MODELING AND SIMULATION OF THREE-WHEELER HYBRID ELECTRIC VEHICLE USING MATLAB SIMULINK SIMSCAPE

Berhanu Kelbessa Shentama

A Thesis submitted to the Department of Mechanical Engineering

School of Mechanical, Chemical and Materials Engineering.

Presented in Partial Fulfillment of the Requirements for the Degree of Master's in Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

May 2024

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled "***Modeling and Simulation of Three-Wheeler Hybrid Electric Vehicle using MATLAB Simulink SimScape***" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Berhanu Kelbessa Shentama	______________________	May 2024
Name of the student	Signature	Date

RECOMMENDATION

I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled "***Modeling and Simulation of Three-Wheeler Hybrid Electric Vehicle using MATLAB Simulink SimScape***" prepared under my/our guidance by Berhanu Kelbessa submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Automotive Engineering. Therefore, I/we recommend the submission of revised version of the thesis to the department following the applicable procedures.

______________________	______________________	______________________
Major Advisor	Signature	Date
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Co-advisor	Signature	Date

APPROVAL

I/we, the advisors of the thesis entitled "***Modeling and Simulation of Three-Wheeler Hybrid Electric Vehicle using MATLAB Simulink SimScape***" and developed by Berhanu Kelbessa hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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Co-advisor	Signature	Date

APPROVAL OF BOARD OF EXAMINERS

We, the undersigned, members of the Board of Examiners of the thesis by Berhanu Kelbessa have read and evaluated the thesis entitled "***Modeling and Simulation of Three-Wheeler Hybrid Electric Vehicle using MATLAB Simulink SimScape***" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Automotive Engineering.

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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ACRONYMS AND ABBREVIATIONS

A	-	*Area of the piston*
AC	-	*Alternating Current*
CD	-	*Charge Depletion*
CS	-	*Charge Sustaining*
DC	-	*Direct Current*
$\frac{d\omega}{dt}$	-	*Angular Acceleration of the Motor*
EM	-	*Electric Motor*
ESS	-	*Energy Storage System*
F	-	*Frictional Force*
h	-	*Hour*
HESS	-	*Hybrid Energy Storage System*
HEV	-	*Hybrid electric vehicles*
HIL	-	*Hardware-in-the-loop*
HMI	-	*Human-machine interface*
ICE	-	*Internal combustion engine*
I_m	-	*Motor Inertia*
i_m	-	*Input Current*
Kg	-	*Kilogram*
K_i	-	*Torque Constant Value*
L	-	*Stroke Length*
MEP	-	*Mean Effective Pressure*
MPPT	-	*Maximum Power Point Tracker*
N	-	*Engine Speed*
PHEV	-	*Plug-in Hybrid Electric Vehicle*
PID	-	*Proportional-integral-derivative*
PMSM	-	*Permanent magnet synchronous motor*
PVHEV	-	*Photovoltaic Hybrid Electric Vehicle*

P_B	-	*Brake Power*
$P_{Battery}$	-	*Battery Power*
P_f	-	*Frictional Power*
P_I	-	*Indicated Power*
P_m	-	*Mechanical Power*
P_{motor}	-	*Electric Motor Power*
Q_o	-	*Heat Supplied*
Q_I	-	*Heat Rejected*
r	-	*Compression Ratio*
REVS	-	*Renewable Energy Vehicle*
SIL	-	*Software-in-the-loop*
SRM	-	*Switched Reluctance Motor*
THMBMS	-	*Three-Wheeler Hybrid Vehicle Multi-Body*
THVDS	-	*Three-Wheeler Hybrid Vehicle Dynamics*
THVS	-	*Three-Wheeler Hybrid Vehicle*
TTR	-	*Through-The-Road*
T_B	-	*Brake Torque*
T_m	-	*Motor Output Torque*
V_c	-	*Clearance Volume*
V_s	-	*Swept Volume*
V_t	-	*Total Volume*
W	-	*Work Done*
w	-	*Watt*
η	-	*Thermal Efficiency*
$\eta_{Battery}$	-	*Battery Discharging Efficiency*
η_{motor}	-	Electric Motor Efficiency

ABSTRACT

Three-wheeler hybrid electric vehicles have become a popular due to their improved fuel efficiency and reduced emissions. However, these three-wheeler hybrid vehicles present a unique set of technical specifications and requirements, and the process of training the drivers and mechanics of these vehicles can be both costly and time-consuming. Thus, in this thesis, three-wheeler hybrid electric vehicle model is developed using MATLAB Simulink based on the real-world three-wheeler vehicle specification for parallel mode using SimScape driveline to simulate their dynamics. The model includes battery, DC-DC converter, electric motor, combustion engine, gearbox, and vehicle body. The model is developed for 3 kW engine, AC induction motor of 5 kW, and Lithium-ion battery of 48 V. The model is simulated for accelerate and decelerate condition for 3600 seconds run time. The model has the ability to simulate the shaft speed of both the combustion engine and electric motor, power of battery and engine, electrical losses of both battery and electric motor. Therefore, in parallel mode hybrid electric vehicle model, the vehicle speed and engine power have inverse relation, and the vehicle speed and battery or motor power have direct relation. Moreover, as the vehicle speed increases by 4.63%, the battery power increases by 127%. Whereas, as the vehicle speed increases by 4.63%, the engine power decreases by 25.8%. Furthermore, as the vehicle speed increases total electrical loss increases. Whereas, as the vehicle speed decreases total electrical loss decreases. This indicates the electrical power loss of battery and motor for hybrid electric vehicle is more in acceleration than deceleration.

Keywords: *Hybrid electric, SimScape, Simulink, Three-wheeler, Vehicle.*

CHAPTER ONE

1. INTRODUCTION

1.1. Background

Three-wheelers vehicles are a type of vehicle that has three wheels instead of four. They are often used in developing countries, as they are relatively inexpensive to purchase and operate. *Figure 1.1* shows typical three-wheeler vehicle used in Ethiopia. Three-wheelers can also be used in urban areas, as they are smaller and more maneuverable than cars (Shaha and Uddin, 2014). They can be powered by a variety of engines, including gasoline, diesel, and electric. In addition, nowadays, hybrid electric vehicles are becoming popular for three-wheelers (Alemayehu and Nallamothu, 2017; Brady, 2022).

Three-wheeler hybrid vehicles have gained significant attention as a potential solution to address urban transportation challenges (Mulhall et al., 2010). Hybrid electric vehicles (HEVs) combines an internal combustion engine (ICE) with one or more electric motors. This combination allows HEVs to achieve better fuel economy and emissions than conventional gasoline-powered vehicles. HEVs are becoming increasingly popular, as governments and consumers look for ways to reduce their environmental impact (Alemayehu and Nallamothu, 2017; Montaleza et al., 2021).

Hybrid powertrains can be classified into three main categories: series, parallel, and power-split. Each configuration has its own advantages and disadvantages, and the choice of configuration depends on the specific application and performance requirements (Tansini et al., 2023). The design of a hybrid powertrain must satisfy various performance criteria, including vehicle performance metrics and energy consumption. The available options for powertrain configurations and components must also be considered (Tran et al., 2021).

Figure 1.1: Three wheeler vehicle (Hambissa et al., 2022)

The combination of a three-wheeler and a hybrid electric powertrain has the potential to create a very efficient and environmentally friendly vehicle. However, the design and modeling of such a vehicle is a complex task (Fraikin et al., 2020). It requires a thorough understanding of various powertrain components and configurations (Tran et al., 2021). As governments and consumers look for ways to reduce their environmental impact, three-wheeler hybrid vehicles are likely to become more popular.

Given the unique characteristics of three-wheeler hybrid vehicles, the development of a specialized model is necessary to accurately model their dynamics and overall performance. Accurate modeling of the three-wheeler hybrid vehicle's dynamics is essential for a realistic simulation. This includes considering factors like suspension, steering, braking systems, and tire characteristics (Singh et al., 2019).

Powertrain modeling is an important aspect of the design process. MATLAB/Simulink is a widely used tool for powertrain modeling, and it allows for the modeling of powertrain components and energy consumption (Tran et al., 2021). Analytical models are commonly used for energy consumption modeling. These models work based on longitudinal vehicle dynamics and electric motor losses estimation from available efficiency maps (Miri et al., 2021). In addition, REVS (Renewable Energy Vehicle simulator) is a simulation and modeling package developed at the University of Manitoba. It assists in the modeling and simulation of a series-parallel hybrid electric vehicle (Gao and Emadi, 2016).

Vehicle model simulations play a crucial role in the design and development of new vehicle prototypes. They allow engineers to conduct virtual testing and experimentation in a controlled environment, which saves time, cost, and resources compared to traditional physical testing (Alemayehu and Nallamothu, 2017). Moreover, they help to train operators, drivers and mechanics to gain enough information and skill about the vehicles. A well-designed three-wheeler hybrid vehicle model can have diverse applications. It can be utilized for research and development purposes, evaluating design alternatives, training drivers, and assessing the impact of different driving and traffic scenarios on vehicle performance and efficiency (Gao and Emadi, 2016). However, in order to create an accurate vehicle model, data such as vehicle kinematics, tire characteristics, and powertrain performance are essential for creating an accurate model (Won, 2021).

1.2. Statements of the Problem

The demand for energy-efficient and eco-friendly vehicles is rapidly increasing in response to the challenges of high fuel consumption and environmental pollution. To address this issue, three-wheeled hybrid vehicles have become a popular alternative due to their improved fuel efficiency and reduced emissions. However, the lack of an accurate model that adequately simulates their dynamics and behavior impedes effective real-time testing. Thus, this study aims to address these limitations by modeling and simulating three-wheeler hybrid vehicles that can precisely model their dynamics.

1.3. Research Question

This thesis is focused on the following research questions:

- How can a three-wheeler HEV be modeled to accurately model the dynamics of a three-wheeler hybrid vehicle?
- How can the dynamics of a three-wheeler hybrid electric vehicle be effectively simulated?
- How to evaluate the effectiveness of the three-wheeler hybrid electric vehicle model?

1.4. Objective

1.4.1. General Objective

The general objective of this thesis is to perform modeling and simulation of three-wheeler hybrid electric vehicle using MATLAB Simulink SimScape.

1.4.2. Specific Objectives

The specific objectives of this thesis are:

- To model the dynamics of the three-wheeler hybrid electric vehicle.
- To simulate the dynamics of the three-wheeler hybrid electric vehicle.
- To evaluate the effectiveness of the three-wheeler hybrid electric vehicle model.

1.5. Scope of the study

The study focuses specifically on the modeling and simulation of three-wheeler hybrid vehicles. It aims to investigate the technical specifications and requirements of the three-wheeler hybrid vehicle. The study is limited to the model and software simulation of the three-wheeler hybrid vehicle. The comprehensive testing and analysis of the model through software simulation is included, however, manufacturing or fabrication of the physical model is not included in this thesis.

1.6. Significance of the Study

The significance of this study is that it models and simulate three-wheeler hybrid vehicles that accurately replicates the behavior and performance of the vehicle under various conditions. The ultimate goal is to contribute to the development of a safe, functional, and efficient three-wheeler hybrid vehicle that meets modern transportation needs while minimizing environmental impact. Moreover, this serves as a valuable tool for researchers and engineers to optimize the model of three-wheeled hybrid vehicles, reducing the reliance on physical testing and saving valuable time and resources.

1.7. Limitation of the Study

While the model successfully captures critical aspects such as shaft speed, power dynamics, and electrical losses, extending the simulation duration could provide a more thorough understanding of the vehicle's behavior over extended operating periods. Thus, a limitation of this study lies in the constrained computational resources which restricted the simulation runtime to 3600 seconds, potentially limiting the comprehensive exploration of long-term performance and dynamic behaviors of the three-wheeler hybrid electric vehicle model. Moreover, based on the literatures reviewed, parallel mode driveline is used for the model development. Hence, the model excludes powertrain driveline comparisons.

1.8. Organization of the thesis

The thesis is divided into five chapters. **Chapter Two** is mainly concerned with the reviews of previous research work, and research gap identified. **Chapter Three** details research materials, tools, and methodologies, along with a visual representation of the thesis's flow. Moreover, it includes the process followed to model and simulate three-wheeler hybrid electric vehicles. **Chapters Four** compares and discusses the results from the previous chapters, in the forms of charts and figures. Finally, **Chapter Five** offer conclusions and recommendations based on the results and findings. Furthermore, a list of references and supplementary appendices are included in the document.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Hybrid Vehicle Technology

The power of the internal combustion engine (ICE) is combined with an electric motor and battery in the hybrid electric vehicles (HEVs). They are becoming popular due to their reduced emissions and fuel efficiency. Other components of HEVs include regenerative braking, which captures and stores the energy normally lost during braking and it stores it in the battery. And power electronics is used to control the flow of energy between the electric motor, battery, and ICE (Montaleza et al., 2021).

There are three primary types of hybrid vehicle technologies. These are, Series hybrids, Parallel hybrids, and Series-Parallel hybrids (Montaleza et al., 2021). In parallel hybrid vehicles, both the electric motor and the internal combustion engine are connected to the transmission and propel the vehicle. In contrast, series hybrid vehicles use the electric motor to propel the vehicle, and the internal combustion engine generates electricity to power the electric motor. Series-Parallel hybrids combine elements from both series and parallel configurations (Singh et al., 2019).

HEVs offer several advantages over traditional vehicles, including improved fuel efficiency and reduced emissions. HEVs achieve better fuel efficiency by using the electric motor to supplement the ICE, reducing the amount of fuel needed to power the vehicle (Taylor, 2001). Regenerative braking also helps to improve fuel efficiency by capturing energy that would normally be lost during braking (Tran et al., 2021). HEVs also produce fewer emissions than traditional vehicles, as the electric motor produces no emissions and the ICE is used more efficiently (Veintimilla Porlán, 2016).

However, hybrid vehicles are more expensive to purchase compared to traditional vehicles due to the complexity of the hybrid system (Northcott, 2007). In addition, the battery pack may require replacement after a certain period due to wear and tear, adding to the maintenance costs of the vehicle (Vasiljevic et al., 2012). Moreover, hybrid vehicles may not be suitable for long-distance driving due to the limited electric-only range of the battery pack (Miri et al., 2021).

Drivetrains in HEVs mainly include parallel, series, and power split designs. HEVs can be classified into six categories. These are parallel, mild/micro parallel, series, combined, power split, and through-the-road (TTR) hybrids. In series HEVs, the power sources supply electrical energy to the DC bus, which is then converted to traction power (Singh et al., 2019).

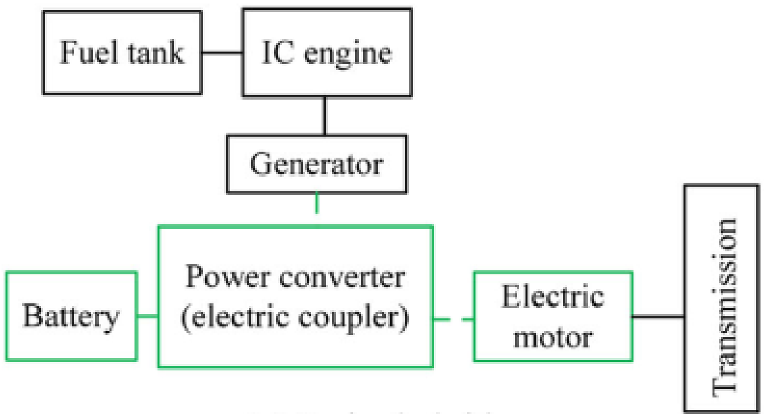

Figure 2.1: Architecture of Series hybrid electric vehicle (Singh et al., 2019)

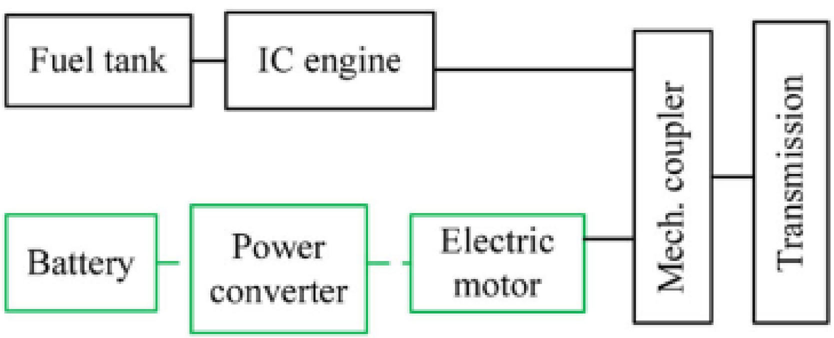

Figure 2.2: Architecture of Parallel hybrid electric vehicle (Singh et al., 2019)

In parallel HEVs, the traction power can be supplied by the engine, electric motor, or both sources together. The electric motor (EM) is used for regenerative braking to charge the hybrid energy storage system (HESS). Parallel mild HEVs offer a good balance between vehicle cost and performance (Singh et al., 2019).

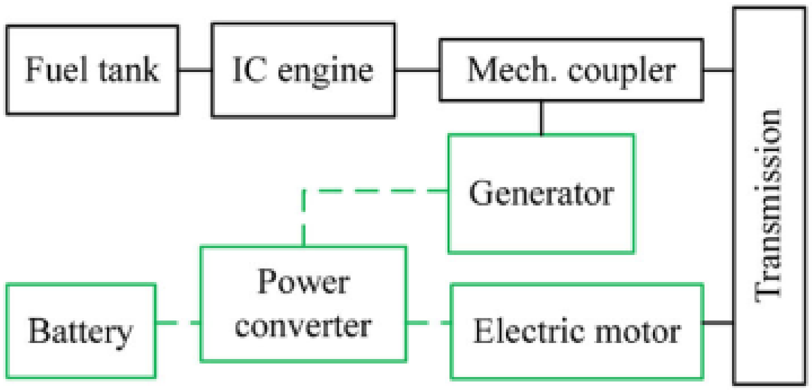

Figure 2.3: Architecture of Series – Parallel hybrid electric vehicle (Singh et al., 2019)

Complex hybrids combine features of both parallel and series architectures, with bidirectional power flow in the motor (Singh et al., 2019).

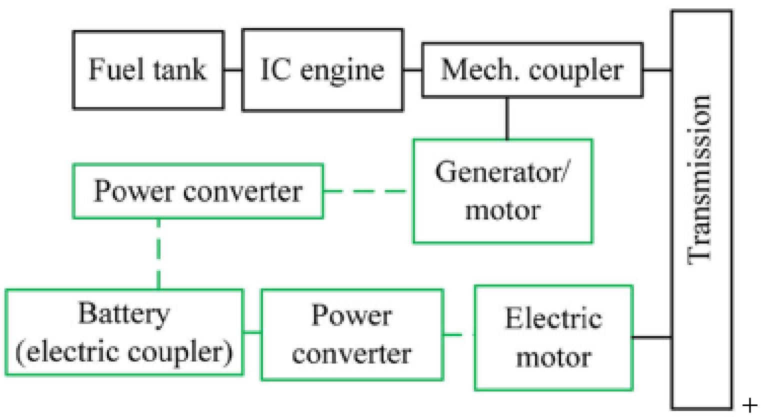

Figure 2.4: Architecture of Complex hybrid electric vehicle (Singh et al., 2019)

Plug-in HEVs (PHEVs) have a similar architecture to HEVs but with a larger onboard battery and more complex control strategies for charge sustaining (CS) and charge depletion (CD) modes. Solar-driven HEVs (PVHEVs) have an additional photovoltaic (PV) panel to charge the battery during sunny days, with maximum power point tracker (MPPT) algorithms used to maximize PV power extraction (Singh et al., 2019).

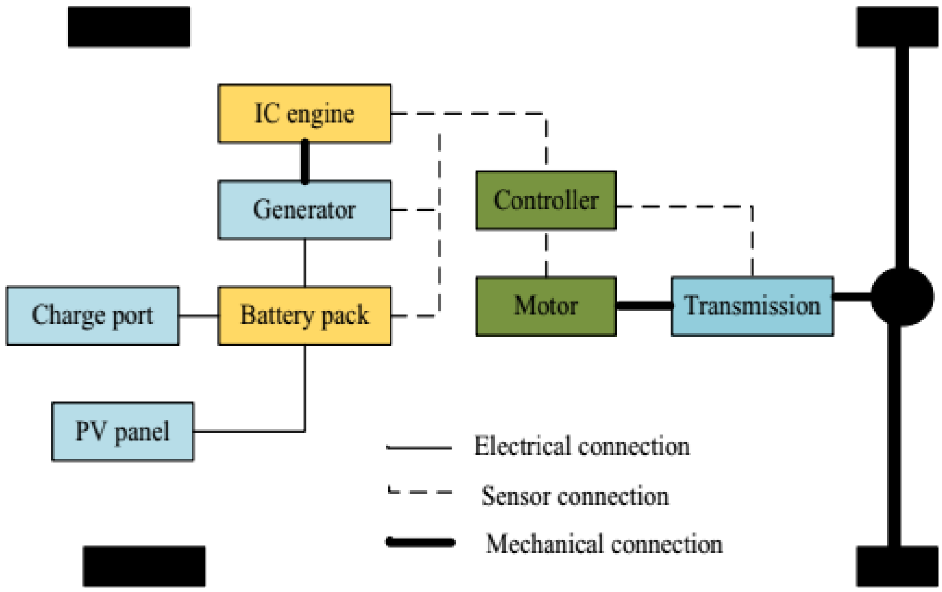

Figure 2.5: Architecture of Plug-in hybrid electric vehicle (Singh et al., 2019)

An Internal combustion engine (ICE) is defined as the machine that converts the chemical energy generated through combustion of a certain fuel, into a mechanical energy that is used to derive a certain vehicle. ICE in the three wheelers can be either two stroke or four stroke depending on the intended use of the vehicle and the budget of the buyer. Two-stroke engines are generally less expensive and have a simpler design, but they are also less fuel-efficient and produce more emissions. Four-stroke engines are more expensive and have a more complex design, but they are more fuel-efficient and produce lower emissions. Thus, the four-stroke engines are becoming more popular due to their better fuel efficiency and lower emissions (George, 2023). On the other hand, three wheelers use the Otto cycle. The Otto cycle is an ICE thermodynamic cycle that is used in gasoline engines.

Otto cycle is the typical cycle for most of the cars ICEs that work using gasoline as a fuel. It consists of the same four major steps: Intake, compression, ignition and exhaust. The Otto cycle is a suitable for three-wheelers due to its efficiency, affordability, and ease of maintenance (Mulhall et al., 2009).

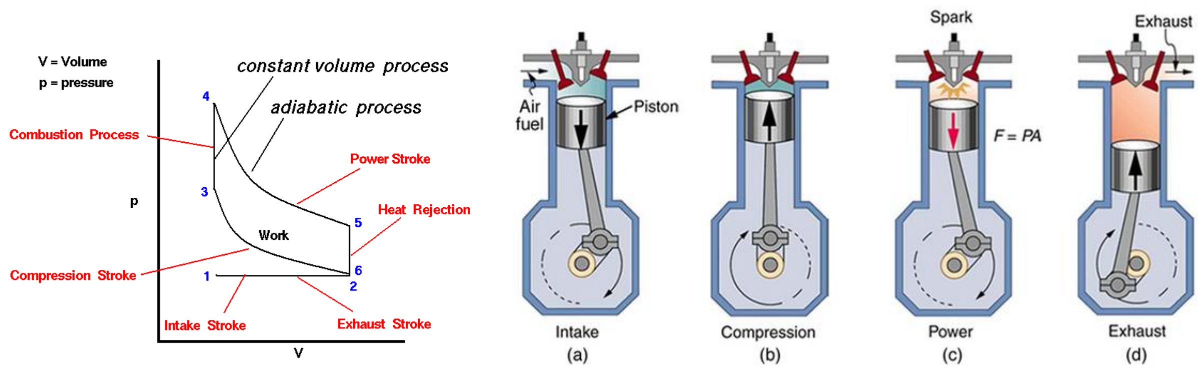

Figure 2.6: Working of the Otto cycle (Alemayehu and Nallamothu, 2017; NASA, 2020)

The electric motor is a crucial component in hybrid electric vehicles (HEVs), serving multiple functions to optimize efficiency. At lower speeds, it powers the HEV and provides additional assistance to the ICE when more power is required. Moreover, the electric motor can function as a generator, converting energy from the engine or regenerative braking into electricity, which is stored in the vehicle's battery (Alemayehu and Nallamothu, 2017). This unique capability is achieved by applying a resistive force to the drivetrain, causing the wheels to slow down. As the wheels decelerate, they turn the electric motor, transforming it into a generator and converting what would normally be wasted energy during coasting and braking into usable electricity (Singh et al., 2019).

Compared to ICEs, electric motors are simpler and significantly more efficient. HEVs demand high torque at low speeds for acceleration, followed by decreasing torque as cruising speed is reached (United States Department of Commerce, 1993). Electric motors deliver maximum torque at low speeds, with torque diminishing as speed increases. In contrast, ICEs produce minimal torque at low speeds and must accelerate through a majority of their speed range to achieve maximum torque (Mulhall and Emadi, 2009).

HEV motors must endure frequent start/stop cycles, high rates of acceleration and deceleration, high-torque low-speed hill climbing, and a wide speed range of operation (Veintimilla Porlán, 2016). These motors need to exhibit both high power density and a favorable efficiency map, ensuring high efficiency across various speed and torque ranges. Additionally, these motors must withstand harsh operating conditions such as high temperatures, adverse weather, and constant vibration, as they are installed in mobile vehicles (Tran et al., 2021). As such, there are four major types of electric motors that are suitable for HEV applications. They are DC motors, induction motors, Permanent magnet synchronous motor (PMSM), and switched reluctance motor (SRM) (Alemayehu and Nallamothu, 2017).

Induction motors, shown in *Figure 2.7*, are highly favored for HEV propulsion due to their ruggedness, exceptional reliability, low maintenance requirements, and high efficiency (Agrawal and Jain, 2021). These motors offer several safety benefits, including de-excitation during inverter faults. Compared to DC machines, induction motors provide a higher power density and improved efficiency. They also offer a wide speed range (Fraikin et al., 2020). Despite the inherent control complexity, the low cost and ruggedness associated with induction motor drives make them widely accepted in HEV propulsion systems (Alemayehu and Nallamothu, 2017).

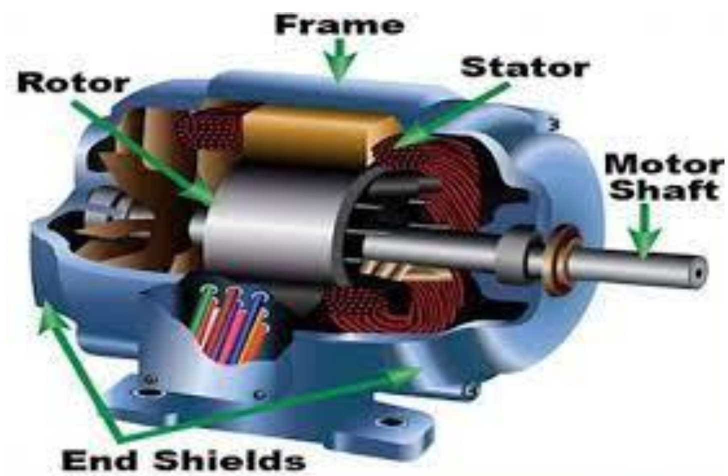

Figure 2.7: Schematics of Induction motor (poly technic hub, 2021)

These days, the SRM, shown in *Figure 2.8*, is becoming popular in HEV applications. These motors have various advantages such as rugged construction, easier control, outstanding torque–speed characteristics, and better fault tolerance capability. An SRM is best suited for the applications where constant power is demanded over a wide operating region. However, SRM has several drawbacks such as torque ripple, electromagnetic interference, requirement of a special convertor topology, and high noise (Singh et al., 2019).

PMSMs, shown in *Figure 2.9*, prove to be strong contenders to induction motor in HEV applications. Its benefits include higher power density, lesser heating, and higher efficiency. That being said, PMSMs, due to armature reaction, suffer from a major drawback of demagnetization (Singh et al., 2019).

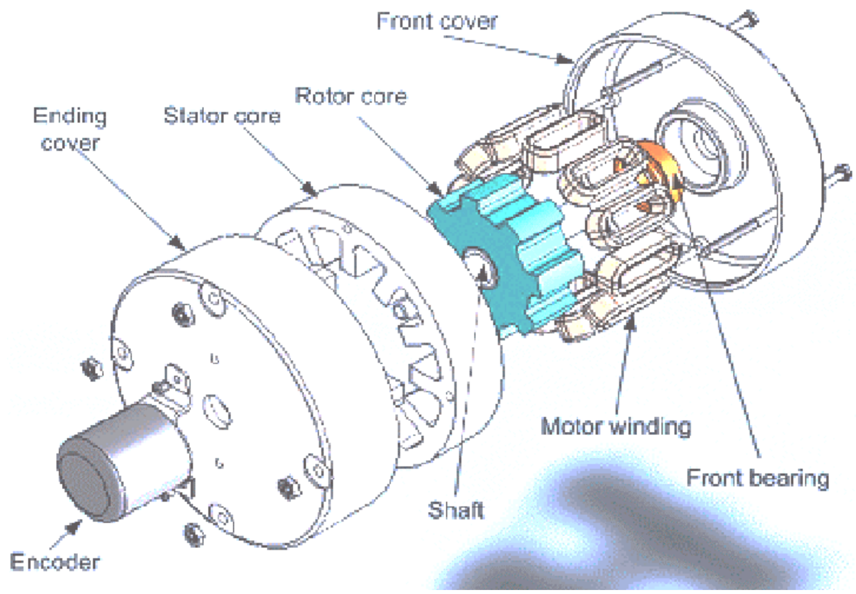

Figure 2.8: Schematics of switched reluctance motor (Lee et al., 2020)

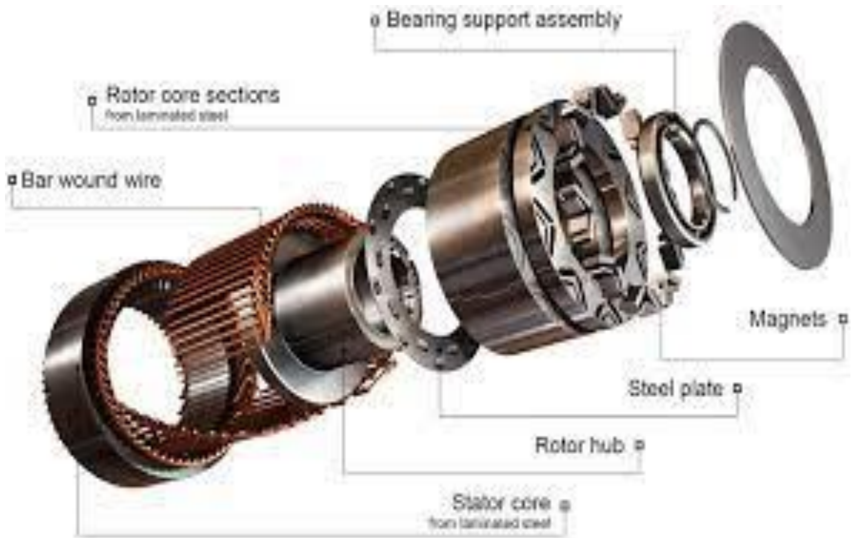

Figure 2.9: Schematics of Permanent magnet synchronous motor (NIDEC Corporations, 2020)

DC motors have long been a popular choice for electric propulsion due to their mature technology and simple control. The introduction of solid-state switches enabled the development of maintenance-free motors known as brushless DC motors. These motors have gained popularity in recent years due to their declining costs and increasing functionality. Unlike AC synchronous motors, brushless DC motors incorporate mechanisms to detect the rotor position or magnetic poles, allowing for precise control through electronic switches (Alemayehu and Nallamothu, 2017; Singh et al., 2019). Brushless DC Motor are compact in size and have powerful output. This motor is, thus, suitable as a source of vehicle power (Alemayehu and Nallamothu, 2017).

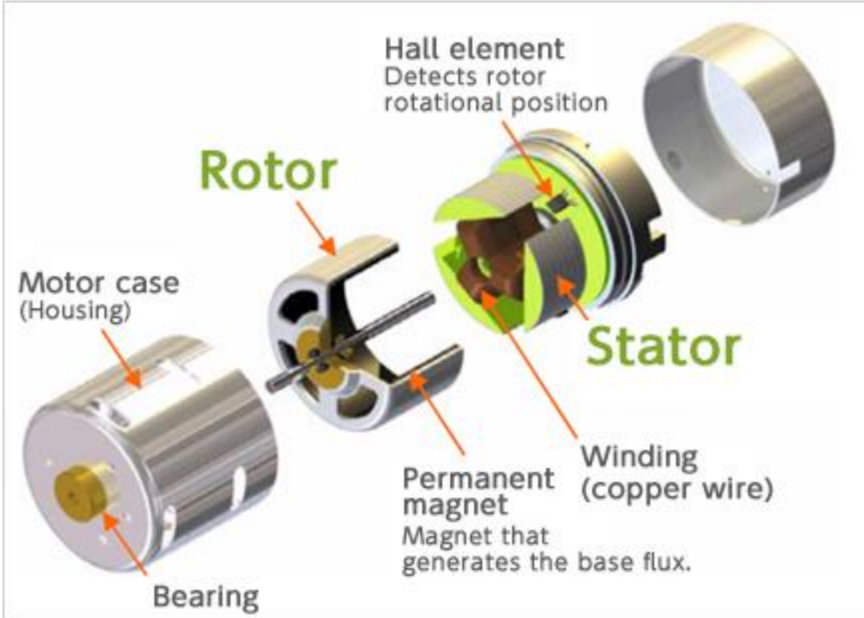

Figure 2.10: Schematics of Brushless DC Motor (NIDEC Corporations, 2020)

The battery is a crucial component of the electric hybrid system in vehicles. It can act as a primary power source or work in conjunction with other power sources to regulate the supply of power to the drive train (Sreejith and Rajagopal, 2017). Consequently, the amount of battery power in an HEV can vary, ranging from a single battery to a pack of interconnected batteries. Currently, batteries are considered the primary energy source for HEVs due to their technological maturity and reasonable cost, and this trend is expected to continue in the foreseeable future (Alemayehu and Nallamothu, 2017).

The size of the batteries must be carefully determined to ensure they store enough energy and provide sufficient peak power for the vehicle to achieve the desired acceleration performance and meet appropriate driving cycles (Montaleza et al., 2021; Sánchez-repila et al., 2006). Batteries play a vital role in HEVs as electrical energy can be drawn from them to power the electric motor, and they can also recapture energy through regenerative braking (Shaha and Uddin, 2014). Given the high cost associated with battery energy storage, it is more cost-effective to rely on the engine as the primary power source for higher loads rather than increasing the amount of energy storage. Therefore, efforts should focus on enhancing existing battery technologies to improve efficiency rather than simply increasing their size for greater output (Alemayehu and Nallamothu, 2017; Sánchez-repila et al., 2006).

The design of the battery can be optimized for capacity or power but not both, so the selection of battery cells must align with the intended application. Specific energy is a crucial parameter for determining the suitability of a battery for achieving the desired driving range, while specific power is essential for grade ability and acceleration (Montaleza et al., 2021). Battery capacity is less critical for HEVs as the range can be extended through engine usage. Therefore, HEV batteries are typically optimized for power (Sánchez-repila et al., 2006).

In a three-wheeled HEV, the transmission system is in responsible for transmitting power from the engine and/or electric motor to the wheels (Alemayehu and Nallamothu, 2017). The vehicle's torque and speed are controlled by the transmission system, enabling effective operation and top performance. It serves as a conduit between the engine and the wheels, enabling the car to accelerate, slow down, and maintain various speeds as required (Ghorbani et al., 2007).

The transmission system in three-wheeler HEVs include the transmission control unit, clutch, gearbox, and differential. The transmission control unit manages the operation of the transmission system by monitoring various parameters and adjusting gear shifts accordingly. The clutch controls the connection between the engine or motor and the transmission, ensuring smooth engagement and disengagement. The gearbox, which contains multiple gears, enables the driver to select different gear ratios, adjusting torque and speed. The differential ensures that power is evenly distributed to the wheels, facilitating smooth cornering. The transmission system in three-wheeler HEVs utilizes planetary gear mechanisms, including a sun wheel, planetary gears, and a gear ring, to transmit power from the engine and electric motor to the wheels (Rajamani, 2006).

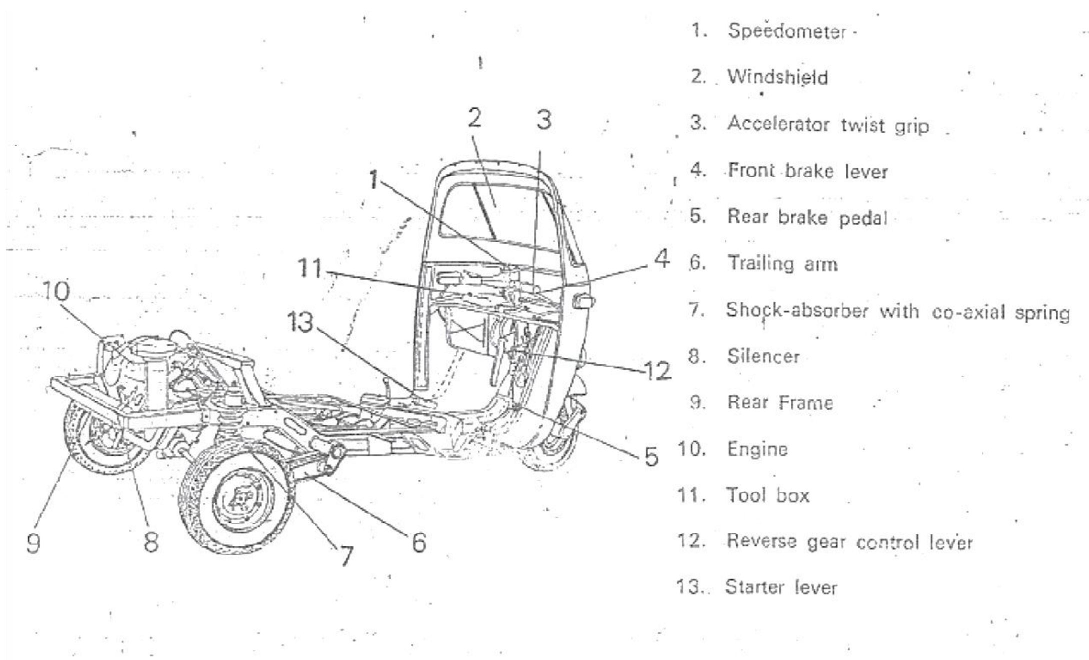

Figure 2.11: Typical transmission system for three-wheeler vehicle (Thorat, 2023)

2.2. Three-Wheeler Vehicles

Three-wheeler vehicles, also known as tricycles or trikes are a unique type of vehicle that has been used for various purposes, including urban mobility, cargo delivery, and recreational activities. They are typically smaller and lighter than four-wheeled vehicles, and they can be powered by a variety of engines, including gasoline, diesel, and electric. They were first produced in the late 1800s as bicycles with one additional wheel, then evolved into motorized versions in the early 1900s (Brady, 2022). They were initially designed as a cheaper alternative to cars and motorcycles, and were used primarily for transportation in rural areas. They offer several advantages over traditional vehicles, including improved maneuverability, lower cost, and reduced emissions (Hambissa et al., 2022).

Three-wheeler vehicles have unique design and performance characteristics characterized by their compact size, light weight, and low power output. They are often designed to operate at low speeds and in congested areas. Additionally, three-wheelers have a narrow track width, which makes maneuvering in tight spaces easier (Hambissa et al., 2022).

Three-wheeler vehicles can be classified into several categories based on their design and purpose. Some common types of three-wheelers include passenger trikes, cargo trikes, and recreational trikes. Passenger trikes are designed to carry one or more passengers, while cargo trikes are designed to carry goods. Recreational trikes are designed for leisure activities, such as cycling or racing (Bako et al., 2019).

Three-wheeler vehicles present unique design challenges, particularly in terms of stability and weight distribution. The placement of the third wheel can affect the vehicle's stability, and designers must carefully consider the weight distribution to ensure that the vehicle remains balanced. Additionally, three-wheelers must comply with different safety regulations than traditional vehicles, which can add to the design complexity (George, 2023).

Fuel economy, low emissions, and mobility are prioritized in the design of the three-wheeled hybrid electric vehicle, which has a compact and streamlined shape. It is more suited for urban environments because it is lighter and smaller than conventional cars (Shaha and Uddin, 2014). The vehicle's chassis is designed to provide a comfortable driving experience while housing the electric motor and battery system. It guarantees stability during turns and braking because to its single front wheel and two back wheels. In addition to providing balance, this configuration lightens the vehicle's overall weight (Mulhall et al., 2009).

Three-wheeled hybrid electric vehicles prioritize occupants' comfort and ergonomics, with a standard seating arrangement providing excellent view and control of the vehicle. The weight distribution is balanced, and the electric motor and battery system are strategically positioned at the back to improve stability (Gyllendahl and Tran, 2012). Lightweight materials like aluminum or composites are used to strike a compromise between strength and weight. The rear wheels stabilize and support the vehicle, while the front wheels are powered by an electric motor to increase traction. The suspension system has separate systems for each wheel, enhancing control, comfort, and handling. The brake system combines hydraulic and regenerative braking, with advanced driver assistance systems, stability control systems, and anti-lock brake systems improving occupant safety and vehicle stability (Vasiljevic et al., 2012).

Despite challenges related to stability and payload capacity, ongoing developments in design and technology are continuously improving their overall performance and expanding their applications (Hambissa et al., 2022).

2.3. Vehicle Dynamics and Control

Vehicle dynamics is the study of the motion of vehicles and the forces that affect their behavior. It includes the study of handling, stability, and maneuverability, as well as the effects of different road conditions and driving scenarios. The motion of a vehicle is generated by the steering action, through which the vehicle is capable of independent motion (Rajamani, 2006). Vehicle dynamics is the study of how vehicles move and respond to various inputs while control refers to the methods used to govern or manipulate vehicle behavior (Yang et al., 2013).

The fundamental concepts of vehicle dynamics and control encompass several key elements. These include mass, moment of inertia, force, moment, suspension, steering system, and brake system. Mass refers to a vehicle's inertial property, with larger masses making it more challenging to alter the vehicle's motion. Moment of inertia measures the resistance of a rotating body to changes in its angular velocity. A greater moment of inertia makes it harder to change the vehicle's rotational motion. Forces, which can be pushing or pulling actions on a body, cause acceleration, deceleration, or changes in direction. Moments, on the other hand, are turning forces that induce rotation in a body. The suspension system, comprised of springs and dampers, connects the wheels to the vehicle's body. Its purpose is to absorb road shocks and maintain the vehicle's body level. The steering system allows for control over the vehicle's direction, usually consisting of a steering wheel, steering column, and steering gear. Lastly, the brake system is employed to slow down or bring the vehicle to a halt, typically comprising brake pads and rotors (Rajamani, 2006; Yang et al., 2013).

Vehicle dynamics encompasses several different aspects, including handling, stability, and maneuverability. Handling refers to a vehicle's ability to change direction smoothly and responsively, influenced by driver inputs (Yang et al., 2013). Three-wheeler vehicles pose unique challenges in terms of handling due to their unconventional design, which can impact both stability and maneuverability (Hambissa et al., 2022). Stability, on the other hand, refers to a vehicle's ability to maintain equilibrium in various conditions and resist tipping over (Yang et al., 2013). Three-wheeler vehicles, especially in situations like high winds or sharp turns, may be less stable compared to traditional four-wheeled vehicles (Hambissa et al., 2022). Design considerations such as center of gravity and weight distribution play a vital role in maintaining stability across different conditions (Yang et al., 2013). Lastly, maneuverability refers to a vehicle's capability to move through tight spaces and perform sharp turns (Rajamani, 2006; Yang et al., 2013). Three-wheeler vehicles generally excel in maneuverability due to their smaller size and lighter weight, making them well-suited for urban mobility and cargo delivery purposes, where maneuverability is critical (Hambissa et al., 2022). Modeling techniques, control algorithms, and optimization methods can be used to simulate and improve the behavior and performance of vehicles (Xu, 2020).

Control algorithms are implemented to govern the actions of vehicles, particularly in circumstances where direct driver control may not be possible (Jayasundara and Munasinghe, 2009). Various control algorithms exist to regulate vehicle behavior. One such algorithm is proportional-integral-derivative (PID) control, which, despite its simplicity, can effectively manage a range of systems, including vehicles. Adaptive control is another type of algorithm that automatically adjusts its parameters to adapt to system changes. Robust control, on the other hand, is designed to remain unaffected by disturbances and uncertainties (Agrawal and Jain, 2021).

Optimization methods are utilized to enhance vehicle performance by optimizing their design and control parameters. These methods span from simple trial-and-error approaches to more sophisticated optimization algorithms. In the realm of vehicle dynamics, several common optimization methods are employed, including genetic algorithms, particle swarm optimization, and simulated annealing. Genetic algorithms are optimization algorithms grounded in the principles of natural selection, while particle swarm optimization takes inspiration from flock behavior. Additionally, Bayesian optimization serves as another optimization algorithm used to identify the most suitable parameters (Xu, 2020).

Modeling techniques are utilized to replicate the performance and behavior of vehicles, ranging from simple mathematical models to intricate computer simulations (Veintimilla Porlán, 2016). Vehicle dynamics extensively employ various modeling techniques. Analytical models, numerical models, and experimental models are among the diverse techniques utilized for simulating vehicle behavior (Tansini et al., 2023). Analytical models encompass mathematical models that forecast vehicle behavior under diverse circumstances. Numerical models refer to computer models that simulate vehicle behavior, usually offering higher accuracy but requiring more computational resources. Experimental models stand as physical models used to replicate vehicle behavior and are generally the most accurate, yet the most costly to construct (Sivtoft, 2002).

2.4. Simulation in Vehicle Design

Simulation has become essential in vehicle design and development, allowing engineers to simulate various configurations and identify design flaws, as well as optimize performance, fuel efficiency, safety, and reliability (Yang et al., 2013). Vehicle s are an essential tool in this process and can train drivers and mechanics safely (Roe, 2017). Different models and simulation methods, including kinematic, dynamic, multi-body, finite element analysis, computational fluid dynamics, and optimization algorithms, are used to analyze vehicle dynamics behavior under various conditions such as different road surfaces and scenarios to optimize vehicle performance and efficiency (Mcwilliams et al., 2017).

Vehicle s can be classified into different types, namely hardware-in-the-loop or software-based s. Hardware-in-the-loop s employ physical components like engines or transmissions to replicate the vehicle's behavior, while software-based s use computer models for the same purpose. Both types have their own set of advantages and disadvantages, and the choice of depends on specific design and development requirements (Roe, 2017). These s serve various purposes including research, training, and entertainment, ranging from simple desktop simulations to sophisticated full-motion s. They commonly offer features such as realistic graphics, vehicle dynamics, and the ability to simulate different driving scenarios. However, it's important to note that these s also have limitations like limited accuracy and availability (Mcwilliams et al., 2017).

In vehicle design and development, simulation is challenging because it requires accurate modeling of the vehicle's behavior, but it can be computationally intensive and time-consuming. Furthermore, simulation results may not always match real-world behavior, which requires validation and verification (Roe, 2017).

Hybrid vehicle simulation uses different approaches and modeling techniques, ranging from simple mathematical models to complex computer simulations, to study the behavior and performance of hybrid vehicles under different conditions (Tansini et al., 2023). Common models include powertrain, energy management, and regenerative braking modeling. Validating and verifying the model's accuracy is important, accomplished through experimental testing, data analysis, and statistical analysis to ensure it accurately represents the real-world behavior and performance of hybrid vehicles (Tran et al., 2021).

Three-wheeler hybrid vehicle s, ranging from simple desktop to complex full-motion s, have been developed for research, training, and entertainment purposes. While offering realistic graphics, dynamics, and different driving scenarios, limitations include limited accuracy and availability (Mcwilliams et al., 2017). Design considerations include simulation software, modeling vehicle components, and validation of the model. Validating techniques include experimental and statistical analysis (Tran et al., 2021). The powertrain, suspension, and tire models are important aspects of three-wheeler hybrid vehicle design. Model can have various applications such as vehicle design, performance optimization, and driver training (Roe, 2017).

There are different approaches in hybrid vehicle simulation including system-level, component-level, and multi-body simulation. The choice of modeling technique depends on the application of the model and can be used to study the overall performance, individual component performance, or dynamic behavior of the vehicle. System-level simulation considers the entire hybrid vehicle as a single system, providing a simplified understanding of the overall performance. Component-level simulation models individual components, allowing for a detailed analysis of each component's impact on the overall performance. Multi-body simulation represents the vehicle as interacting rigid bodies, and is particularly useful for studying the vehicle's dynamic behavior (Jayasundara and Munasinghe, 2009).

The design of a three-wheeler hybrid vehicle model depends on the specific application, including the choice of simulation software, modeling components, and validation methods. In addition, there are several existing three-wheeler hybrid vehicle s, including the Three-Wheeler Hybrid Vehicle simulator (THVS), a system-level developed by the University of Michigan; the Three-Wheeler Hybrid Vehicle Dynamics simulator (THVDS), a component-level developed by the University of Twente; and the Three-Wheeler Hybrid Vehicle Multi-Body simulator (THMBMS), a multi-body developed by the Indian Institute of Technology, Delhi. These s can be used to study the overall performance, individual component performance, and dynamic behavior of three-wheeler hybrid vehicles, respectively (Sreejith and Rajagopal, 2017).

The human-machine interface (HMI) is an essential component of vehicle s, as it plays a crucial role in providing a realistic driving experience and facilitating effective hybrid vehicle control and experimentation. User-friendly HMIs are essential in vehicle s, as they allow drivers to interact with the model in a natural and intuitive way. A well-designed HMI can provide a realistic driving experience, allowing drivers to feel as though they are actually driving a vehicle (Mcwilliams et al., 2019).

A well-designed HMI can provide drivers with realistic feedback, such as the feel of the steering wheel and the sound of the engine. Additionally, the HMI can provide drivers with information about the vehicle's speed, direction, and other important parameters, allowing them to make informed decisions while driving (Xing et al., 2021).

2.5. Research gap

The development of HEVs has gained significant momentum due to their potential for improved fuel efficiency and reduced emissions, particularly in urban environments. Prior studies have explored various aspects of HEVs and their dynamics, emphasizing the importance of accurate modeling for performance evaluation and optimization. Simulation techniques have been widely employed to predict the behavior of HEVs under different operating conditions, aiding in the design and development process. While extensive research exists on conventional four-wheeled HEVs, the specific nuances of three-wheeler HEVs warrant dedicated investigation. However, the specific focus on three-wheeler HEVs introduces a unique dimension to this research, as it targets a niche segment with distinct design considerations and operational characteristics.

Despite the growing demand for three-wheeled hybrid vehicles as an energy-efficient and eco-friendly alternative, there is a lack of an accurate and comprehensive model that adequately simulates their dynamics and behavior. This knowledge gap hinders effective real-time testing and training of drivers and mechanics, leading to costly and time-consuming processes. Therefore, further research is needed to address this limitation by modeling and simulating three-wheeler hybrid vehicles that can precisely model their dynamics.

CHAPTER THREE

3. METHODOLOGY

Due to the lack of an accurate model that adequately simulates the dynamics and behavior of three-wheeler hybrid electric vehicle (HEV), modeling and simulation of three-wheeler hybrid electric vehicle was performed. The methodology for the modeling and simulation consists of several steps. *Figure 3.1* represents the key procedures followed in this study.

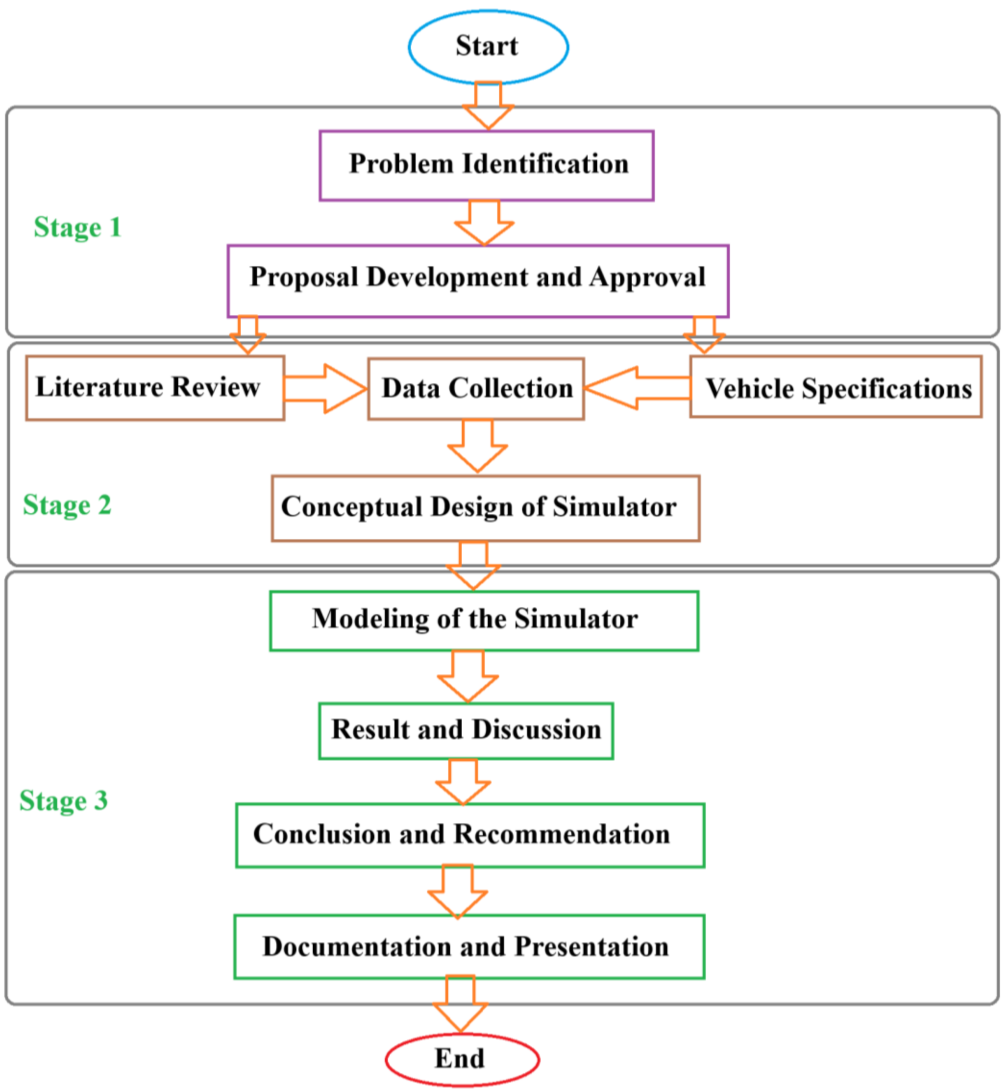

Figure 3.1: A methodology flowchart

3.1. Research Design

The sole focus of this thesis is to model and simulate a three-wheeler hybrid electric vehicle model. The study uses a mixed-methods approach, combining both qualitative and quantitative methods to study a research problem. In this case, the quantitative methods were used to collect data on the performance of the three-wheeler HEV using the simulation. The qualitative methods were used to understand the factors that affect the performance of the vehicle. Moreover, a simulation-based research design is appropriate. The research design involves developing a mathematical model of the three-wheeler hybrid electric vehicle, including its powertrain, energy storage system, and control algorithms. The designed model was implemented in a simulation software. The model allows for the virtual testing and evaluation of different control strategies, energy management algorithms, and driving scenarios.

3.2. Data Collection

Here, in this thesis, relevant data are collected using a mixed-method approach. The approach consists of document review, and the data collection of vehicle specification.

3.2.1. Document review

Relevant literatures and documents related to three-wheeler vehicles, hybrid electric vehicles and simulations are comprehensively reviewed. This consists of studying literature on three-wheeler vehicle components, processes and procedures to model and simulate vehicles. In addition, various hybrid electric vehicle manufacturers official website and flyers are consulted. Moreover, MATLAB (Miller, 2023), CarSim (CarSim, 2023) and ADVISOR (Sahoo, 2021) software official websites are investigated on the processes of modeling hybrid electric vehicles. The objective is to gather insights from existing data to inform the research.

3.2.2. Vehicle Specification

In order to simulate the performance of three-wheeler hybrid vehicle, the specifications of this vehicle are necessary. Thus, the specifications of the three-wheeler hybrid electric vehicle like that of geometry of the vehicle, the engine and battery characteristics of the vehicle is collected from the website of the manufacturer (Vidhya and Mahadevan, 2019). Hence, the specification shown in *Table 3.1* are collected accordingly.

Table 3.1: Specification of the three-wheeler hybrid electric vehicle (Vidhya and Mahadevan, 2019)

S.No.	Parameter	Specification
1	Dimensions (LxWxH)	2635mm x 1300mm x 1700
2	Wheelbase	2000mm
3	Ground Clearance	170 mm
4	Vehicle kerb Weight	390 Kg
5	Payload	559 Kg
6	Gross Weight	1085 Kg
7	Engine	3 kW
8	Displacement	470.5 cc
9	Fuel tank capacity	8L
10	Electric Motor	5 kW
11	Motor Type	AC Induction Motor
12	Battery Type	Lithium-ion
13	Battery Capacity	48 V, 168 – 224 Ah
14	Transmission	Direct
15	Seating Capacity	4 persons (with Driver)
16	Max power	6.24 kW @ 3000 rpm
17	Max Torque	24 Nm @ 1800 rpm
18	Gradeability	18%

19	Clutch	Dry, Single plate
20	Max speed (Km/hr)	40
21	Fuel type	Hybrid

3.3. Data Analysis

There are two results that can be obtained from the data collection. These are, the specification of the three-wheeler hybrid electric vehicle, and the performance characteristics of this vehicle. Hence, these two results are recorded and analyzed accordingly.

3.4. Theoretical Framework of Three-Wheeler Hybrid Vehicles

After determining the technical specification of the three-wheeler hybrid electric vehicle, and their performance characteristics, the theoretical frameworks of the three-wheeler hybrid vehicle are generated. This was done by considering various driving conditions so that the simulation accurately models the vehicle's behavior and dynamics.

A three-wheeled hybrid electric vehicle's powertrain is crucial for achieving the desired acceleration, top speed, and fuel efficiency. The powertrain is designed for minimal emissions and high fuel efficiency, and it consists of numerous components, including the engine, motor, battery, and gearbox (Shaha and Uddin, 2014).

The decision of the size of each component is the initial stage in the design of a HEV. Internal Combustion Engine (ICE), electric motor (EM), convertor, fuel tank, control board, and energy storage system are regarded as the most important components of HEV. Proper component selection would primarily impact the characteristics and performance of the vehicle. These components can be categorized into three groups (Singh et al., 2019):

- Drivetrains – it physically integrates the engine power source and electric drive.
- Battery or energy storage system (ESS) – it emphasizes the large or modest energy storage and power capabilities.

- Control system – is used to instruct electric systems or engine and manages the Hybrid energy storage system (HESS).

3.4.1. Drivetrains

For this particular model parallel HEV architecture is used. In parallel HEVs, as shown in *Figure 3.2*, the traction power can be supplied by the engine, electric motor, or both sources together. The electric motor (EM) is used for regenerative braking to charge the hybrid energy storage system (HESS). Parallel mild HEVs offer a good balance between vehicle cost and performance (Singh et al., 2019).

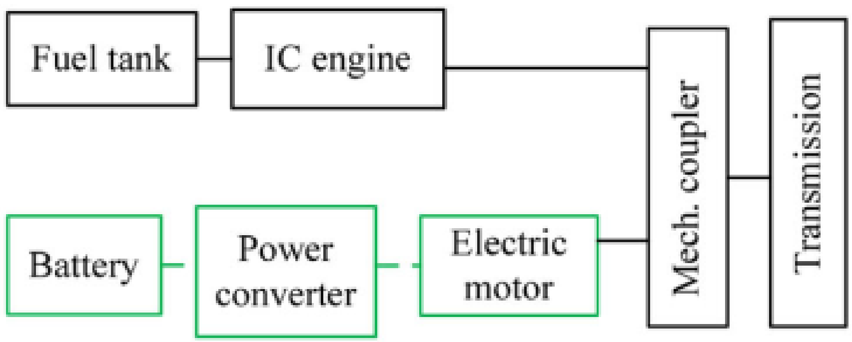

Figure 3.2: Architecture of Parallel hybrid electric vehicle (Singh et al., 2019)

3.4.2. Internal Combustion Engine

When designing ICE, there are several general considerations to take into account. First and foremost, engine performance, including power and torque output, must be optimized across the operating range. Fuel consumption and cost are important factors to consider, aiming for efficiency and affordability. Engine emission and noise levels should be minimized to meet environmental regulations and provide a quieter experience. Engine cost and ease of installation are also important aspects, ensuring that the engine is cost-effective and can be easily integrated into different applications. Lastly, factors such as maintenance requirements, durability, and safety should be considered to ensure a reliable and long-lasting engine (Alemayehu and Nallamothu, 2017; Mulhall et al., 2010).

In order to determine the internal combustion engine performance, it is necessary to measure various results and express them in standard engineering terms and parameters, which can be used as an indicator of performance (Alemayehu and Nallamothu, 2017).

Thus, compression ratio of the Otto cycle engine can be determined from:

$$r = \frac{V_t}{V_c} \qquad \text{Equation 3.1}$$

$$r = \frac{V_s + V_c}{V_c} \qquad \text{Equation 3.2}$$

Where:

- r is the compression ratio,
- V_t is the engine cylinder total volume,
- V_c is the clearance volume, and
- V_s is the swept volume.

Then, the thermal efficiency of this cycle can be determined as:

$$\eta = \frac{W}{Q_I} \qquad \text{Equation 3.3}$$

$$\eta = \frac{Q_I - Q_o}{Q_I} \qquad \text{Equation 3.4}$$

$$\eta = 1 - \frac{Q_o}{Q_I} \qquad \text{Equation 3.5}$$

Where:

- η is the cycle thermal efficiency,
- W is the work done of the cycle,
- Q_I is the heat supplied during the cycle, and
- Q_o is the heat rejected from the cycle.

In the Otto cycle, during the compression and expansion process, there is no heat transfer as they are estimated to be reversible adiabatic processes. Thus, heat is supplied only during the combustion assumed to be constant volume process and, heat is rejected only during the exhaust. It is assumed to be constant volume process.

The mean effective pressure is another parameter used to measure the performance of the engine, and it is the average pressure acting on the piston during the power stroke. It can be determined from:

$$\text{MEP} = \frac{\text{W}}{V_s} \quad \text{Equation 3.6}$$

Where:

- MEP is the mean effective pressure,
- W is the work done of the cycle, and
- V_s is the swept volume.

Indicated power of the engine is the net power developed actually at the piston face during the events of mechanical cycle.

$$P_I = \frac{\pi N V_s(\text{MEP})}{60} \quad \text{Equation 3.7}$$

$$P_I = \frac{\pi NLA(\text{MEP})}{60} \quad \text{Equation 3.8}$$

Where:

- P_I is the indicated power,
- N is the speed of the engine in revolutions per minute (rpm),
- V_s is the swept volume,
- MEP is the mean effective pressure,
- L is the stroke length, and
- A is the area of the piston.

The actual power output of the engine is less than the indicated power due to the losses due to friction and heat. The frictional force is the force that opposes the motion of the piston and crankshaft. It is caused by the friction between the moving parts of the engine. The frictional power can be then determined from:

$$P_f = FN \qquad \text{Equation 3.9}$$

Where:

- P_f is the frictional power,
- F is the frictional force, and
- N is the speed of the engine in revolutions per minute (rpm).

Thus, the mechanical power of the engine can be obtained from:

$$\mathrm{P_m = P_I - P_f} \qquad \text{Equation 3.10}$$

Where:

- P_m is the mechanical power,
- P_I is the indicated power, and
- P_f is the frictional power.

Brake power is the actual work output of an engine or, the actual available work at the crankshaft. And, it can be determined from

$$P_B = \frac{2\pi N T_B}{60} \qquad \text{Equation 3.11}$$

Where:

- P_B is the brake power in watts,
- N is the speed of the engine in revolutions per minute (rpm), and
- T is the brake torque in newton-meters (Nm).

Brake torque is one of an engine performance parameter which determine how hard the engine can work across the engine speed range.

$$T_B = \frac{60P_B}{2\pi N} \qquad \text{Equation 3.12}$$

Where:

- T is the brake torque in newton-meters (Nm),
- P_B is the brake power in watts, and
- N is the speed of the engine in revolutions per minute (rpm).

Engines used in an hybrid electric vehicles (HEV) are typically smaller than that of a conventional vehicle of the same size, and the size selected depends on the total power needs of the vehicle (Alemayehu and Nallamothu, 2017). The engine in a three-wheeler hybrid electric vehicle works in tandem with an electric motor. The ICE is the primary source of power for the vehicle, and the electric motor is the secondary source of power (Shaha and Uddin, 2014).

3.4.3. Electric Motor

For electric motor, the torque can be determined from:

$$T_m = K_i i_m \qquad \text{Equation 3.13}$$

$$T_m = I_m \frac{d\omega}{dt} \qquad \text{Equation 3.14}$$

Where:

- T_m is the output torque of the motor,
- K_i is the constant value of the torque,
- $\frac{d\omega}{dt}$ is the angular acceleration of the motor,
- i_m is the input current, and
- I_m is the motor inertia.

3.4.4. Battery

Given the diverse range of HEV configurations and performance requirements, a wide variety of batteries is needed. For the Parallel Hybrid configuration, the load of the electric motor load can range from zero to 100% based on design goals and operating conditions. The capacity of the battery for HEVs can be as low as 2 kWh, but it must be capable of delivering short-duration boost power, demanding high currents of up to 40A for acceleration, cruising and hill climbing. Key considerations in battery design include capacity, discharge characteristics, and safety (Alemayehu and Nallamothu, 2017). Traditionally, higher power and capacity is associated with increased size and weight, while the dynamic response of electrical components in extracting or supplying energy to the battery is determined by discharge characteristics. Various types of batteries are currently being utilized or developed for use in HEVs, reflecting the ongoing advancements in battery technology (Montaleza et al., 2021; Sánchez-repila et al., 2006). The most common use batteries in HEV are given in *Table 3.2*.

Table 3.2: HEV Battery types along with their common characteristics (Alemayehu and Nallamothu, 2017; Sánchez-repila et al., 2006)

S.No.	Battery type	Max. energy density (Wh/kg)	Max. power density (W/kg)	Cycle life
1	Lead-Acid	35	150	200 – 400
2	Advanced Lead-Acid	45	250	500 – 800
3	Nickel-Cadmium	50	200	1000 – 2000
4	Nickel-metal Hydride	70	200	600 – 1500
5	Lithium-ion	120 – 150	120 – 150	400 – 1200

There are two factors that determine size of the battery pack in a HEV. First, motor peak power should be delivered by the battery pack. Then, the battery energy should meet the requirement of keeping battery state of charge within a specified limit in case of charge sustainable HEVs. Whereas, the size of the battery pack depends on the vehicle range specification for charge depleting HEVs. HEV batteries operate momentarily and share similarity with a starter battery by applying short power bursts for acceleration rather than long, continuous discharges as with the EV. Under normal condition and use, a parallel HEV consumes less than 2% of the available battery capacity per kilometer. HEV battery still works well with less than half the original capacity, capacity fade goes unnoticed, and an (Alemayehu and Nallamothu, 2017).

The motor power is only delivered by the battery during the positive motor power demand, such as cruising and acceleration. The power out of the battery is given by:

$$P_{Battery} = \frac{P_{motor}}{\eta_{Battery}\eta_{motor}} \qquad \text{Equation 3.15}$$

Where:

- $P_{Battery}$ is the battery power,
- P_{motor} is the power of electric motor,
- $\eta_{Battery}$ is the discharging efficiency of the battery, and
- η_{motor} is the efficiency of electric motor.

3.4.5. Transmission

The most common type of transmission in the three-wheeler HEVs is the manual transmission, where the driver manually operates the clutch and shifts gears (Wagner, 2018). This type provides a high level of control but requires the driver's intervention. Another option is the automatic transmission, which eliminates the need for manual gear shifting by employing a torque converter or a dual-clutch mechanism. Automatic transmissions offer convenience and smooth gear changes, making them suitable for urban driving conditions (Roe, 2017). In terms of transmission level, three-wheeler HEVs can have either single-speed or multi-speed transmissions (Mulhall et al., 2010). Single-speed transmissions, also known as direct-drive transmissions, have a fixed gear ratio, allowing the vehicle to operate efficiently within a specific speed range. On the other hand, multi-speed transmissions offer multiple gear ratios, enabling the vehicle to operate optimally across a wider range of speeds.

Multi-speed transmissions provide better acceleration and fuel efficiency, particularly in situations that require frequent speed changes, such as uphill climbs or overtaking maneuvers (Xu, 2020).

3.4.6. Energy management

A three-wheeled hybrid electric vehicles (HEVs) energy management system (EMS) is crucial to maximize fuel efficiency and reduce pollutants. The EMS controls the flow of energy between the engine, electric motor, and battery pack to optimize energy distribution based on driving conditions, power demands, and storage requirements (Miri et al., 2021). The EMS can optimize power generation by using the engine when it is most efficient and maximize power regeneration by using the electric motor during braking (Jayasundara and Munasinghe, 2009).

Regenerative braking is a key feature in three-wheeler HEVs that significantly improves energy efficiency, especially in urban driving conditions with frequent braking. By converting the kinetic energy into electrical energy that is stored in the battery pack for future use, the electric motor acts as a generator (Sánchez-repila et al., 2006). The challenges of managing energy in a three-wheeler HEV include the cost of battery packs, limited driving range of electric vehicles, and the complexity of control algorithms. However, advancements in battery management systems, precise control over the electric motor, optimal energy recovery during regenerative braking, and predictive energy management algorithms are helping to address these challenges and improve overall energy efficiency and vehicle performance (Montaleza et al., 2021).

3.5. Modeling of the Three-Wheeler Hybrid Vehicle

After the size, shape and performance characteristics of the model are obtained through data collection, the software modeling was performed. There are various software that can perform the intended simulation on the three-wheeler hybrid electric vehicle, as discussed in (Alemayehu and Nallamothu, 2017). Among these, MATLAB (Miller, 2023), CarSim (CarSim, 2023) and ADVISOR (Sahoo, 2021) software are usually considered for modeling and simulation of the vehicle. And for this thesis, MATLAB Simulink SimScape drive line is selected for modeling and simulation of the three-wheeler hybrid electric vehicle.

Modeling of the three-wheeler hybrid vehicle is performed using MATLAB Simulink based on SimScape Driveline. The modeling is performed considering parallel mode. The model includes seven basic subsystem modeling, as shown in *Figure 3.3*. These are: Battery modeling, DC-DC Converter modeling, Electric Motor Modeling, Engine Modeling, gearbox modeling, Vehicle body modeling, and simulating the model. The detail procedures followed in each modeling steps are discussed below.

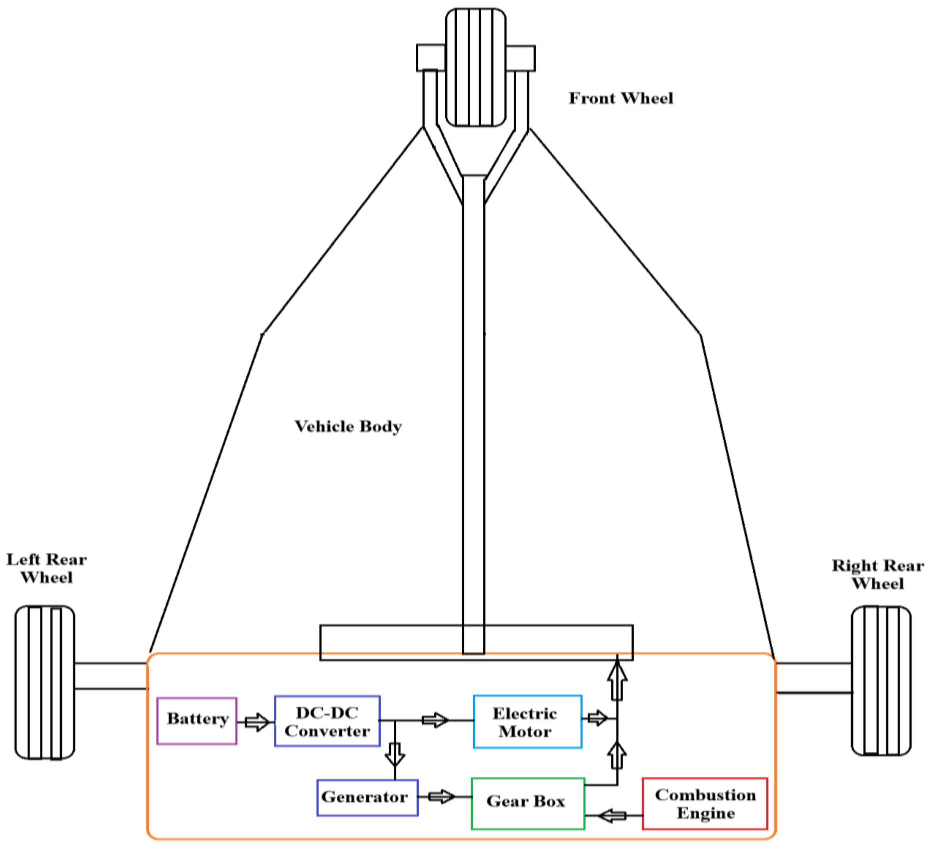

Figure 3.3: The general layout of hybrid electric three-wheeler vehicle

3.5.1.Vehicle Body Modeling

Vehicle body generally consists of a body mass, axles, hub and wheels and tires. Vehicle body modeling in SimScape represents a vehicle body in longitudinal motion. The model consists of four basic components such as vehicle body mass, front tire, and two rear tires, as shown in *Figure 3.4*.

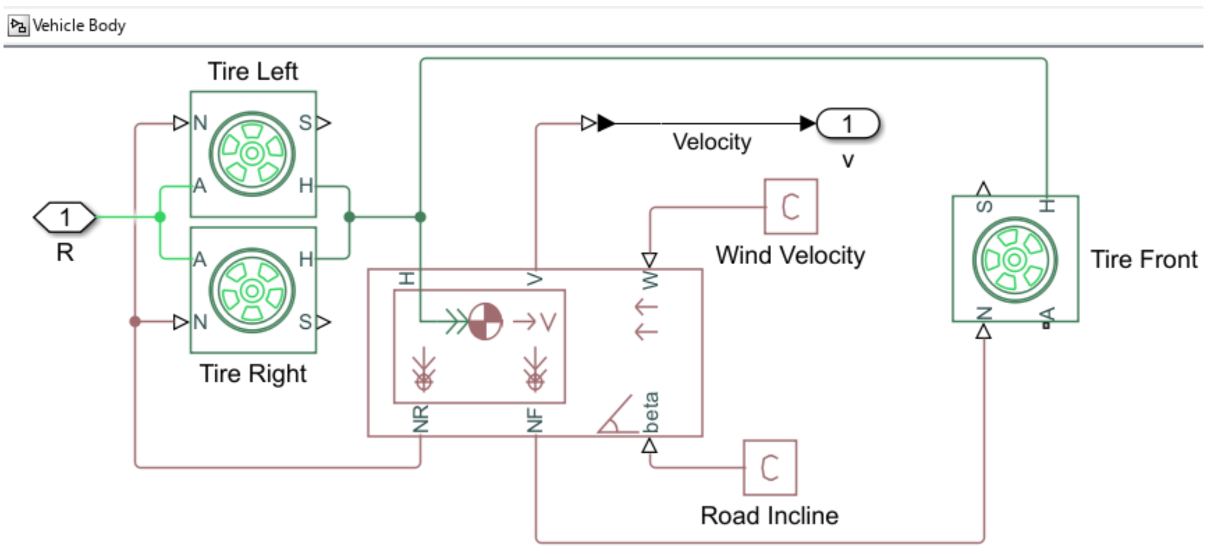

Figure 3.4: Three-wheeler vehicle body modeling in SimScape

The block of vehicle body mass accounts for aerodynamic drag, the body mass, inclination of the road, and distribution of the weight between axles due to acceleration and road profile the vehicle, as shown in *Figure 3.5*.

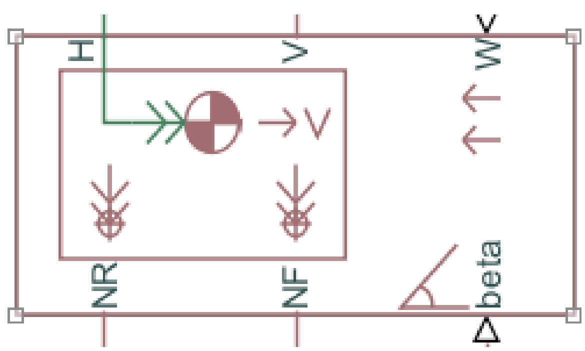

Figure 3.5: Vehicle body mass block modeling in SimScape

It generally consists of six connection ports. These are:

- Connection H is the conserving port of the mechanical translational associated with the horizontal motion of the vehicle body. The resulting traction motion tires developed should be connected to this port.
- Connection V is vehicle velocity physical signal output port.
- Connection NF is front normal wheel force physical signal output port.
- Connection NR is rear normal wheel force physical signal output port.
- Connection W corresponding to headwind speed physical signal input port.
- Connection beta corresponding to road inclination angle physical signal input port.

Hence, accordingly, vehicle body mass is modeled based on the vehicle specification given in *Table 3.1*, as shown in *Figure 3.6*.

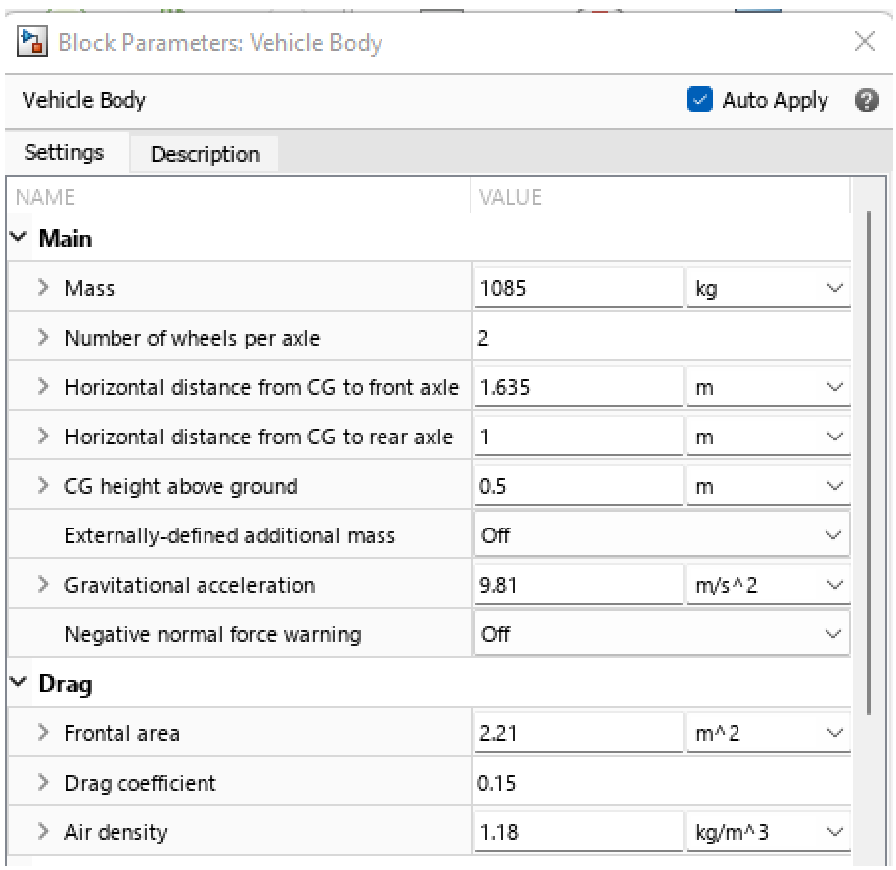

Figure 3.6: Vehicle body block parameters

The tires are modeled in SimScape based on the magic formula. It represents the longitudinal behavior of a highway tire characterized by the tire magic formula. It generally consists of four connection ports, as shown *Figure 3.7*. These are:

- Connection A is the conserving port of mechanical rotational for the wheel axle.
- Connection H is the conserving port of mechanical translational for the wheel hub through which the developed trust by the tire is applied to the vehicle.
- Connection N is a physical signal input port that applies the normal force acting on the tire. If the force acts downwards, it is considered positive.
- Connection S indicates a physical output port of the tire slip.

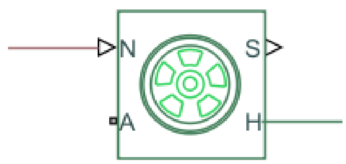

Figure 3.7: Tire block modeling in SimScape

Hence, accordingly, tires are modeled as shown in *Figure 3.8* and *Figure 3.9*, based on the vehicle specification given in *Table 3.1*.

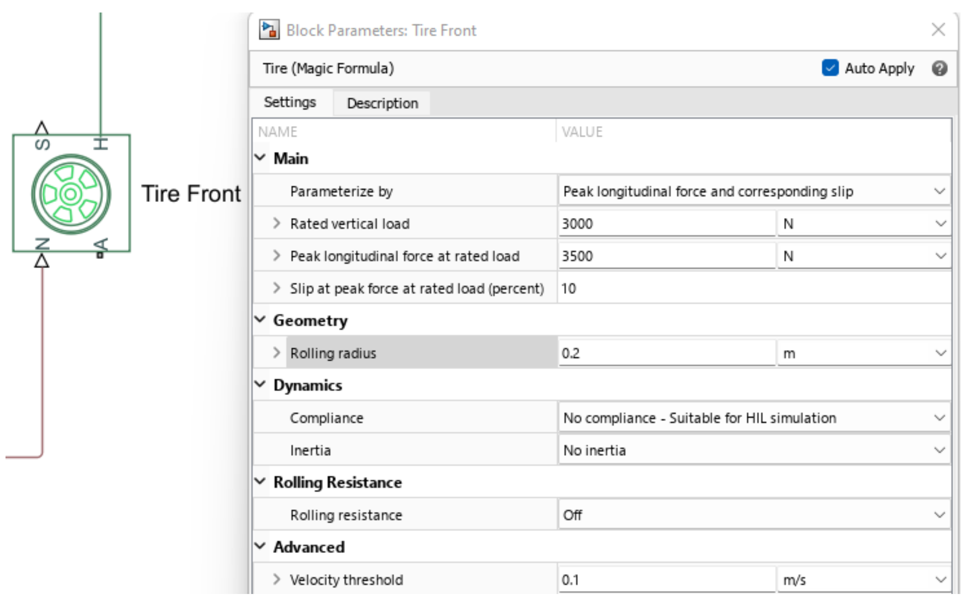

Figure 3.8: Front Tire modeling in SimScape

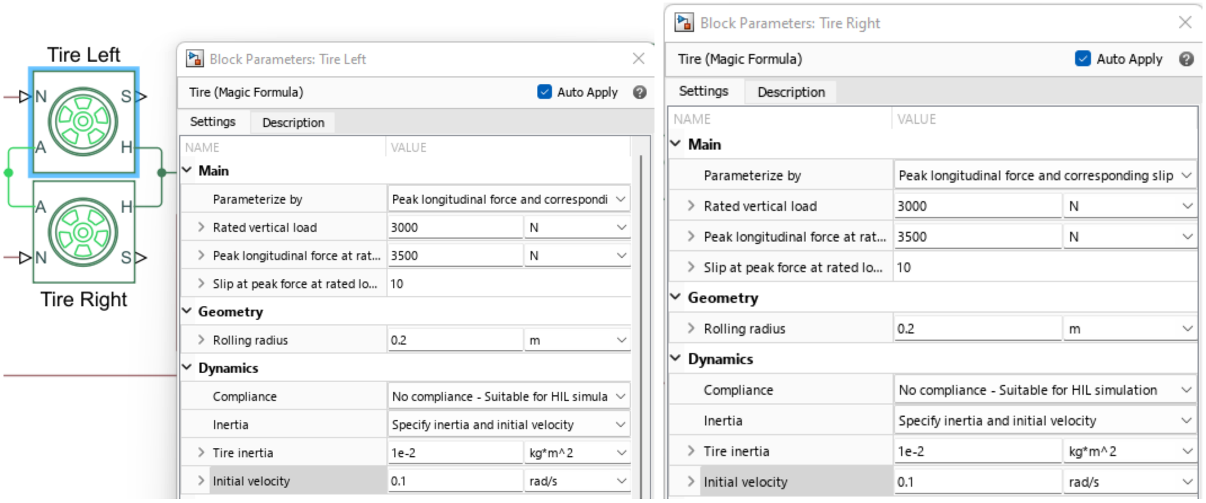

Figure 3.9: Rear Tire modeling in SimScape

Moreover, the vehicle body mass also considers wind velocity and road inclination. As such, as shown in *Figure 3.10* and *Figure 3.11*, 3 m/s wind velocity and 5-degree road inclination are considered for this particular model.

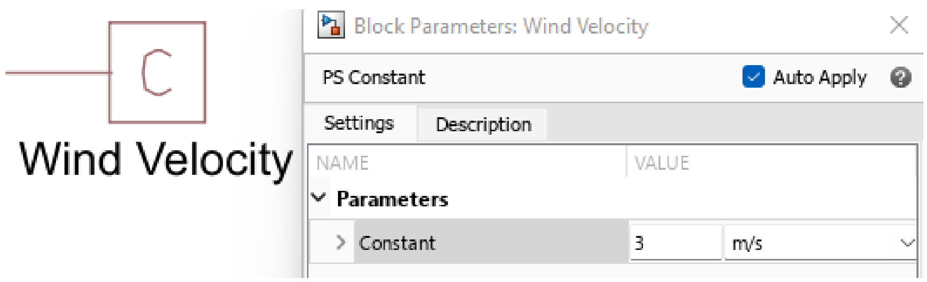

Figure 3.10: Wind velocity consideration for vehicle modeling

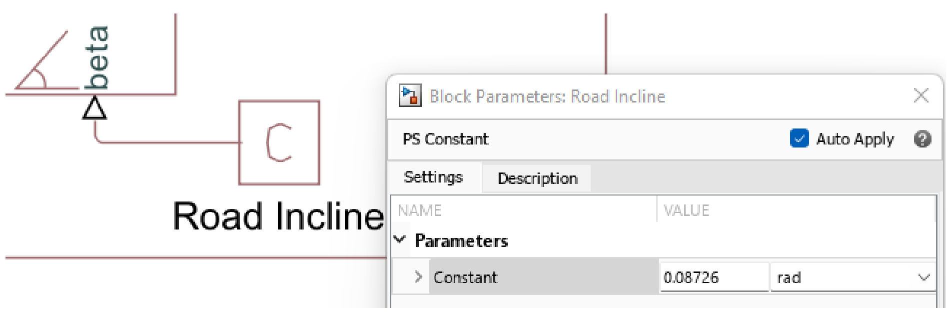

Figure 3.11: Road inclination consideration for vehicle modeling

3.5.2. Engine Modeling

Engine modeling in SimScape consists of three basic components such as internal combustion engine, engine management system, and RPM sensor, as shown in *Figure 3.12*.

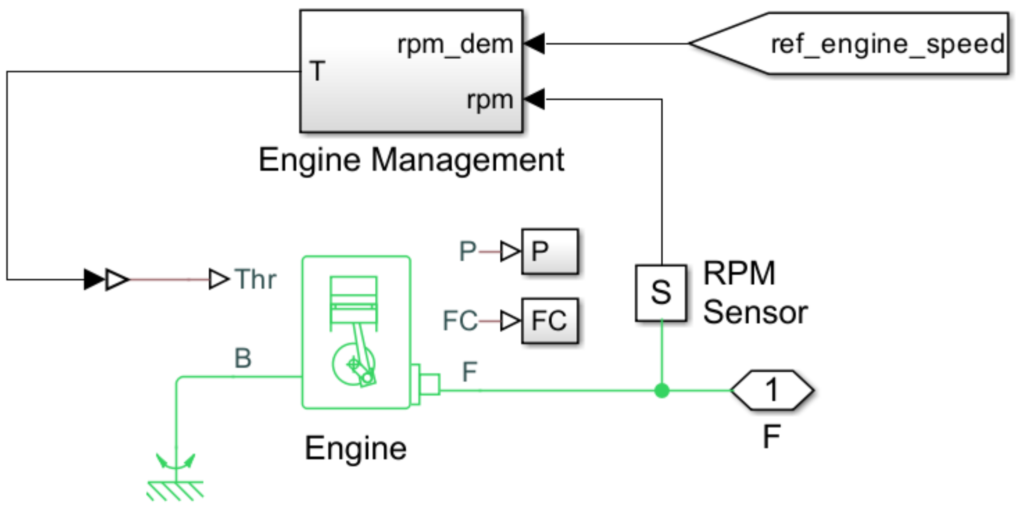

Figure 3.12: Engine modeling blocks in SimScape

Among these components, internal combustion engine block represents the performance parameters of the combustion engine. It has five connection ports. These are:

- The connection Thr is the input signal of the throttle which is between 0 and 1. In addition, it specifies the demanded torque from the engine as a fraction of the maximum possible torque. It can take throttle or torque command as input.
- Connection F is the conserving port of mechanical rotational associated with the engine crankshaft.
- Connection B is the conserving port of mechanical rotational of the engine block.
- Connection P is the engine power rate physical signal output port.
- Connection FC is the engine fuel consumption rate physical signal output port.

Hence, accordingly, engine is modeled as shown in *Figure 3.13*, based on the vehicle specification given in *Table 3.1*.

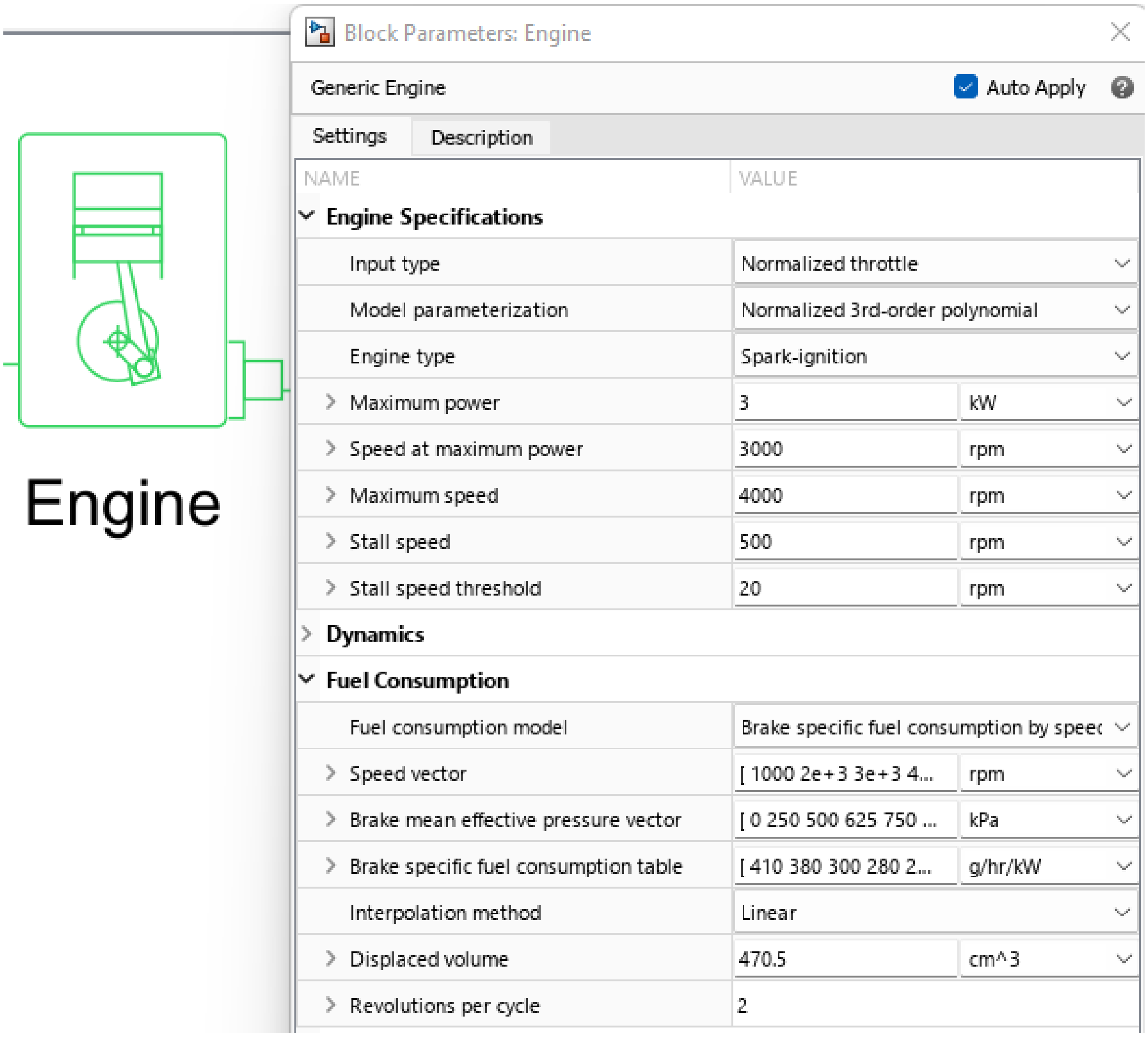

Figure 3.13: Engine block model parameters

The torque command input signal T takes torque reference value between zero and the maximum torque. If the engine speed fails below the speed determined by the sum of stall speed threshold and stall speed or the first element of speed vector, the engine torque is becoming zero. The simulation reports the error message and stops, if the engine speed is greater than the maximum speed.

Moreover, the engine management takes RPM signal and delivers the output signal as Torque, as shown in *Figure 3.14*.

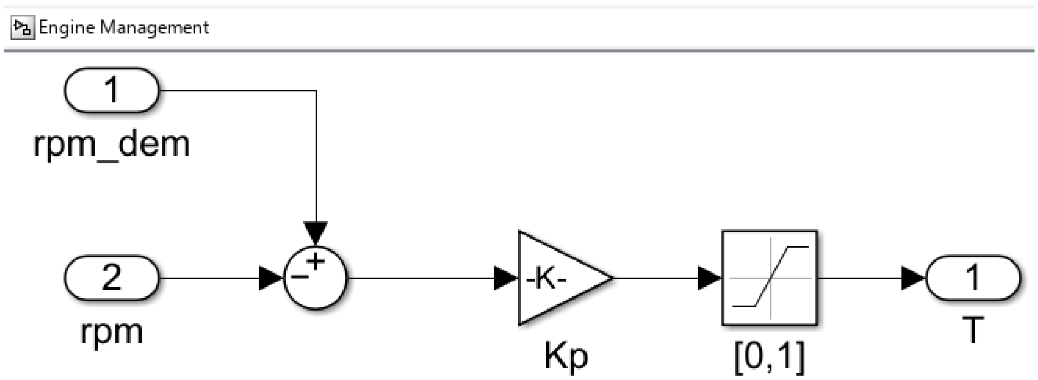

Figure 3.14: Engine management block in SimScape

Furthermore, the engine modeling consists of RPM sensor, as shown in *Figure 3.15*. It consists of rotational motion sensor measures angular velocity. The physical signal ports o, W, and A report the angular acceleration, velocity and position, respectively, of port R relative to port C. the measured angular velocity is positive when the angular velocity at port R is greater than the angular velocity at port C. optionally disable port C and measure with respect to ground.

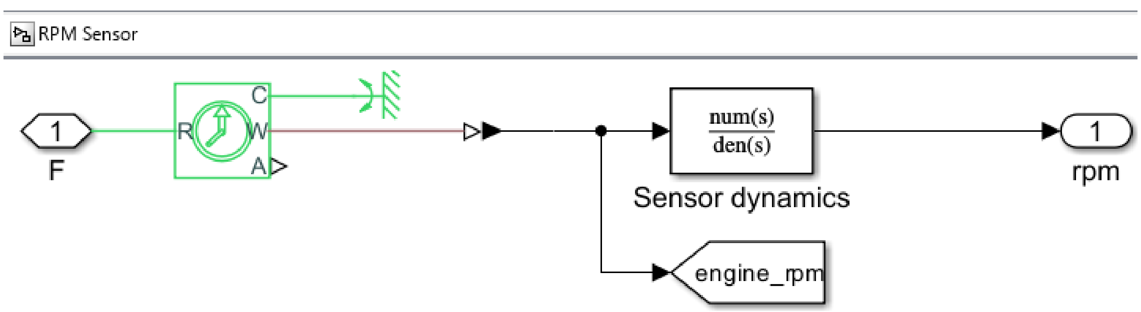

Figure 3.15: RPM Sensor block in SimScape

3.5.3. Battery modeling

Battery modeling in SimScape consists of six basic components such as DC Voltage source, voltage sensor, current sensor, electrical reference, internal resistance block, and computational block called calculation, as shown in *Figure 3.16*.

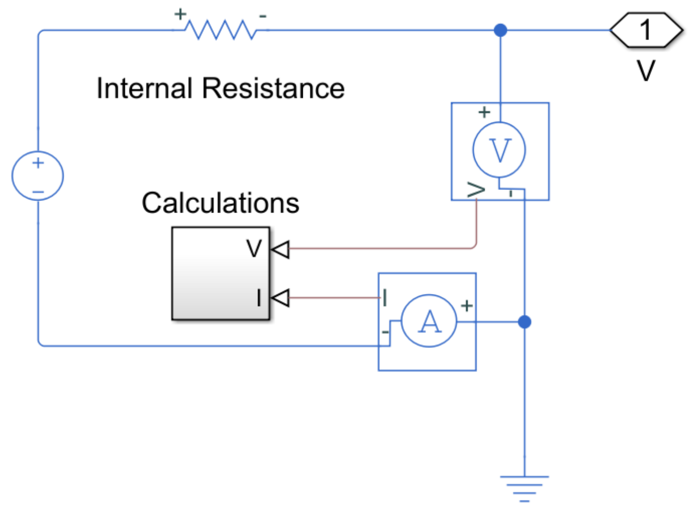

Figure 3.16: Battery Modeling in SimScape

DC Voltage source is modeled based on the vehicle specification given in *Table 3.1*, as shown in *Figure 3.17*. Similarly, internal resistance block is modeled, as shown in *Figure 3.18*.

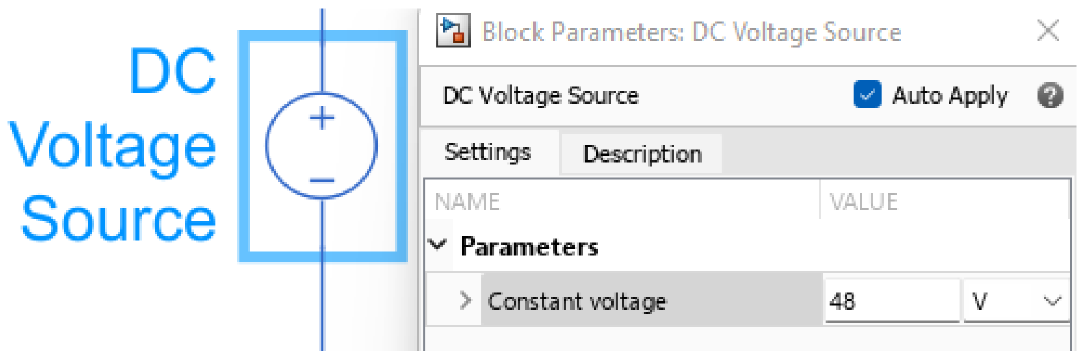

Figure 3.17: Parameter for DC Voltage source block in SimScape

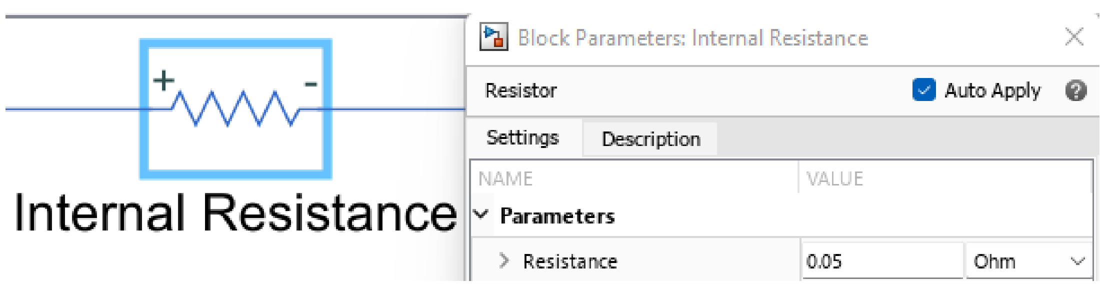

Figure 3.18: Parameter for Internal resistance block in SimScape

A device that converts the current measured in any electrical branch into a physical signal which is proportional to the current is known as current sensor. In SimScape, current sensor, as shown in *Figure 3.19*, consists of two connection ports. These are:

- The sensor is inserted into the circuit through a conserving electrical port of connections + and –.
- Output current value is displayed through a physical signal port that connection I.

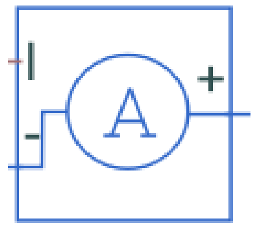

Figure 3.19: Current Sensor block in SimScape

Moreover, since the battery must contain at least one electrical reference port also can be called as electrical ground, electrical reference port, shown in *Figure 3.20*, is added to the battery modeling.

Figure 3.20: Electrical Ground block in SimScape

In addition, battery modeling consists of voltage sensor. Voltage measured between any electrical connections is converted into a physical proportional to the voltage by the voltage sensor. Voltage sensor, as shown *Figure 3.21*, in SimScape consists of two connection ports. These are:

- The voltage sensor is connected to the circuit conserving electrical ports of connections + and –.

- Outputs voltage value is displayed through a physical signal port connection V.

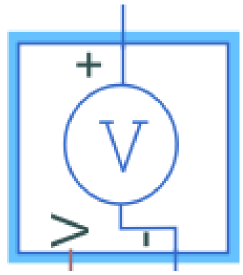

Figure 3.21: Voltage Sensor block in SimScape

Furthermore, the modeling consists of the block used for calculating battery performances and characteristics, as shown in *Figure 3.22*. The block take voltage and current as input, and perform calculations for battery power, charge, battery losses.

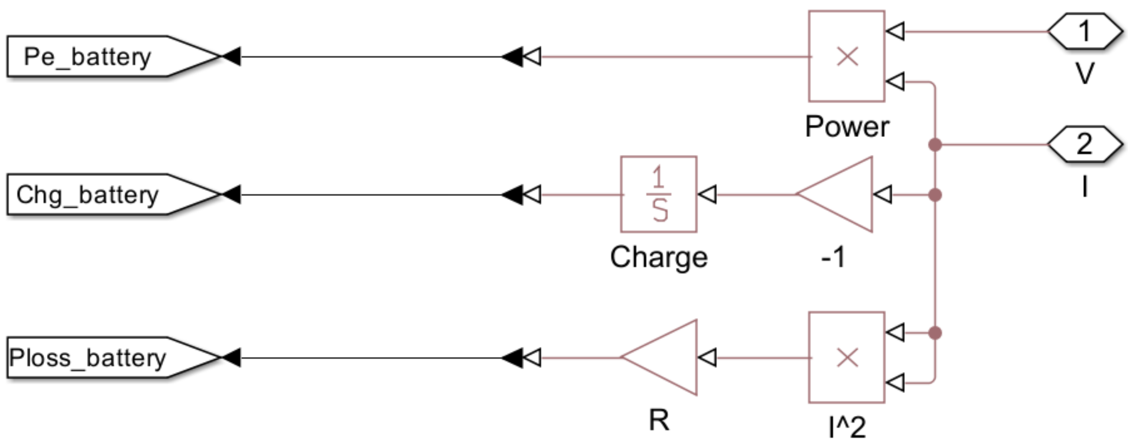

Figure 3.22: Block for calculation of battery performance

3.5.4. DC-DC Converter Modeling

DC-DC Converter modeling in SimScape consists of transformer, and two electrical grounds, as shown in *Figure 3.23*. And the parameter of the transformer is shown in *Figure 3.24*. The transformer is modeled based on *Equation 3.16* and *Equation 3.17*.

$$V_1 = NV_2 \qquad \text{Equation 3.16}$$

$$I_2 = NI_1 \qquad \text{Equation 3.17}$$

Where:

- N is the winding ratio,
- V_1 and V_2 are the primary and secondary voltages, and
- I_1 and I_2 are the current flowing into the primary and secondary terminal.

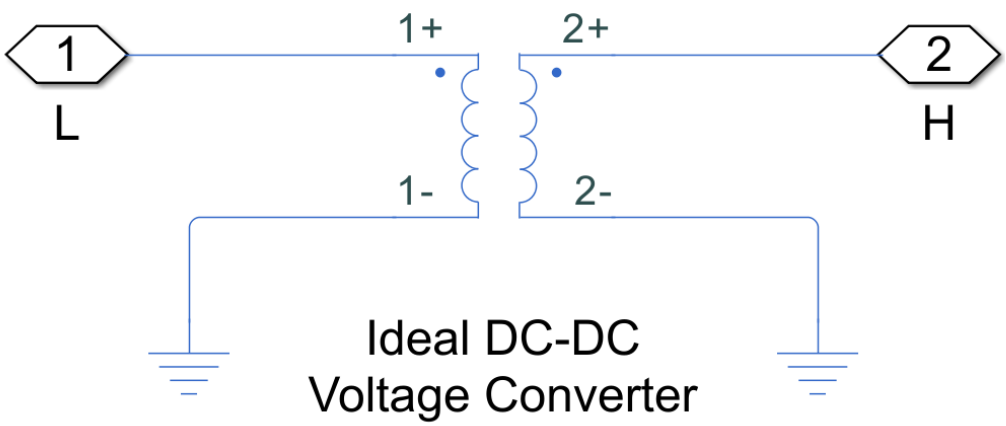

Figure 3.23: DC-DC Voltage converter Modeling in SimScape

Hence, accordingly, transformer is modeled as shown in *Figure 3.24*, based on the vehicle specification given in *Table 3.1*.

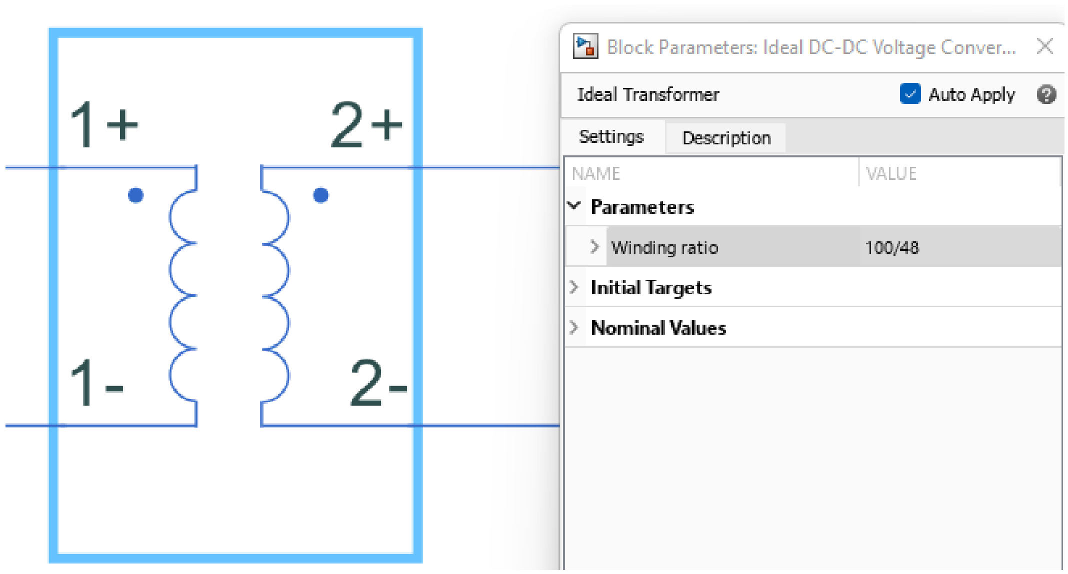

Figure 3.24: Parameter of transformer modeling in SimScape

3.5.5. Motor Modeling

Motor modeling in SimScape consists of four basic components such as motor and drive, RPM sensor, Speed controller, and Mechanical reference, as shown in *Figure 3.25*.

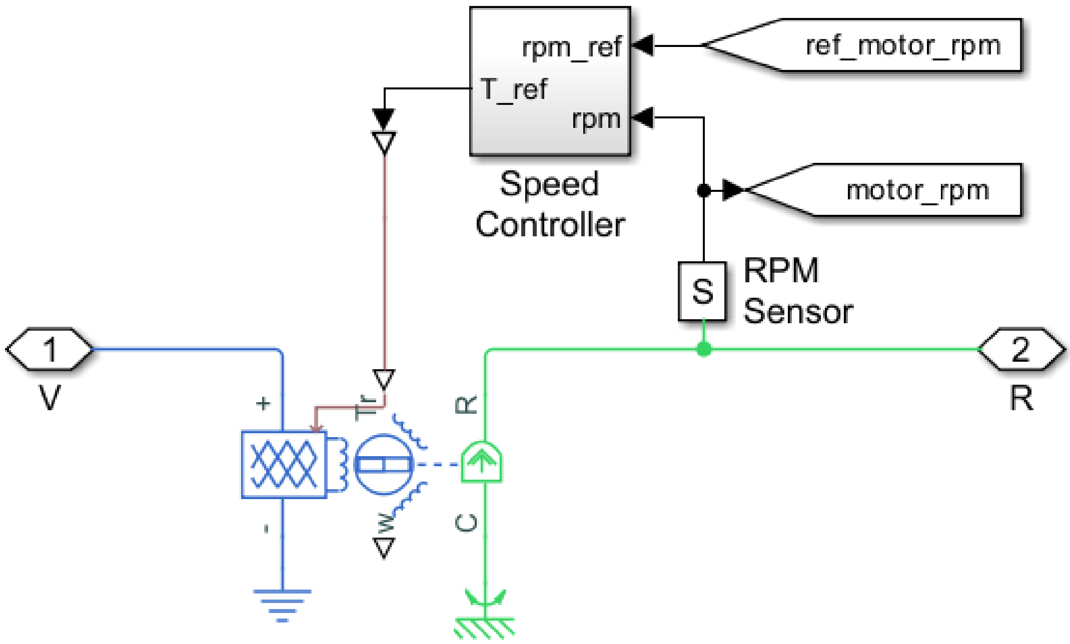

Figure 3.25: Motor Modeling in SimScape

Motor and drive block in the sim-scape operate either in torque-control mode, or equivalently current-control mode. The block supports both motor applications and generator regimes applications, and it can be used to represent traction applications and servomotor at a system level. The torque-speed envelope defines motor's permissible range of torques and speeds, and the output torque tracks the torque reference demand Tr with time constant Tc. The DC supply network must be connected to a block. The electrical losses are proportional to the square of the torque. The block produces a positive torque acting from the mechanical C to R ports.

Hence, accordingly, engine is modeled as shown in *Figure 3.26*, based on the vehicle specification given in *Table 3.1*.

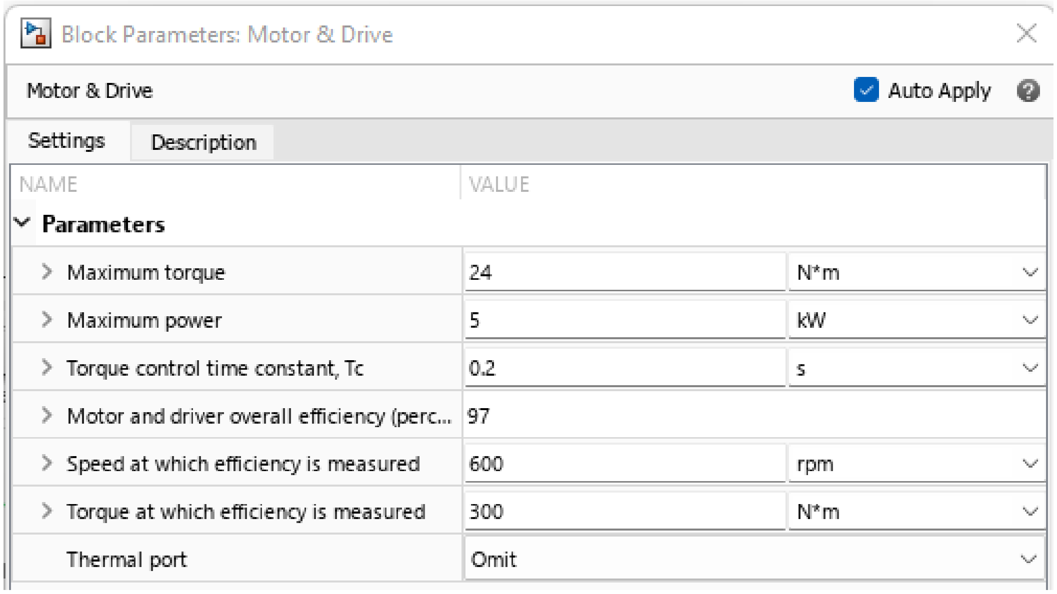

Figure 3.26: Parameter of the Motor and Drive modeling in SimScape

Moreover, the motor modeling consists of RPM sensor, as shown in *Figure 3.27*.

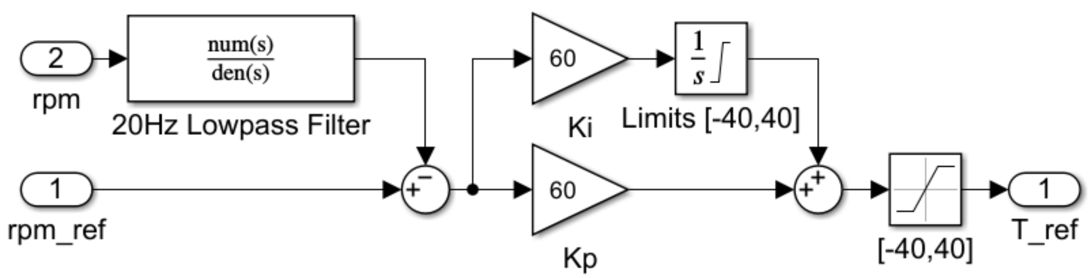

Figure 3.27: RPM sensor modeling for motor in SimScape

Furthermore, the motor modeling consists of speed controller, as shown in *Figure 3.28*.

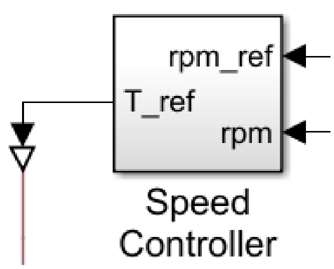

Figure 3.28: Speed controller for motor in SimScape

3.5.6. Gearbox Modeling

Gearbox consists of fixed ratio gear having of gear, and follower. It consists of three connection ports. These are:

- Connections B or Base is the mechanical rotational conserving port associated with the base, and
- Connections F or Follower is the mechanical rotational conserving port associated with the follower.

Hence, accordingly, gear box is modeled as shown in *Figure 3.29*.

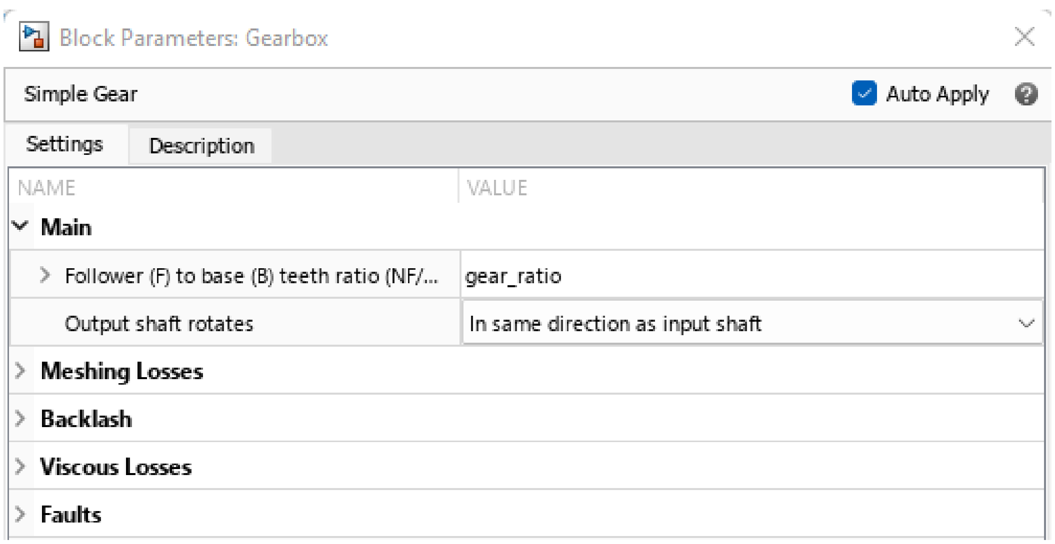

Figure 3.29: Parameter of the Gearbox modeling in SimScape

3.5.7. Model Simulation

The developed model for thee-wheeler hybrid electric vehicle using SimScape driveline based on parallel mode is simulated for accelerate and decelerate condition, as shown in *Figure 3.30*. And the model is programmed to simulate battery power, motor power, engine power, battery loss, motor loss and engine loss over acceleration and deceleration of the vehicle for 3600 seconds. In addition, the simulating includes the shaft speeds of both combustion engine and electric motor, as shown in *Figure 3.31*.

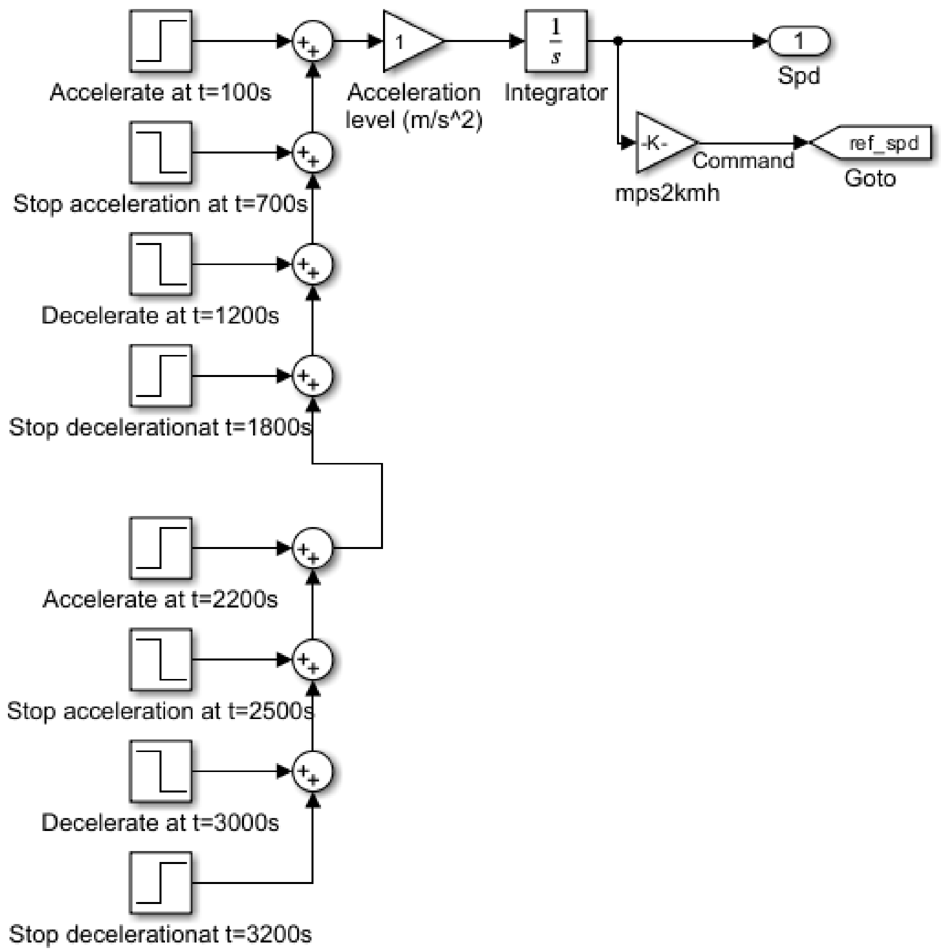

Figure 3.30: Engine command of accelerate and decelerate for model simulation

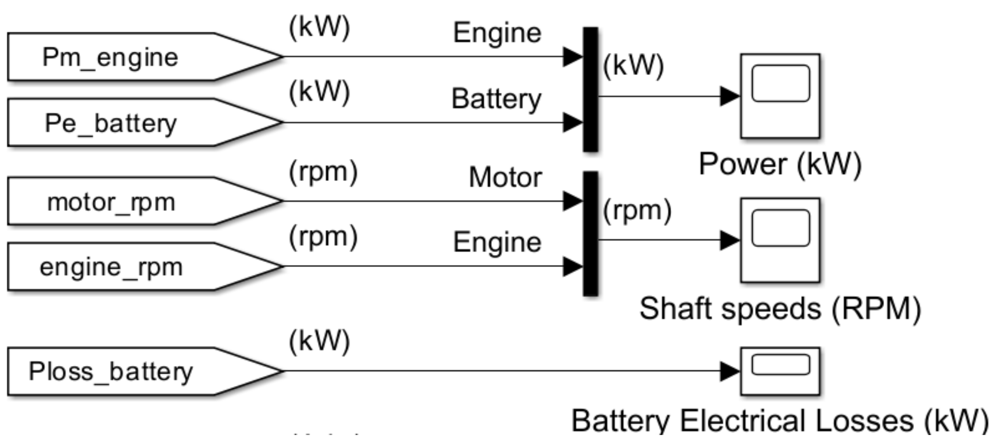

Figure 3.31: Simulation input parameters

CHAPTER FOUR

4. RESULTS AND DISCUSSION

Three-wheeler hybrid electric vehicle model is developed using MATLAB Simulink. The model is developed based on the vehicle specification given in *Table 3.1*. The model is developed and simulated on the MATLAB Simulink for parallel mode using SimScape driveline. It includes Battery modeling, DC-DC Converter modeling, Electric Motor Modeling, Engine Modeling, gearbox modeling, and Vehicle body modeling, as shown in *Figure 4.1*. The model is simulated for accelerate and decelerate condition for 3600 seconds run time. From the model various results are obtained.

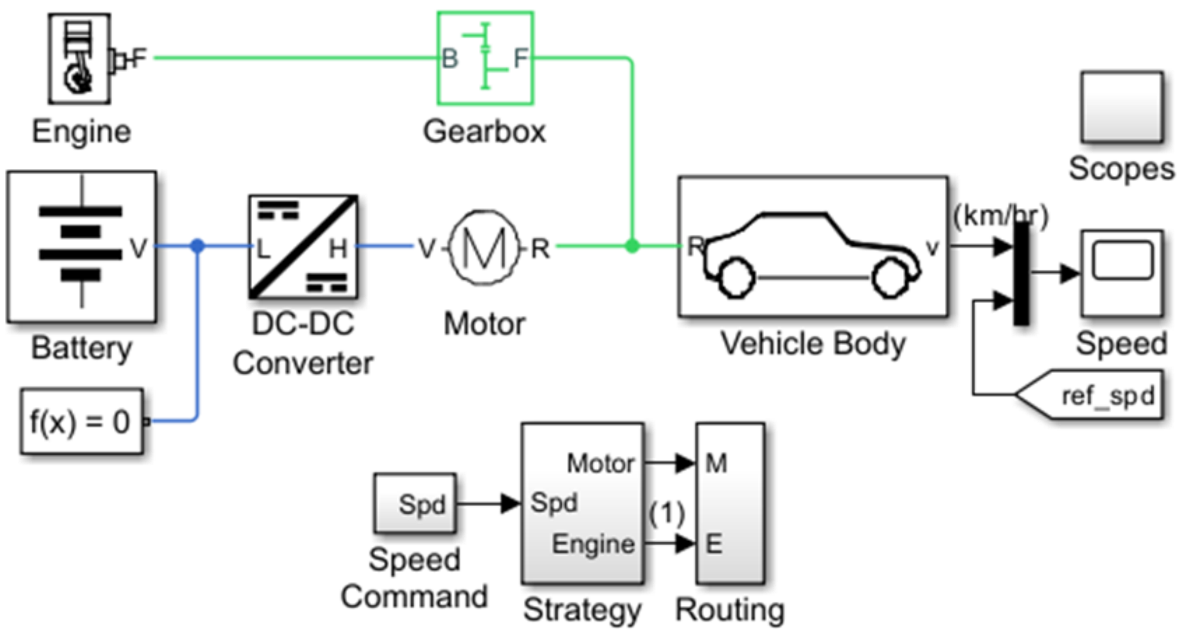

Figure 4.1: The complete vehicle architecture model in SimScape

As shown in *Figure 4.1*, in addition to the basic components of parallel mode hybrid electric vehicles, the model includes the scopes for displaying various simulating parameters. Moreover, the speed command, the power strategy and vehicle routing are included in the model to make more real-world scenario. Accordingly, the simulate results obtained are discussed below.

4.1. Shaft Speeds

Since both the electric motor and combustion engine have their own shaft, the shaft speeds for both of these components are simulated over the accelerate and decelerate simulating scenario of the model. Accordingly, as shown in *Figure 4.2*, when the vehicle accelerates both the engine shaft and motor shaft speeds increase at about 100s and 2200s from the graph. In addition, when the vehicle decelerates both the engine shaft and motor shaft speeds decrease at about 1800s from the graph. Moreover, when the vehicle travels at constant speed, both the engine shaft and motor shaft speeds remain constant.

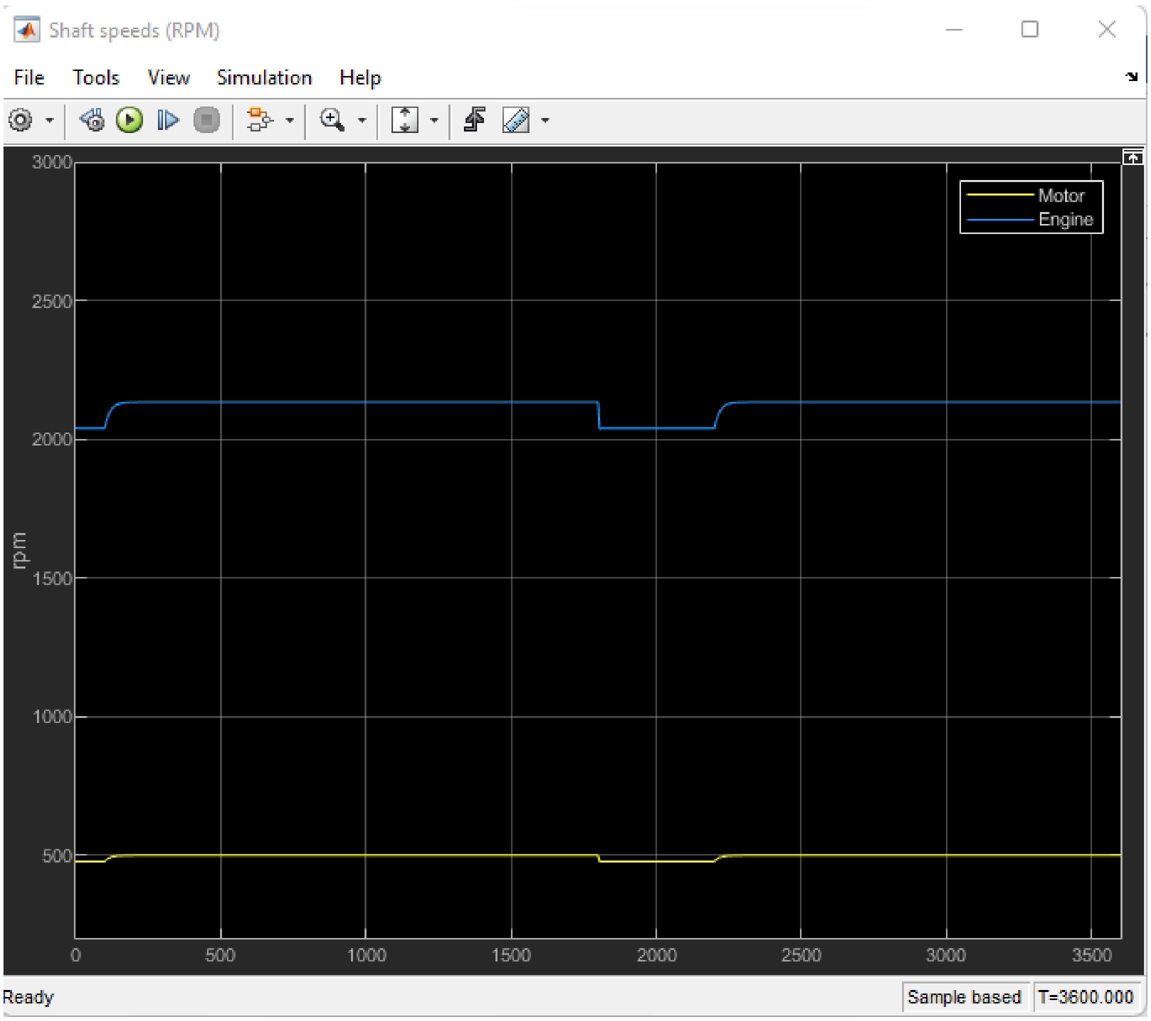

Figure 4.2: Shaft Speeds of Electric Motor and Combustion Engine for 3600s run time

4.2. Power

In parallel mode hybrid electric vehicle, both the battery and combustion engine generate power to run the vehicle. However, the power battery is usually needed when the vehicle accelerates. Since both the electric motor and combustion engine have their own shaft, the power generation for both of these components is simulated over the accelerate and decelerate simulating scenario of the model. Accordingly, as shown in *Figure 4.3* and *Figure 4.4*, when the vehicle accelerates the engine power decreases and motor power increase at about 100s and 2200s from the graph. Whereas, when the vehicle decelerates both the engine power increase and motor power decrease at about 1800s from the graph. Moreover, when the vehicle travels at constant speed, both the engine power and motor power remain constant.

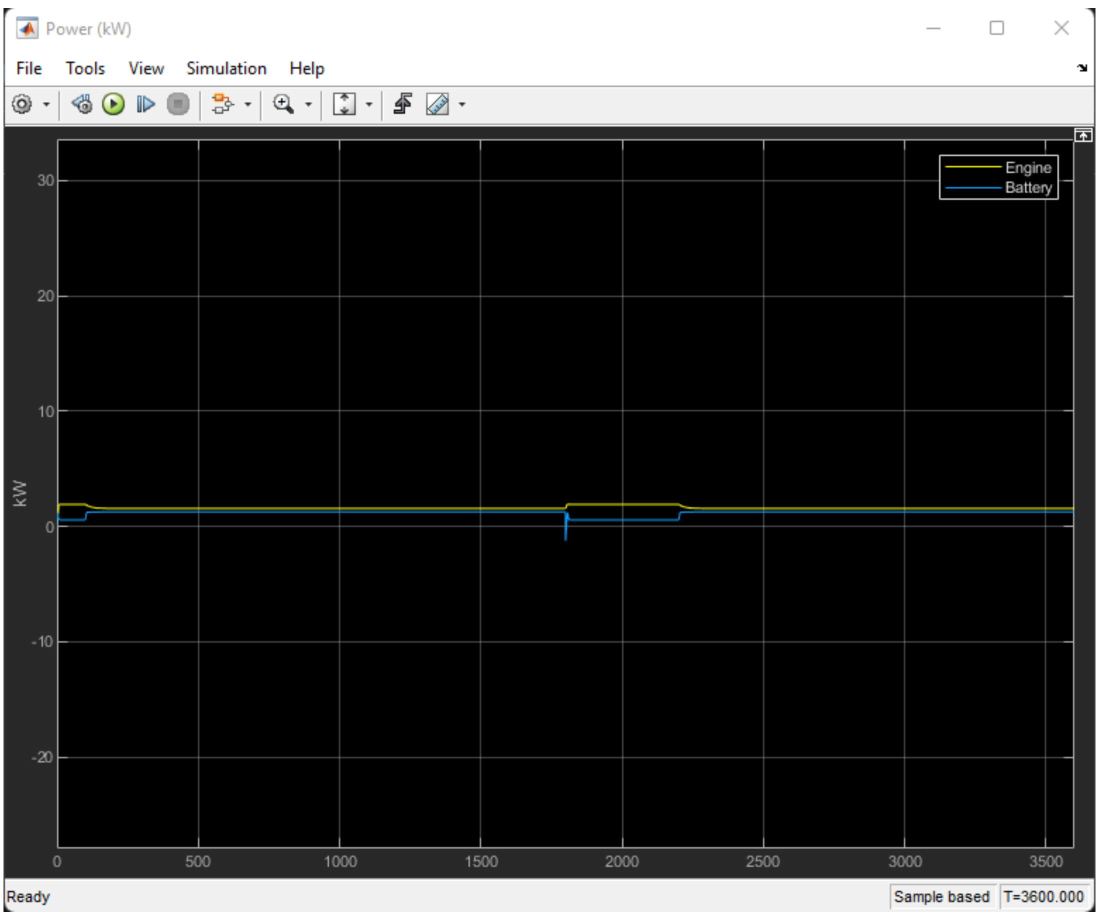

Figure 4.3: Power of Electric Motor and Combustion Engine for 3600s run time

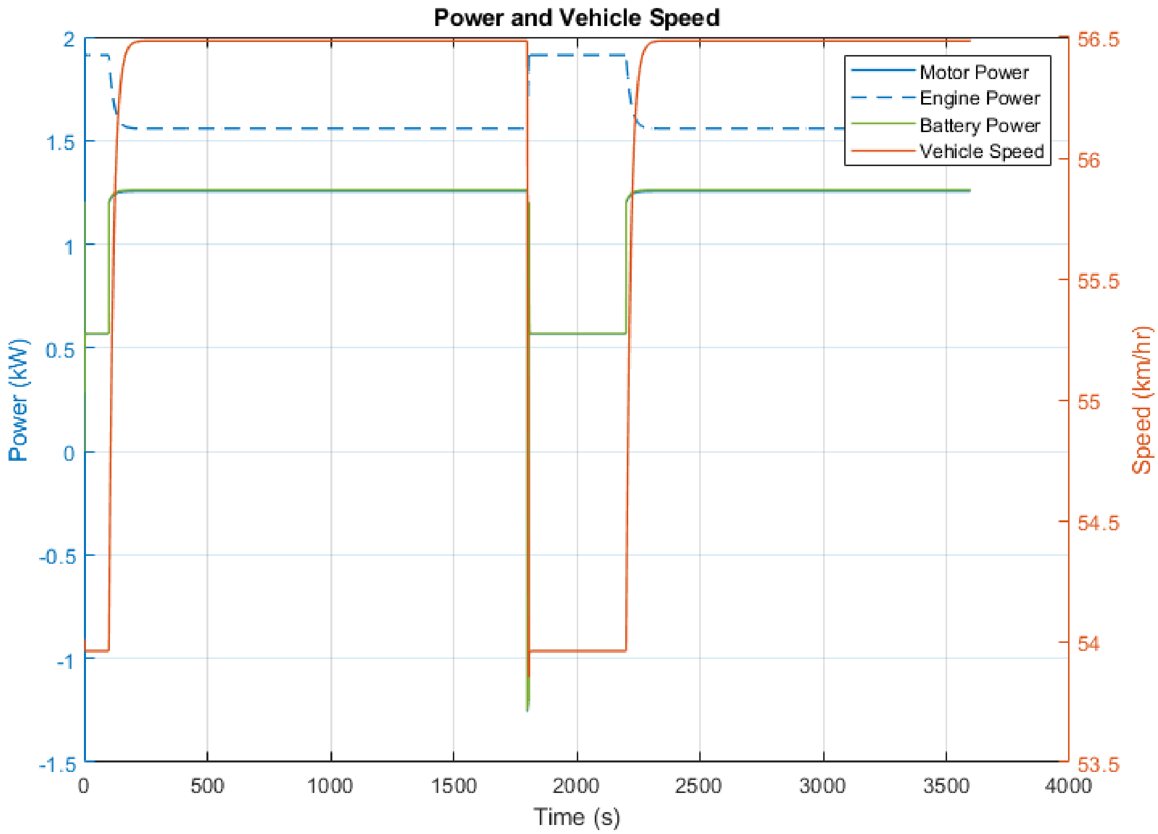

Figure 4.4: Power and vehicle speed for 3600s run time

Thus, in parallel mode hybrid electric vehicle model, the vehicle speed and engine power have inverse relation, and the vehicle speed and battery or motor power have direct relation. Moreover, as shown in *Figure 4.4*, electric motor power and battery power overlap. This indicates that the power delivered from the battery to electric motor without a significant loss. As discussed earlier, when the vehicle speed increases, there was a sharp increase in the power of battery and motor. As the vehicle speed increases from 54 km/hr to 56.5 km/hr, the battery power increases from 0.55 kW to 1.25 kW. That is, as the vehicle speed increases by 4.63%, the battery power increases by 127%. Whereas, as the vehicle speed decreases from 56.5 km/hr to 54 km/hr, the engine power increases from 1.55 kW to 1.95 kW. That is, as the vehicle speed decreases by 4.63%, the engine power increases by 25.8%.

4.3. Electrical Losses

In parallel mode hybrid electric vehicle, the power battery or motor is usually needed when the vehicle accelerates. That is, when the vehicle speed increases, there was a sharp increase in the power of battery and motor, and when the vehicle speed decreases, there was a sharp decrease in the power of battery and motor. This leads to the increase in the electrical losses of these components. Accordingly, as shown in *Figure 4.5*, when the vehicle accelerates the battery electrical loss and motor electrical loss increases. Whereas, when the vehicle decelerates battery electrical loss and motor electrical loss decreases.

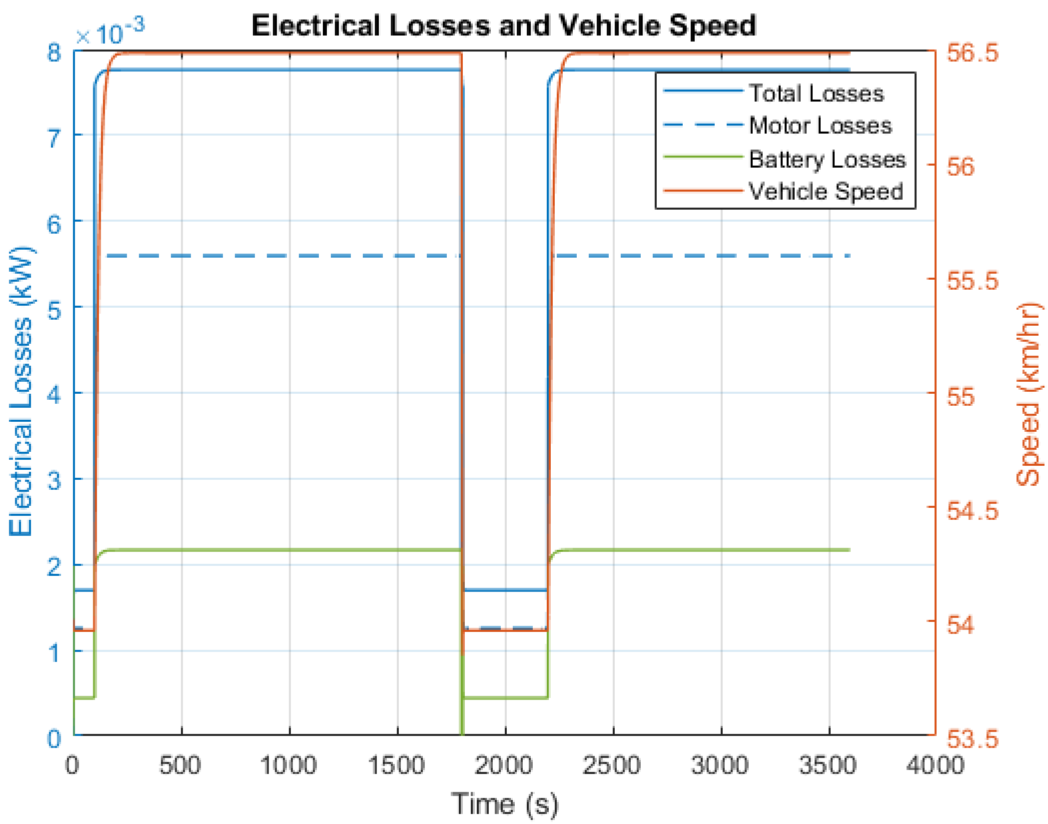

Figure 4.5: Losses and vehicle speed for 3600s run time

As the vehicle speed increases from 54 km/hr to 56.5 km/hr, the battery lost about 0.0021 kW of electric power, and the motor lost about 0.0057 kW of electrical power. That is, as the vehicle speed increases total electrical loss is 0.0078 of electrical power. Whereas, as the vehicle speed decreases from 56.5 km/hr to 54 km/hr, the battery lost about 0.0005 kW of electric power, and the motor lost about 0.0012 kW of electrical power. That is, as the vehicle speed decreases total electrical loss is 0.0017 kW of electrical power. This indicates, the electrical power loss of battery and motor for hybrid electric vehicle is more in acceleration than deceleration.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The demand for energy-efficient and eco-friendly vehicles is rapidly increasing in response to the challenges of high fuel consumption and environmental pollution. As such, three-wheeler hybrid electric vehicles have become a popular due to their improved fuel efficiency and reduced emissions. However, the lack of an accurate model that adequately simulates their dynamics and behavior impedes effective real-time testing. Thus, in this thesis, three-wheeler hybrid electric vehicle model is developed using MATLAB Simulink. The model is developed based on the real-world three-wheeler vehicle specification, shown in *Table 3.1*. The model is developed and simulated on the MATLAB Simulink for parallel mode using SimScape driveline, including battery, DC-DC converter, electric motor, combustion engine, gearbox, and vehicle body. The model is simulated for accelerate and decelerate condition for 3600 seconds run time.

The model is able to simulate the shaft speed of both the combustion engine and electric motor at different driving condition including acceleration, deceleration and constant speed. In addition, the model estimates the power of battery and engine at all driving scenario. Moreover, the model was able to calculate the electrical losses of both battery and electric motor.

Therefore, in parallel mode hybrid electric vehicle model, the vehicle speed and engine power have inverse relation, and the vehicle speed and battery or motor power have direct relation. As the vehicle speed increases by 4.63%, the battery power increases by 127%. Whereas, as the vehicle speed increases by 4.63%, the engine power decreases by 25.8%. Furthermore, as the vehicle speed increase total electrical loss increase. Whereas, as the vehicle speed decrease total electrical loss decreases. This indicates the electrical power loss of battery and motor for hybrid electric vehicle is more in acceleration than deceleration.

Since the model is developed by considering wind effect and elevation effect. It is close to the real-world scenario where the drag effect is produced due to the wind effect, and power consumption is increased due to elevation of the road effect. As such, the dynamics and the result of this model can be used to train the drivers of the three-wheeler HEV.

5.2. Recommendation

Three-wheeler hybrid electric vehicle model is developed using MATLAB Simulink for parallel mode using SimScape driveline. The model is able to simulate the shaft speed and power of engine, motor, and electrical losses of both battery and electric motor. However, due to limited computation power the model is simulated for 3600s runtime. Thus, it is recommended that:

- if the high computational power is available, the simulate should be run for longer run time,
- driveline such as powertrain driveline should be considered for result comparison, and
- drive mode such as split power mode may be considered for result comparison.

5.3. Future Works

While this study successfully developed a three-wheeler hybrid electric vehicle model in MATLAB Simulink for parallel mode, future work can further enhance its capabilities and explore additional aspects. Given the current model's capabilities in simulating shaft speed, power distribution between the engine and motor, and electrical losses, extending the simulation runtime beyond the 3600-second mark would provide a more comprehensive understanding of the vehicle's performance under varied conditions. Additionally, incorporating drivelines such as powertrain drivelines for comparative analysis could offer valuable insights into the effectiveness of different drivetrain configurations.

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APPENDIX

Appendix I: Current Sensor

current.ssc

```
component current
% Current Sensor
% The block represents an ideal current sensor, that is, a device that
% converts current measured in any electrical branch into a physical signal
% proportional to the current.
%
% Connections + and - are conserving electrical ports through which
% the sensor is inserted into the circuit.
% Connection I is a physical signal port that outputs current value.

% Copyright 2005-2019 The MathWorks, Inc.

outputs
    I = { 0.0, 'A' }; % I:right
end

nodes
    p = foundation.electrical.electrical; % +:left
    n = foundation.electrical.electrical; % -:right
end

variables(Access=private)
    i1 = { 0, 'A' }; % Current
end

branches
    i1 : p.i -> n.i;
end

equations
    n.v == p.v;
    I == i1;
end

end
```

Appendix 1: Current Sensor block modeling MATLAB code

Appendix II: Voltage Sensor

voltage.ssc

```
component voltage
% Voltage Sensor
% The block represents an ideal voltage sensor, that is, a device that
% converts voltage measured between any electrical connections into a
% physical signal proportional to the voltage.
%
% Connections + and - are conserving electrical ports through which
% the sensor is connected to the circuit.
% Connection V is a physical signal port that outputs voltage value.

% Copyright 2005-2019 The MathWorks, Inc.

outputs
    V = { 0.0, 'V' }; % V:bottom
end

nodes
    p = foundation.electrical.electrical; % +:top
    n = foundation.electrical.electrical; % -:bottom
end

equations
    V == p.v - n.v;
end

end
```

Appendix 2: Voltage Sensor block modeling MATLAB code

Appendix III: Electrical Reference Block

reference.ssc

```
component reference
% Electrical Reference :0.5
% Electrical reference port. A model must contain at least one
% electrical reference port (electrical ground).

% Copyright 2005-2016 The MathWorks, Inc.

nodes
    V = foundation.electrical.electrical; % :top
end

connections
    connect(V, *);
end

end
```

Appendix 3: Electrical Reference block modeling MATLAB code

Appendix IV: Mechanical Reference Block

reference.ssc

```
component reference
% Mechanical Rotational Reference :0.5
% This block represents a mechanical rotational reference point, that
% is, a frame or a ground. Use it to connect mechanical rotational ports
% that are rigidly affixed to the frame (ground).

% Copyright 2005-2016 The MathWorks, Inc.

nodes
    W = foundation.mechanical.rotational.rotational; % :top
end

connections
    connect(W, *);
end

end
```

Appendix 4: Mechanical Reference block modeling MATLAB code

Appendix V: Transformer Modeling

ideal_transformer.ssc

```
component ideal_transformer
% Ideal Transformer :2.0
% Models an ideal power-conserving transformer satisfying V_1 = N*V_2
% and I_2 = N*I_1 where N is the Winding ratio, V_1 and V_2 are the
% primary and secondary voltages, I_1 is the current flowing into the
% primary + terminal, and I_2 is the current flowing out of the secondary
% + terminal.
%
% This block can be used to represent either an AC transformer or a
% solid-state DC to DC converter. To model a transformer with
% inductance and mutual inductance terms, use the Mutual Inductor block.
%
% Note that the two electrical networks connected to the primary and
% secondary windings must each have their own Electrical Reference block.

% Copyright 2005-2016 The MathWorks, Inc.

nodes
    p1 = foundation.electrical.electrical; % 1+:left
    n1 = foundation.electrical.electrical; % 1-:left
    p2 = foundation.electrical.electrical; % 2+:right
    n2 = foundation.electrical.electrical; % 2-:right
end

parameters
    n = 1;    % Winding ratio
end

variables
    i1 = { 0, 'A' }; % Primary current
    v1 = { 0, 'V' }; % Primary voltage
    i2 = { 0, 'A' }; % Secondary current
    v2 = { 0, 'V' }; % Secondary voltage
end

branches
    i1 : p1.i -> n1.i;
    i2 : p2.i -> n2.i;
end

equations
    assert(n>0)
    v1 == p1.v - n1.v;
    v2 == p2.v - n2.v;
    v1 == n*v2;
    i2 == -n*i1;
end

end
```

Appendix 5: Transformer block Modeling MATLAB code