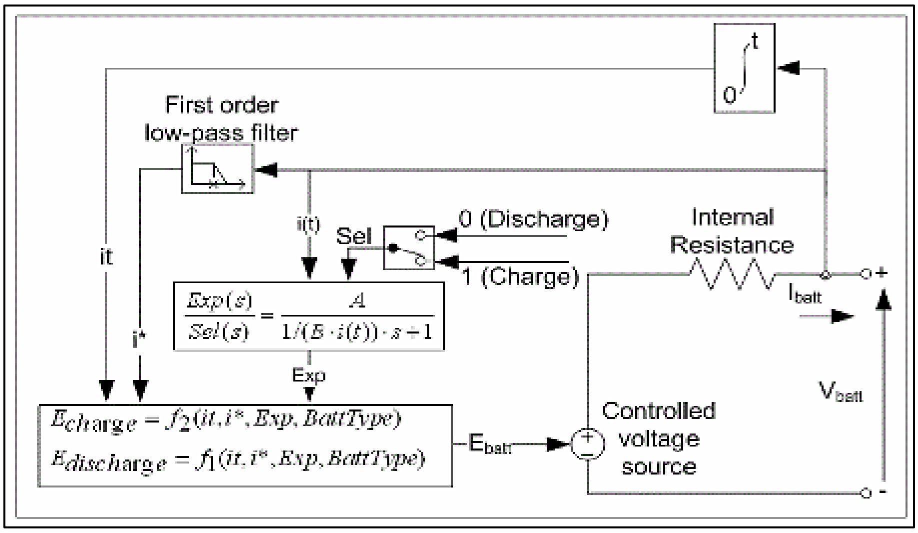

Figure 4.26 Internal Circuit of Battery Block

Bus Selector

In the project thesis, the Bus Selector block efficiently retrieves specified elements from the input bus hierarchy by name. This block offers the flexibility to output the selected elements individually or within a new virtual bus. In the case of individual output, each selected element corresponds to its own output port. Alternatively, when generating a new virtual bus, the block provides a single output port containing all selected elements within the virtual bus.

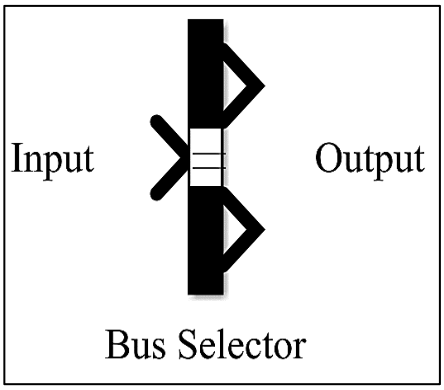

Figure 4.27 Bus Selector Block

4.4 Longitudinal Driver

The Longitudinal Driver block serves as a controller for longitudinal speed tracking. Utilizing reference and feedback velocities, this block generates normalized acceleration and braking commands ranging from 0 to 1. It proves invaluable for modeling driver dynamics or generating commands required to replicate a longitudinal drive cycle accurately.

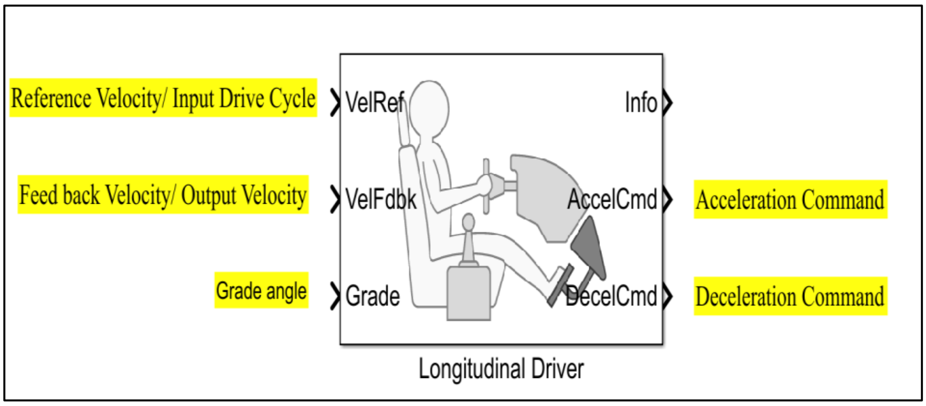

Figure 4.28 Longitudinal Driver Block

4.5 Drive Cycle Source Block

The Drive Cycle block in MATLAB Simulink encapsulates a predefined set of velocity or power profiles, representing typical driving scenarios. It provides a structured framework for simulating vehicle performance under various operating conditions. By selecting an appropriate drive cycle, we can evaluate the vehicle's energy consumption, emissions, and overall efficiency. This block facilitates accurate modeling and analysis, aiding in the development and optimization of vehicle control strategies and powertrain designs.

In our project, we considered three drive cycles and checked our model result based on these drive cycles which, are as follows:

- MIDC Modified Indian Driving Cycle
- JC08 Japanese Driving Cycle
- EUDC Extra-Urban Driving Cycles

MIDC Cycle

The Modified Indian Driving Cycle (MIDC) is a standardized test protocol devised to simulate typical driving conditions encountered in urban areas of India. It comprises a sequence of driving modes, including idling, acceleration, deceleration, and cruising, replicating real-world traffic scenarios such as congestion and stop-and-go traffic. By subjecting vehicles to the MIDC, manufacturers and researchers can evaluate key performance metrics like fuel efficiency, emissions, and drivability under Indian driving conditions. This facilitates the development of vehicles that align better with the needs and expectations of Indian consumers while ensuring compliance with local regulatory standards. Ultimately, the MIDC serves as a crucial tool for optimizing vehicle design and technology to meet the demands of India's urban environment, contributing to improved sustainability, efficiency, and overall driving experience.

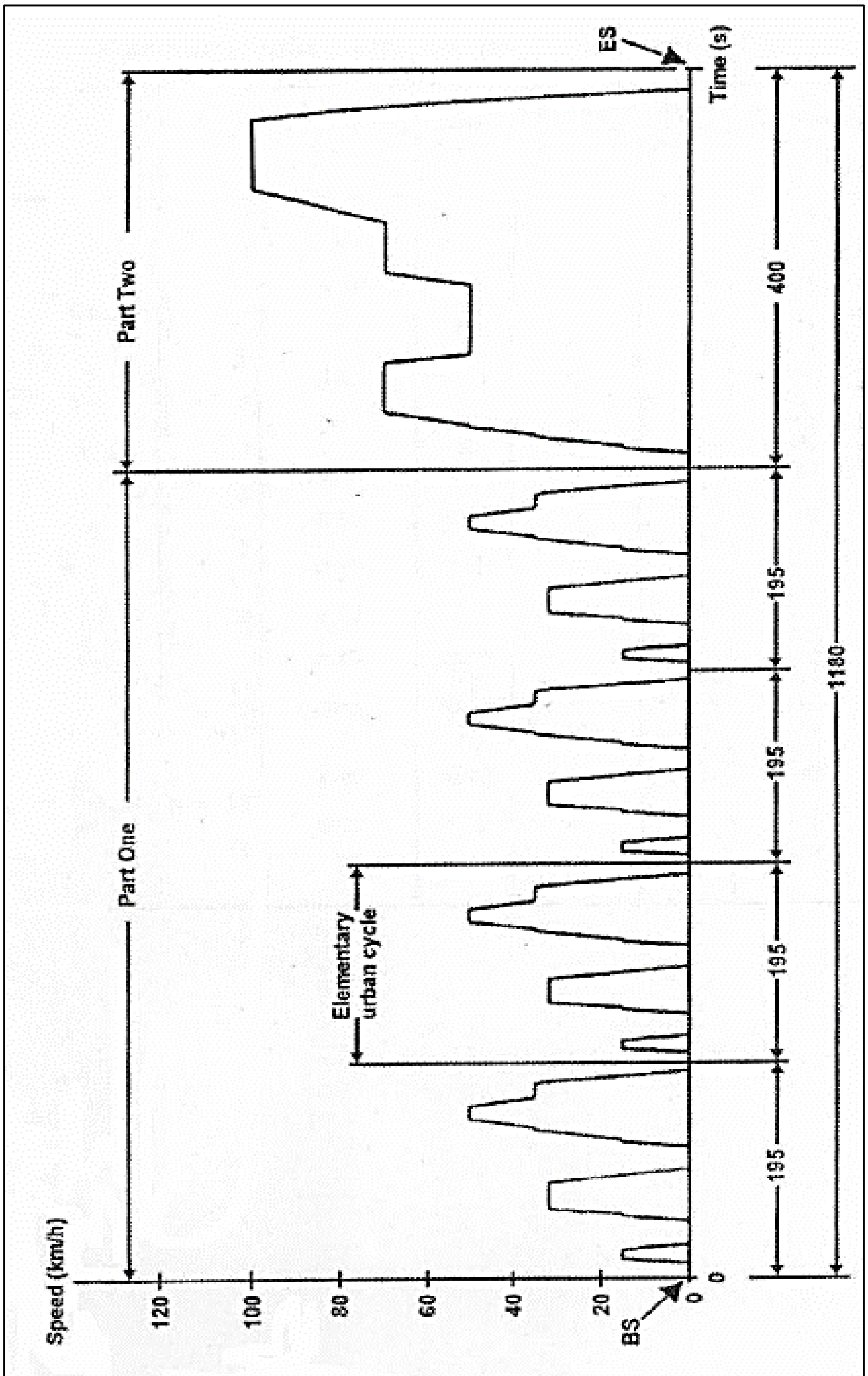

Figure 4.29 MIDC Drive Cycle [14]

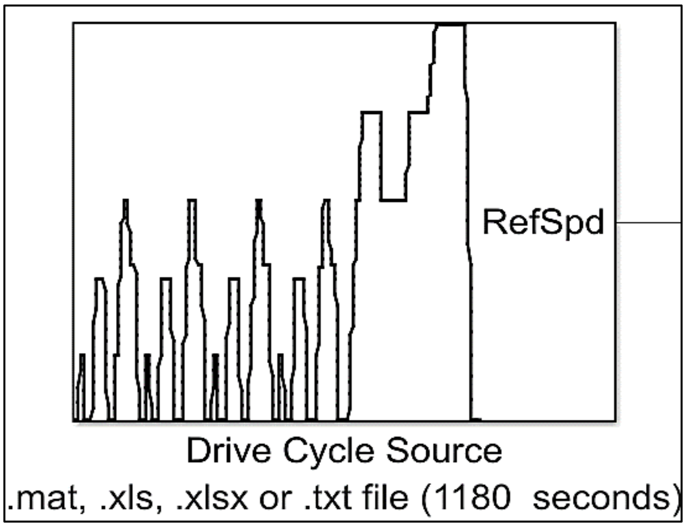

Figure 4.30 MIDC Drive Cycle Source Block

JC08 Driving Cycle

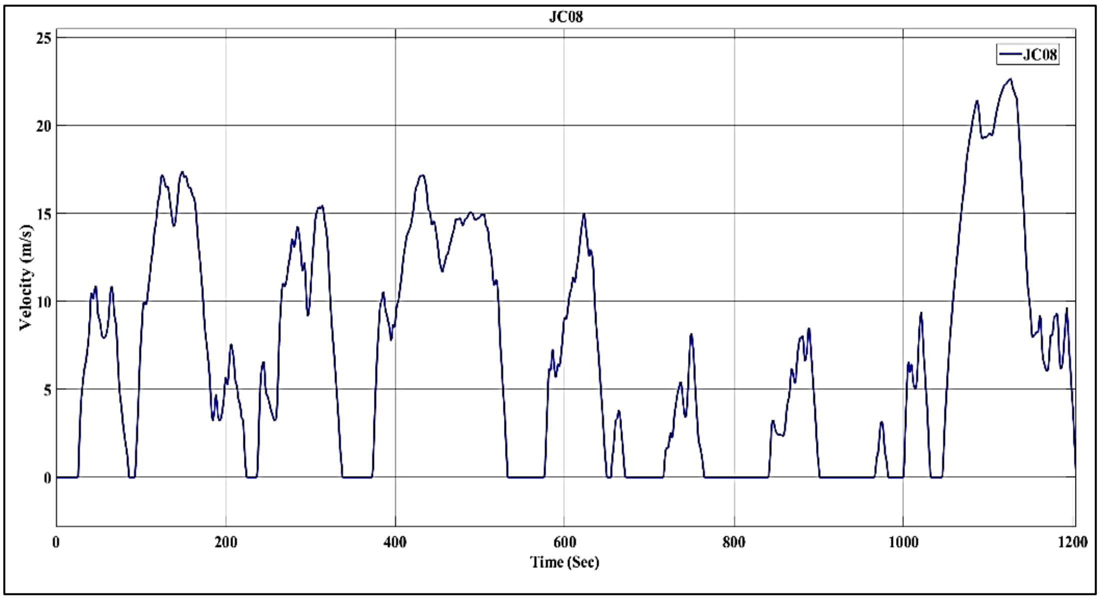

Figure 4.31 JC08 Driving Cycle

The Japanese 10-15 Mode Cycle (JC08) is a standardized test cycle used in Japan to evaluate vehicle performance and emissions. It comprises urban, suburban, and highway driving scenarios, with defined speed and acceleration profiles. By replicating real-world driving patterns, the JC08 provides a more accurate assessment of fuel efficiency and emissions compared to previous test cycles. Manufacturers and researchers utilize the JC08 to assess vehicle performance under Japanese driving conditions, aiding in the development of more sustainable and efficient automotive technologies to meet regulatory standards and consumer expectations in Japan.

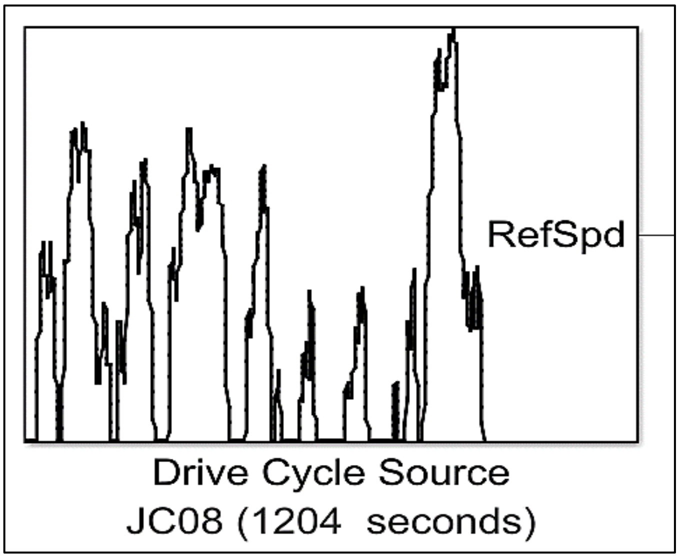

Figure 4.32 JC08 Drive Cycle Source Block

EUDC Driving Cycle

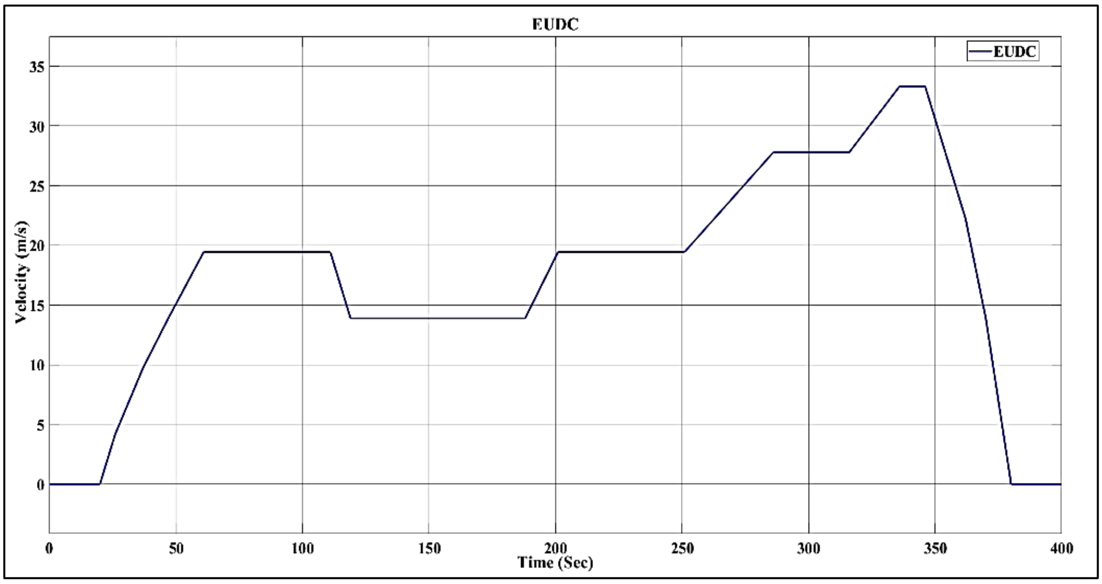

Figure 4.33 EUDC Driving Cycle

The Extra-Urban Driving Cycle (EUDC) is a standardized test cycle employed to evaluate vehicle performance and emissions during extra-urban driving conditions. It encompasses steady state driving at higher speeds typical of highway or rural roads, with minimal acceleration and deceleration. The EUDC aims to replicate real-world driving patterns outside urban areas, providing insights into fuel efficiency and emissions during extended highway cruising. Manufacturers and researchers utilize the EUDC to assess vehicle performance under extra-urban driving conditions, facilitating the development of more sustainable and efficient automotive technologies compliant with regulatory standards and consumer demands.

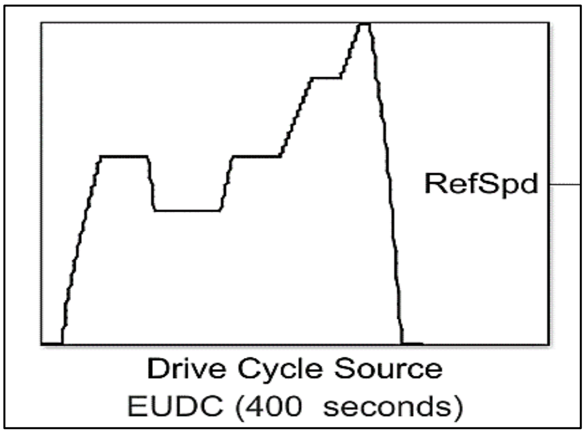

Figure 4.34 EUDC Drive Cycle Source Block

For the sake of simplicity, the EUDC drive cycle serves as the primary input drive cycle for the results and discussion chapter.

4.6 MATLAB HEV Simulation

This section encompasses the specifications provided as inputs to the components of the HEV model, along with a detailed explanation of the model's operation.

4.6.1 Vehicle Specification

The major and important specifications have been provided for the components of the HEV Model. The specifications listed in the table below pertain to the Toyota Prius 4th generation vehicle, specifically the XW50 2016-2022 model.

Table 4.2 Vehicle Body Parameters [15]

Vehicle Body Parameters	Value
Gross Vehicle Weight	1775 kg
Drag Coefficient	0.24
Density Of Air	1.293 kg/m3
Frontal Area	2.5872 m2
Wheel Radius	0.3175 m
Fuel Tank Capacity	43 L

Table 4.3 Gear Ratios as per Calculations

Gear Ratio	**Value**
Planetary Gear	2.6
65T Fix Gear to 53T Axle Gear	0.815
21T Axle Gear to 73T Wheel Gear	3.476
17T Motor Gear to 53T axle Gear	3.117

Table 4.4 Power Source Block Parameters [15]

Block Parameters	**Value**
Engine • Displacement • Max. Power • Max Torque	• 1.8 L • 72 @ 5200 rpm • 142 @ 3600 rpm
MG2 • Max. Power • Max Torque	PMSM • 53 kW • 163 Nm
MG1 (Generator) • Max. Power • Max Torque	PMSM • 53 kW • 163 Nm
Battery • Nominal Voltage • Battery Capacity	Nickel-metal hydride • 201.6 V • 1.31 kWh

4.6.2 MATLAB Model & it's Working.

The HEV MATLAB model is built using Simscape and Simulink library blocks, as discussed in the preceding section. It comprises four main systems: mechanical, electrical, energy storage, and logic. The mechanical and electrical systems are modeled using Simscape library components, while the energy storage and logic systems utilize Simulink library blocks.

The primary input to the HEV model is the reference Drive Cycle Source, which feeds into the longitudinal driver block. This block outputs signals ranging between 0 and 1 to control the voltage source. The longitudinal driver incorporates a built-in PID controller with a K_P value of 15 and a K_I value of 1, continuously monitoring vehicle output velocity via a feedback loop to match the reference velocity.

The signal from the longitudinal driver controls the voltage source to power the main motor, MG2, directly connected to the wheel axle via a gear train with a gear ratio of 10.835:1. The engine assists MG2 only when vehicle torque demand exceeds MG2's maximum torque. The vehicle torque demand is calculated based on the drive cycle input. The engine throttle operates based on a logic controller, adjusting between 0 and 1 based on vehicle torque requirements, ensuring optimal engine operation.

During engine assistance, any surplus power is directed to MG1, connected to the sun gear in the planetary gear system. MG1 functions as a generator when the engine is running, charging the battery. Similarly, during vehicle deceleration, MG2 acts as a generator, facilitating regeneration.

The specifications of the HEV model correspond to the Toyota Prius 4th generation vehicle, as discussed previously. The model is tested with various drive cycles as inputs to calculate vehicle range, fuel consumption, and power consumption, detailed in the subsequent chapter.

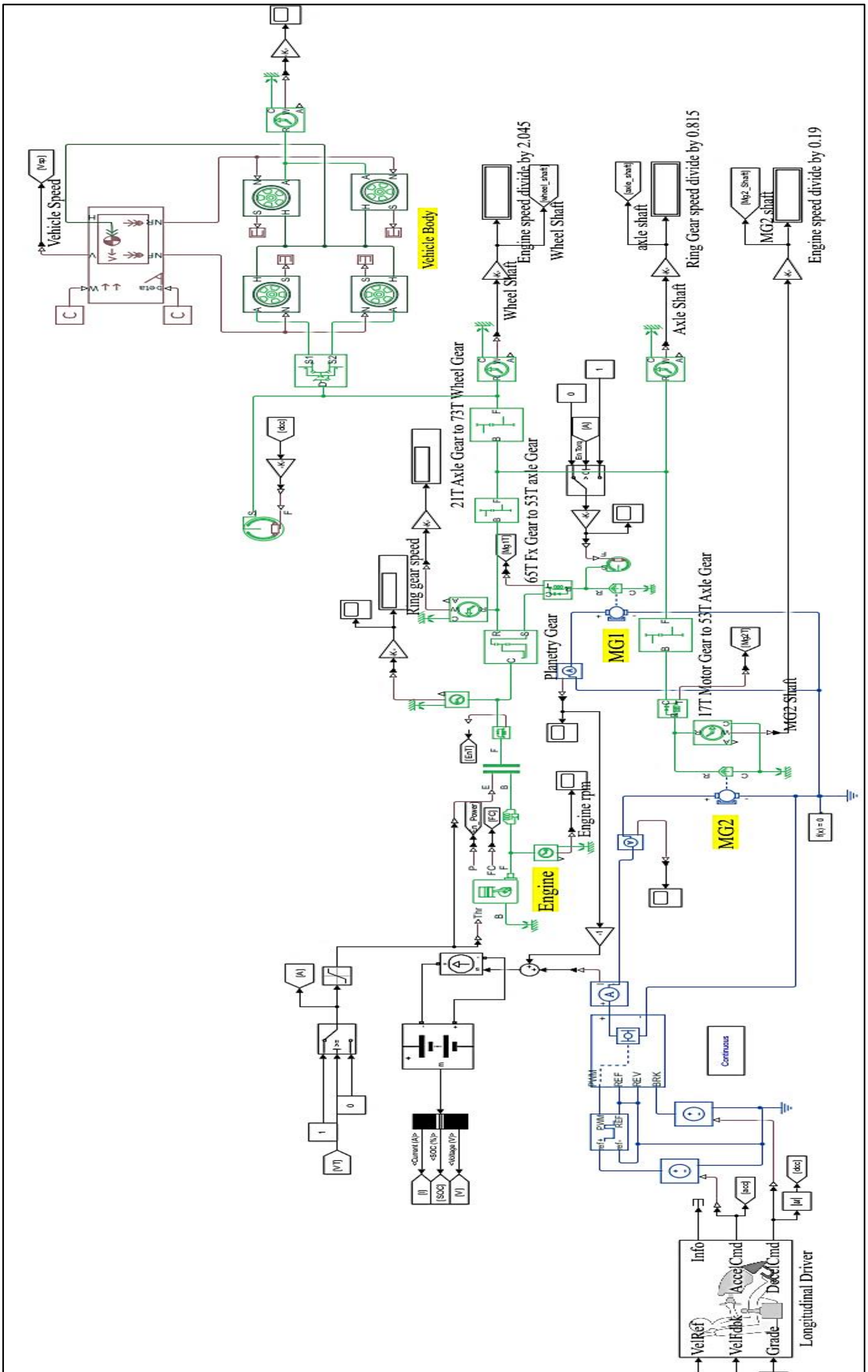

Figure 4.35 Complete Power-split HEV Model

4.7 Summary

Chapter 4 of the project thesis delves into the modeling of a Power-split Hybrid Electric Vehicle (HEV), aiming to optimize performance and fuel consumption through Simulink simulation. Beginning with an overview of mechanical systems, the chapter explores forces acting on the vehicle body, including rolling resistance, aerodynamic resistance, and grade resistance, modeled using Simscape and Simulink libraries. Transmission system modeling follows, incorporating gear blocks arranged in a series-parallel configuration like the Toyota Prius 4th generation vehicle. The engine block, sourced from the MATLAB Simscape library, is provided with input data specific to the Prius, including torque-speed characteristics and brake-specific fuel consumption. Mechanical sensors are employed to measure parameters directly, aiding in real-time monitoring. The chapter transitions to electrical systems, detailing MG2 motor circuitry, engine assistance via MG1 generator, battery circuits, and control elements like PWM voltage sources and current sensors, all modeled using Simscape. Longitudinal driver and drive cycle source blocks facilitate the accurate representation of vehicle behavior under different driving scenarios. The chapter culminates in a comprehensive MATLAB HEV simulation model, integrating mechanical, electrical, energy storage, and logic systems, tested with various drive cycles to evaluate range, fuel consumption, and power consumption. The model's specifications align with those of the Toyota Prius 4th generation vehicle, ensuring relevance and applicability.

Chapter 5

5 Results and Discussion

5.1 Results

For the sake of simplicity and improved comprehension of the output data, the EUDC driving cycle is considered the primary focus. The cycle runs for 400 seconds, and the resulting graph is computed using the scope block sourced from the MATLAB Simulink library. This section will comprehensively discuss all output parameters, including Torque demand of the vehicle, Vehicle speed, Shaft angular speed, Torque of all three power sources, Generation by MG2 & MG1, Battery parameters such as current and state of charge (SOC), Battery power, engine power, and Fuel consumption. These models then have been analyzed in three different cycles which are discussed in section 4.5.

5.1.1 Torque Demand of the Vehicle

The torque demand of the vehicle is determined through an analysis of the forces acting upon it, as elaborated in section 4.2.1.

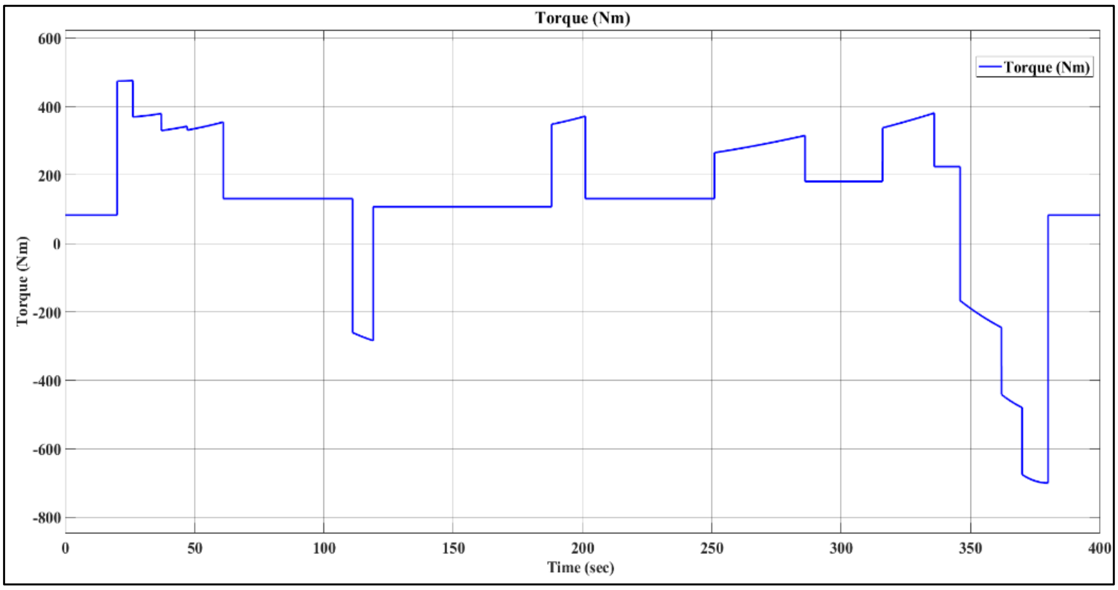

Figure 5.1 Torque Demand of the Vehicle

This graph depicts the torque variation with changes in the velocity of the reference input driving cycle over time. From the graph we can see at 10 sec which is the start point of the cycle torque is more and wherever acceleration is there is a spike of torque. A negative toque in the graph implies deceleration.

5.1.2 Vehicle Speed Vs Reference Speed

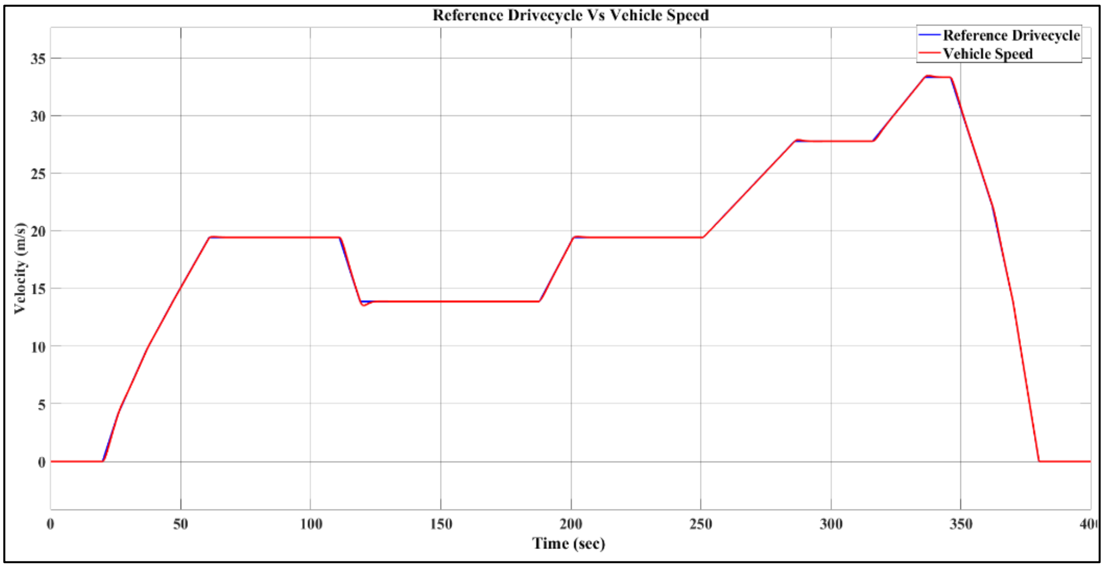

Figure 5.2 Vehicle Speed Vs Reference Speed

In a graph presented it becomes evident that the vehicle closely mirrors the characteristics of the reference drive cycle which is blue. Notably, the graph depicts that the vehicle attains a maximum speed of approximately 33 m/s within a defined time interval, indicative of its adherence to the prescribed velocity profile. Furthermore, over 400 seconds, the vehicle traverses a distance spanning nearly 6.956 kilometers. This alignment with the reference drive cycle parameters underscores the effectiveness of the vehicle's performance in replicating real-world driving conditions. Such detailed analysis provides valuable insights into the vehicle's operational behavior and its ability to meet designated performance benchmarks as outlined by the reference drive cycle.

5.1.3 Angular speed of the shaft of the transmission system

The graph below displays the angular speeds of three distinct shafts: the wheel gear shaft, the axle shaft, and a shaft linked to the MG2 motor, as detailed in section 4.2.2. The angular velocity of the shaft is measured using the Rotational sensor which will give output in radians per second which is converted to rpm using the Physical signal to Simulink converter tool.

In the below graph, the angular speed of the axle shaft appears negative, indicating counterclockwise rotation relative to the wheel and axle shaft.

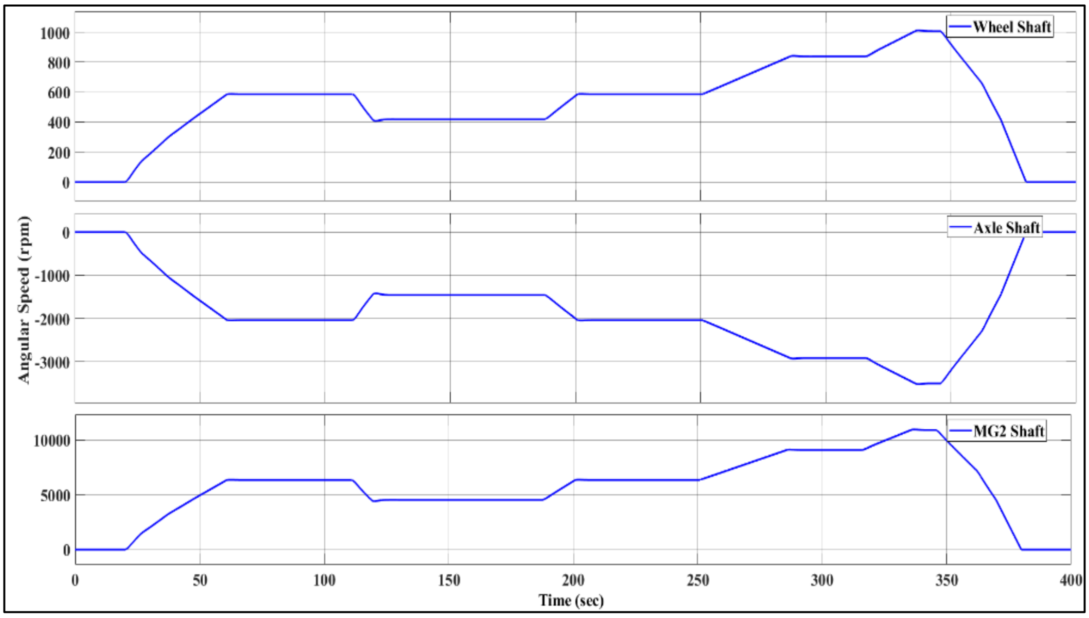

Figure 5.3 Angular Speeds of Output Shafts

5.1.4 Torque Deliver by Power Source

The graph illustrates the torque delivered by the MG2 motor, the engine, and the MG1 motor for the specified input driving cycle.

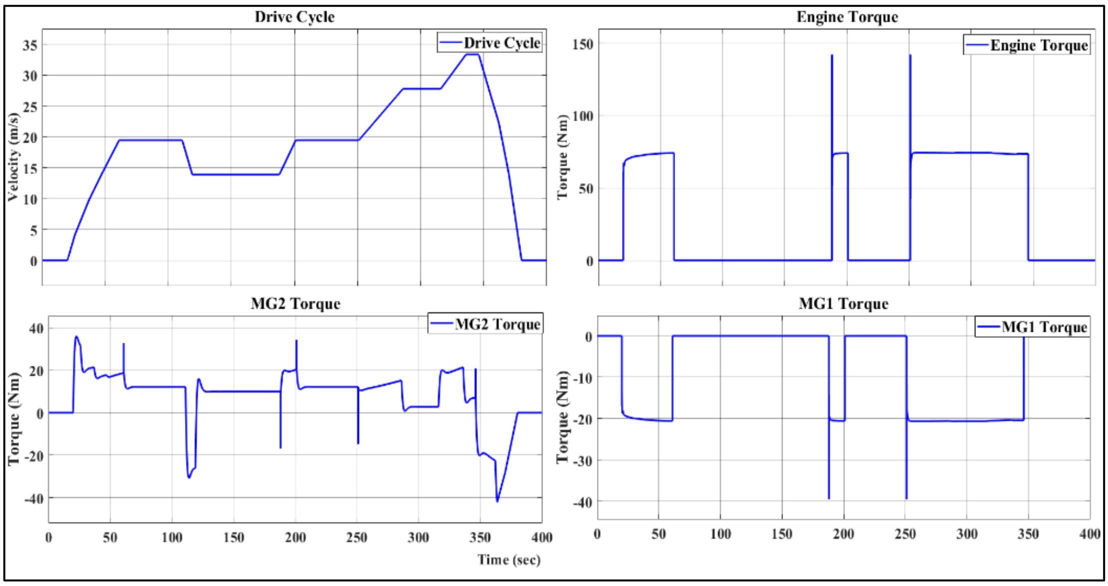

Figure 5.4 Torque of Power Sources

Here, you can observe that when the motor surpasses its maximum torque threshold which is 163Nm, at the same time the engine gets started and fulfills the remaining torque demand of the vehicle. A negative torque direction for MG1 implies that while the engine assists the MG2 motor, it concurrently provides power to the MG1 generator for battery charging purposes.

5.1.5 Battery Parameters

The graph below illustrates the current consumption and state of charge (SOC) of the battery for the specified input driving cycle.

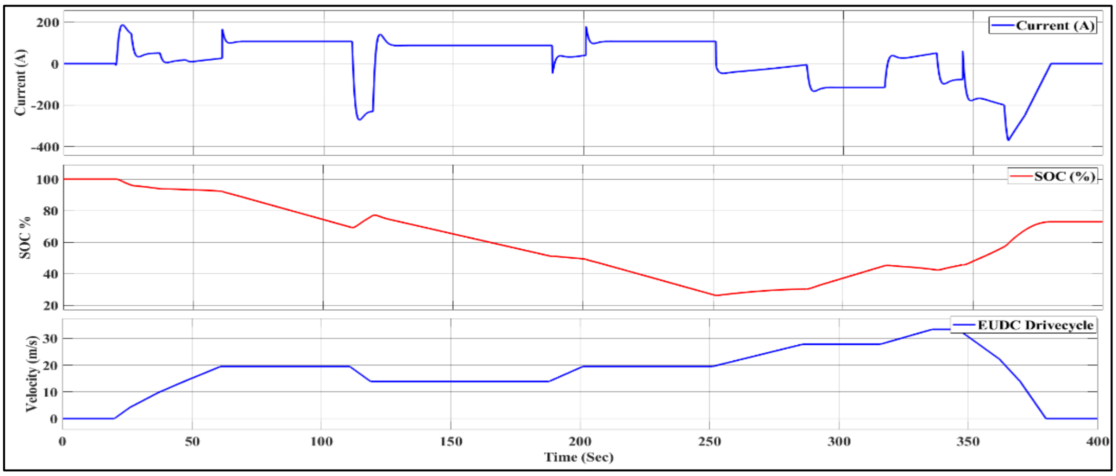

Figure 5.5 Battery Current & SOC

Here, you can observe the current graph fluctuating both above and below zero. A positive value indicates consumption by the MG2 motor, while negative values imply battery charging by the MG2 and MG1, which will be further elaborated upon. For 400 seconds, the battery's SOC decreases by approximately 25%.

5.1.6 Generation by MG2

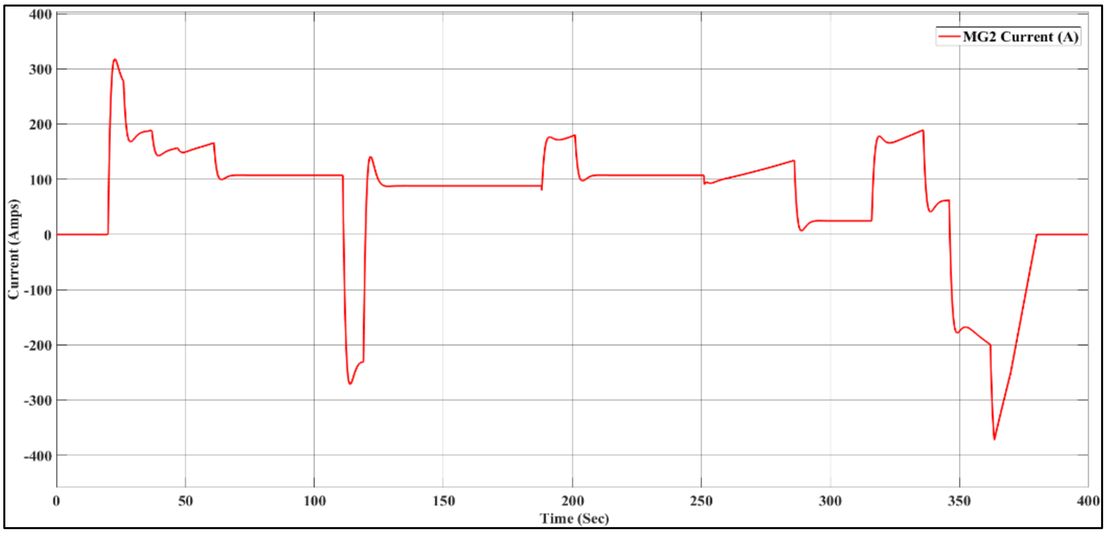

Figure 5.6 Generation by MG2

In intricate scrutiny of the graph presented it emerges that positive current values correspond to instances where the MG2 motor draws power from the battery to facilitate the vehicle's forward motion. Conversely, negative current values are observed during deceleration phases, indicating that the MG2 motor transitions into a regenerative mode, acting as a generator to replenish the battery's charge. This dynamic interplay between positive and negative currents showcases the dual functionality of the MG2 motor, serving both as a motive force provider and a recuperative system during braking or deceleration events. Such detailed analysis underscores the versatility and efficiency of the vehicle's propulsion system, enhancing its overall performance and energy management capabilities.

5.1.7 Generation by MG1

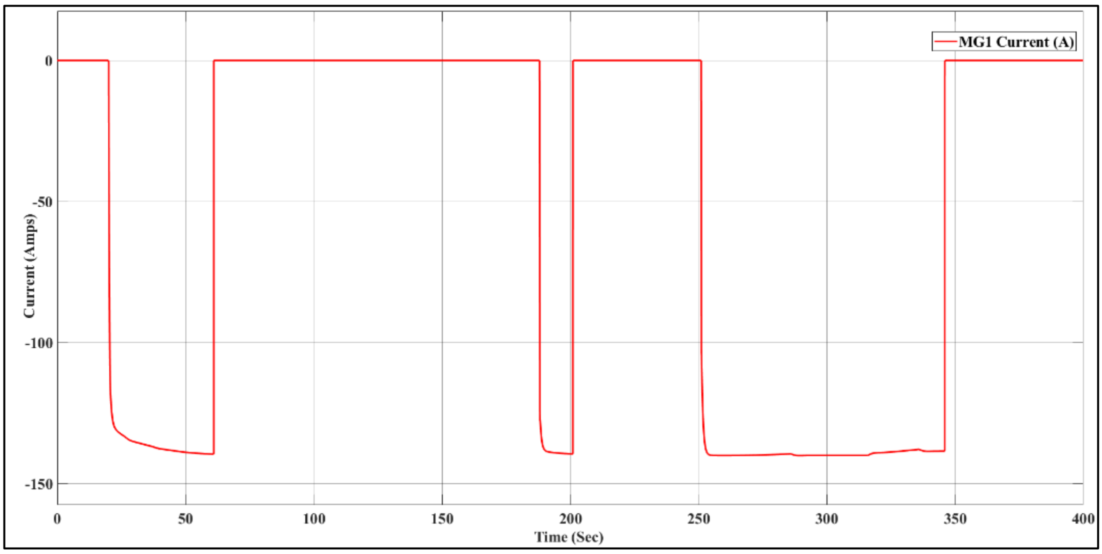

Figure 5.7 Generation by MG1

Upon closer examination of the graph below, it becomes evident that negative values represent instances where the MG1 generator is actively involved in replenishing the battery's charge. This occurs specifically when the engine is operational to support the MG2 motor. Such a scenario typically arises during periods of increased power demand or when additional assistance is required for vehicle propulsion. Thus, the negative values serve as indicators of the charging process initiated by the MG1 generator, effectively contributing to the maintenance or enhancement of the battery's state of charge.

5.1.8 Engine Torque vs Battery SOC

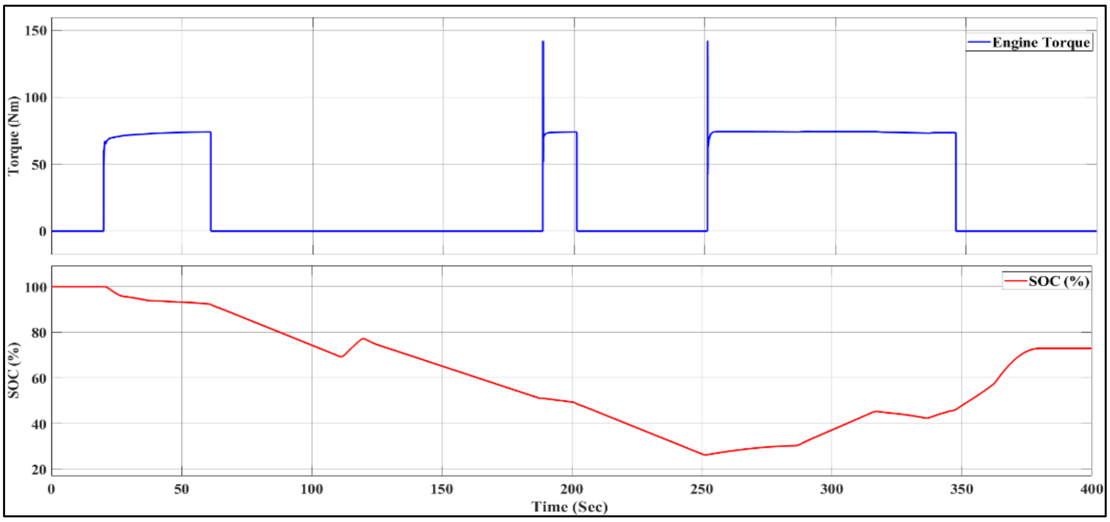

Figure 5.8 Engine Torque Vs Battery SOC

In the figure, detailed observation reveals that the battery SOC exhibits a less steep slope when the engine is activated to assist the MG2 motor. Conversely, when the engine is not in operation, the slope of the battery SOC tends to be steeper. This suggests that the presence of the engine attenuates the rate of battery discharge, resulting in a more gradual decline in SOC over time.

5.1.9 Power Consumption

Battery Power Consumption

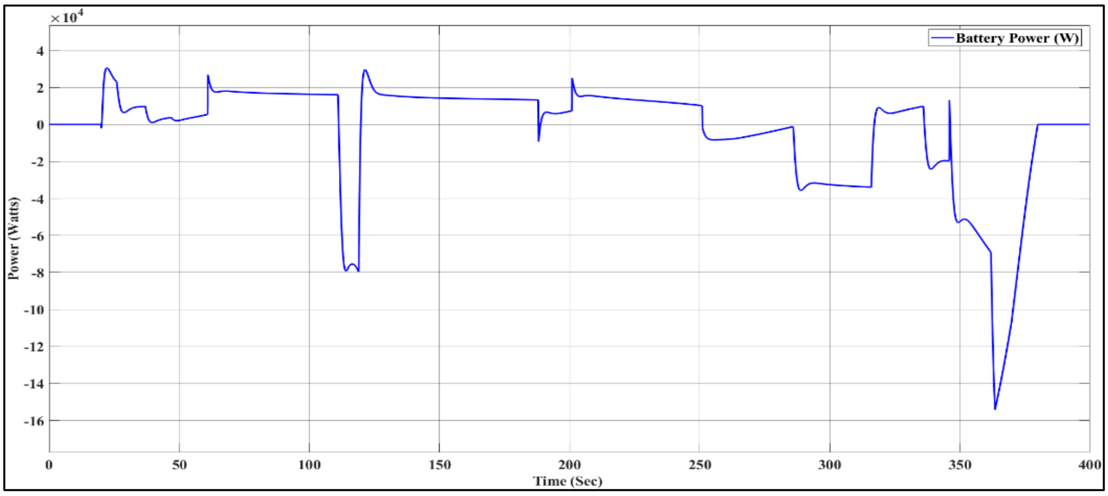

Figure 5.9 Battery Power Consumption

Based on the battery parameter section discussed previously, battery power consumption is computed as depicted in the figure, with maximum power consumption reaching approximately 25 kW.

Engine Power consumption

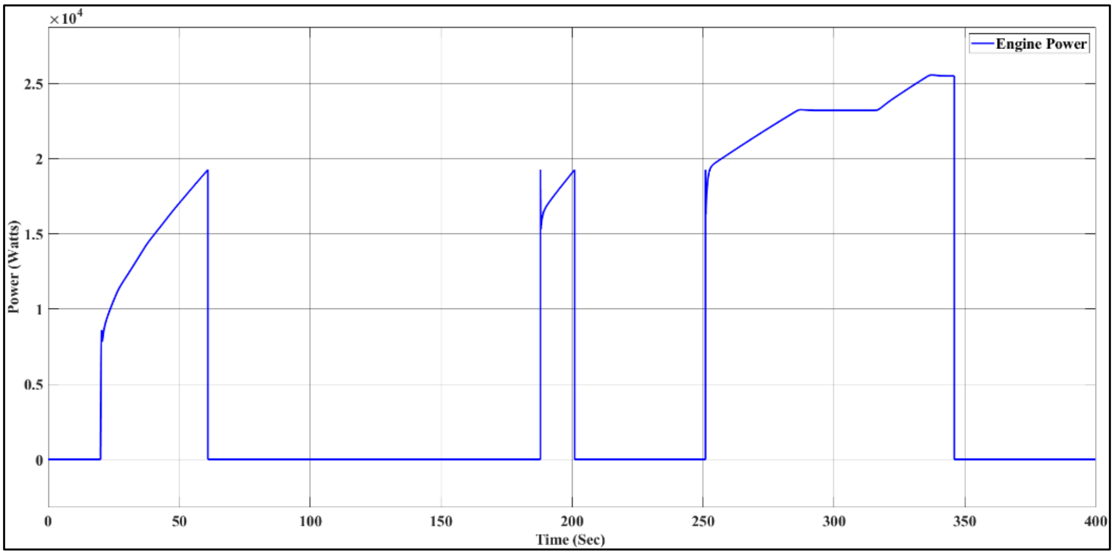

Figure 5.10 Engine Power Consumption

The graph illustrates the maximum power delivered by the engine while assisting the MG2 motor. It reveals that the engine reaches its peak power output during instances when the vehicle requires significant acceleration, notably between 250 seconds and 350 seconds. During this interval, the engine delivers approximately 25 kW of power to meet the heightened acceleration demands.

5.1.10 Fuel Consumption

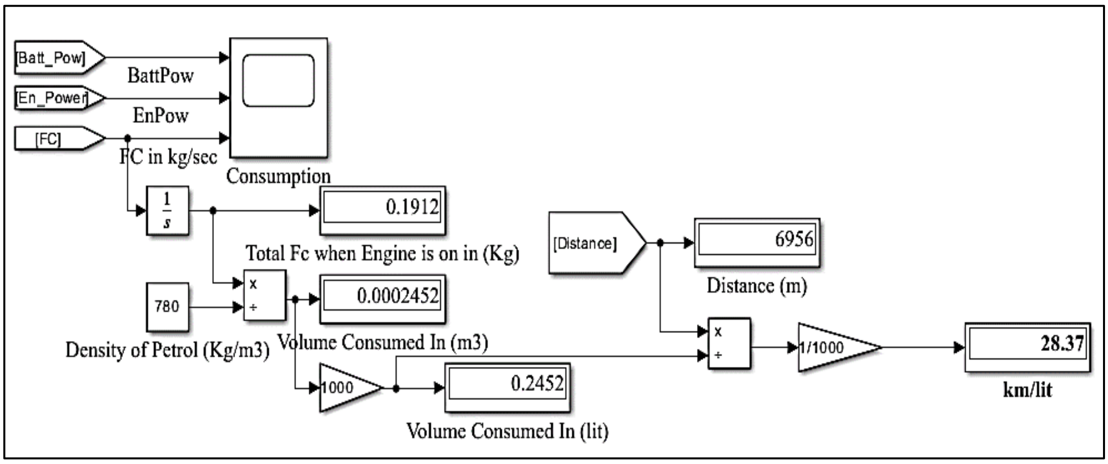

Figure 5.11 Simulink Diagram of Fuel Consumption

The simulation is executed over 400 sec EUDC cycle as shown in **Figure *5.11***, during which the vehicle traverses 6.956 km following the input drive cycle. Throughout this time interval, whenever the engine engages to support the MG2 motor, it operates within its optimal Brake-Specific Fuel Consumption (BSFC) zone, resulting in a minimal fuel consumption of 28.37 km/lit. For calculating the fuel consumption in liters, the density of petrol is assumed to be 780 kg/m^3.

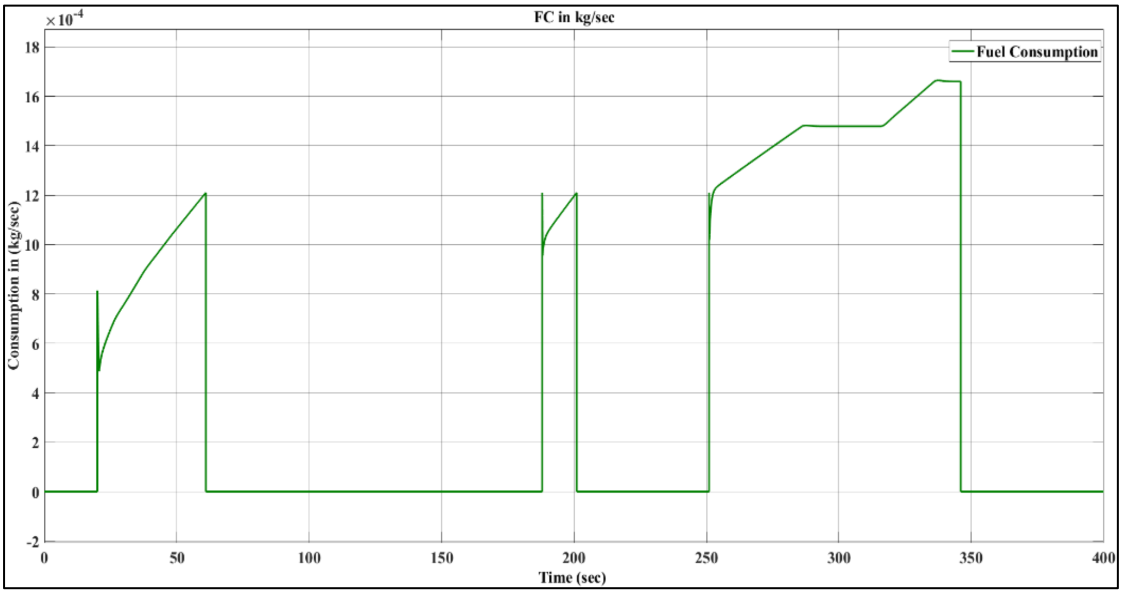

Figure 5.12 Fuel Consumption Vs Time

This model has been tested on both the JC08 and MIDC driving cycles also, and the mileage obtained is presented in the table below:

Table 5.1 Mileage Calculation for Different Drive Cycles

Sr. No.	Parameters	EUDC	JC08	MIDC
1.	Time (sec)	400	1204	1180
2.	Distance in (km)	6.929	8.172	10.67
3.	Mileage in (km/lit)	28.37	27.95	28.10
4.	Actual (km/lit)	-	30.30	-
5.	Top Speed (km/hr.)	120	~82	90

5.2 Summary

In Chapter 5, the EUDC driving cycle, running for 400 seconds, serves as the primary focus for evaluating the Power-split Hybrid Electric Vehicle (HEV) model. Using the MATLAB Simulink scope block, the output parameters are analyzed, including torque demand, vehicle speed, shaft angular speed, torque from three power sources, and generation by MG2 and MG1. The analysis reveals that torque demand spikes during acceleration and drops during deceleration, while vehicle speed closely follows the reference cycle, reaching a maximum of 33 m/s over 6.956 kilometers. The angular speed of transmission shafts shows counterclockwise rotation for the axle shaft. The torque graph indicates that when MG2 exceeds its maximum torque, the engine activates to meet additional demand and charges the battery through MG1. Battery parameters show a 25% SOC decrease over the cycle, with MG2 functioning as both motor and generator. Power consumption peaks at 25 kW for the battery and engine during high demand. Fuel consumption results in mileage of 28.37 km/l, with the model performing similarly under JC08 and MIDC cycles, achieving mileages of 27.95 km/l and 28.10 km/l respectively. This detailed analysis underscores the model's efficiency and its capability to simulate real-world driving conditions effectively.

Chapter 6

6 Conclusions & Future Scope

6.1 Conclusions

The following conclusions were made based on performing simulations and calculations:

1) Transmission System Configuration: Analysis and discussion led to the selection of a series-parallel transmission system configuration like that of the Toyota Prius 4th generation vehicle.
2) Gear Ratios Determination: By calculating and considering vehicle specifications, appropriate gear ratios for the transmission system are determined, ensuring optimal performance and efficiency.
3) Simscape Modeling: Utilizing Simscape library components, a comprehensive transmission system model is developed, incorporating gear blocks and power flow diagrams to simulate the system's behavior accurately.
4) Mechanical Systems Modeling: Detailed examination and modeling of mechanical components, including the vehicle body, forces acting on the vehicle, rolling resistance, aerodynamic resistance, and grade resistance, provide insights into vehicle dynamics and energy consumption.
5) Transmission System Simulation: The series-parallel transmission system is simulated using Simscape library components, emphasizing power flow, gear ratios, and system behavior under different driving conditions.
6) Electrical Systems Modeling: Utilizing Simscape libraries, the electrical subsystem of the HEV, including the MG2 motor circuit, MG1 generator circuit, battery circuits, and control elements, is modeled to simulate power distribution, regeneration, and energy management.
7) Comprehensive Analysis of Output Parameters: Through simulation results and graphical representations, various output parameters such as torque demand, vehicle speed, shaft angular speed, torque from power sources, battery parameters, generation by MG2 and MG1, engine torque versus battery SOC, power consumption, and fuel consumption are comprehensively analyzed.
8) Alignment with Reference Drive Cycles: The vehicle's performance closely aligns with prescribed velocity profiles of reference drive cycles, demonstrating

effectiveness in replicating real-world driving conditions and achieving designated performance benchmarks.

9) Efficiency and Sustainability: Analysis of fuel consumption, power distribution, and energy management strategies indicates the hybrid powertrain's efficiency and potential for sustainable transportation solutions, with minimal fuel consumption and adherence to driving cycle parameters.
10) Conclusion: The study concludes that the developed HEV model holds promise as an efficient and sustainable transportation solution, offering insights into energy management strategies, powertrain optimization, and fuel efficiency across diverse driving scenarios. The integration of mechanical and electrical systems enables dynamic control and optimization, enhancing overall vehicle performance and sustainability.

6.2 Future Scope

To further enhance the simulation model, future optimization efforts could focus on designing a refined control system aimed at effectively operating the engine and motor within their respective efficient zones. Specifically, in the current simulation setup, engine activation occurs at the onset of vehicle operation due to initial torque demands surpassing the motor's maximum torque capacity. Developing a robust control algorithm capable of managing engine start and stop conditions by torque demands would be instrumental in optimizing system performance. Additionally, the allocation of torque between power sources could be enhanced through the utilization of appropriate Simscape library blocks, thereby refining the system's overall efficiency.

Expanding the scope of the simulation model presents opportunities to leverage HEV vehicle data to enhance its eco-friendliness and operational efficiency. By integrating advanced simulation techniques, the sizing of components can be tailored to meet specific requirements, potentially resulting in reduced vehicle weight and enhanced cost-effectiveness. Moreover, the adoption of eco-friendly fuels in the engine stands to further augment the environmental sustainability of HEVs.

In the realm of emissions analysis, the implementation of an emission model holds promise for evaluating emissions across diverse drive cycles, providing valuable insights into the environmental impact of HEV operation. Through these future endeavors, the simulation model can evolve into a comprehensive tool for not only optimizing HEV performance but also advancing its eco-friendly attributes.

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