CHALMERS
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Optimization of Hybrid Driveline Configuration

Optimal component sizing to obtain the best possible fuel efficiency while maintaining performance characteristics

Master's thesis in Automotive Engineering

Manoj Ramesh

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

Master's thesis 2018:08

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Abstract

Innovation is an important driving force in engineering and the goal of reducing emissions and creating a greener environment is pushing companies to create new technologies or improve existing technologies to achieve higher efficiency. Use of electric machines along with the standard powertrain in a vehicle can be defined as hybridization. Vehicle hybridization can be achieved in various levels, starting with the use of electric machines which aid starting and stopping of the vehicle all the way up to being able to drive the wheels. In order to achieve sufficient reduction in fuel consumption levels it is necessary to choose a balanced configuration of ICE and electric machines. This master thesis work deals with finding the optimum driveline configuration for passenger vehicles. Optimization of the hybrid driveline can lead to a solution of choosing a balanced configuration while maintain performance characteristics. Global optimization methods are used as optimization can be performed across 'n' variables in the configuration.

Heuristic algorithms require lesser computational power when compared other global optimization methods. These are optimization methods which employ a practical approach to a problem. Using Genetic algorithm (GA) an Nelder-Mead Simplex method (NM0 as the optimization strategies, simulations were performed across multiple drive cycles to obtain the optimum value of component sizes for Internal Combustion Engine, Electric Motor, number of cells in the battery pack, number of gears in each gear-box and also the respective gear ratios.

Keywords: Genetic Algorithm, Parallel Hybrid vehicles, Optimization, Component sizing, Quasi-Static Modeling

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Manoj Ramesh, Gothenburg, June 2018

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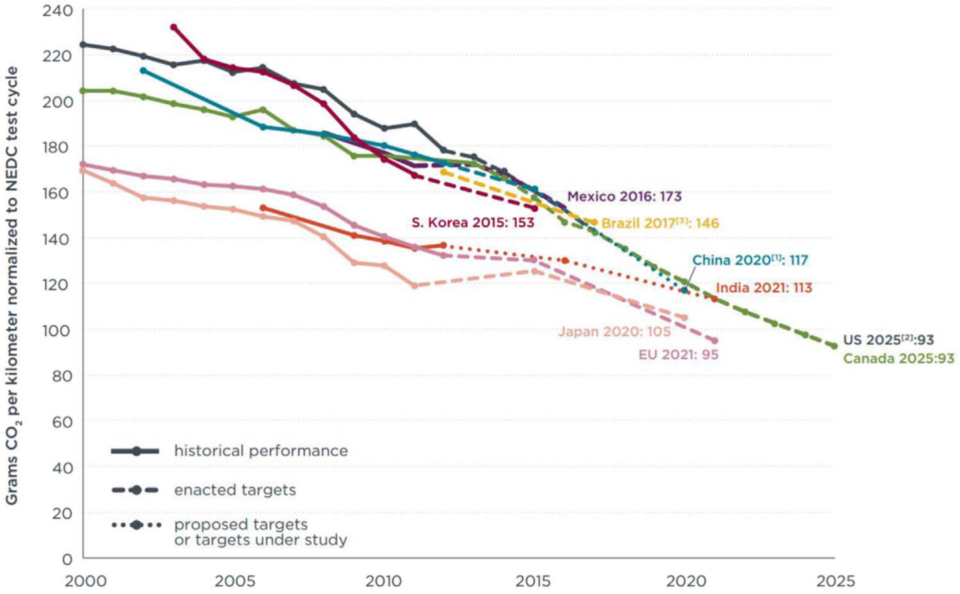
1

Introduction

Reduction of usage of fossil fuels has been a key consideration for the protection of the environment as pollution is one of the biggest contributors in global warming. Stricter regulations are being enforced to decrease the effect of pollution caused by the burning of fossil fuels. These regulations enforced over the years, by means of targets for emission levels can be observed in Figure 1.1. This has been an important driving factor behind many significant advancements in the automotive industry to increase efficiency and decrease fuel consumption.

In order to meet regulation requirements, the usage of alternate sources of energy to propel vehicles is increasing. These alternate sources can be used as a standalone form of energy for propulsion or be combined with existing propulsion systems to decrease the harmful effects on the environment. The use of these two systems combined for propulsion of the vehicle can be defined as hybridization. An example representation for the powertrain can be viewed from Figure 1.2. The most common sources of energy in such systems are the use of an internal combustion engine and an electric motor.
Internal Combustion Engine (ICE), Electric Machine (EM), Battery pack or super-capacitor and gearboxes form the crucial components of a hybrid powertrain system. Sizing of these components is essential in order to achieve high levels of efficiency of each of the sub-system individually and when combined. This efficient sizing can be achieved by the process of optimization. Apart from the above mentioned components, the power management strategy or the controller plays an equally important role in the hybrid powertrain.



[1] China's target reflects gasoline vehicles only. The target may be higher after new energy vehicles are considered.
[2] US standards GHG standards set by EPA, which is slightly different from fuel economy stadards due to low-GWP refrigerant credits.
[3] Gasoline in Brazil contains 22% of ethanol (E22), all data in the chart have been converted to gasoline (E00) equivalent
[4] Supporting data can be found at: http://www.theicct.org/info-tools/global-passenger-vehicle-standards

Figure 1.1: CO_2 regulations for passenger cars [1]

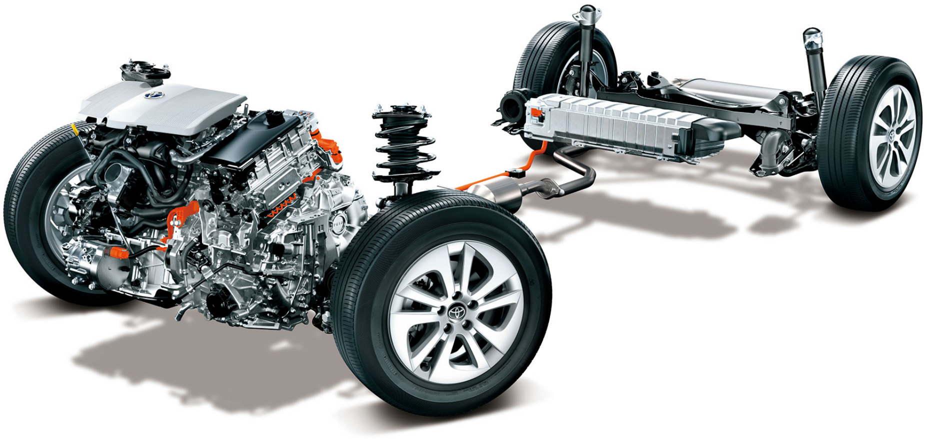


Figure 1.2: Example of a Hybrid powertrain - Toyota Prius[2]

Various methods can be employed to obtain the solution of this optimization problem. Several authors have performed optimization of various components of hybrid drive-lines using different methods. Mangun et. al [9] performed a study on Design optimization of a Hybrid Electric Vehicle Powertrain for where Genetic Algorithm (GA) has been implemented to optimize internal combustion engine (ICE), electric machine (EM), battery pack and supercapacitor. Biros et. al[10] and Wu et. al[11] have performed optimization using different algorithms for vehicles simulated in ADVISOR. Several others authors such as Gao et. al [12], Fang et. al [13], Chirag et. al[14], Fellini et. al[15] and Assanis et. al[16] have all performed studies on optimization related to hybrid electric vehicle power-trains using various optimization methods. Optimization in this master thesis has been performed using Genetic Algorithm (GA) and also Nelder-Mead Simplex method (NM) for vehicle modeled and simulated using MATLAB and Simulink.

1.1 Methodology

Work was primarily divided into two stages. The first stage involved study of the concept of hybridization and existing hybrid systems in the industry, optimization processes that could be employed in achieving the desired outcome. The second stage involved building and simulation of the vehicle model with the necessary constraints using MATLAB/Simulink as the primary tool. Once the working of the tool had been familiarized with, work was focused on developing a refined, flexible model to obtain the optimum hybrid driveline configuration. Primary focus during modeling was to implement a single-objective optimization algorithm for a base vehicle model with limited variable for optimization. Upon completion, more variables were included to increase of scope for optimization across the entire vehicle.

1.2 Project Goal

The goal of this master's thesis is to create a model to obtain the optimal hybrid driveline configuration for any given performance criteria.

1.3 Deliverables

The deliverables of this thesis are listed below:

- Implementation of optimization algorithm in order to achieve the best possible hybrid driveline configuration based on the given criteria
- Achieve optimum gear ratios with the optimization algorithm
- Identification of criteria to determine the optimum level of hybridization and driveline configuration
- Comparison of optimal driveline configurations obtained from different optimization algorithms
- Investigation of how different battery technologies and characteristics affect the model

Sizing of the components remains a crucial process of designing a hybrid system. Bigger component sizes of internal combustion engine, electric motor and energy sources such as batteries or super-capacitor, result in a heavier vehicle which can lead to ineffective and higher energy consumption and energy losses. Optimization is necessary to determine the proper design of such a system.

2

Theory

This section describes the theoretical approach taken to solve the problem of optimization of a hybrid driveline configuration. The concepts of different hybrid configurations, optimization methods and algorithms are all studied in this section.

2.1 Classification of hybrid vehicles

The type of hybridization achieved can be differentiated based on the scale of power of the secondary source, the design of the powertrain system and/or the power source of the propulsion system. The various classification of hybrid vehicles are explained in the following part of this section. The classification of hybrid vehicles based on the level of hybridization can also be viewed in Figure 2.1.

2.1.1 Based on level of hybridization

Micro Hybrids

Vehicles where the reliance of the electric power to drive the vehicle is very little is known is an Micro hybrids. Such electric machines are also known as crankshaft synchronous. In the current day however, crankshaft synchronous machines are not regarded as hybrids anymore due to the lack of enough electric power to drive the vehicle.

Mild Hybrids

Mild hybrid systems contain electric machines with slightly more power than micro hybrid systems but not enough power to drive the wheels for a long range. Such systems vary from start-stop functions and also regenerative braking systems in modern cars. The power generated from braking can be used to perform in-built functions of the car and electric motors to drive the wheels

Full Hybrids

Electric machines in vehicles which can drive the wheels on it's own for a sufficient amount of time is known as full hybrid vehicles. Such machines are primarily known as Non-Crankshaft synchronous machines.

2.1.2 Based on powertrain design/architecture

Series Hybrid Vehicle

This type of architecture generally consists of a battery pack, an internal combustion engine (ICE) to charge the batteries, an electric machine (EM) to transmit power to propel the vehicle and a gearbox to transmit the power from the motor to the wheels. As it can be observed in Figure 2.1, the level of influence of batteries and electric machine (EM) are significantly high in the case of series hybrid vehicles as the electric motor is the only source of propulsion with the batteries being the primary source of power.

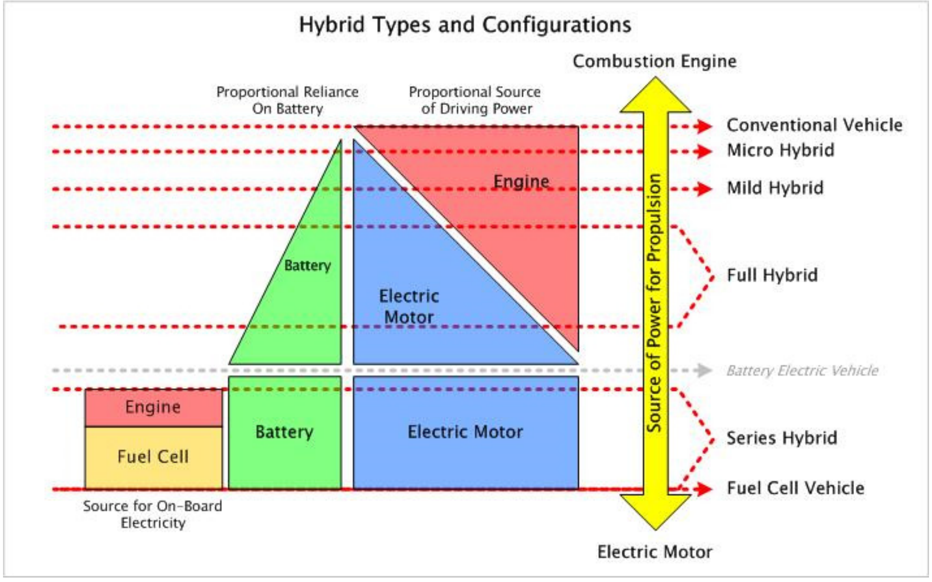


Figure 2.1: HEV Classification based on level of hybridization [3]

When there is sufficient charge in the batteries, the electric motor draws power from these batteries until a certain limit to power the wheels. As the charge level goes below a pre-defined limit the ICE which is coupled to a generator, can be switched on to charge the batteries. During breaking the negative torque can be used as regeneration to charge the batteries. The various modes of power flow in this type of powertrain design can be observed in Figure 2.2.

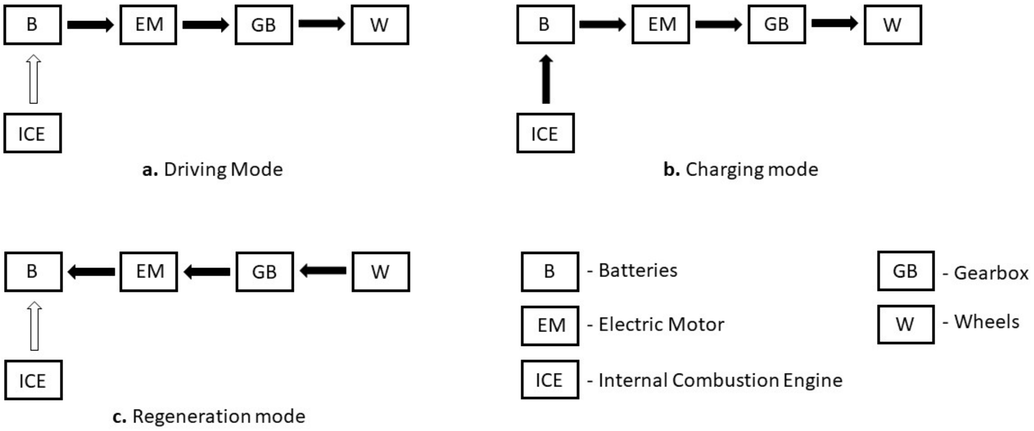


Figure 2.2: Architecture and Power-flow in a series hybrid vehicle

Parallel Hybrid Vehicle

This is a type of powertrain design where the internal combustion engine (ICE) and electric machine (EM) can power the wheels individually under certain conditions or they can be used to power the wheels together when there is demand for higher power. The source of power can be determined based on the amount of power demand and also the control strategy any given moment. Due to this there exists various modes of power flow which can be observed from the Figure 2.3.

At low speeds or initial acceleration conditions, the vehicle can function on pure Electric Vehicle (EV) mode given that the internal combustion engine (ICE) operates at less efficient regions and the torque capacity of the electric machine (EM) is very high. At high power demand conditions, can power the wheel simultaneously to compensate for the lower power output of a downsized engine. Under normal running conditions, the vehicle can operate under pure internal combustion engine (ICE) mode as it operates under a better efficiency region when compared to that of an electric machine (EM).

Series-Parallel Hybrid Vehicle

Commonly referred to as 'Split Hybrids', this system as the name suggests contains elements of both series and parallel hybrid systems. The primary difference between a split hybrid and the conventional hybrid systems is the presence of two motors/generators compared to the single motor/generator in a regular series and parallel hybrid vehicles. The power flow is managed via a planetary gearbox and belt driven Continuously Variable Transmission (CVT).

2.2 Optimization

Optimization can be defined as the process used to achieve a higher level of efficiency in an existing system. The aim of this master thesis is to optimize critical components of a Parallel Hybrid vehicle to reduce fuel consumption while maintaining the performance characteristics. This can be achieved by employing different methods as there exists numerous components in a vehicle which when optimized can lead to higher efficiency operating conditions.

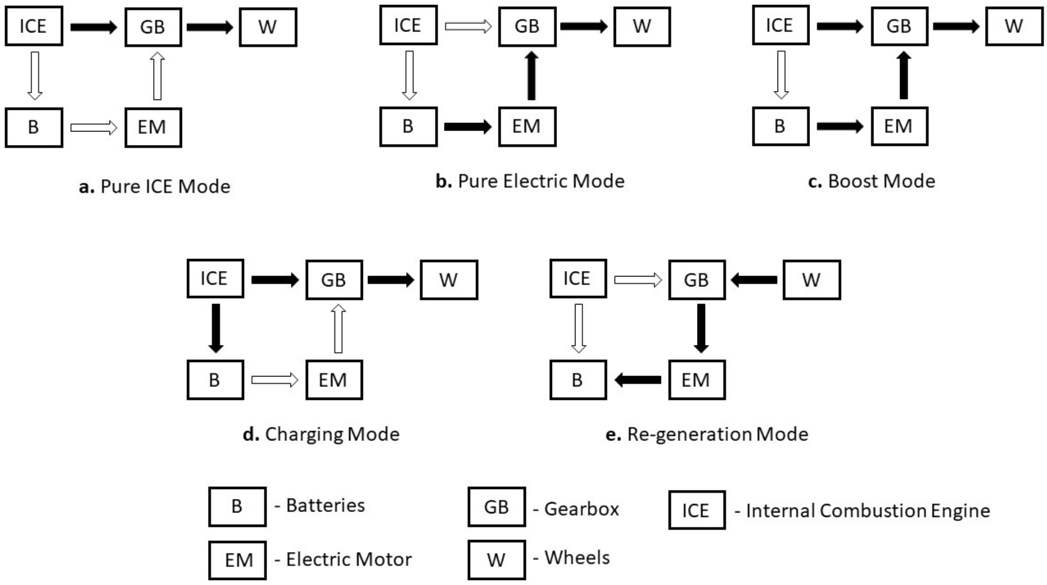


Figure 2.3: Power-Flow in a parallel hybrid vehicle

Local minima can be defined as the solution obtained based on the optimization performed across single input variable. Global minima is the solution that is obtained by optimization across multiple input variables. The difference between these two minima can be observed across the optimization minima curve in Figure 2.4. Hence Global Optimization (GO) methods are preferred over local optimization methods.
There are three methods of GO which are listed and explained below.

- Deterministic Methods: Within the given set of boundary conditions, this method can provide a theoretical guarantee of having obtained the global minima. This method can be used when the exact value of the global minima needs to be achieved.
- Stochastic Methods: This method involves the generation and use of random variables within the formulation of the optimization problem itself. Stochastic optimization method generalizes deterministic methods for deterministic problems
- Heuristic/Meta-Heuristic Methods: A heuristic strategy is an approach to obtain satisfactory results by employing a practical approach. This method does however results in multiple solutions due to the fact that a slight change in one of the factors can lead to changes in results with massive differences between them

Although the deterministic method results in a more definite and optimal result, this method requires far more computational time and power whereas heuristic methods achieve fairly optimal results with far less computational requirements. The various optimization algorithms that can be implemented under heuristic methods are discussed in the following sections. However it has be noted that under heuristic methods, there can be no one definitive optimal solution as it is a trade off between multiple values.

2.2.1 Genetic Algorithm

Genetic Algorithm (GA) is a heuristic algorithm that imitates Darwin's theory of evolution, "Survival of the fittest". Therefore, the primary principle of this algorithm is the elimination of the weakest solution at the end of each iteration. This principle can be visualized from the flowchart in Figure 2.5.
The algorithm begins by generating a random number of initial generations or iterations which is defined as population. The solution of each of the iteration is the value of the objective defined in the objective function. This value is defined as the fitness of the solution. The algorithm moves on modify this initial generation of in search of the best solution. Upon reaching the best solution, the algorithm generates a second set of random population and continues modification until it reaches the best fitness. The comparison of the two solutions for the best among the fitness solutions provides the direction in which the algorithm moves for the next set of population generation.
This algorithm can be used to perform optimization using one or more objectives which can be defined based on necessity. Single objective optimization can be achieved by defining the required fitness function and constraint function. To achieve optimization for more than one objectives, a Multi-Objective Genetic Algorithm (MOGA) has to be employed. MOGA was first proposed by Carlos M Fonseca and Peter J Fleming [17] in 1995. Since then, many authors such as Milan Biroš et. al[10], C.Osornio-Correa et. al[18] and Brian Su-Ming Fan have employed the MOGA to optimize the drive-train components.
However there is exists one major drawback to the use of this optimization method. Finding the optimal solution to a complex high-dimensional multi-modal problems often requires very expensive fitness function evaluations thereby resulting in significant increase in computational demand.

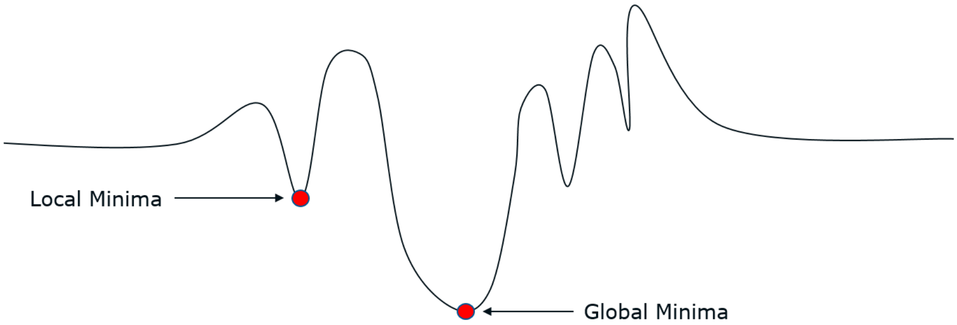


Figure 2.4: Variation of local and global minima

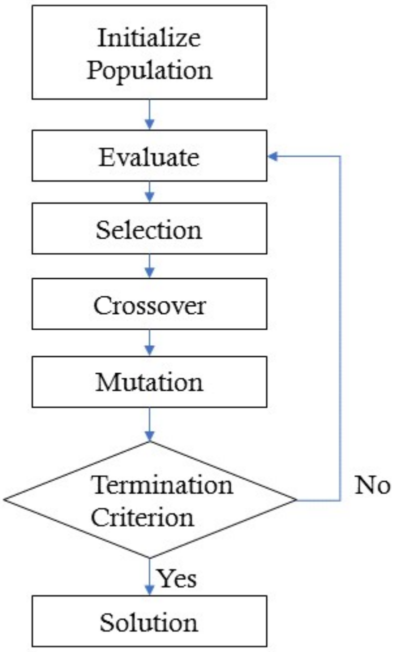


Figure 2.5: Principle of Genetic Algorithm[4]

2.2.2 Nelder-Mead Method

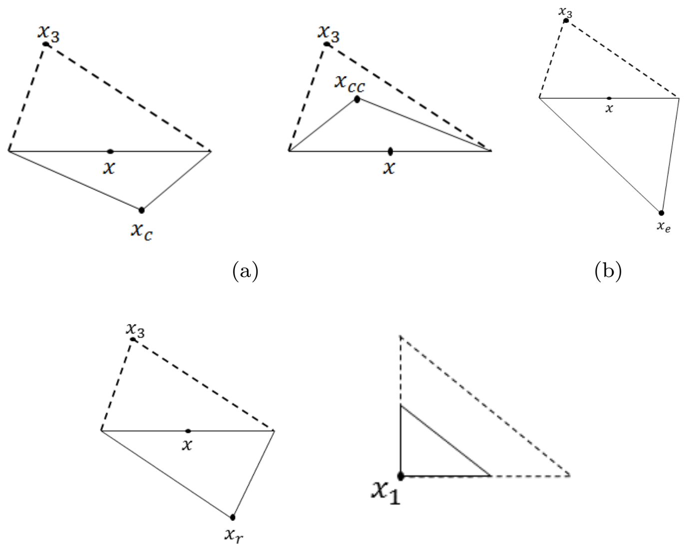
The Nelder-Mead method (NM) which is also referred to as the downhill simplex method is a heuristic optimization method which can be used to find the global minima of an objective in multidimensional space. This algorithm was first published in the year 1965 J. A. Nelder and R. Mead[20]. This method is a heuristic non-linear constrained optimization.

In principle, the method uses a simplex which is a geometric object with flat sides as a simplex to converge on the global minima. Using this strategy the global minima across 'n' dimensions can be obtained. This main principle of the Nelder-Mead Simplex method is also described in Lagarias et. al[5]. Three different operations takes place during each iteration which are **1:** Reflection, **2:** Contraction and **3:** Expansion. The changes based on any of the operations on the simplex can be observed from Figure 2.6. An additional operation known 'Shrinkage' of the simplex is also performed in certain cases. In these figures the dotted lines represent the original state.

The algorithm moves in the direction of the minimum function value on each of vertices of the simplex until it reaches it's minimum. The dotted lines in the figure represent the initial position of the simplex.

2.2.3 Particle Swarm optimization

Particle Swarm Optimization (PSO) is a swarm based meta-heuristic global optimization strategy which is inspired by the actions of a swarm of bees or flock of birds. This method was developed by Kennedy and Eberhart in 1995[21]. PSO methods works on the strategy of improving an obtained solution against a given reference value. The particles move about the entire search space searching for the minima. This principle can also be observed from the Figure 2.7. Xiaolan WU et al[11] used PSO approach to obtain optimal component sizes to minimize fuel consumption and emissions while maintaining the vehicle performance parameters. The biggest limitation to the use of this optimization method is its tendency to converge on the local minima rather than the global minima.



(a) (b)

(c) (d)

Figure 2.6: Operations: (a) Contraction (b) Expansion (c) Reflection and (d) Shrinkage

2.2.4 Simulated Annealing Method

Simulated Annealing (SA) is a meta-heuristic strategy that is employed when finding a close approximation of the global minima is given higher preference than finding the exact local minima in a given time. This method is inspired from the process of annealing in metallurgy which is the slow heating and cooling of metals to reduce defects and increase the strength. The process is associated with the the decrease in probability of obtaining worse solutions. At every step, the algorithm analyses a solution close the current solution where, based on the given criteria, the algorithm decides to stay with it or move away from it.

Due to simulation and time constraints only Genetic Algorithm and Nelder-Mead strategy were implemented in this master's thesis work.

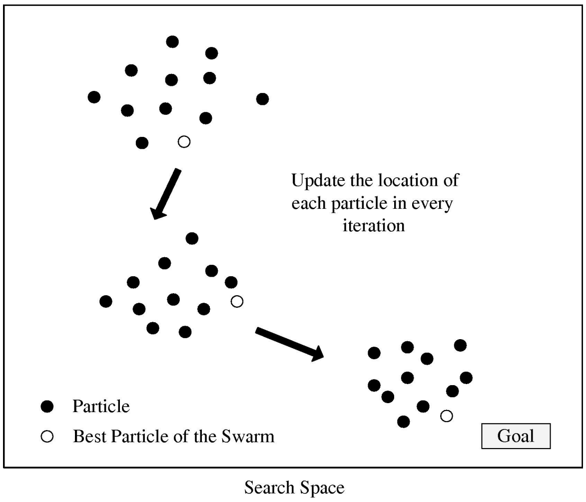


Figure 2.7: Principle of Particle Swarm Optimization [6]

3

Methods

The approach to vehicle modeling, the key components during each of the modeling process are all explained in this section. The optimization strategy used in this master thesis based on different optimization algorithms described in the previous chapter is also explained in this chapter.

In vehicle modeling, there exists two different approaches namely Dynamic approach and Quasi-Static approach. The formulation of the vehicle model in dynamic modeling is based on the input from the driver. Based on this input, the necessary amount of power is generated from the powertrain components to the wheels. The direction of power-flow of a vehicle modelled using this dynamic approach can be seen in Figure 3.1 The most significant feature of this approach is that it can almost reproduce the exact behaviour of the vehicle and its components.
However this ability to reproduce real life behaviour is delivered at a very high computational cost.

Quasi-Static modeling on the other hand is performed by calculating the required power of the vehicle for a pre-defined drive cycle. Using the values of velocity, acceleration and road inclination levels from the drive cycle, power required to overcome resistance forces is calculated. The power-flow of the vehicle modeled using this approach can be observed in Figure 3.2. The key distinction between the above mentioned approaches is the reduction in computational complexities when using quasi-static approach.

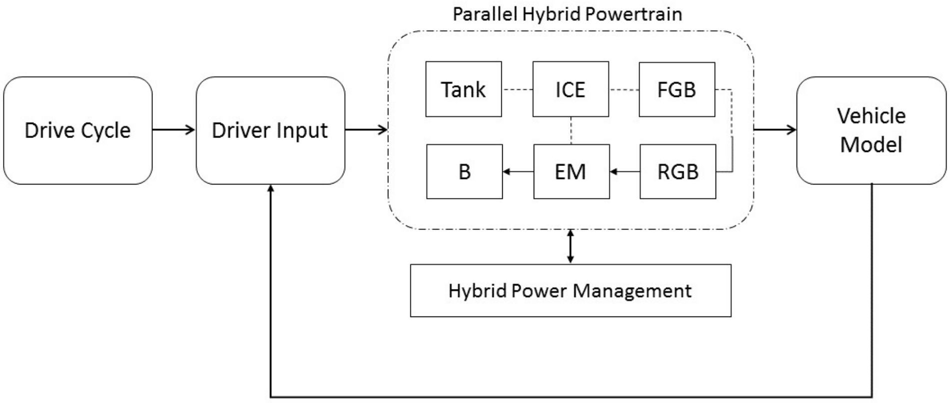


Figure 3.1: Vehicle structure for Dynamic approach

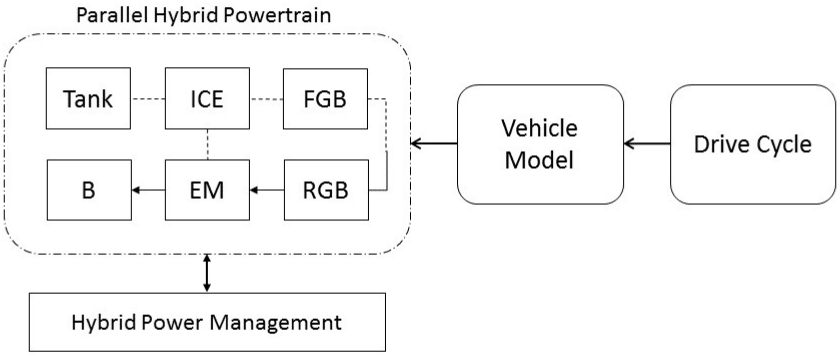


Figure 3.2: Vehicle structure for Quasi-Static approach

3.1 Vehicle Model

The vehicle is modeled using blocks taken from QSS-Toolbox library[22], Figure 3.3, developed by ETH Zurich (Swiss Federal Institute of Technology, Zurich).The hybrid architecture modeled is a parallel hybrid configuration with an individual gearbox on both the front and rear axles. The blocks used in the vehicle model are briefly explained the following sections. The top view of the vehicle model in MATLAB/Simulink can be seen in Figure 3.4.

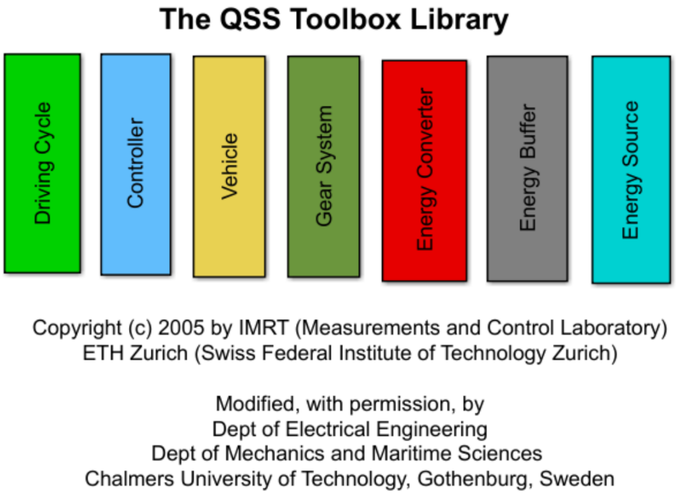


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Figure 3.3: QSS-Toolbox Library

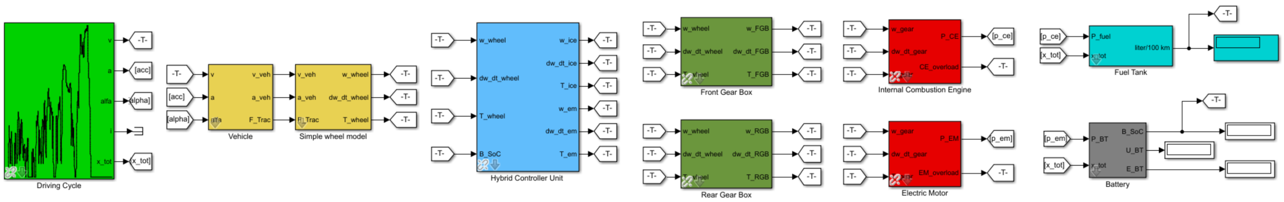


Figure 3.4: Top view of the vehicle model built in MATLAB/Simulink using QSS-Toolbox

3.1.1 Drive Cycle

Drive cycle is the most crucial part of the entire model when using quasi-static approach. The standard drive cycle consists of set of speed, acceleration, time and elevation profiles. The amount power required by the vehicle is calculated using these values of acceleration and velocity which is explained in the following section. The total distance driven, x_{tot} (3.1) is defined as the sum of all velocity steps v_i multiplied by step size h.

$$x_{tot} = \sum_{i=0}^{n} v_i * h \tag{3.1}$$

The optimization was performed for different drive cycles to identify the critical component of the driveline for any drive cycle. Four different drive cycles were used during the course of this thesis. The various drive cycles used are briefly explained in following section.

1: **WLTP(Worldwide harmonized Light Vehicle Test Procedure)** - The drive cycle, in general is divided into 3 classes with average and maximum speed achievable increases with increase in class. Each class is further divided into various parts namely low speed, medium speed, and high speed. Class 3 of the drive cycle however is divided into 4 parts with an extra high speed along with the standard three parts. Since the goal is to have an optimized drive-train for a passenger car fairly high performance standards, class 3 of WLTP is taken as the standard drive cycle. The four parts of drive cycle can be observed clearly from the velocity profile shown in Figure 3.5.

Simulations for all configurations are primarily performed with the WLTP cycle as it is the most modern and updated drive cycle in use in the automotive industry.

2: **FTP-75** - The Environmental Protection Agnecy (EPA) of the United States of America defined the drive cycle for analysis of fuel consumption and emission levels at the end of the tailpipe for cars. Figure 3.6 shows the velocity and acceleration profiles for FTP-75. This drive cycle represents the typical daily commute for passenger cars in the US.

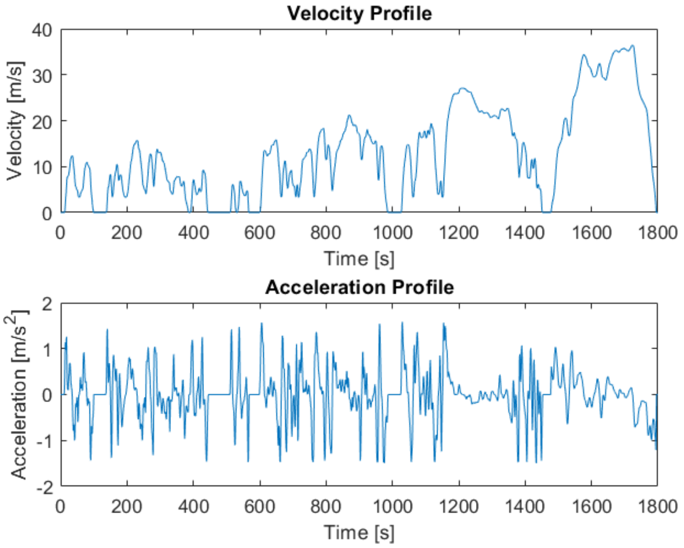


Figure 3.5: Velocity and acceleration profiles in WLTP: Class 3

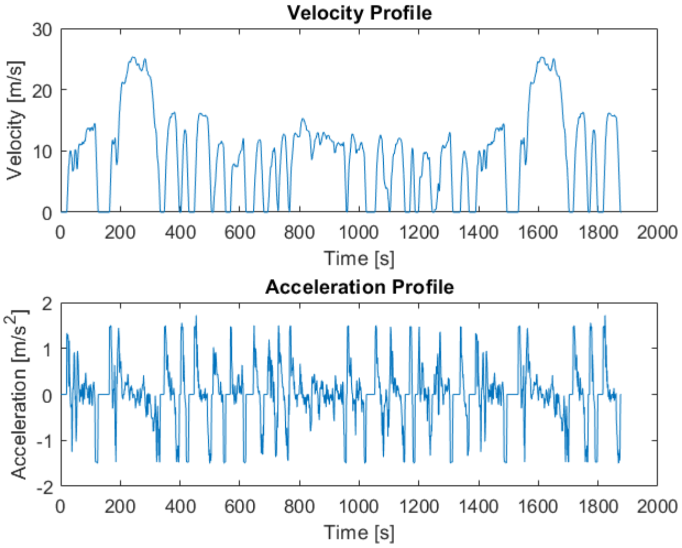


Figure 3.6: Velocity and acceleration profiles in FTP-75

3: **NEDC(New European Driving Cycle)** - The NEDC, which is supposed to represent the typical car usage in Europe consists of a repeated cycles of Urban Drive Cycle (ECE-15) as phase-1 and EUDC as phase-2. The two phases of the driving cycle can be viewed in Figure 3.7. However, the reliance on this drive cycle is steadily decreasing due to the cycle not being representative enough of real life driving conditions for fuel consumption and emission analysis.

4: **EUDC(Extra Urban Driving Cycle)** - The EUDC is a short driving cycle which was designed to represent aggressive, high speed driving modes. Figure 3.8 represents the velocity and acceleration profiles of the extra urban driving cycle.

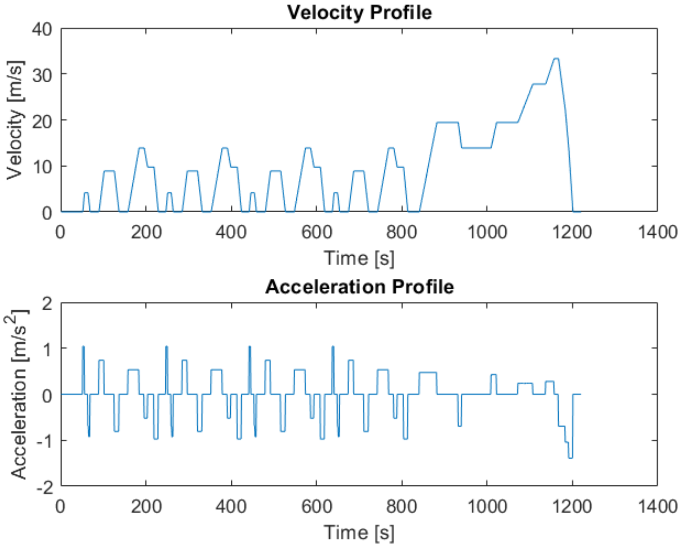


Figure 3.7: Velocity and acceleration profiles in NEDC

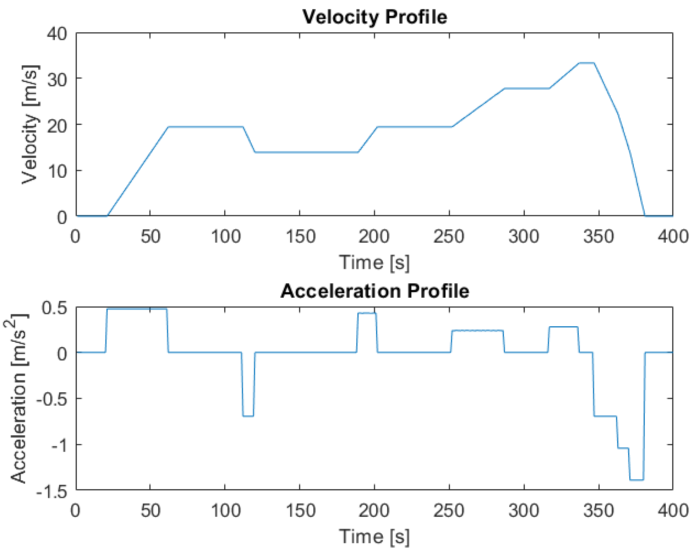


Figure 3.8: Velocity and acceleration profiles in EUDC

3.1.2 Vehicle

The vehicle block in the model is built taking into account the various forces acting on the vehicle at different time and speed intervals. The forces which primarily consist of resistive forces, gravitational force and tractive force during initial acceleration can be observed from Figure 3.9. The various forces listed are explained below.

- Aerodynamic resistance/drag force - Drag force (3.2) can be defined as force acting on the vehicle due to flow of air, taking into consideration the frontal area of the vehicle, density of air and the speed at which the vehicle is travelling. It can be observed from the relation that the aerodynamic drag increases significantly with increase in vehicle speed

$$F_{air} = \frac{1}{2} * \rho * A_f * c_d * v^2 \tag{3.2}$$

- Rolling resistance force - The longitudinal force acting on the vehicle primarily effected by the coefficient of rolling resistance, can defined as the rolling resistive force

$$F_{roll} = m_{tot} * g * c_r * Cos(\alpha) \tag{3.3}$$

- Gravitational force - Forces acting on the vehicle due to the effects of the vehicle mass, road inclination and the effects of gravity is known as the resistance due to gravitational forces

$$F_g = m_{tot} * g * Sin(\alpha) \tag{3.4}$$

- Acceleration force - Longitudinal force acting against the vehicle during acceleration is defined as resistance due to acceleration. This is force is particularly high at low speeds where the levels of acceleration is high as compared to high speeds where levels of acceleration is lower.

$$F_{acc} = m_{tot} * a \tag{3.5}$$

Where A_f - Frontal area of the vehicle $[m^2]$, c_d - Coefficient of drag, v - Vehicle speed $[m/s]$, α - Inclination level, m_{tot} - Total mass of the vehicle [kg], a - Acceleration of the vehicle $[m/s^2]$

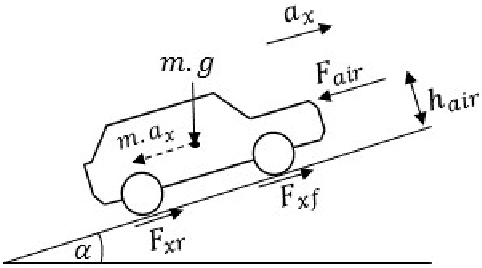


Figure 3.9: Longitudinal vehicle model of a passenger car during acceleration

The sum of all these forces is defined as the total traction force on the vehicle(Equation 3.6). The maximum power required by the vehicle can be defined as the amount required to overcome the highest level of longitudinal force on the powertrain. This required amount of power is calculated as a product of force and speed. Naturally, the highest traction force is obtained at high speeds as the aerodynamic drag at high speeds is significantly higher than initial acceleration forces. Hence maximum power required is calculated based on the traction force at the desired maximum speed of the vehicle.

$$F_{traction} = F_{air} + F_{roll} + F_g + F_{acc} \tag{3.6}$$

$$P_{max,req} = F_{traction} * v_{max} \tag{3.7}$$

$$T_{max,req} = F_{traction} * r_{wheel} \tag{3.8}$$

Where r_{wheel} - Radius of the wheel [m], T_{req} - Required level of torque [Nm], $P_{max,req}$ - Maximum power required [W]

3.1.3 Gear system

In quasi-static modeling, the wheel speed and wheel torque is calculated from the defined driving cycle. Based on the defined gear ratio the crank speed and torque at the gearbox is calculated. This modeling approach can be observed in Figure 3.10.
In an ideal system, the following relations hold true for power transmission from gearbox to wheels.

$$T_{gb} = \frac{T_w}{i_g} \quad : \quad \omega_g = \omega_{wheel} * i_g \tag{3.9}$$

3.1.4 Internal Combustion Engine [ICE]

The ICE used in modeling of this vehicle is based on fuel consumption map or an engine performance map. Under quasi-static approach, as it can be observed from Figure 3.11 the inputs to the ICE model are the torque T_e and speed ω_e required at the shaft and output being the power delivered by the engine.

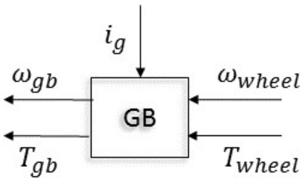


Figure 3.10: Quasi-static approach to Gear box modeling

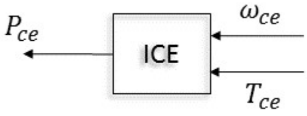


Figure 3.11: Quasi-static approach to ICE modeling

Using the values of T_e and ω_e along with enthalpy flow P_c, we can calculate the thermodynamic efficiency of the engine, where the enthalpy flow can be expressed in terms of mass of fuel flow $\dot{m}$ and lower heating value of fuel H_u. This can be seen from equations 3.10.

$$\eta_e = \frac{\omega_e * T_e}{P_c} \quad : \quad \dot{m} = \frac{P_c}{H_u} \tag{3.10}$$

Fuel consumption or mass flow can be calculated based on the corresponding speed and torque demand. this calculation is performed using a 2-dimensional map for the combination of torque and speed values. A general fuel consumption map can be observed in the Figure 3.12. The curves in the plot represent the various regions of fuel consumption. The values denoted on these curves is defined as the BSFC (Break specific fuel consumption) values at any given operational point of the engine.

3.1.5 Electric Motor [EM]

The EM model is very similar to that of ICE with the input variables being the values of torque and speed required which are T_{em} and ω_{em} respectively. A representation of this modeling can be observed from the Figure 3.13. The fundamental representation of the power output of the motor can be expressed in terms of the current I_{em} and voltage U_{em}.

$$P_{em} = U_{em} * I_{em} \tag{3.11}$$

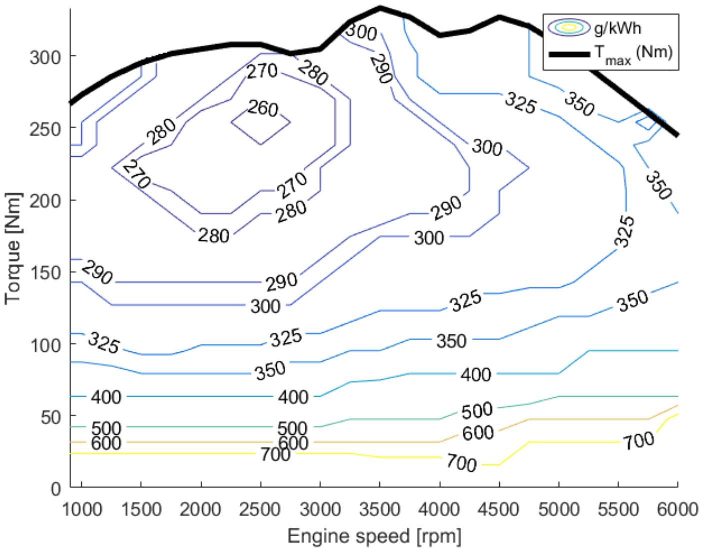


Figure 3.12: Typical performance map of a gasoline engine [7]

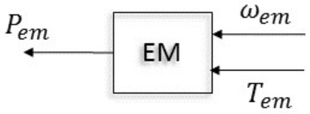


Figure 3.13: Quasi-static approach for EM modeling

The model is based on a performance map, a combination of torque and speed values, similar to that of a consumption or performance map of an ICE. This efficiency map of an EM as a function of torque and speed is shown in the Figure 3.14. Power from this map can be evaluated under two driving conditions according to Equations 3.12 and 3.13.

- $T_{em} > 0$, i.e. torque demand is greater than zero

$$P_{em} = \frac{T_{em} * \omega_{em}}{\eta_{em}(\omega_{em} * T_{em})} \tag{3.12}$$

- $T_{em} < 0$, i.e. torque demand is lesser than zero

$$P_{em} = T_{em} * \omega_{em} * \eta_{em}(\omega_{em} * T_{em}) \tag{3.13}$$

The two equations 3.12 and 3.13 make up the top and bottom quadrants of the performance map respectively.

3.1.6 Battery

The battery model used in the vehicle can be represented in terms of a basic physical model with the help of an equivalent circuit. This representation is done with an ideal open-circuit voltage source in series with an internal resistance[23].

State of Charge

State of charge φ, is defined as the amount of charge Q that can be delivered to the nominal battery capacity Q_o.

$$\varphi = \frac{Q}{Q_o} \tag{3.14}$$

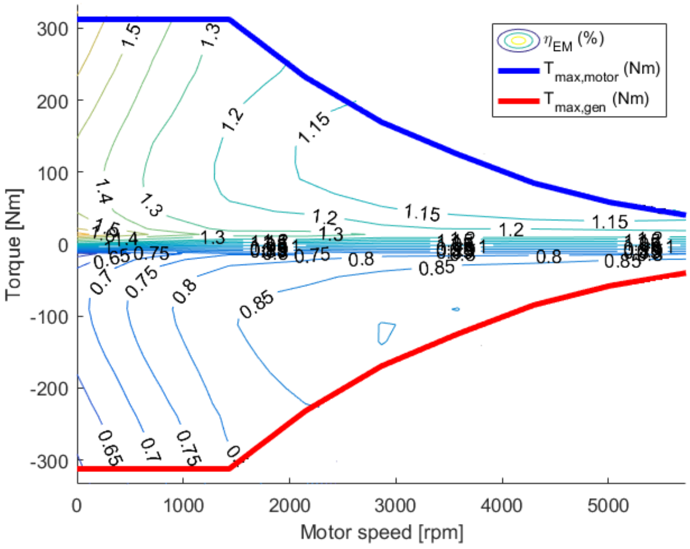


Figure 3.14: Typical efficiency map of an Electric Motor [8]

3.1.7 Controller

Control strategy of the vehicle model can be defined as the, method used to control the distribution of power between the front and rear wheels. This can be achieved with the help of rule based strategy or optimization based strategy. Rule based strategies are modeled on certain heuristics or rules which can easily split the power between the respective energy components. Optimization strategies on the other hand work on the principle of minimizing or maximizing a certain cost function. Based on the requirement this cost function can be defined as either minimization of effective energy consumption or maximization of battery energy consumption.
In this master's thesis, the strategy used for splitting the power is a simple deterministic rule based strategy. This method is chosen primarily due to its lower computational demand when compared to optimization based control strategy. Power is divided between the front and rear axle based on the torque demand obtained from the drive cycle and the levels of state of charge in the batteries.
The top view of this controller block can be seen in Figure 3.15. It can be seen from this figure that the respective outputs are divided between the gearboxes on the front and rear axles respectively i.e. between the internal combustion engine (ICE) and the electric machine (EM).
Based on the general torque demand from the drive cycle, driving conditions can be split into four modes. These modes are listed and described below.

E-Mode

During initial acceleration and low speed driving conditions, power from the batteries is used to power the electric motor which drives the rear wheels. This strategy is implemented as the electric motor can produce very high levels of torque in low speed conditions and gradually decreases as the speed increases. This can be particularly be observed in Figure 3.14. It can also be observed from Figure 3.12 that the internal combustion engine (ICE) runs at a lower level of efficiency at low speed driving conditions. Hence for initial acceleration and low speed driving, the power from the battery will be used to drive the wheels.

General driving conditions

During general driving conditions, both the ICE and EM power the wheels individually or simultaneously based on the defined power split after taking into account the torque demand and state of charge of the batteries. If the state of charge is lesser than the lower limit, power from the ICE is split between the wheels and battery pack based on the amount of torque needed during that part of the drive cycle.

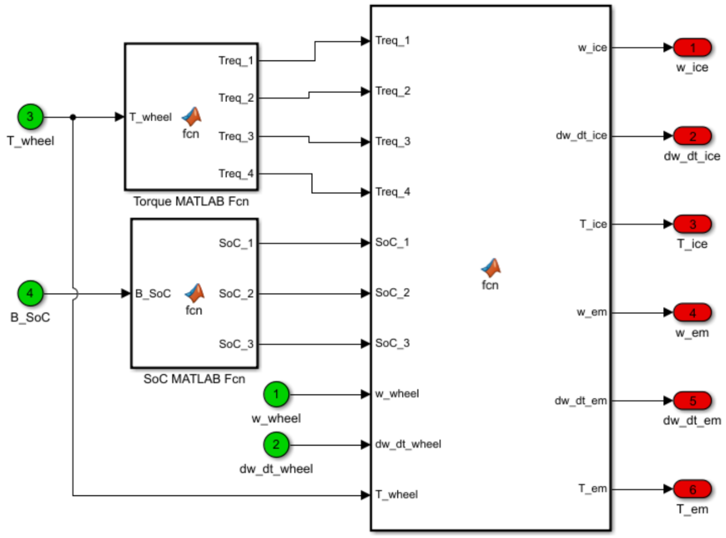


Figure 3.15: Overview of the Heuristic controller

High speed driving

The engine model used in this thesis is a naturally aspirated gasoline engine. The size of the internal combustion engine (ICE) and front gear box (FGB) gear ratios are selected such that the desired top speed can be attained. However, based on the selected gear ratio, the electric machine (EM) can be used to power the wheels alongside the internal combustion engine (ICE).

Regenerative and charging conditions

Kinetic energy from the wheels during deceleration and braking is also used to charge the batteries. The internal combustion engine (ICE) is also used to charge the batteries below a certain limit of state of charge which is pre-defined in the controller.

3.2 Vehicle Specifications/Requirements

The modeled vehicle is passenger vehicle with certain performance capabilities. Based on current trends in the automotive industry, it was decided that the vehicle should have a top speed of about 250 km/h. The base vehicle mass (mass excluding the weight of internal combustion engine (ICE), electric machine (EM) and battery pack) is kept constant at 1200kg. The gear ratios in each of the gear box is calculated based on the desired top speed and acceleration capabilities. The weight of the excluded components such as internal combustion engine (ICE), electric machine (EM) and Battery pack are estimated using certain mass estimating equations[9] based on the respective sizes during each iteration.

Mass of the Internal Combustion Engine:

$$M_{ICE} = 1.62 * P_{ICE} + 41.8 \tag{3.15}$$

Mass of the Electric Motor:

$$M_{EM} = 0.83 * P_{EM} + 21.6 \tag{3.16}$$

Mass of Battery pack: This can be defined as the ratio battery capacity and battery specific energy. Battery capacity is calculated as the product of the total number of series and parallel cells with the cell energy.

$$B_{capacity} = (n_{series} + n_{parallel}) * 205 \tag{3.17}$$

The ratio between the battery capacity and specific energy of the battery gives us the total mass of the battery pack.

$$M_B = \frac{B_{capacity}}{B_{specific}} \tag{3.18}$$

Mass of the body: A base weight of 1200 kg was assumed for the frame, auxiliary body parts, gearbox and so on.
Total mass of the vehicle is the sum of all the above individual estimations which is

$$M_{vehicle} = M_{ICE} + M_{EM} + M_B + M_{body} \tag{3.19}$$

3.3 Function Evaluations

3.3.1 Constraint Function

With equations for estimating the total mass of the vehicle, a constraint was defined to make sure that this total mass of the vehicle was within 1800kg. A minimum acceleration of 2.7 m/s^2 (0 - 60 km/h in around 6s) was also defined as a constraint. This lower limit was assumed considering the maximum acceleration levels in the drive cycles chosen for vehicle simulations. However an upper limit was not defined for this master thesis work. The definition of the above mentioned constraints are done in the constraint function.

3.3.2 Objective Function

The sole objective of the optimization work carried out in this master thesis was minimization of fuel consumption. In this case the effective energy consumption between battery and the fuel tank however, was not considered.

3.4 Vehicle Configurations

In order to optimize the drive-train architecture, various models with varying component architecture were built with the base vehicle mass kept constant throughout the configurations with varying front and rear gear boxes (FGB and RGB). The drive-train varied from a 3-Speed FGB; 2-Speed RGB all the way up to 6-Speed FGB; 1-Speed RGB. The list of configurations built and simulated during this thesis work can be observed from the Table 3.1. Gear ratios are calculated based on the desired top speed, maximum and engine speed and maximum torque level based on the the size of the ICE selected for each iteration. The same is done for the rear gear box with respect to the size of the electric motor. The highest and lowest required gear ratios are calculated for any of the configurations with the rest of the gear ratios calculated using progressive stepping. Since the gear ratios have to realizable in real life a geometric law is often chosen which defines the value of the constant[23].

Table 3.1: Various configurations used for simulations

Gearbox architecture	Front Gear Box [FGB]	Real Gear Box [RGB]
Configuration 1	3-Speed Automatic	2-Speed Automatic
Configuration 2	4-Speed Automatic	1-Speed Automatic
Configuration 3	4-Speed Automatic	2-Speed Automatic
Configuration 4	5-Speed Automatic	1-Speed Automatic
Configuration 5	5-Speed Automatic	2-Speed Automatic
Configuration 6	6-Speed Automatic	1-Speed Automatic

3.5 Optimization Model

The general optimization method is depicted as a flow process in Figure 3.16. Necessary variables not included in the optimization are defined through a common initialization module for the solver and the vehicle model. The model proceeds to initialize the vehicle model while simultaneously checking the values against the desired constraint levels with the process repeating if the chosen values do not satisfy the necessary constraint limits. After satisfying the constraint limits, the function of the optimization problem is evaluated.

The process explained above describes a single iteration of the entire genetic algorithm optimization strategy. Nelder-Mead simplex strategy uses a very similar method in evaluating the defined fitness function in each iteration. The algorithms repeats this process for a maximum number of specified iterations or until the convergence of the solution.

Definition of the objective function is the crucial part of the entire optimization problem as a clean, detailed definition of the objective will lead to optimal results.

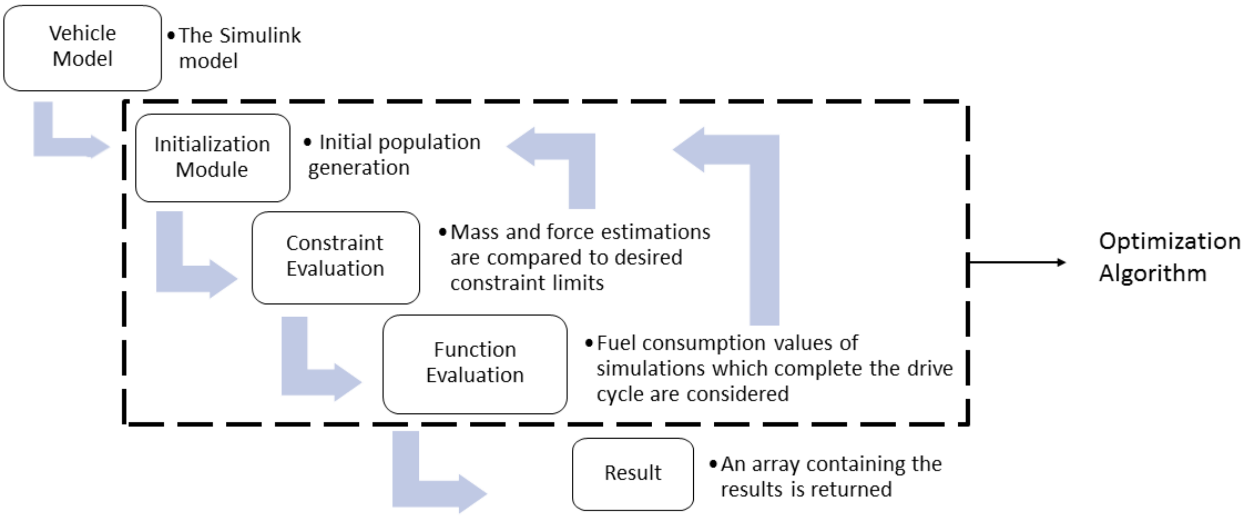


Figure 3.16: Optimization model

Optimization Parameters

General parameters of the optimization strategies are defined below in Tables 3.2 and 3.3.

Table 3.2: General Algorithm parameters for simulation

Initial Population Generation	Maximum Generation	Function Tolerance	Constraint Tolerance
200	3000	1e-4	1e-4

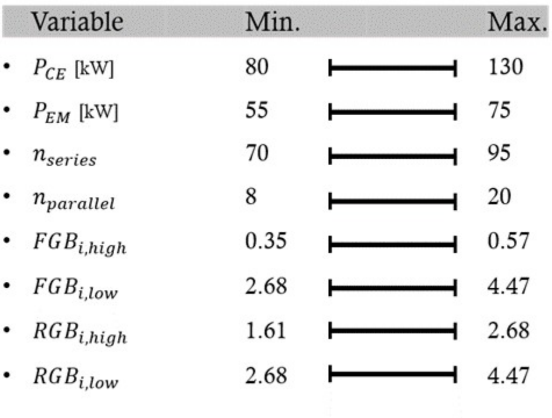
Table 3.3: Nelder-Mead strategy parameters for simulation

Maximum Generation	Function Tolerance	Constraint Tolerance
2000	1e-4	1e-4

3.6 DOE - Genetic Algorithm approach

Due to significant computational demands when using both Genetic Algorithm and Nelder-Mead Simplex strategy, Design of Experiments (DOE) was performed for the defined search space where DOE is a process which aims at predicting the variation of the parameters within the specified range. DOE was performed using AVL CAMEO where the parameters generated from DOE were then used as inputs to the vehicle model in MATLAB/Simulink. The vehicle model was simulated for the desired drive cycle and the results exported back to CAMEO.

These results are then interpolated in the defined search space using Genetic Algorithm, with the same acceleration and mass constraints as defined in the MATLAB optimization model. This interpolated search space can be visualized from Figure 3.18. This method resulted in significant decrease in simulation time from a minimum of $\approx$ 8hrs to $\approx$ 1.5hrs.



Variable	Min.	Max.
P_{CE} [kW]	80	130
P_{EM} [kW]	55	75
n_{series}	70	95
$n_{parallel}$	8	20
$FGB_{i,high}$	0.35	0.57
$FGB_{i,low}$	2.68	4.47
$RGB_{i,high}$	1.61	2.68
$RGB_{i,low}$	2.68	4.47

Figure 3.17: Range for Design of Experiments (DOE) [*Gear ratios are excluding the final drive ratio as final drive is kept constant]

Similar to the process in the MATLAB/Simulink model the simulation yields a solution or in certain cases multiple solutions. The green point in the search space represents the optimal solution or the configuration for the specified simulation parameters.

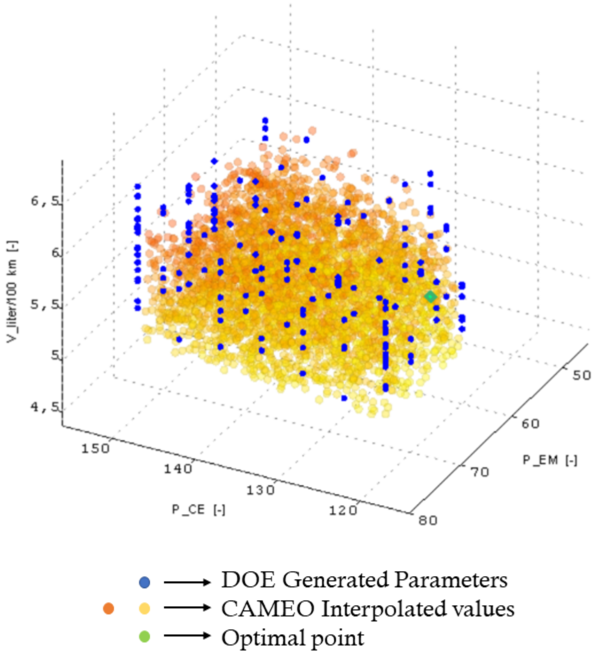


Figure 3.18: 3D Search space visualization of ICE and EM with respect to fuel consumption.

4

Results

The results of the optimization routine performed are analyzed in this section. Simulations were performed for different drive cycles keeping the search space constant. However the solution presented in the following section includes results for the WLTP drive cycle only as it is the modern drive cycle which is more commonly used in the automotive industry in the present day.

4.1 Optimization results

4.1.1 Configuration comparison

In order to compare the difference in fuel consumption, a vehicle model with a conventional powertrain was built with the same vehicle and performance criteria. The vehicle is a passenger car capable of achieving a top speed of 250 km/h along with the same constraint criteria of 2.7 m/s^2, 1800kg acceleration and total vehicle mass levels respectively. The drivetrain in this model is a 6-Speed automatic gearbox. Results from the simulation of the vehicle model with this conventional powertrain can be observed in Table 4.1.

Table 4.1: Conventional driveline configuration

Configuration: 6-Speed FGB								
P_{ICE} [kW]	P_{EM} [kW]	n_{series}	$n_{parallel}$	$F_{i1,tot}$	$F_{i6,tot}$	$R_{i1,tot}$	$R_{i2,tot}$	V [l/100kms)]
142	-	-	-	14.52	1.33	-	-	7.8

The vehicle model was then converted to a hybrid driveline configuration with the addition of an Electric Machine (EM), a battery pack as an energy buffer for the electric machine and controller for power management between the two axles. The addition of mass due to hybridization was taken into account using the same mass estimation equations described in Section 3.2. The drive-train architecture coupled to Internal Combustion Engine (ICE) remained the same whereas the Electric Machine (EM) was coupled to a single speed gearbox on the rear axle. The value of fuel consumption obtained as the solution from the simulation of this vehicle model is tabulated in Table 4.2

Table 4.2: Base parallel hybrid driveline configuration

Configuration: 6-Speed FGB, 1-Speed RGB								
P_{ICE} [kW]	P_{EM} [kW]	n_{series}	$n_{parallel}$	$F_{i1,tot}$	$F_{i6,tot}$	$R_{i1,tot}$	$R_{i2,tot}$	V [l/100kms)]
110	55	86	12	14.52	1.33	2.25	-	4.55

It can be observed that there is significant decrease of 42% in fuel consumption between the conventional and base hybrid driveline configurations. Table 4.3 shows further decrease of 28% in fuel consumption as a result of optimization of the driveline configuration.

Table 4.3: Optimized hybrid driveline configuration

Configuration: 4-Speed FGB, 2-Speed RGB								
P_{ICE} [kW]	P_{EM} [kW]	n_{series}	$n_{parallel}$	$F_{i1,tot}$	$F_{i4,tot}$	$R_{i1,tot}$	$R_{i2,tot}$	V [l/100kms)]
88	65	70	10	7.63	1.1	3.8	3.1	3.27

4.1.2 Comparison of results using different Optimization Strategies

The list of tables below show the optimal configurations obtained as a result of individual optimization strategies. Tables 4.4, 4.5 and 4.6 show the optimal configurations as a result of Nelder-Mead simplex method (NM), Genetic Algorithm (GA) optimization and DOE - GA optimization respectively.

Table 4.4: Optimized hybrid driveline configuration: Nelder-Mead Simplex method (NM)

Configuration: 4-Speed FGB, 2-Speed RGB								
P_{ICE} [kW]	P_{EM} [kW]	n_{series}	$n_{parallel}$	$F_{i1,tot}$	$F_{i4,tot}$	$R_{i1,tot}$	$R_{i2,tot}$	V [l/100kms)]
130	75	95	20	6.1	1.1	4.38	2.9	3.5

Table 4.5: Optimized hybrid driveline configuration: Genetic Algorithm (GA)

Configuration: 4-Speed FGB, 2-Speed RGB								
P_{ICE} [kW]	P_{EM} [kW]	n_{series}	$n_{parallel}$	$F_{i1,tot}$	$F_{i4,tot}$	$R_{i1,tot}$	$R_{i2,tot}$	V [l/100kms)]
88	65	70	10	7.63	1.1	3.8	3.1	3.27

Table 4.6: Optimized hybrid driveline configuration: DOE - GA Strategy

Configuration: 4-Speed FGB, 2-Speed RGB								
P_{ICE} [kW]	P_{EM} [kW]	n_{series}	$n_{parallel}$	$F_{i1,tot}$	$F_{i4,tot}$	$R_{i1,tot}$	$R_{i2,tot}$	V [l/100kms)]
128	77	95	18	8.71	1.39	3.8	3.1	3.9

From these results, for the given optimization problem and parameters it can be concluded that the MATLAB/Simulink model which utilizes the Genetic Algorithm strategy results in the optimal driveline configuration. Results for the simulation of various configurations for the MATLAB/Simulink model using Genetic Algorithm can be observed from Table A.1.

5

Discussion

The solutions obtained from the optimization routines performed on the driveline configuration are analyzed and discussed in this section.

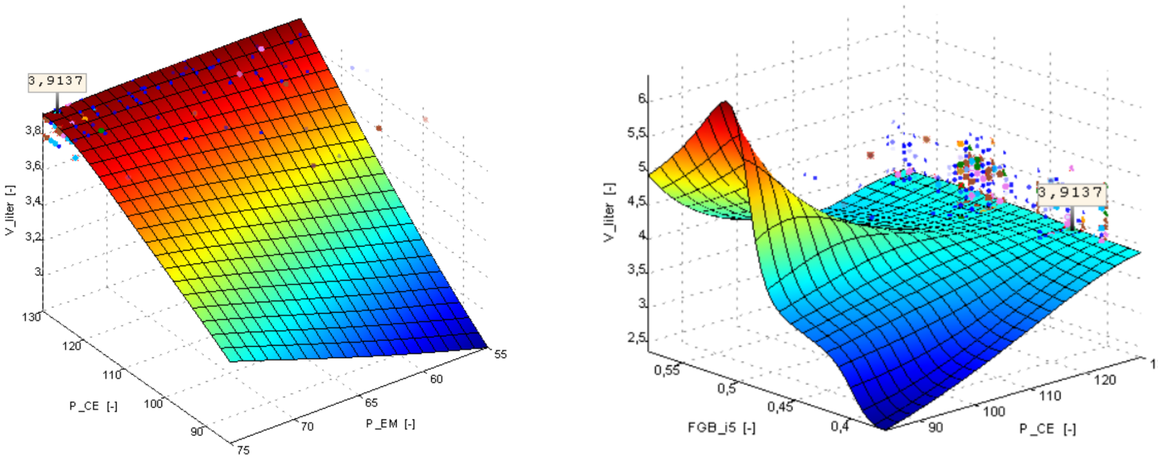
5.1 Trade-off Property

It can be noted that while there is a single solution mentioned for each configuration as tabulated in Table A.1, multiple solutions were obtained for the same amount of fuel consumption at the end of each simulation. The solution with the least vehicle mass for each configuration has been considered as the optimal configuration. Since this vehicle model is a surface model and does not consider and dynamic losses, having a vehicle with lower vehicle mass can be very beneficial when dynamics such as weight transfer during acceleration or cornering are being considered as well.

Obtaining multiple solutions for each simulation can be attributed to the heuristic nature of the optimization algorithm. All the optimal solutions exist as a trade-off between each variable. The clear effect of this trade off property can be observed in the 3D maps plotted using AVL CAMEO[24].

From the plots it can be observed that the relation between the component sizes of internal combustion engine (ICE) and electric machine (EM) with respect to fuel consumption is linear i.e. increase in size leads results in increase in fuel consumption and that smaller component sizes will lead to reduction of fuel consumption. However, this can also result in component overload and the model not completing the drive cycle.

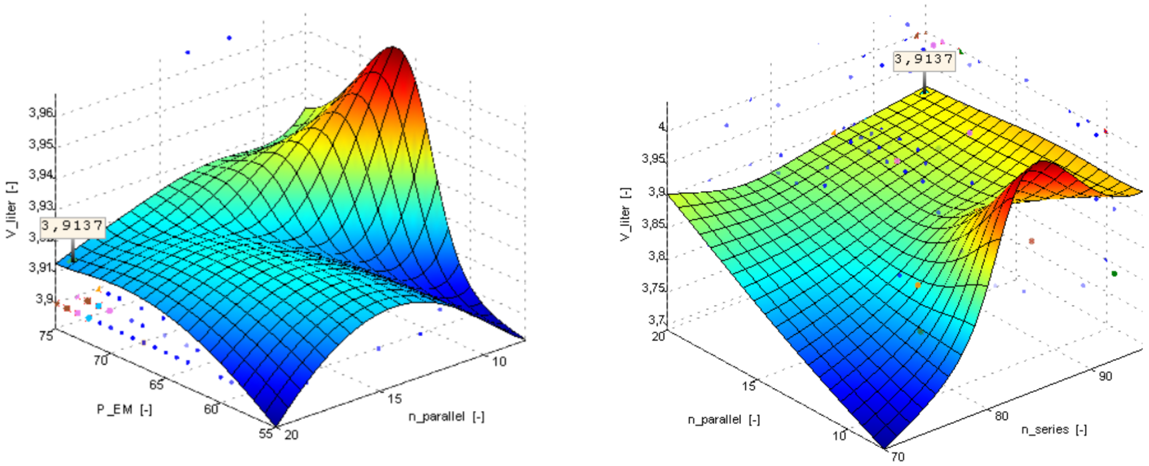
The trade of between other component values such as gear ratios and the number of cells is observed to have a far greater impact on fuel consumption when compared to change in size of internal combustion engine (ICE) and electric machine (EM). In a comparison between gear ratios and the number of cells itself, gear ratios was found to have a bigger impact on fuel consumption and hence it can concluded that the gear ratios are the crucial component of the driveline configuration.



(a) Trade off relation between ICE and EM component sizes

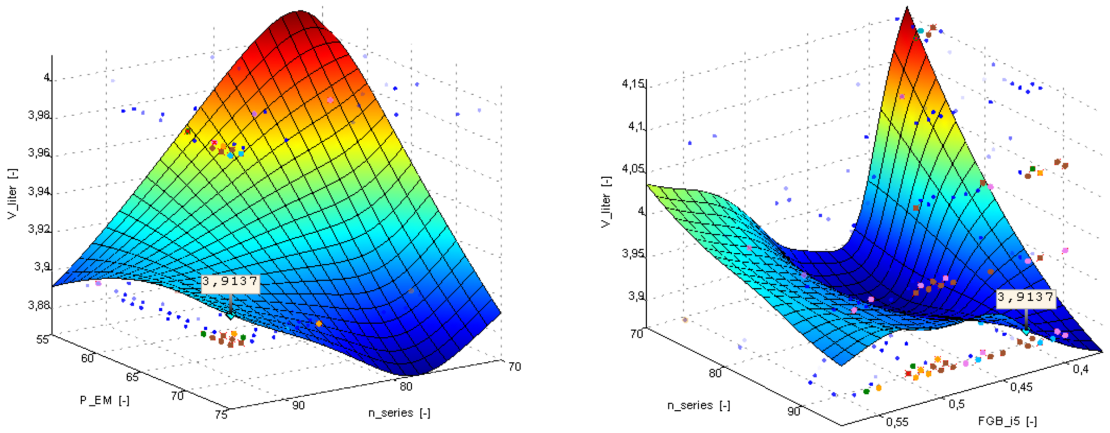
(b) Trade off relation between 5^{th} gear ratio and ICE component size

Figure 5.1: Effect of trade off on fuel consumption



(a) Trade off relation between size of EM and number of cells in parallel

(b) Trade off relation between number of cells in series and parallel

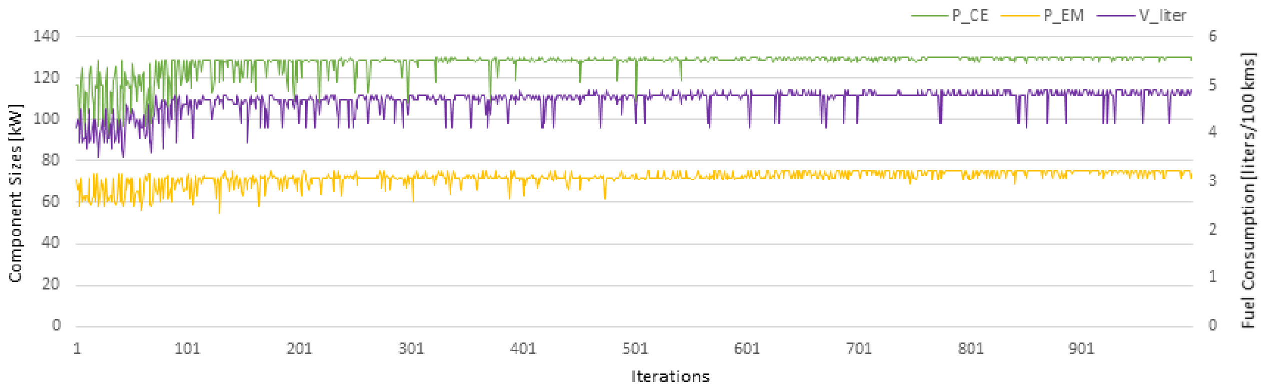


(c) Trade off relation between size of EM and number of cells in series

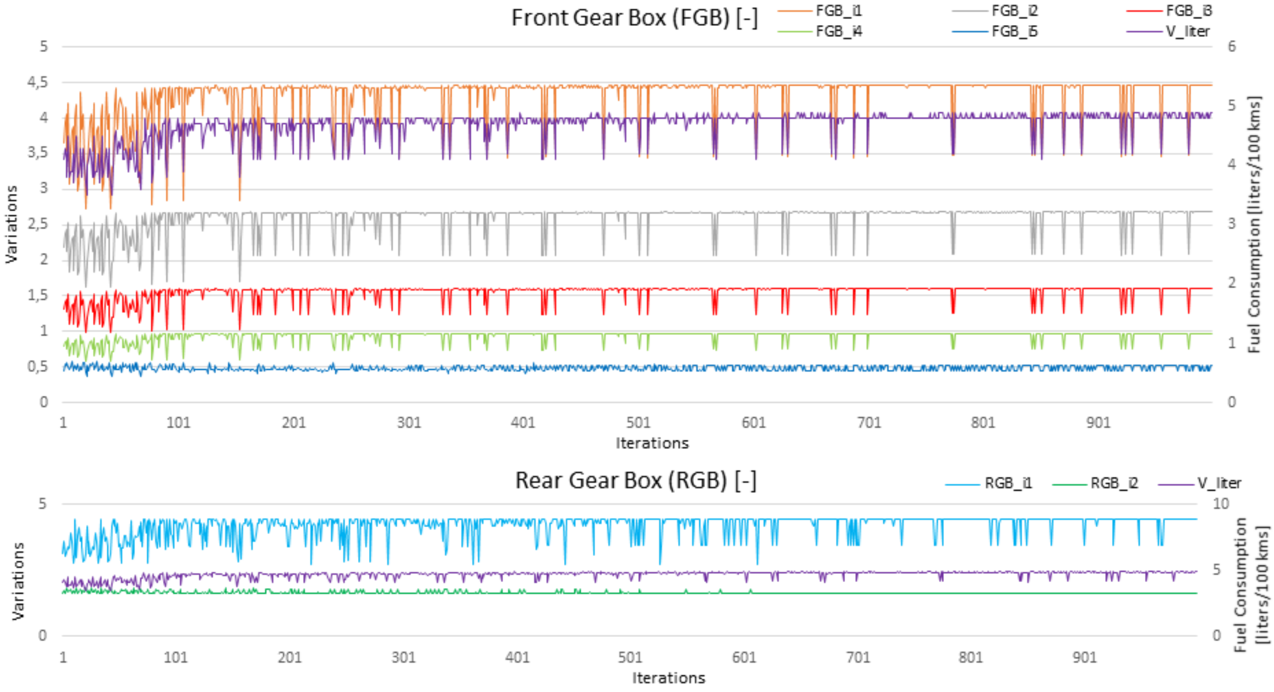
(d) Trade off relation number of cells in series and 5^{th} gear ratio

Figure 5.2: Effect of trade off on fuel consumption

The search for the optimal component size is carried out by the strategy by varying the sizes in defined search space. Variation of component sizes or gear ratios primarily depend on the drive cycle. The differences in variation of various optimization variables depending on the drive cycle can be observed from the variation plots.

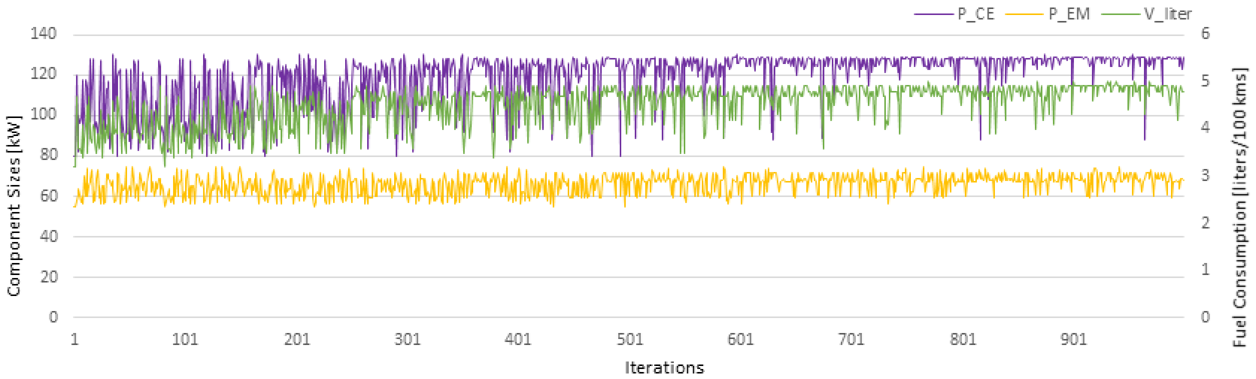


(a) Variation of component sizes of ICE and EM



(b) Variation of gear ratios in the front and rear gearboxes

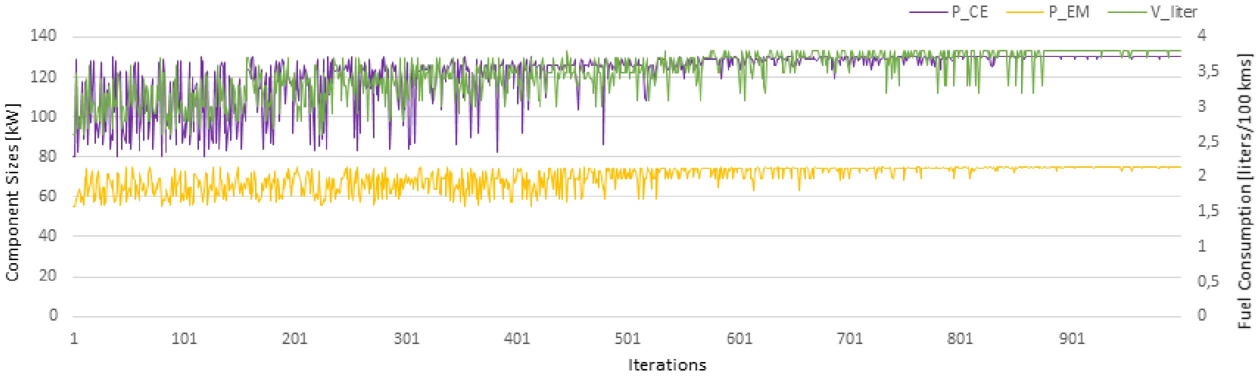
Figure 5.3: Variations in WLTP drive cycle



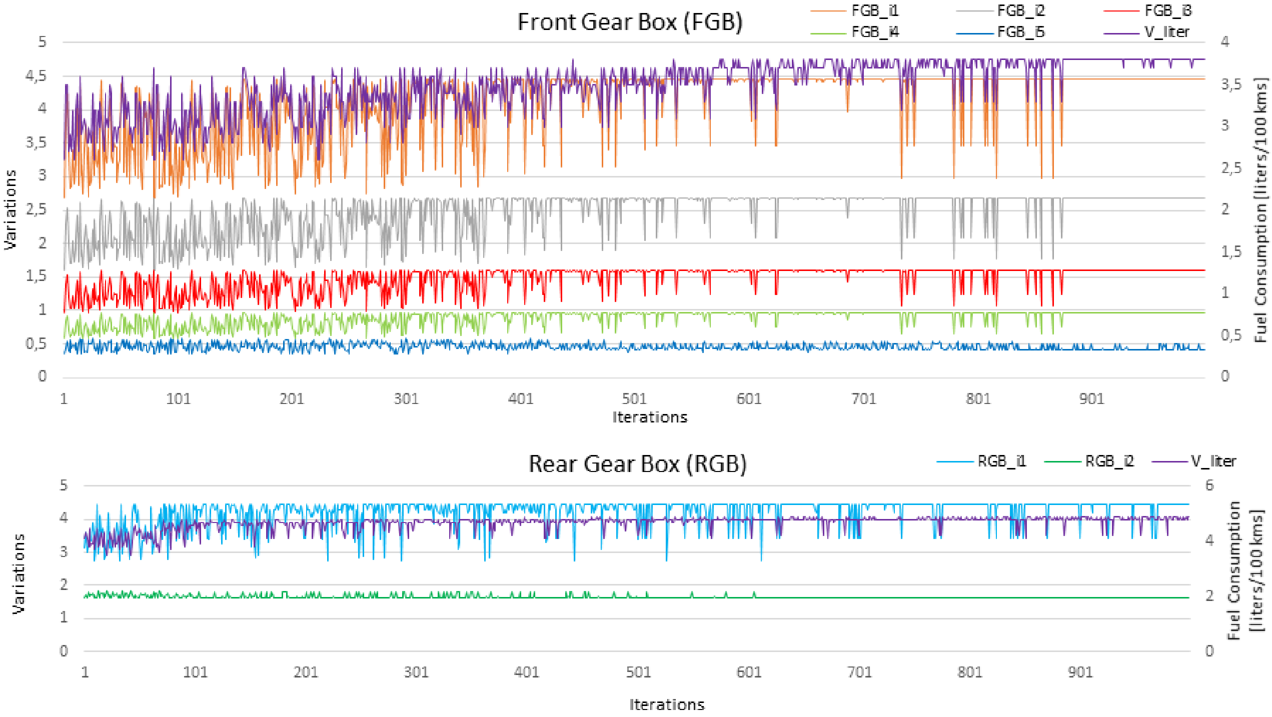
(a) Variation of component sizes of ICE and EM

(b) Variation of gear ratios in the front and rear gearboxes

Figure 5.4: Variations in NEDC drive cycle

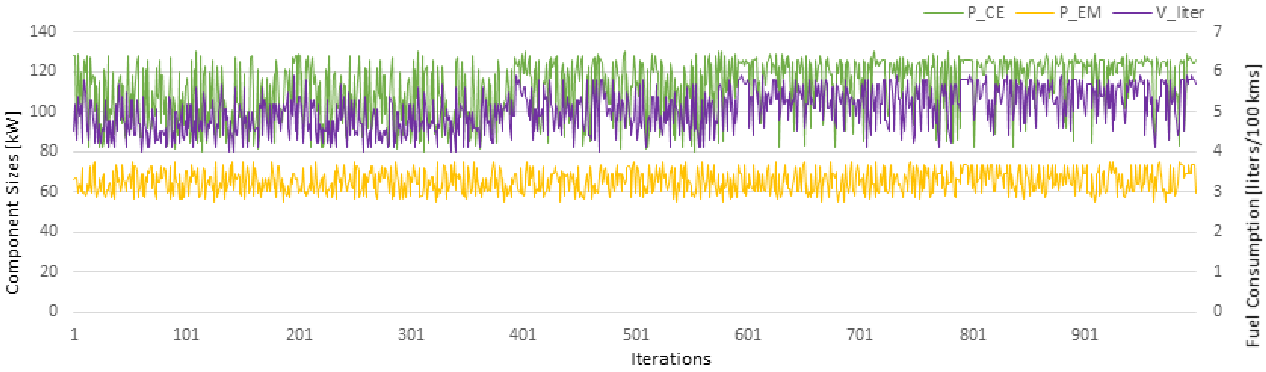


(a) Variation of component sizes of ICE and EM

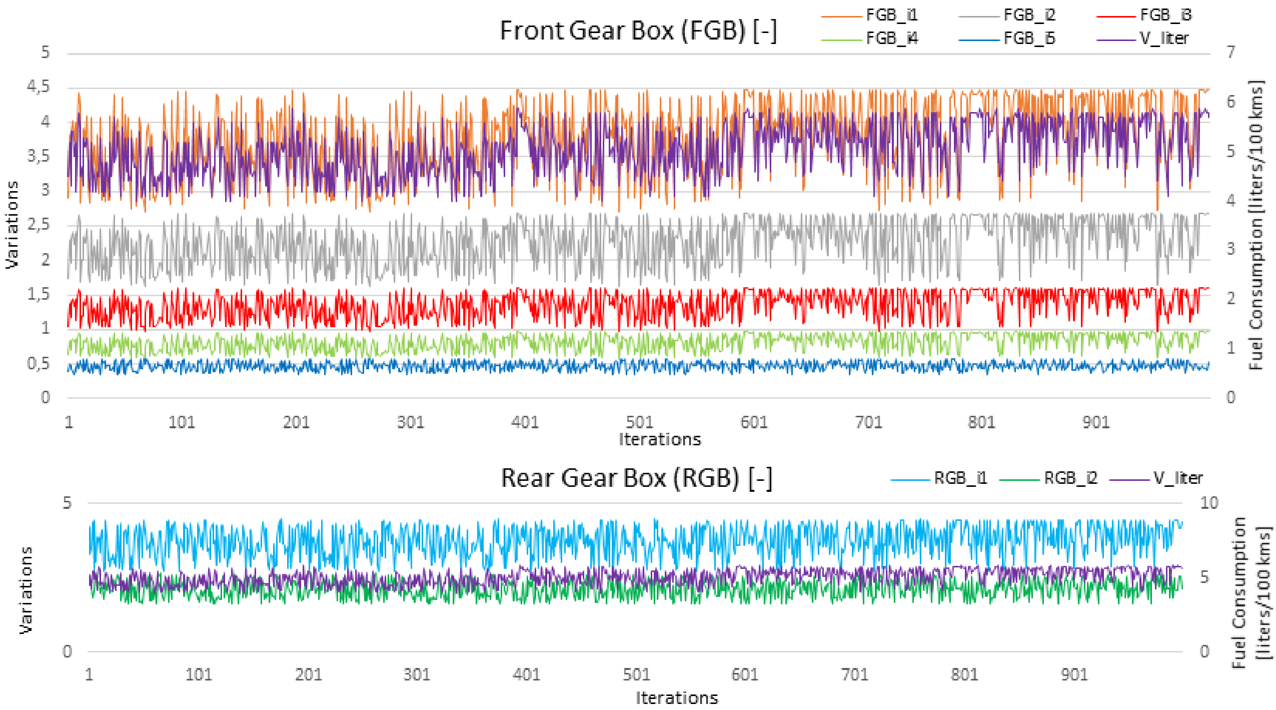


(b) Variation of gear ratios in the front and rear gearboxes

Figure 5.5: Variations in EUDC drive cycle



(a) Variation of component sizes of ICE and EM



(b) Variation of gear ratios in the front and rear gearboxes

Figure 5.6: Variations in FTP-75 drive cycle

From all of the variation plots it can be observed that the pattern of variation is different for each drive cycle. This can be attributed to the property of the drive cycles itself wherein different velocity and acceleration profiles along with changing torque demand result is different variations during the search for the optimal configuration. Depending on the defined search space, change in optimization strategy and parameters these variations can differ as well. Hence the trade-off nature.

5.2 Verification of Acceleration Performance

Apart from the comparison of theoretical and calculated values for maximum longitudinal force, a single configuration was simulated with varying values of base vehicle mass in order to verify the acceleration criteria specified in the constraint function. The vehicle model and it's respective masses simulated can be seen in Table 5.1. With optimization performed for each configuration, the power/weight ratio from the combined power of Internal Combustion Engine and Electric Motor along the full vehicle speed was plotted. This plot can be seen in Figure 5.7.
It can be observed from the plot that the difference in combined power/weight ratios for varying base vehicle

Table 5.1: Base vehicle mass variation

Gearbox architecture	Config. 5a	Config. 5b	Config. 5c	Config. 5d
FGB: 5-Speed, RGB - 2-Speed	1000 kgs	1150 kgs	1300 kgs	1450 kgs

masses is very light during the initial acceleration period from which one can conclude that the acceleration constraint defined is adhered to during the optimization process. Optimal configurations obtained as a result of the optimization for the above mentioned configurations can be observed in Table A.2.

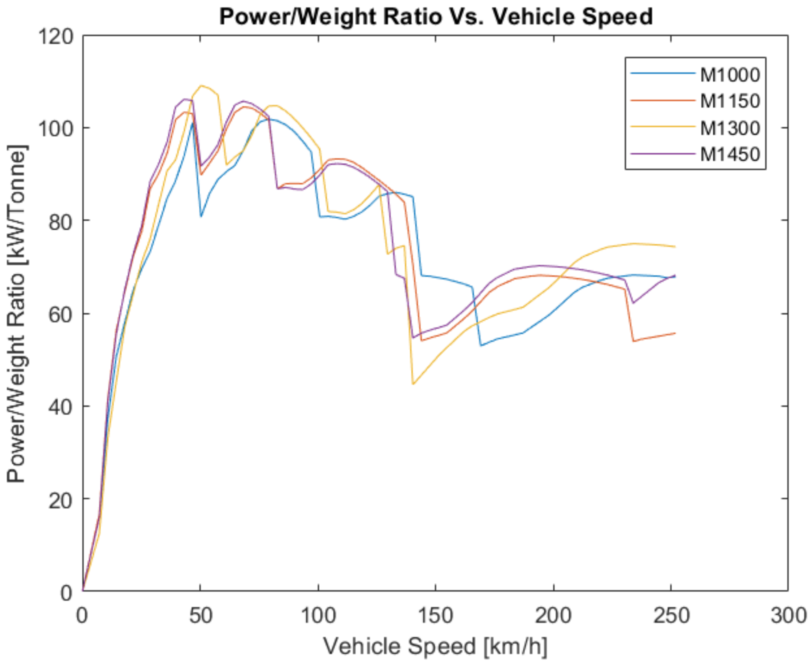


Figure 5.7: Power/Wight ratio of the vehicle Vs. Vehicle Speed

6

Conclusions and Future Work

The parallel hybrid vehicle model built in MATLAB/Simulink using QSS-Toolbox was simulated for various driving cycles. It can be summarized from the results that all the desired criteria set for optimization has been achieved. The process of optimization resulted in decrease in component sizes with increase in effective fuel consumption. The key deliverables listed during the planning phase of the master thesis have been achieved.

- An optimization algorithm was implemented to in order to achieve the best possible driveline configuration
- Gear ratios were optimized along with the component sizes using the optimization algorithm
- The gear ratios were found to be the crucial component for the determination of the optimal driveline configuration
- Reduction in fuel consumption compared to the non-optimized driveline and conventional powertrain configuration
- Model can be used to include more variables and/or objectives for optimization

6.1 Future Work

- Due to lengthy simulation times, the optimization was limited to only two strategies. However, as it is not a deterministic optimization method the solution obtained might not necessarily be the definitive optimal solution. Using other optimization algorithms can result in different optimal configurations
- The optimization algorithm can also be used to optimize the rules used in the deterministic controller
- Since the vehicle model is not a plug-in hybrid, it was necessary that the state of charge at the end of the drive cycle is the same as the initial value of state of charge. However with a heuristic controller, the state of charge at the end of the driving cycle is not necessarily the same value as the initial state of charge. In order to ensure charge sustenance, an Equivalent Control Management Strategy (ECMS) can be implemented. This however will result in significant increase in computational demand
- Optimization in this thesis work was performed for a single objective i.e. minimization of fuel consumption. However multi-objective optimization can be performed to optimize the driveline for both minimization of fuel consumption and maximization of performance
- Different battery technologies can be implement in the vehicle model to observe its effects on the driveline configuration

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A

Appendix 1

A.1 Optimal driveline configuration for different architectures

$$FGB_{i,final} = 3.25$$

$$RGB_{i,final} = 2.25$$

Table A.1: Optimized Driveline for various gearbox configurations

P_{ICE}	P_{EM}	n_s	n_p	F_{i1}	F_{i2}	F_{i3}	F_{i4}	F_{i5}	F_{i6}	R_{i1}	R_{i2}	m_{tot}
Configuration 1: 3-Speed FGB and 2-Speed RGB												
109	63	76	11	2.23	0.89	0.56	-	-	-	2.99	0.93	1622
Configuration 2: 4-Speed FGB and 1-Speed RGB												
88	65	70	10	2.31	1.39	0.83	0.37	-	-	-	-	1576
Configuration 3: 4-Speed FGB and 2-Speed RGB												
88	65	70	10	2.31	1.39	0.83	0.37	-	-	1.69	1.35	1576
Configuration 4: 5-Speed FGB and 1-Speed RGB												
93	63	73	10	3.44	2.06	1.24	0.74	0.4	-	-	-	1588
Configuration 5: 5-Speed FGB and 2-Speed RGB												
102	57	73	14	3.31	1.99	1.19	0.72	0.49	-	4.09	1.69	1604
Configuration 6: 6-Speed FGB and 1-Speed RGB												
82	64	78	8	4.54	2.72	1.63	0.98	0.59	0.44	-	-	1578

Table A.2: Optimized Driveline for various base mass configurations

P_{ICE}	P_{EM}	n_s	n_p	F_{i1}	F_{i2}	F_{i3}	F_{i4}	F_{i5}	F_{i6}	R_{i1}	R_{i2}	m_{tot}
Configuration 1: Base mass - 1000kg												
113	60	83	19	2.85	1.71	1.03	0.62	0.56	-	4.14	1.7	1657
Configuration 2: Base mass - 1150kg												
113	62	83	19	2.85	1.71	1.03	0.62	0.46	-	4.14	1.7	1658
Configuration 3: Base mass - 1300kg												
129	59	91	29	2.86	1.72	1.03	0.62	0.42	-	3.38	1.86	1721
Configuration 4: Base mass - 1450kg												
113	60	60	19	3.46	2.08	1.25	0.75	0.53	-	3.97	1.85	1609

A.2 Performance Plots

The plots displayed below displays various performance attributes of the optimized configurations tabulated in Tables A.1 and A.2.

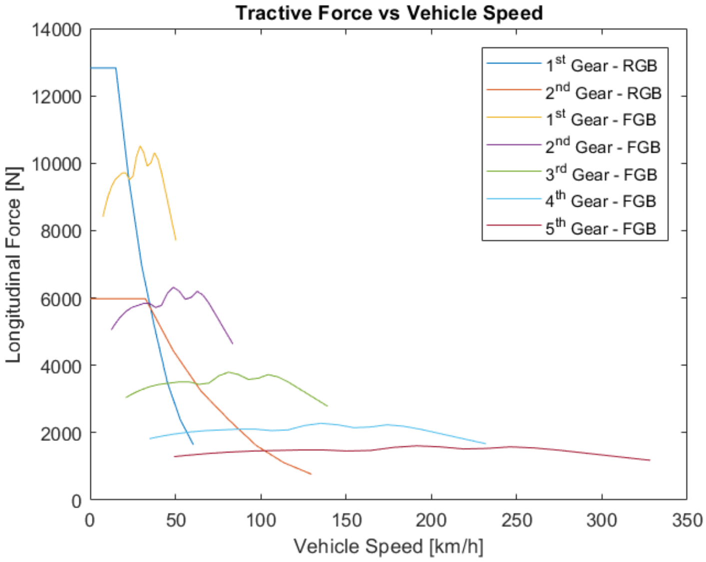
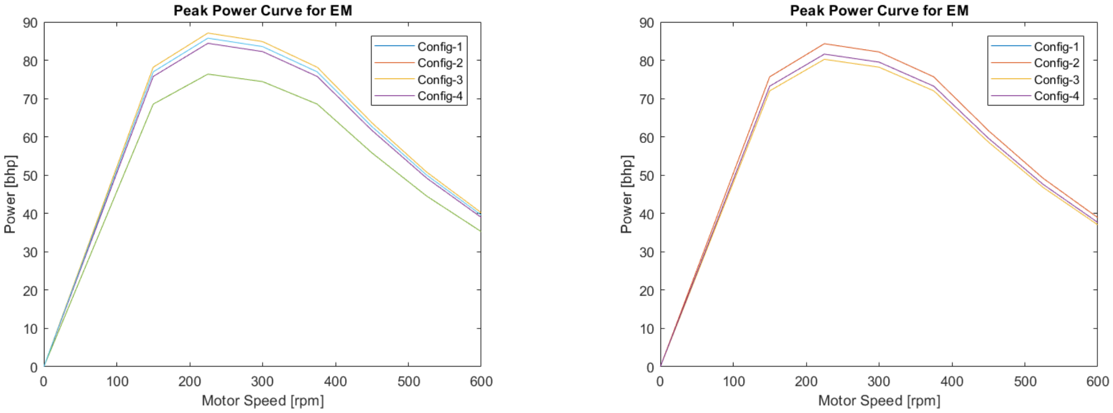


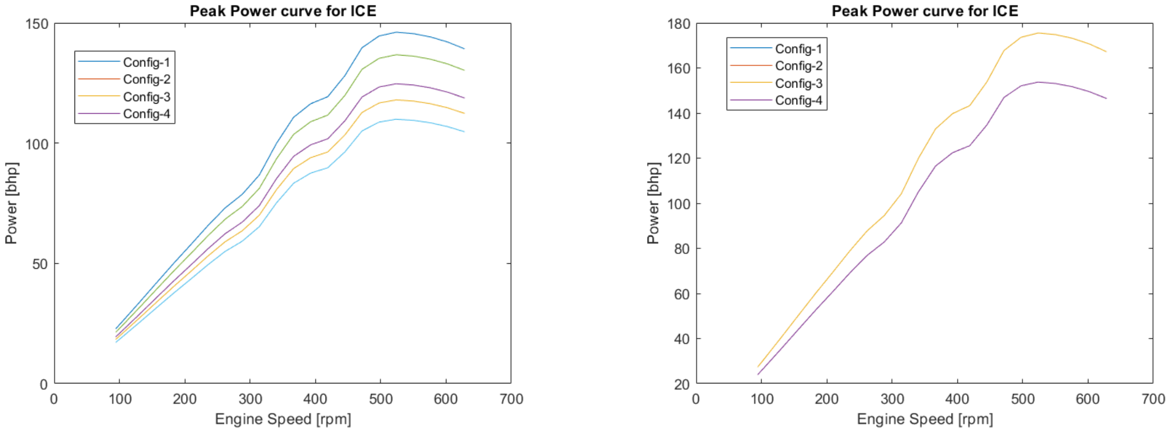
Figure A.1: Tractive Force of the Optimal Hybrid System



(a) Peak Power curve of the EM for Table A.1

(b) Peak Power curve of the EM for Table A.2

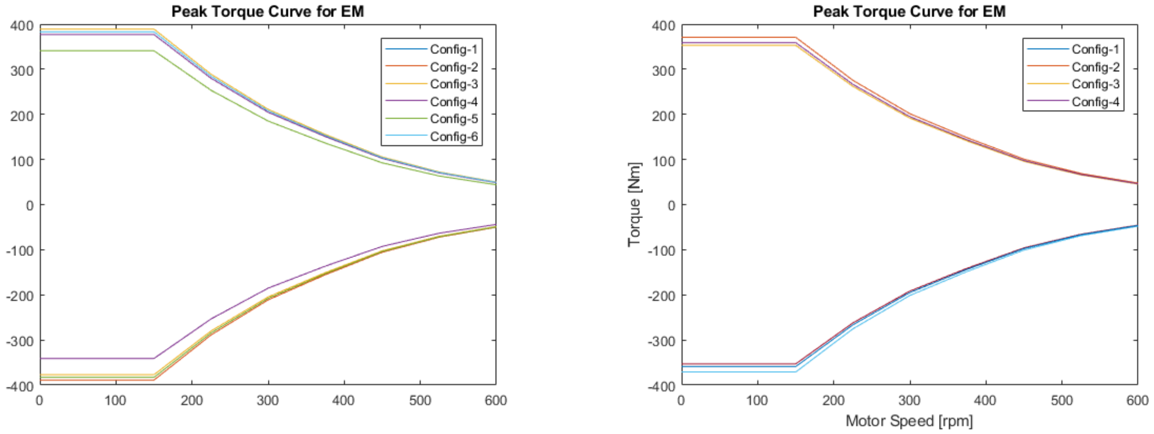
Figure A.2: Performance characteristics



(a) Peak Power curve of the ICE for Table A.1

(b) Peak Power curve of the ICE for Table A.2

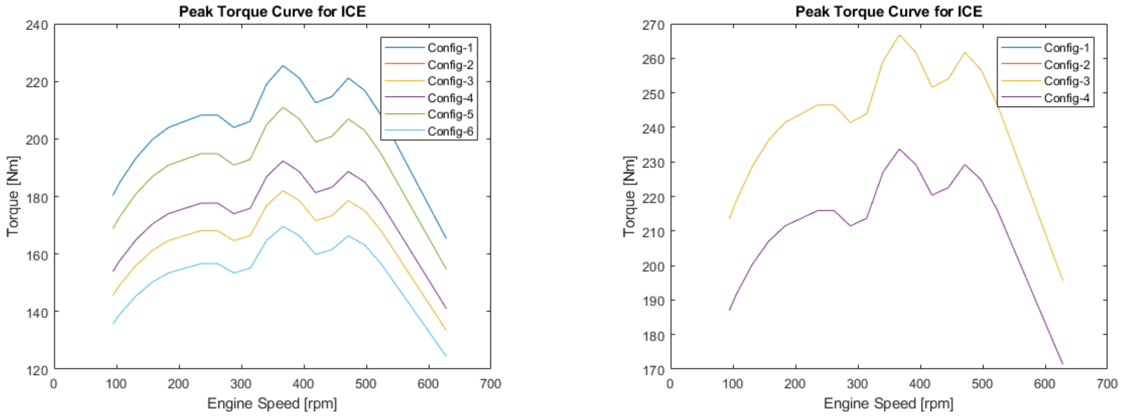
Figure A.3: Performance characteristics



(a) Peak Torque curve of the EM for Table A.1

(b) Peak Torque curve of the EM for Table A.2

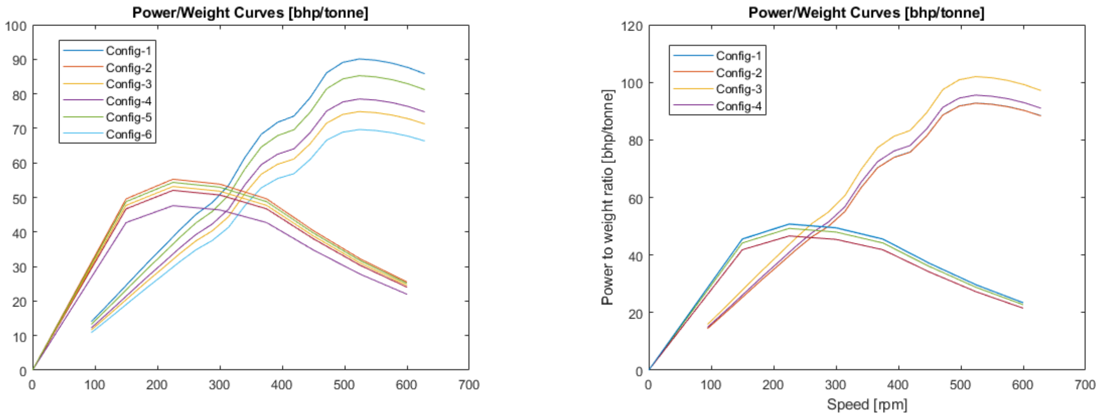
Figure A.4: Performance characteristics



(a) Peak Torque of ICE for Table A.1

(b) Peak Torque of ICE for Table A.2

Figure A.5: Performance characteristics



(a) Power/weight ratio for Table A.1

(b) Power/weight ratio for Table A.2

Figure A.6: Performance characteristics

B

Appendix 2

B.1 Planning Report

The following section includes the planning report of the Master's thesis work.

Master thesis
MMSX30

PLANNING REPORT

Hybrid Driveline Configuration

30 January 2018

Manoj Ramesh manojr@student.chalmers.se

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Appendix i

1 Background

Innovation is the most important driving force in engineering and the goal of reducing emissions and creating a greener environment is pushing companies hard to create new technologies or improve existing technologies to achieve higher efficiency values. Use of electric machines along with the standard powertrain of a vehicle is defined as hybridization. Vehicle hybridization can be achieved in various levels, starting with the use of electric machines which aid starting and stopping of the vehicle all the way up to being able to drive the wheels.

In order to achieve sufficient reduction in fuel consumption levels it is necessary to choose a balanced configuration of ICE and electric machines. This master thesis work deals with finding the optimum driveline configuration for passenger vehicles. In order to obtain the optimum configuration it is first necessary to understand the types of hybrid systems and various levels of hybridization in today's vehicles.

Levels of Hybridization

The level of influence of battery power and electric motor in vehicles define the level of hybridization.

Micro Hybrids

Vehicles where the reliance of the electric power to drive the vehicle is very little is known is an Micro hybrids. Such electric machines are known as crankshaft synchronous. In the current day however, crankshaft synchronous machines are not regarded as hybrids anymore due to the lack of enough electric power to drive the vehicle.

Mild Hybrids

Mild hybrid systems contain electric machines with slightly more power than micro hybrid systems but not enough power to drive the wheels for a long range. Such systems vary from start-stop functions to regenerative braking systems in modern cars. The power generated from braking can be used to perform in-built functions of the car or used to drive the wheels for a very short distance.

Full Hybrids

Electric machines in vehicles which can drive the wheels on it's own for a sufficient amount of time is known as full hybrid vehicles. Such machines are also known as Non-Crankshaft synchronous machines.

Types of Hybrid Vehicles

There are mainly three types of hybrid systems

- **Parallel Hybrid systems**: These are the systems where both, an ICE or an electric machine can drive the vehicle individually or when coupled power the vehicle together when there is requirement for additional power.
- **Series Hybrid systems**: In this hybrid system although there is a presence of an ICE, it's function is to generate electric power to help power the electric motor and drive the wheels
- **Series-Parallel Hybrid systems**: Commonly referred to as Split hybrid, this system as the name suggests contains elements of both series and parallel hybrid systems. The power flow is managed via a planetary gearbox and belt driven CVT.

Optimization of Driveline Configuration

Global optimization (GO) deals with optimization of a certain characteristics based on a given set of criteria. This optimization method is used since the entire driving cycle is known before hand, which is also defined as the search space for the global minima or the point where the goal is achieved by satisfying all the given criteria. In the case of this master thesis, the global minima is defined as the minimization of multiple objectives. The objectives considered for optimization are the Internal Combustion Engine (ICE) , Transmission , Electric Motor (EM) and the Energy Management System (EMS) or the batteries.

The optimization of transmission involves finding the optimized gear ratios while sizing of ICE, EM and EMS is considered critical for achieving optimization. There are three methods of GO. These are:

- Deterministic Methods: Within the given set of boundary conditions, this method can provide a theoretical guarantee of having obtained the global minima. This method can be used when the exact value of the global minima needs to be achieved.
- Stochastic Methods: This method involves the generation and use of random variables within the formulation of the optimization problem itself. Stochastic optimization method generalizes deterministic methods for deterministic problems
- Heuristic/Meta-Heuristic Methods: A heuristic strategy is an approach to obtain satisfactory results by employing a practical approach. This method does however results in multiple solutions due to the fact that a slight change in one of the factors can lead to changes in results with massive differences between them

Although the deterministic method results in a more definite and optimal result, this method requires far more computational time and power whereas heuristic methods achieve fairly optimal results with far less computational requirements. The various optimization algorithms that can be implemented under heuristic methods are Genetic Algorithm[1], Particle Swarm Optimization method[2], Simulated Annealing method and Nelder-Mead method[3]. A better understanding of these algorithms can be achieved upon studying them in detail during the literature review, thereby enabling implementation to obtain the optimum hybrid driveline configuration.

2 Players, Shareholders & Stakeholders

The players of this project will be the student(s) performing the thesis work. The shareholders of this project is the department of Mechanics and Maritime Sciences at Chalmers University. The stakeholders for the project will be Vicura AB , who came up with the thesis statement. The demands and the deliverables from the project are set after discussions with both the shareholders and stakeholders.

3 Project goal statement

The goal of the master thesis is to create and implement an optimization algorithm to achieve the best possible hybrid driveline configuration for the given criteria using MATLAB/Simulink.

4 Methodology

Work is primarily divided into two stages. The first stage involves study of the concept of hybridization and existing hybrid systems in the industry. This stage also includes study of various types of battery and motor technologies and characteristics that can affect performance and fuel consumption in cars.

The second stage involves using the QSS-Toolbox and MATLAB/Simulink to build and simulate a vehicle model with the necessary constraints. Once the working of the software has been familiarized with, work will focused on developing a refined, flexible model to obtain the optimum hybrid driveline configuration. Primary focus during modeling is to implement a multi-objective optimization algorithm. Upon completion, focus is shifted to obtain the optimum gear ratios for the existing vehicle model. The last part of this stage is the comparison between multiple optimization algorithms and the conventional drive-train to obtain an optimized hybrid driveline configuration.

5 Deliverables

The deliverables of this thesis are listed below:

- Implementation of optimization algorithm in order to achieve the best possible hybrid driveline configuration based on the given criteria
- Achieve optimum gear ratios with the optimization algorithm
- Identification of criteria to determine the optimum level of hybridization and driveline configuration
- Comparison of optimal driveline configurations obtained from different optimization algorithms
- Investigation of how different battery technologies and characteristics affect the model

6 Timeline

The thesis work is mainly divided into 4 major milestones, each corresponding to the various targets set to be achieved at the end of the thesis work. The final milestone of the thesis work is the thesis report and presentation. A detailed view of the tentative timeline can be observed in the Gantt chart attached in the appendix.

7 Limitations

During the course of the project there might be several limitations to achieving the set goals and deliverables. Some of them are discussed in this section. The level of impact and probability have been assigned to each limitation on a scale of 1 - 10 with 10 being the highest. Actions/mitigation are considered to reduce the probability and impact of these limitations.

Table 1: Limitations

Limitation	Impact	Probability	Action/Mitigation
Initial Model failure	8	9	Check model before start of simulation. Edit the model for improvement
Inappropriate or Unreal results	6	7	Check the model and edit accordingly
Missing Deadlines	6	6	Manage deadlines, schedules and update them accordingly

8 Infrastructure, Organization & Game Rules

The project will be carried out mostly in the office of Vicura AB, Trolhattan under the supervision of Per Rosander. Sven B Andersson is the examiner at Chalmers University of Technology. Weekly updates will be sent on every Monday unless discussed and changed earlier. Additional meetings if and when necessary will be orgainesed with Per Rosander and Sven B Andersson. A midterm status report of the project will be presented during week 13. Final presentation for the project will be given during week 23(tentative) . A draft version of the final report will be submitted during week 21 while the final report will be submitted no later than week 25

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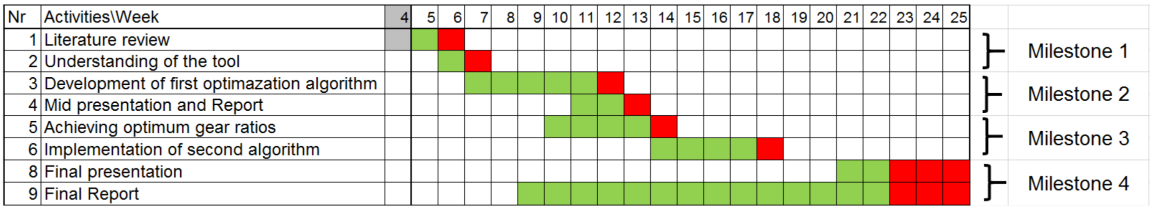
Appendix A: Gantt chart



Nr	Activities\Week	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
1	Literature review		🟩	🟥																				Milestone 1
2	Understanding of the tool			🟩	🟥																			
3	Development of first optimazation algorithm				🟩	🟩	🟩	🟩	🟩	🟥														Milestone 2
4	Mid presentation and Report								🟩	🟩	🟥													
5	Achieving optimum gear ratios							🟩	🟩	🟩	🟩	🟥												Milestone 3
6	Implementation of second algorithm											🟩	🟩	🟩	🟩	🟥								
8	Final presentation																		🟩	🟩	🟥	🟥	🟥	Milestone 4
9	Final Report						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	

Figure 1: Project Gantt chart