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Performance of a Parallel Hybrid Electric vehicle with Liquefied Natural Gas

CAPSTONE PROJECT

B.Sc. Mechanical Engineering

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Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfilment of the requirements for the award of Bachelor of Science degree in Mechanical Engineering.

Kwamina Essandoh Amoako

2019

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

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I hereby declare that preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University College.

Supervisor's Signature:

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Abstract

Fossil Fuels are currently classified as some of the leading producers of greenhouse gases which are major agents of Global warming. This study establishes the benefits Liquified Natural Gas (LNG) would have when used as a fuel in a hybrid-electric vehicle. The study establishes a Parallel-Hybrid vehicle model equipped with a control system to determine the mode of operation of the vehicle. Simulations using the vehicle models developed were performed in AVL Cruise. The results generated from the simulations the vehicle's fuel consumption and CO_2 emissions are compared to that of a traditional gasoline/diesel Internal Combustion Engine. The results show a lower acceleration time and better fuel consumption in the LNG hybrid vehicle operation. Further tests are needed to properly ascertain the CO_2 emission and overall efficiency of the LNG hybrid vehicle model.

Keywords: LNG, AVL Cruise, ICE

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Chapter 1: Introduction

With the increase in the demand for energy all over the world, it has become more than important for cleaner energy sources to be explored. As of 2006, the world energy consumption had reached 499 exajoules and it has been projected to rise to 680 exajoules by 2030 [1]. Fossil fuels are expected to be responsible for the production of 80% of the energy that would be used during this period. The burning of these fossil fuels would have a corresponding increase in the presence of Greenhouse gases in the atmosphere, pushing the world closer to a global warming crisis. This project proposes to design and evaluate the validity of a Liquified Natural Gas (LNG) Hybrid Electric Vehicle. LNG is being considered for this study as it can be described as the cleanest fossil fuel [2]. The burning of LNG results in the production of Carbon dioxide and water vapor, in similar quantities as when humans exhale [3]. LNG gas exhausts contain 5-10% of Carbon dioxide and no Sulphur or solid particle content [4]. Combining LNG with an Electrical system which has zero carbon emissions, would make the proposed hybrid vehicle model capable of reducing the world's carbon footprint when universally adopted. Using simulations, the performance and efficiency of this hybrid electric vehicle are compared to that of traditional fossil fuel power hybrid electric vehicle [5].

1.1 Background

Fossil fuels are currently used in a large number of industries across the world. With all the expected increases in the level of greenhouse gases in the years to come, the threat of the earth becoming uninhabitable is gradually becoming a reality. As of 2010, the transportation sector contributed 14% of global greenhouse gas emissions with 95% of the energy used is derived from gasoline and diesel [6]. With the increase in technology and modernization, this significantly reduces man's time on earth, as fossil fuels are estimated to produce 80% of the world's energy as of 2030 [1]. The estimated increase in fossil fuel usage would increase the production of greenhouse gases which rise to form a layer around the earth. This layer prevents heat from escaping the earth's atmosphere, thus, increasing the earth's ambient temperature and over time, increasing to a temperature that would be unable to support humanity, this concept is what is known as Global warming [7].

1.2 Objectives of the Project Work

- Validate the combination of LNG Internal Combustion Engine (ICE) and an electric powertrain to power a salon passenger vehicle. The Hybrid vehicle would implement the parallel powertrain architecture containing an ICE of at least 1500 cc capacity, and an electric motor of 50 kW at 1200 – 1540 rpm with a torque of 400 Nm at 0 – 1200rpm.
- Evaluate the performance of the Hybrid vehicle focusing on the engine and electrical machine output power and torque, the fuel consumption and CO_2 emissions.

1.3 Research Methodology

1.3.1 Research tools

Research would focus on obtaining information from literature on LNG use in powering automobiles. The information gathered would be used to develop a hybrid vehicle model which combines an ICE using LNG and an electric powertrain. The vehicle model would be simulated through different situations using the AVL Cruise software.

1.3.2 Procedure

The following steps were completed in the execution of this project;

- Selection of an appropriate hybrid vehicle architecture to use in the design of the vehicle model.
- Design and development of hybrid vehicle model implementing architecture selected.

- Design and programming of a control system to determine the mode in which the vehicle would operate at all times.
- Set vehicle specifications within model components.
- Perform standard drive cycle, climbing performance and acceleration from standstill simulations in AVL Cruise with the developed model.
- Review results generated from simulation runs, focusing on the engine and electrical machine output powers and torques, the fuel consumption and CO2 emissions.
- Make conclusions on the performance of the LNG hybrid vehicle model by comparing to the performance of a Petrol hybrid vehicle model in the same situations.

1.3.3 Validation

The control system developed would be tested using known conditions that satisfy the selection of each mode the hybrid vehicle can operate. This test would also verify the accuracy of the control system.

Chapter 2: Literature Review

Electric vehicles (EVs) began to be appreciated in the 1970s due to the crude oil crisis during the period [8]. Improvements in battery technology and motor efficiency have led the way in advancements made in the developments of EVs further growing its consumer market and share in the transportation industry. EVs have an efficiency of about 80% [9] with an added advantage of having zero CO, CO_2 and NO_x emission. Current trends focus on increasing the range of EVs through advancements in more efficient charging systems and battery-swapping technology.

Hybrid Electric Vehicles (HEV) are a relatively new field of study in the Automobile industry to smoothen the transition for consumers from the use of ICE vehicles to EVs. Huge advancements have been made over the period, providing inventors within the automobile industry with a wide range of options to choose from concerning the vehicle's architecture and control. The main characteristic of a Hybrid Electric car is the combination of two or more power sources and the relationship between them during the vehicle's operations. There are three main powertrain architectures used in HEV design, namely; Series HEVs, Parallel HEVs and Dual mode HEVs [10]. HEVs makes use of the start-stop technology which improves the vehicle's fuel efficiency by shutting the engine down when the vehicle is not moving and automatically turns it back on when the driver releases the brake pedal, or the accelerator pedal is pressed [11].

2.1 Series Hybrid Electric Vehicles

In this architecture, the vehicle is mainly driven by the electric motor power by a battery or fuel. This architecture presents a more efficient vehicle as the electric motor operates at 85% efficiency as compared to the 30% efficiency an ICE provides [9]. The primary role of the ICE in this architecture is to continuously charge the electrical energy source (i.e., Battery) which powers the electric motor within the powertrain. This architecture allows for the battery to be charged through regenerative braking when the vehicle is brought to a halt. Figure 2.1 shows the layout of components within a series HEV architecture.

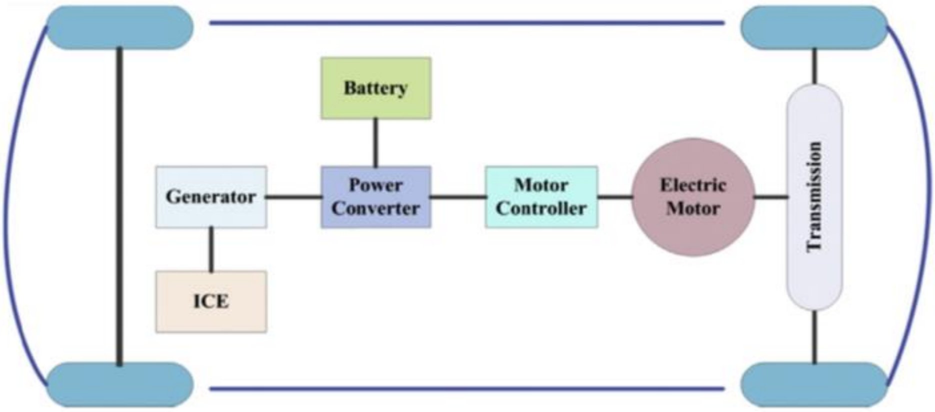

Figure 2.1 Series Hybrid Electric Vehicle Architecture

2.2 Parallel Hybrid Electric Vehicles

For the Parallel HEV architecture, the electric motor and ICE are connected directly to the transmission of the vehicle to supply the power required by the vehicle at any given instance [12]. The system includes a controller that switches to the electric powertrain to power the vehicle for short distances, and to the ICE or both powertrains to power the vehicle for long distances and hill climbs [10]. The Battery of the electric motor is charged when the ICE is in use and also through regenerative braking. ICEs are known to have an efficiency of 30% due to the losses that occur during its operation. These losses can largely be attributed to the friction that exists between the moving parts of the engine and the fact that the operation of the engine is governed by the second law of thermodynamics. Friction further leads to the creation of heat which dissipates into the environment and prevents the efficient conversion of the fuel's chemical energy to the vehicle's mechanical energy. Regenerative breaking aims to increase the vehicle's fuel efficiency by converting the vehicle's kinetic energy to electrical energy to be stored in a battery or mechanical energy in a flywheel [13]. This stored electrical and mechanical energy can then be used when the vehicle begins to move again.

Figure 2.2 shows the layout of components within the Parallel HEV architecture.

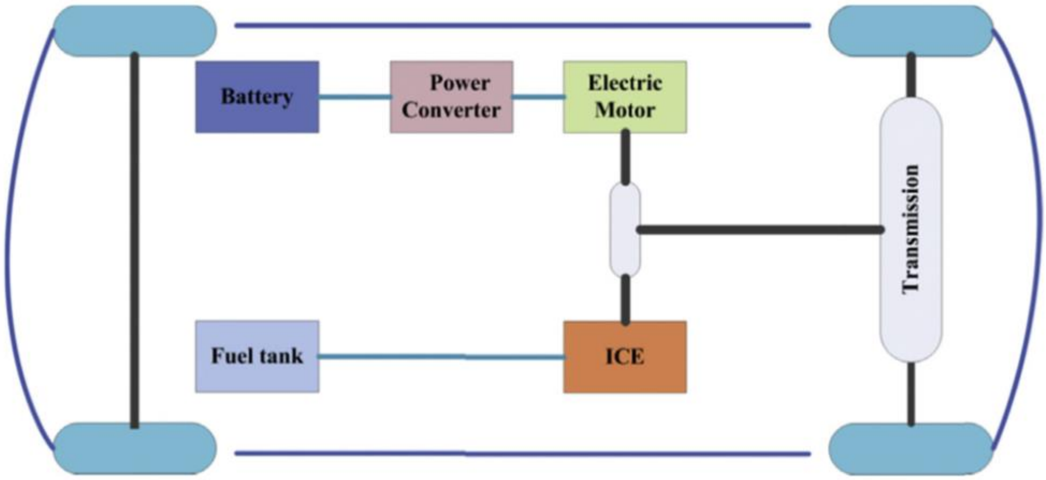

Figure 2.2 Parallel Hybrid Electric Vehicle Architecture

2.3 Dual-Mode Hybrid Electric Vehicles

Dual Mode HEV architectures combine the complexities and advantages of both Series and Parallel HEV architectures [14]. For stop-and-go conditions, a Dual Mode HEV would make use of the series configuration within it while making use of the Parallel configuration for long distances. Figure 3 shows the layout of components within Parallel HEV architecture.

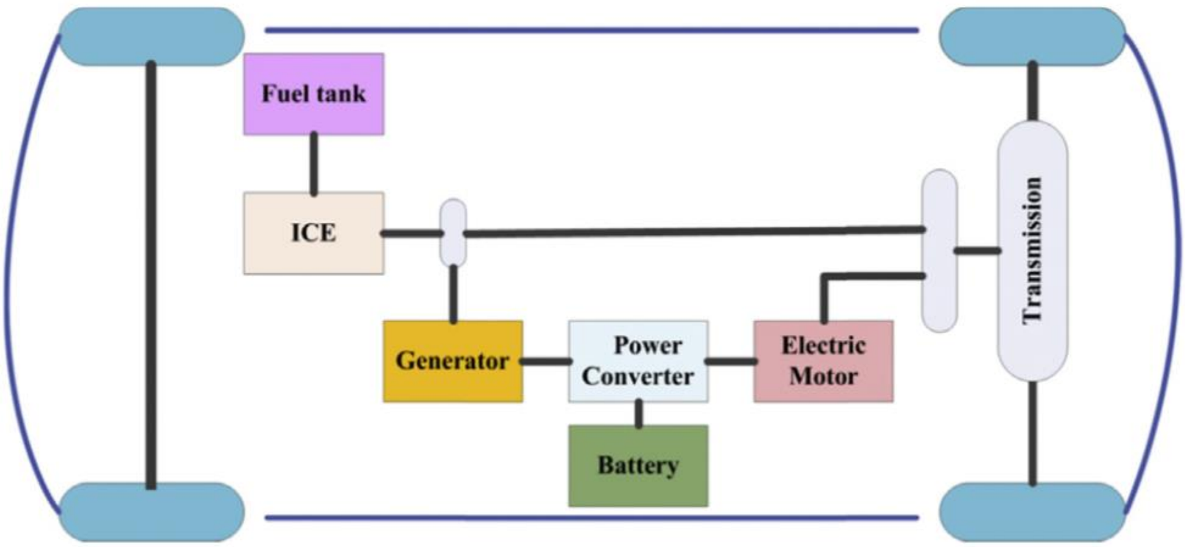

Figure 2.3 Dual-Mode Hybrid Electric Vehicle Architecture

2.4 Liquified Natural Gas (LNG)

Liquified Natural Gas (LNG) is described as the cleanest fossil fuel available today. LNG should be considered as an alternative fuel for powering automobiles as it leaves the least carbon footprint during its use [15]. Although LNG has the potential to revolutionize the automobile industry, the adoption of LNG as a fuel to power vehicles faces some hinderances due to the following reasons [16];

- LNG needs to be stored at cryogenic temperatures (i.e. about -162 °C) and as such the vehicle would need to be modified to accommodate cryogenic containers to store the fuel. This introduces new design requirements and costs which end up making such a vehicle more expensive for producers and customers.
- The annual mileage of passenger vehicles is considered to be too low to compensate for the boil-off losses that would occur when using LNG as a fuel source. Heavy-duty vehicles generally have higher mileages and make them more ideal to use LNG as an alternative fuel.

CLNG is recommended as a substitute for LNG in passenger vehicles as it can compensate for the boil-off losses that occur due to the low duty cycle of passenger vehicles. LNG holds a strong potential of aiding in the reduction of the carbon footprint of the transportation sector. Acceptance frameworks needed to introduce LNG successfully have been developed and the results from models created within it suggest that by creating the demand, increasing the availability and improving the ecological effects of LNG improves the chances of the adoption of LNG as an alternative fuel [15].

An experiment was conducted to investigate the integration of an LNG engine with an electric control system and a diesel marine engine [17]. The fuel economy and emission of the hybrid engine was compared to the original ICE engine. All of the performance experiments were carried out according to the propulsion characteristics and load characteristics. The results of some of the experiments show marginal improvements in the hybrid engine as well as present the drawbacks of the hybrid engine observed in the remaining experiments. This experiment gives an unbiased view of a Duel-fuel engine detailing the advantage and disadvantages with experimental data.

This goes to prove the benefits that can be derived when an LNG-Electric Hybrid vehicle is developed.

Chapter 3: Design

This chapter details out how the design of the vehicle, which would be used for the simulations was selected.

3.1 Thesis Design Objectives

The vehicle's architecture would focus on characteristics that would improve the vehicle's operation. The characteristics to be focused on is the vehicle's energy efficiency, CO_2 Emissions, performance and complexity. These characteristics would be considered in the following context:

i. **Energy Efficiency**- The energy efficiency of a vehicle refers to the amount of energy from the energy source, be it, electric or an ICE, which would be converted to mechanical power. The ideal efficiency of an HEV would be greater than the efficiency of an ICE vehicle which is about 30% and close to the efficiency of an electric vehicle which is about 85% [9].

ii. **Vehicle Emissions** – This characteristic would capture the amount of Greenhouse gases, mainly Carbon dioxide that would be produced by the HEV.

iii. **Performance** – This would refer to the constant power output of the engine in different operational situations. These situations would be classified on the bases of the terrain on which the HEV would be used, and the manner in which it performs in its operations.

iv. **Complexity** – This refers to the number of components and control systems that would be used in the vehicle's design. An ideal HEV should have an appropriate number of components to function effectively and also make it cost effective for the manufacturers.

3.2 Design Criteria

The characteristics outlined above of all three hybrid electric vehicle architectures were considered and the results are displayed in the Pugh chart below. The baseline for this comparison was an Electric or an ICE Vehicle.

3.2.1 Pugh Matrix

Table 3.1 Pugh Matrix for Vehicle Architecture selection

			Baseline		Series Configuration	Parallel Configuration	Dual mode Hybrid Configuration
1	Energy Efficiency		0		1	1	1
2	Vehicle Emissions		0		1	0	1
3	Performance		0		0	1	1
4	Complexity		0		1	1	-1
	Total				3	3	2

3.3 Design selection

This study's vehicle model employs the parallel hybrid Electric configuration. The pugh chart justifies the selection of this configuration as it has one of the highest marks with respect to the design criteria.

In addition to satisfying the design criteria, the parallel configuration is the best fit for the African continent. Africa is currently struggling to catch up on technological bases with the rest of the world and as such, does not currently have the infrastructure, such as charging stations to support the use of electric vehicles. The parallel configuration solves this problem as the ICE is used to recharge the battery of the vehicle at some points during its operation.

Chapter 4: Methodology

4.1 Computational Setup

Vehicle Model

To achieve simulation, a model of a hybrid vehicle which employs a parallel configuration was developed using the AVL Cruise software. The AVL Cruise software provides a wide range of analytic and comparison tools which can be used to simulate and evaluate the operation of a vehicle to optimize its performance. AVL cruise simulations give results, on the fuel consumption, emissions and overall vehicle performance [18].

Figure 4.1 shows the vehicle model developed. The ICE powertrain consists of the four-cylinder engine with a maximum speed of 62 mph and torque of 142 Nm; Table 2 contains details of the vehicle model' specifications used in its design.

Table 4.1 Vehicle Model Specifications

Vehicle Specification	Value
Curb Weight	1450 kg
Gross Weight	1930 kg
Wheelbase	2650 mm
Distance from Hitch to Front Axle	3300 mm
Drag Coefficient	0.32
Frontal Area	1.88 m^2
Final Drive Transmission Ratio	3
Engine Displacement	2478 cm^3
Engine Maximum Speed	6000 1/min

The ICE powertrain also consists of an automatic clutch which connects to a five-speed gearbox. The electric powertrain train consists of a battery to store and provide power and an electric machine which can operate as an electric motor or a generator depending on the mode in which the vehicle is operating. Both the electric and ICE powertrain are connected to a single ratio gear to serve as the final drive. The configuration and placement of the final drive in this model enable the vehicle to easily receive power from each powertrain and when required, combined the power produced from both powertrains. The torque produced by the final drive is transmitted to a differential which transfers it to rear wheels to propel the vehicle. The model contains a monitor component which would show all the values of selected outcomes while the simulation is running. The cockpit component would be used to interface with a control system to determine how the other components of the vehicle would function. This component is likened to the driver of a vehicle.

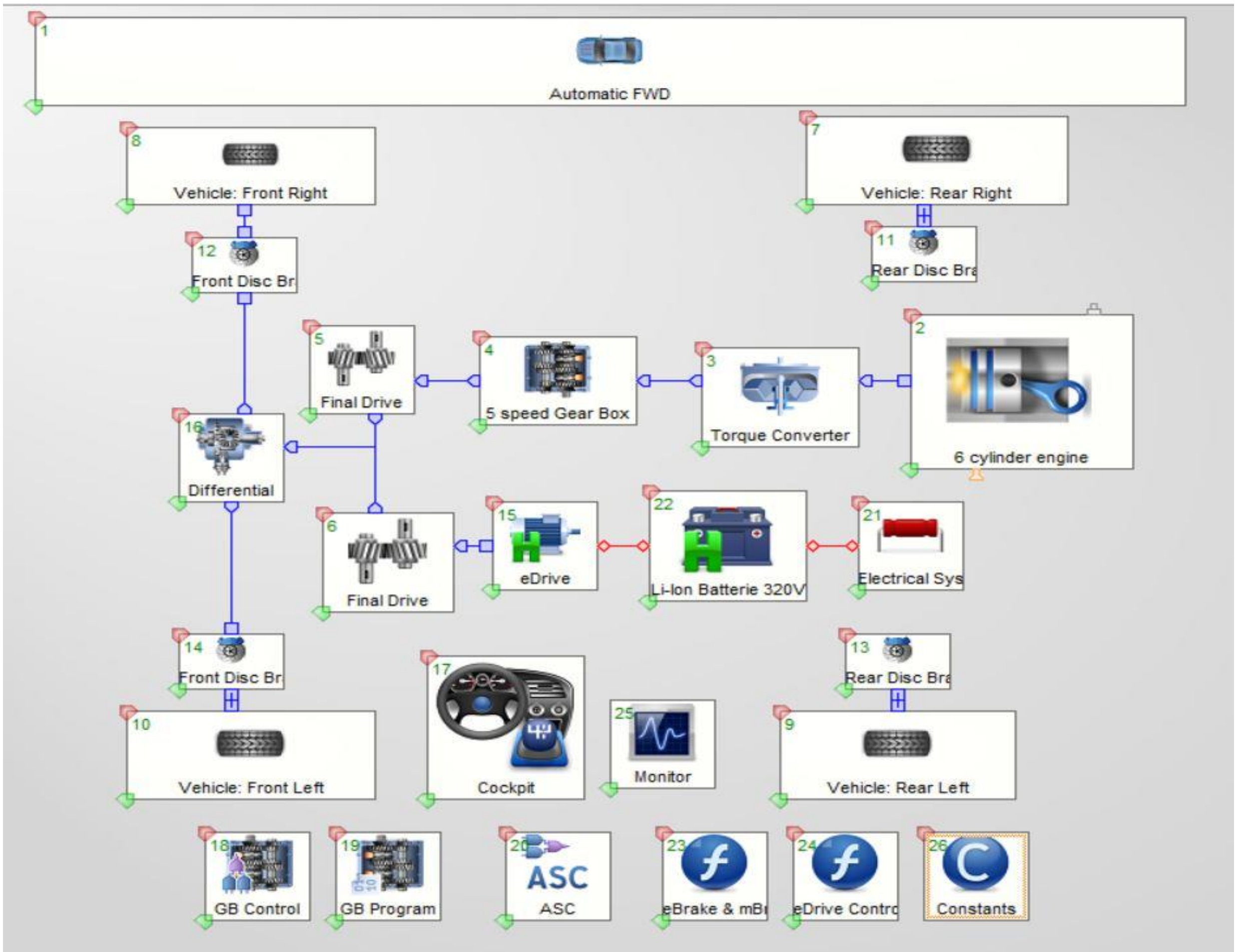

Figure 4.1 Vehicle Model Created in AVL Cruise

Control System

The control system is designed to determine the mode in which the vehicle would operate. The control system is designed in MATLAB's SIMULINK and imported into the AVL Cruise model as an executable file. The control system is set up to interface with the vehicle model via the cockpit component [19].

The control system receives real-time data from the vehicle components such as the accelerator pedal or brake pedal as well as calculations from other components. These real-time signals are computed within the control system to determine the mode in which the vehicle would operate. The mode is determined on the bases of the power and torque required by the vehicle at any point in time.

The control system is designed to select from four distinct modes depending on the required torque of the vehicle [19].

The first mode is described as the engine-alone mode. In this mode, the torque required by the vehicle is provided solely by the ICE powertrain. In the control logic, for this mode to be selected, the torque required by the vehicle would have to be less than the maximum torque produced by the ICE powertrain and the voltage of the battery would be less than the minimum discharge voltage or greater than the maximum discharge voltage.

The second mode is described as the Hybrid-drive mode. For this mode, the vehicle's required torque is provided by both the ICE and electric powertrain. In this mode, the following conditions are satisfied; the required vehicle torque is greater than the maximum torque of the ICE and the battery voltage is greater than the discharge voltage.

The third mode is described as the generator mode. This mode operates simultaneously with the engine-alone mode. In this mode, the electric machine in the electric powertrain operates as a generator and charges the battery. For this mode to be activated, the required vehicle torque would have to be less than the ICE torque and the battery voltage would be less than the minimum discharge voltage.

The fourth mode is described as the regenerative braking mode. This mode is activated when the vehicle is braking. The operation of this mode is characterized by the ICE shutting off and the electric machine operating as a generator to charge the battery. This mode goes a long way in reducing the vehicle's fuel consumption. Figure 4.2 shows the architecture of the control system developed. The control system is designed using a Stateflow chart with the vehicle's four modes being the states and the input being the real-time signals received from the vehicle's model.

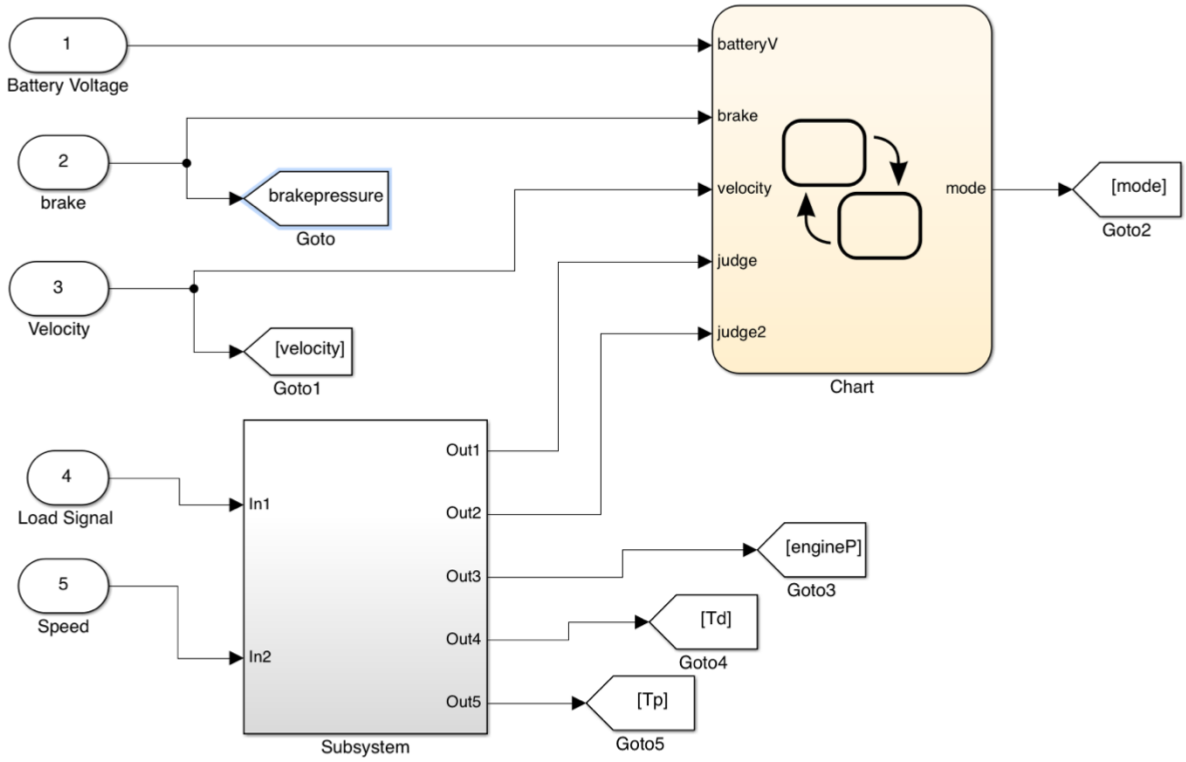

Figure 4.2 Control System developed for vehicle mode selection.

Figure 4.3 shows an elaborate mode judge which is used within the control system to determine how much power would be needed from each power train.

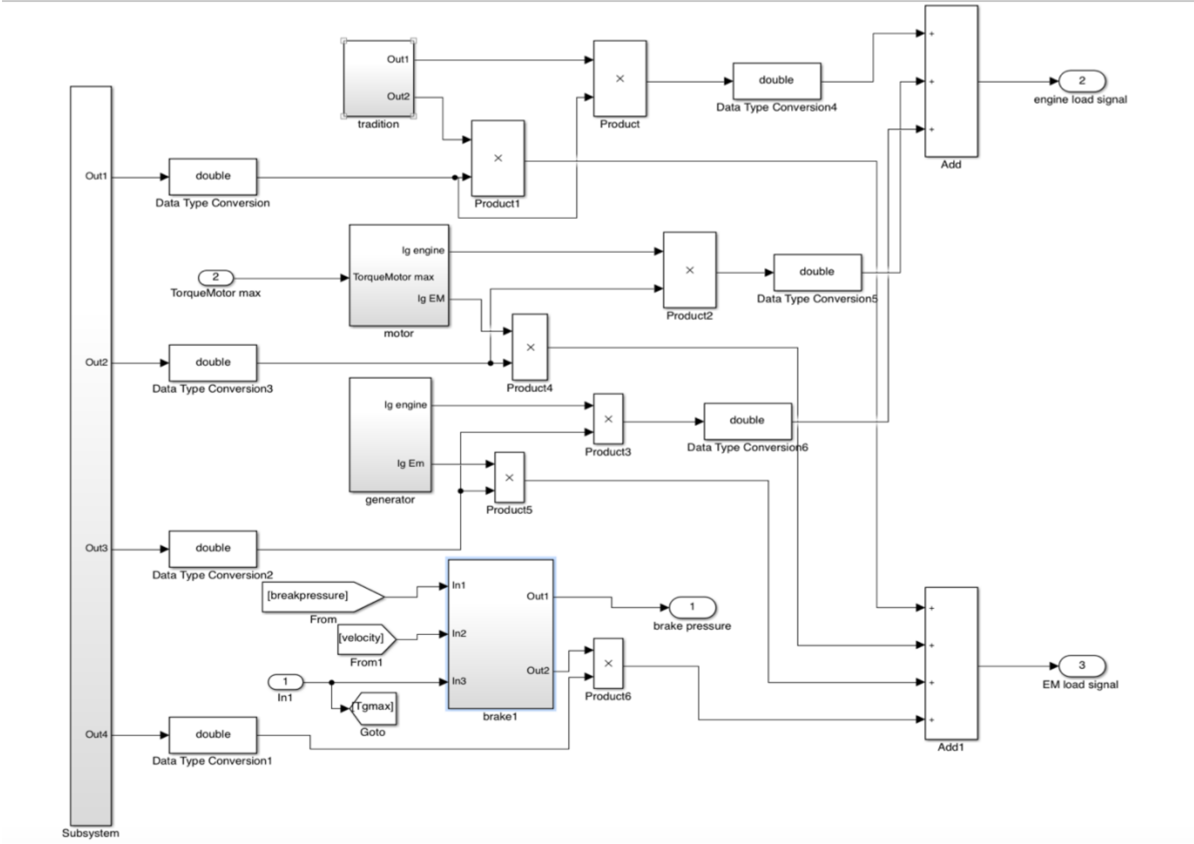

Figure 4.3 Elaborate Mode Judge in the Control System.

Chapter 5: Results

5.1 Drive Cycle Run Results

Figure 5.1 shows the drive cycle characteristics the developed vehicle model would be simulated through. The cycle run consists of a variety of vehicle operations such as constant acceleration and deceleration, maintaining constant velocity and the vehicle being at complete rest all over a 1000m distance.

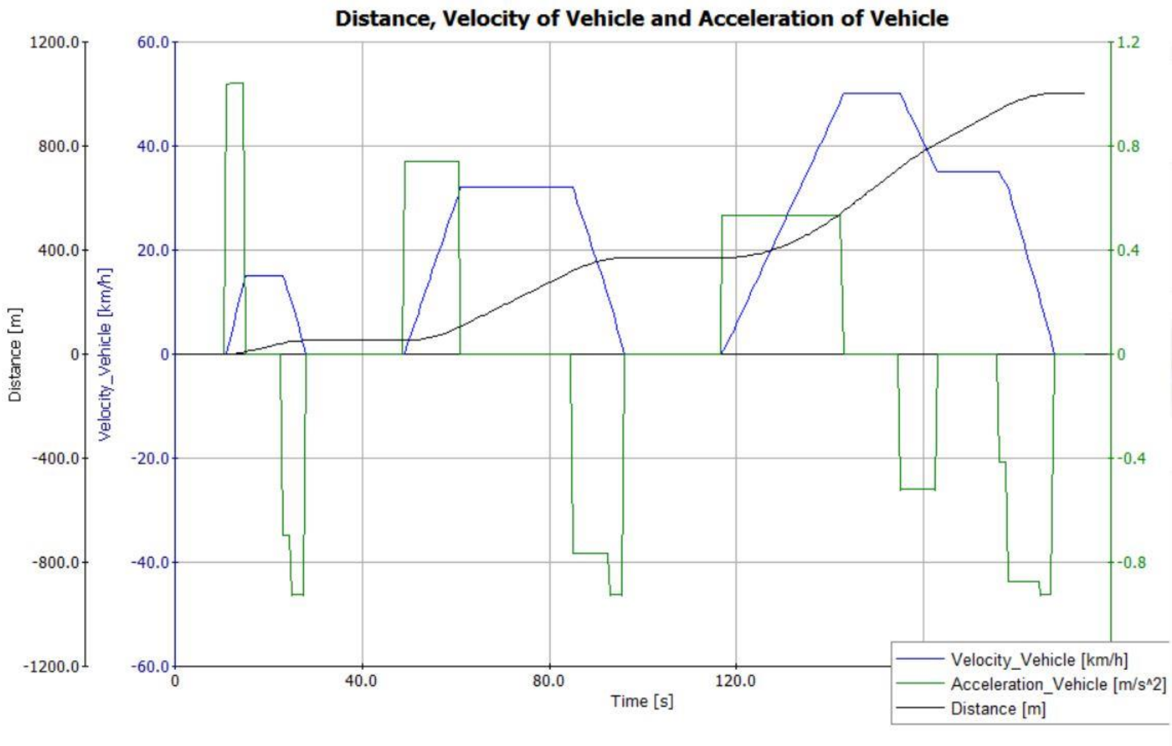

Figure 5.1 Standard Drive Cycle

Figure 5.2 contains the results generated from the simulation of the model through the drive cycle. The figure highlights the vehicle's engine power, speed and torque. Maximum engine torque of 67.59 Nm measured at time 14.26 s corresponding to the maximum acceleration in the drive cycle. The results recorded a maximum engine speed of 2947.26 1/min at 60.9 s. A maximum engine power of 18.6754 kW was recorded at the maximum velocity of 50 km/h.

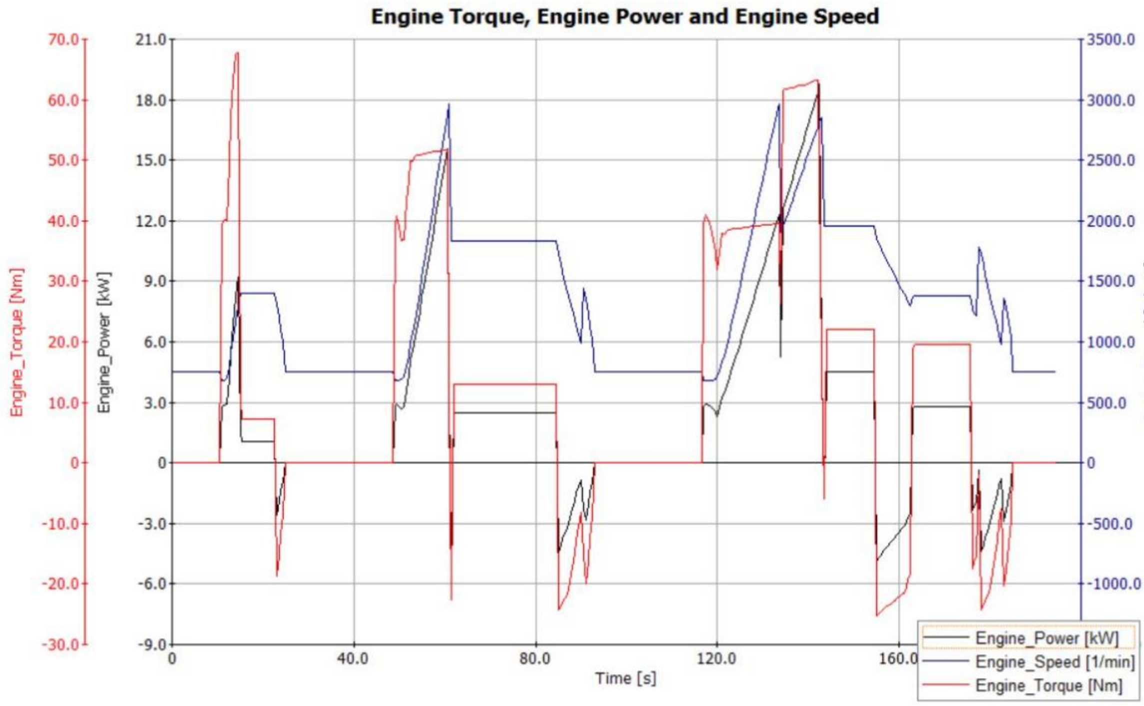

Figure 5.2 Engine Characteristics of Vehicle during the Drive Cycle

Figure 5.3 shows the performance of the electric machine within the vehicle model during the drive cycle.

Figure 5.3 Performance of Electric Machine during drive cycle

Figure 5.4 shows the results of the fuel consumption characteristics during the drive cycle. The figure shows the mass and volumetric flow of the LNG in the engine during the drive cycle. The figure also contains the cumulated mass and volume of LNG during the cycle run.

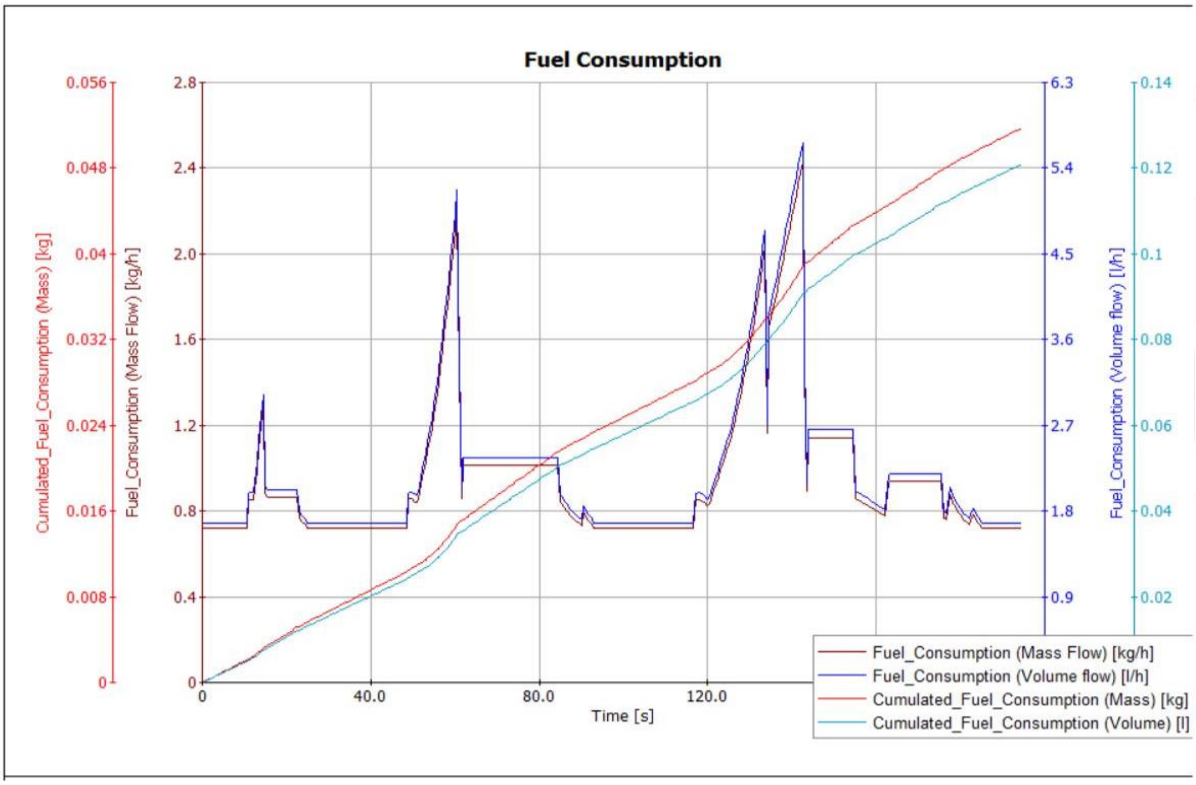

Figure 5.4 Fuel Consumption during Drive cycle

Figure 5.5 presents the results of the Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x) and other emissions produced during the model's simulation.

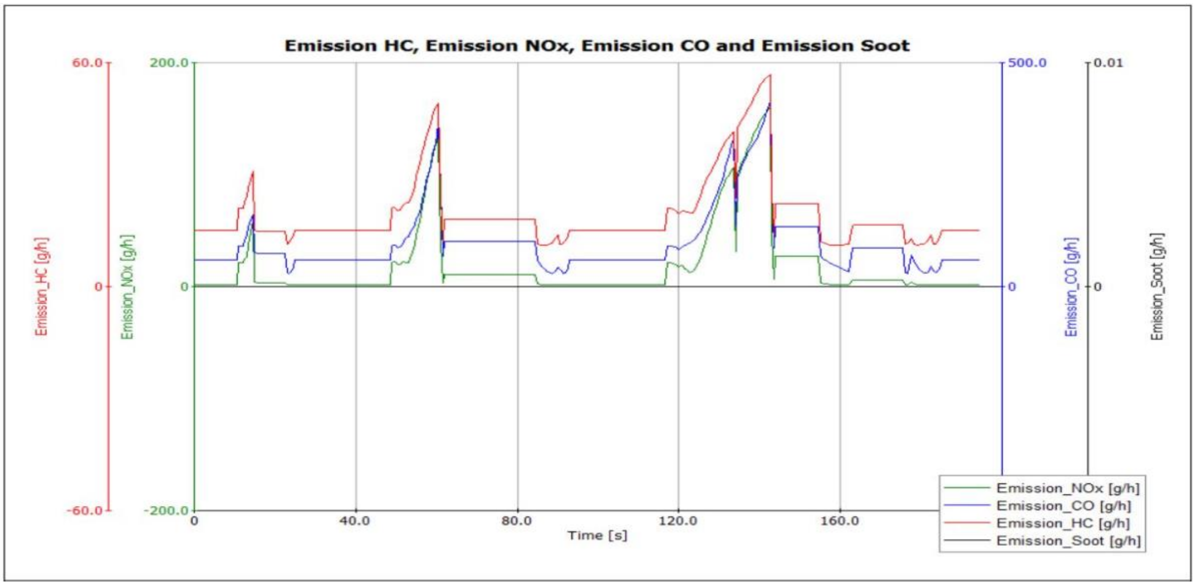

Figure 5.5 Vehicle Emissions during Cycle run

5.2 Climbing Performance Run Results

Figure 5.6 shows the climbing performance simulation characteristics the vehicle model would be tested through. The figure shows five distinct situations having a decreasing percentage of inclinations which are meant to simulate roads with varying steepness.

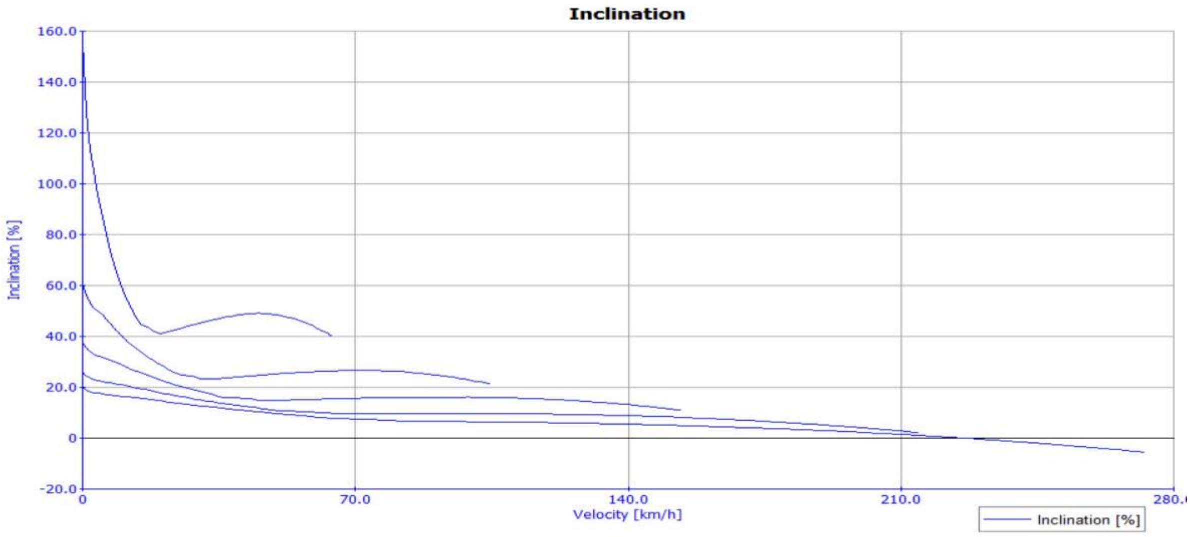

Figure 5.6 Climbing Performance characteristics

Figure 5.7 shows the behavior of the vehicle's engine during the climbing performance simulation, showing the results from each situation.

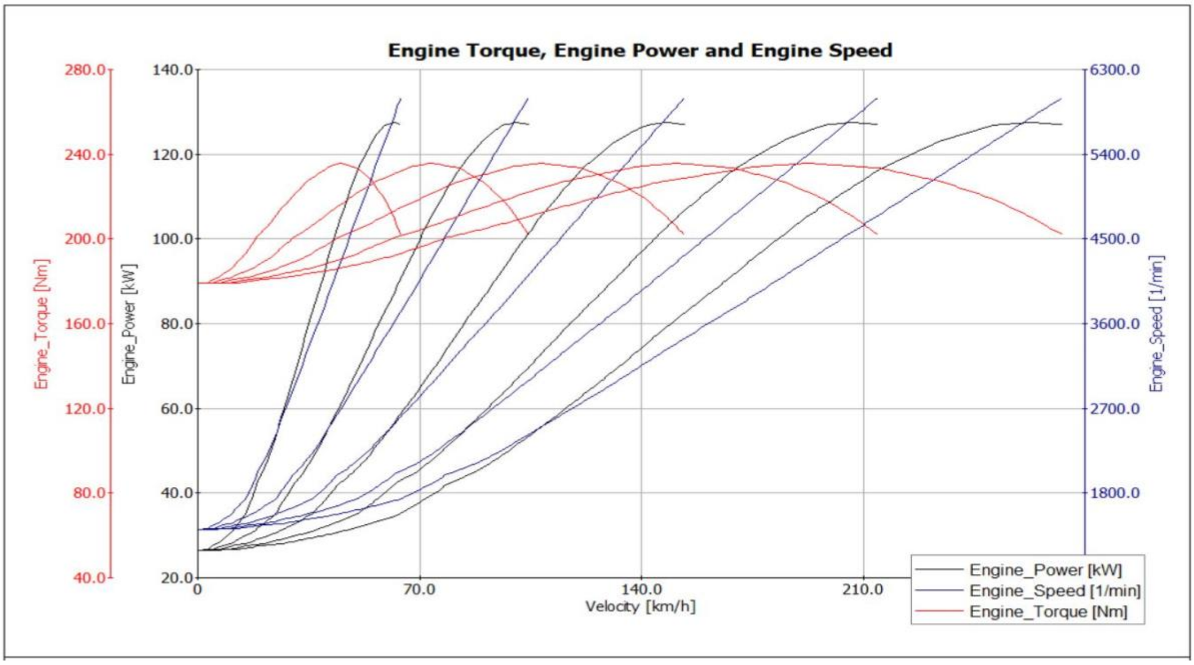

Figure 5.7 Engine Performance results from Climbing performance simulation

Figure 5.8 presents the results of the Electric machine performance during the climbing performance simulation.

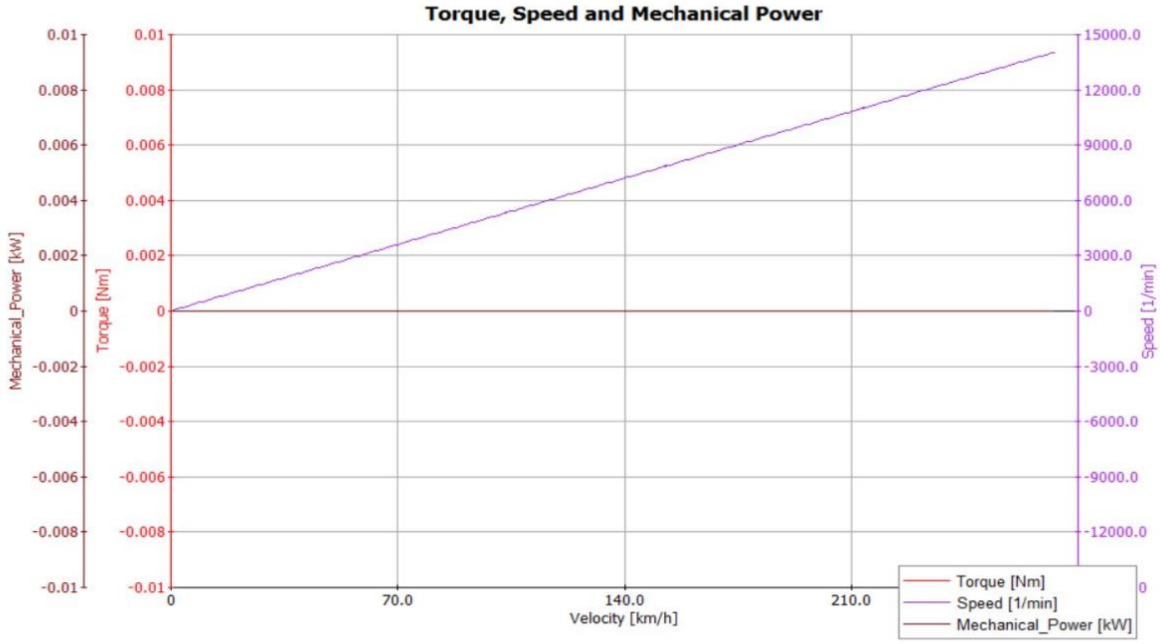

Figure 5.8 Electric Machine Performance in Climbing Performance

5.3 Acceleration from Standstill Run Results

Figure 5.9 shows the acceleration simulation which would be used to evaluate the vehicle's behavior when accelerated from a standstill.

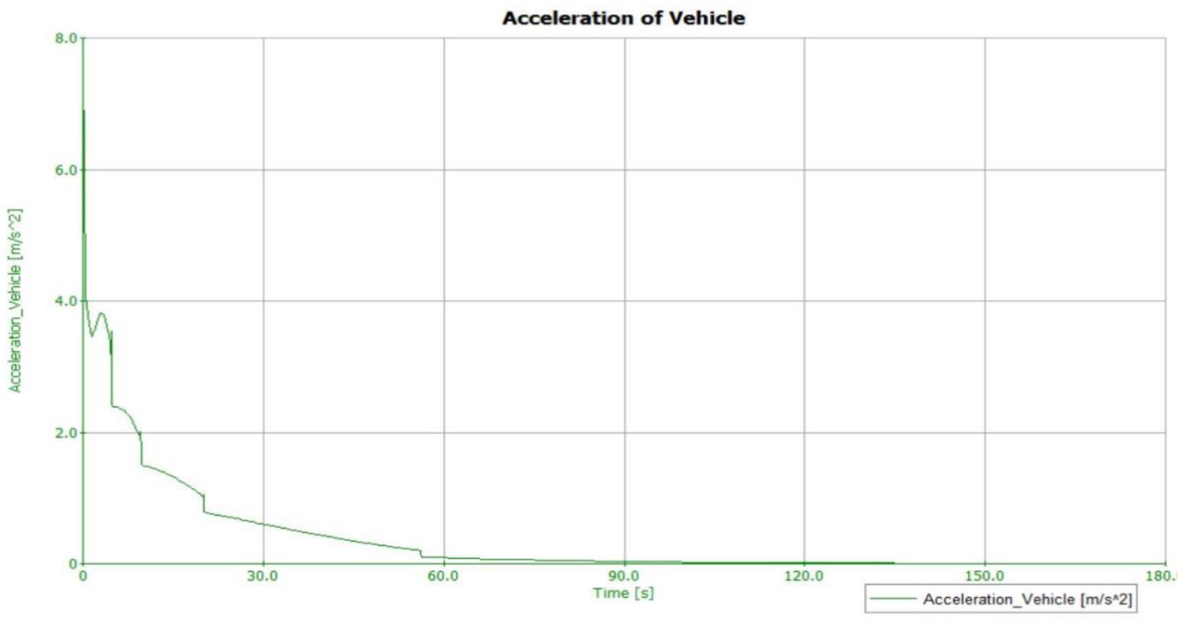

Figure 5.9 Acceleration from a standstill simulation model

Figure 5.10 shows the results of the engine in the acceleration process from a standstill.

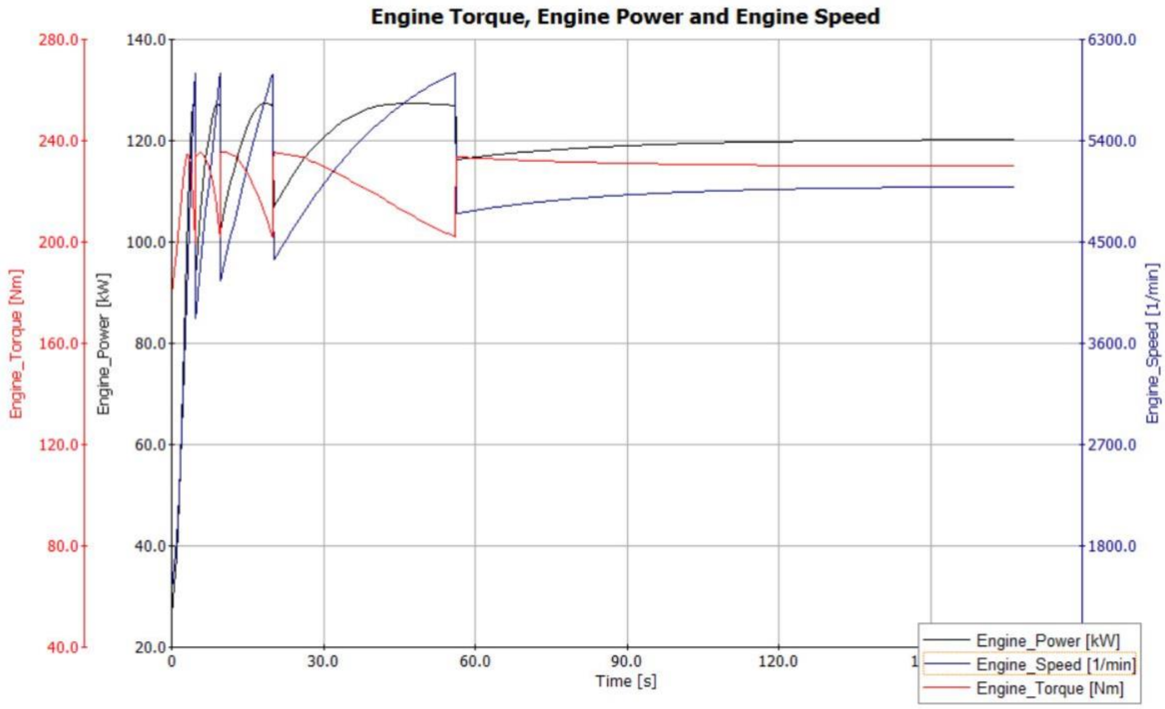

Figure 5.10 Engine Performance during acceleration from standstill.

Figure 5.11 presents the results of the electric machine during the acceleration process.

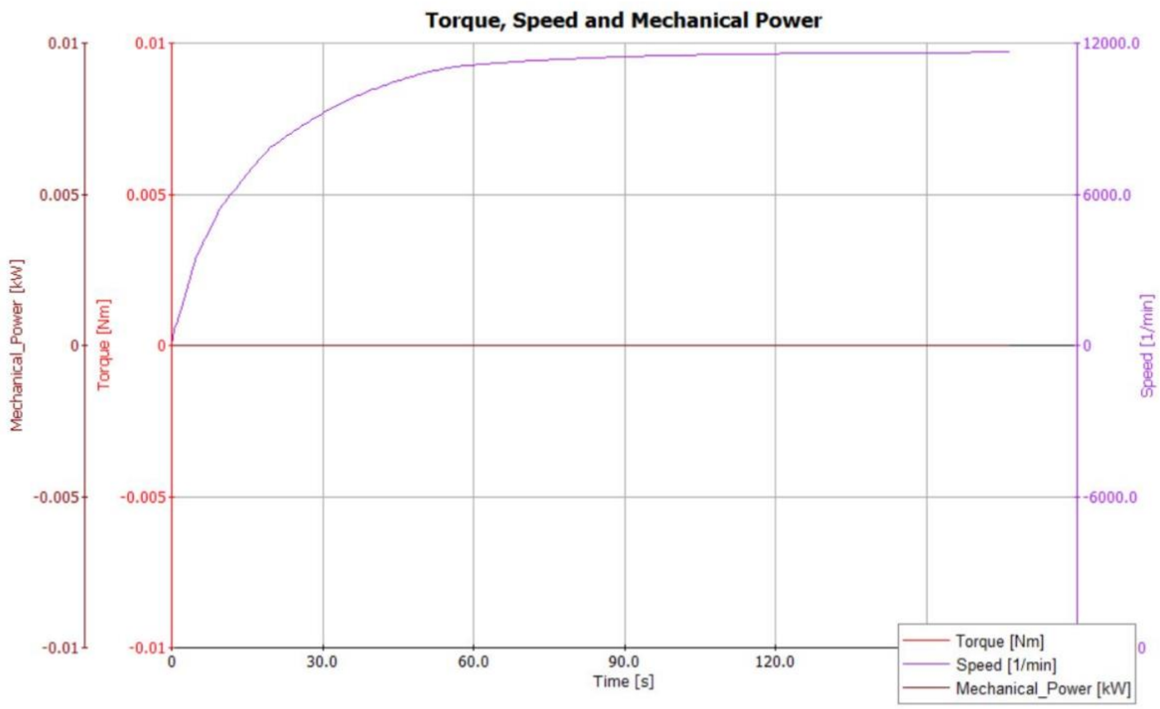

Figure 5.11 Electric Machine Performance in the Acceleration process

5.4 Analysis of Results

Analysis of the developed LNG Hybrid Model would be done in comparison with a Conventional Petrol Hybrid model which was simulated through the scenarios discussed above. Table 5.1 presents the key results from the simulations ran on both vehicle models.

Table 5.1 Caparison of results of Vehicle models

	LNG Hybrid Model	**Petrol Hybrid Model**
Acceleration time from a standstill to the maximum velocity of 50km/h.	4.2 s	4.4 s
Maximum Electric Machine Torque Output	240 Nm	240 Nm
Maximum engine Power Output	18.6754 kW	18.596 kW

Cumulated results regarding the engine's performance in both LNG and Petrol Hybrids point to the LNG hybrid model having a fairly better performance due to it have a lower acceleration time from 0-50km/h and a slightly higher engine power output.

Results were inconclusive about the Hybrid model with better fuel consumption and Less CO_2 emissions.

Chapter 6: Conclusion

6.1 Limitations and Future Work

Theoretically, it has been determined that LNG has a lower heating value as compared to other fossil fuels and would have little to no CO_2 emissions when combusted. For these reasons it can inferred that LNG would make a cleaner, more efficient fuel for automobiles. This project was able to validate the improvements that could be expected in the use of LNG. The composition of LNG is known to vary as a result of different processing methods and the different sources from which they are derived. This variations in composition could significantly affect the results of the simulations performed and as such, should be factored in for more precise outcomes in the future. The components used to create the model in the AVL Cruise software were standard components designed for mainly diesel and petrol vehicles. For more precise results, custom components would need to be developed to accommodate the use of LNG.

With the promise that LNG holds for the transportation industry, it would be of great benefit to all stakeholders within the industry to begin to invest more in the development of LNG facilities as well as LNG powered innovations.

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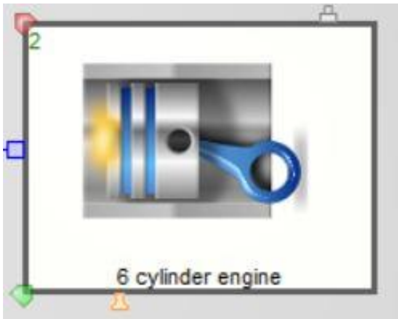
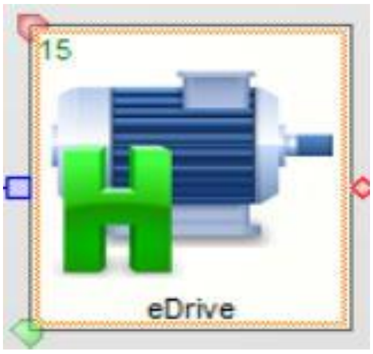
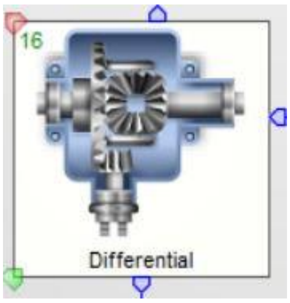
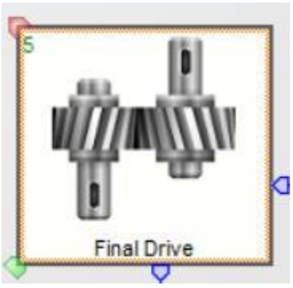
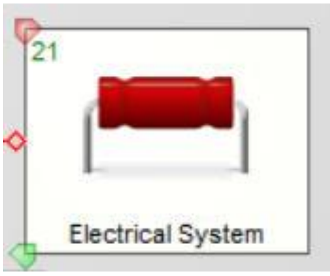
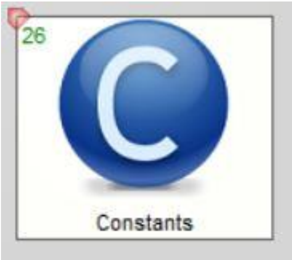
Appendix A: Components and Specifications used to develop Vehicle Model

Component	Description	Specifications
	This component is used to represent the physical characteristics of the vehicle.	Refer to Table 4.1
	This component represents the ICE with the system.	6 cylinders 4 strokes Inertia Moment = 0.134 kg*m^2
	This component represents the electrical machine which can serve as a motor or generator.	Nominal Voltage = 320 V Maximum speed = 1000 1/min Inertia Moment = $1*e^4$ kg*m^2
	This component represents the gearbox which would determine the gear in which the vehicle would operate.	
	This component transfers the torque generated by the engine to the gearbox component	Inertia Moment of Pump with oil = 0.16 kg*m^2 Inertia Moment of Turbine with oil = 0.11 kg*m^2 Max Torque lock-up clutch = 0.001 Nm

	This component transfers the torque generated to the wheels.	Inertia Moment in = 0.015 kg*m^2 Inertia Moment out 1= 0.015 kg*m^2 Inertia Moment out 1= 0.015 kg*m^2
	This component transfers the rotational torque generated to the wheels.	Inertia Moment in = 0.01 kg*m^2 Inertia Moment out= 0.015 kg*m^2 Transmission Ratio = 3.0
	This component stores and provides electrical power in the electrical powertrain.	Maximum Charge = 10 Ah Nominal Voltage = 320 V Maximum Voltage = 420 V Minimum Voltage = 220 V
	This component maintains the electrical parameters in the electrical drivetrain	Nominal Voltage = 320 V Threshold Value = 0.5
	This component represents the brakes the vehicle would have.	Brake piston Surface = 1500 mm^2 Specific Brake Factor = 1 Efficiency = 0.99 Friction Coefficient =. 0.25 Effective friction radius = 110mm Inertia moment = 0.015 kg*m^2

	This component represents the tires the vehicle would have.	Friction Coefficient =. 0.95 Reference wheel load = 2500 N Wheel Load Correction Coefficient = 0.02
	This component serves as the control system of the vehicle model.	Forward = 5 Reverse = 1 Maximum brake Force = 100 N
	This component monitors the vehicle's behavior during a simulation.	
	This component controls the behavior of the electric machine, determining if it would operate as a generator or motor.	
	This component controls the behavior of the electric powertrain to enable the regenerative braking capability.	

	This component contains the constraints that wish to be maintained in the simulation process.	