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Vehicle Fuel Economy & Performance Modelling with Focus on an Engine

Master's thesis in Automotive Engineering

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MASTER’S THESIS AUTOMOTIVE ENGINEERING

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Abstract

Recently, it has been a growing interest in introducing hybrid electric vehicles in the market. To improve vehicle fuel consumption, a transition is observed from vehicles driven by purely internal combustion engines to hybrid electric vehicles with different levels of electrifications. In this journey, it is very important to consider the match between the engines and the new hybrid electric vehicle configurations. This is because the engine operation would be different in each configuration. Consequently, these engines could be further improved to be well-fitted to the hybrid vehicles. In view of this, a method to integrate engine models with vehicle models is required in the early phases of engine development. This thesis aims to fulfil this gap and implement a modelling method to be able to understand how an engine would work in a new vehicle configuration in the absence of detailed information of different subsystems such as electric machine, vehicle and transmission.

The first section involves understanding the 48V battery system, P2 Hybrid Electric Vehicle concepts and engine model calibration. With the knowledge acquired, the second phase of the thesis involves calibrating the engine model in GT-POWER against latest measurement data that was received from a test rig at Volvo Cars. After the engine model calibration, the third phase includes modelling the Volvo XC60 vehicle along with all its subsystems in GT-SUITE software. Upon understanding each subsystem, multiple engine performance maps are extracted from the engine model to represent the engine in the vehicle model. Subsequently, based on the driving cycles, simulations are performed to extract the vehicle fuel consumption for different cases.

Different subsystems and technologies are varied to assess the sensitivity of the modular vehicle. On comparing all the different cases, a critical observation on two interesting technologies is made i.e. cylinder deactivation and P2 hybrid electrification. The effects of cylinder deactivation and P2 hybrid electrification are comparable in WLTC; however, the benefit of P2 hybrid is significantly higher than that of cylinder deactivation in other driving cycles including NEDC and aggressive driving cycles. Moreover, there is a reduction in the benefit of cylinder deactivation at the presence of electrification. This observation is valid for all the studied driving cycles for instance, the cylinder deactivation benefit is very low in a really aggressive driving cycle and at the presence of electrification. Furthermore, a smaller electric machine is included in P0 hybrid vehicle configuration to assess the impact of Start-Stop feature alone on the vehicle's fuel consumption. In terms of performance test of the vehicle, an acceleration test of the vehicle from stand still to 100km/h is conducted. The engine-vehicle model is fairly accurate and performs this test in 7s as compared to the reality of 6.95s.

Keywords: Hybrid electric vehicles, P2 and P0 hybrid configurations, 48V battery system, drive cycles, engine model, GT-SUITE, GT-POWER and vehicle fuel consumption.

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Göteborg, 2018-08-02

SHREYAS KOGALUR MALLIKARJUNAPPA

Notations

ICE	Internal Combustion Engine
EM	Electric machine
HEV	Hybrid Electric Vehicles
MHEV	Mild Hybrid Electric Vehicles
GHG	Global Greenhouse Gas
LDV	Light-Duty Vehicles
ICCT	International Council of Clean Transportation
FHEV	Full Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
BISG	Belt Integrated Starter Generator
CISG	Crank Integrated Starter Generator
TIMG	Transmission Integrated Motor Generator
NEDC	New European Driving Cycle
WLTC	Worldwide harmonized Light vehicles Test Cycle
S-FTP	Supplemental Federal Test Procedure
RTS	Random Test Sequence
GDI	Gasoline Direct Injection
AWD	All Wheel Drive
BMEP	Brake Mean Effective Pressure
FMEP	Friction Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
1D	1 Dimensional
2D	2 Dimensional
PID	Proportional Integral Differential
SOC	State Of Charge
ECU	Engine Control Unit
TCU	Transmission Control Unit
BMS	Battery Management System

Contents

1 Introduction

1.1 Background

The automotive industry is facing multiple challenges with high cost of fuel and talk of green technology solutions. With the combination of stringent government regulations for emissions, fuel consumption and shifting customer demand for more efficient vehicles, automotive engineers are researching solutions to these problems. Electrification of the powertrain has clearly taken a huge section of the public discussion as a future solution. However, the sales of electrified vehicles are majorly inhibited by high initial cost along with lack of charging infrastructure and limited range of powertrains as the current solution. This has directed the development of increasingly complex powertrain technologies and control strategies to help minimize fuel consumption and maximize engine efficiency while maintaining good vehicle performance.

Global greenhouse gas (GHG) emission and fuel economy standards for light-duty vehicles (LDVs) have progressed significantly in a little more than a decade according to International Council of Clean Transportation (ICCT) [1]. The aim of GHG and fuel economy standards is to limit the carbon dioxide emissions from vehicles and limit the consumption of fossil fuels. Figure 1.1 shows the country standards for passenger vehicles in terms of grams of CO_2 equivalent per kilometre adjusted to European NEDC test cycle. It is evident that the European Union has transcended the world with the lowest fleet average aim of 95g CO_2/km by 2021. With proposed emission standards like these and global market shift, the automotive industry have accelerated the development and deployment of fuel-efficient technologies.

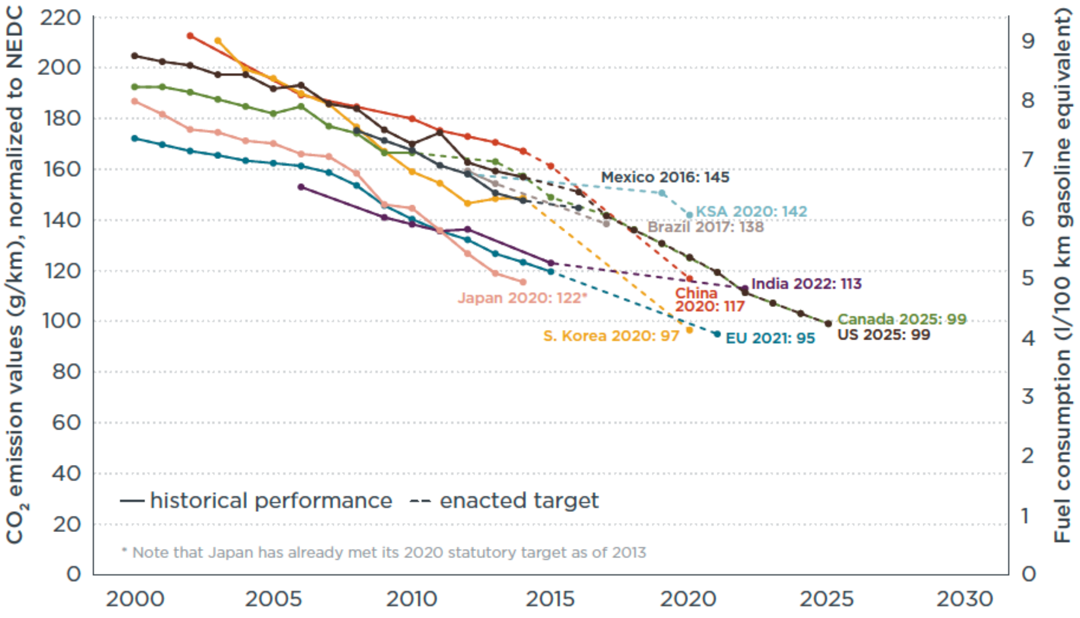


Figure 1.1 Historical fleet CO2 emissions performance and current standards (g/km normalized to NEDC) for passenger cars [1]

Hybrid Electric Vehicles (HEV) have become the order of the day in the automotive industry and a lot of research is spent on new hybridization technologies. Mild Hybrid Electric Vehicles (MHEV) with 48-volt (48V) system have recently appeared in the European light-duty vehicle market as 48V mild hybrid would be the first apparent step toward hybrid vehicles. Additionally, the use of this technology is an alternative to the diesel engine vehicles which is plummeting in the industry. Expensive after-treatment systems will be needed to make diesels comply with tougher emissions regulations standards. This introduction of 48V battery system has activated development in this system to perform improved driving performance of the vehicle. Along with assistance to propulsion of the vehicle through motor(s), the high capacity battery is used for an electrically-driven charge air boosting system to deliver improved fuel efficiency values.

1.2 Aim

The aim of this thesis is to integrate an engine model with a vehicle model in a common platform (GT-SUITE) to simulate it in different driving cycles to calculate the vehicle's average fuel consumption. Additionally, a concept evaluation of the next generation 48V MHEV is performed in different driving cycles.

1.3 Demarcations

To limit the scope of this thesis, certain limitations are imposed:

- Focused primarily on engines and a little on vehicle components.
- Details of the vehicles are limited to 4 wheeled Volvo passenger vehicles.
- A standard Volvo engine model along with 48V motor/generator is considered for the MHEV.
- NEDC, WLTP, US06 and RTS95 are the chosen test driving cycles.
- The subsystems that should be considered in the integrated model includes vehicle body, road, environment, transmission, electric motor (EM), 48V battery, vehicle supervisory control strategy, driving cycles with a driver and an engine model

1.4 Specification of issue under investigation

The thesis work will identify the challenges involved in a new simulation methodology in the early phase of engine development. The unification of the vehicle model in GT-SUITE and an engine model in GT-POWER is performed. The task will be to combine the models to work in harmony with each other to yield accurate results on vehicle fuel economy and performance characteristics. With the results of operation of the engine along with the vehicle, the engine can be better developed with required technologies. Moreover, an integrated base model is to be created and documented for future investigation. Additionally, the following questions will be answered in this investigation:

- What are the possibilities of integration of the two models?
- What are the challenges faced during the unification of an engine model with a vehicle model?
- What are the different complexities of engine model that can be integrated with the vehicle model?
- How sensitive is the model to variations?
- What are the weighting factors of different load points at different speeds on the engine map?

- How do cylinder deactivation, battery, motor etc. influence fuel economy and performance of the vehicle?
- How effective do cylinder deactivation and electric launch feature of the vehicle work together and individually?

1.5 Literature survey

There are three main modelling approaches that can be used to estimate fuel consumption and pollutant emission of a vehicle model. A scholarly article writes about different levels of modelling and modelling methodologies [2]. With intension of evaluating engine fuel consumption and pollutant emission in different driving conditions, the most commonly used modelling approaches suitable for this application is explained in this article. This article helped in understanding the correct modelling approach used in GT-SUITE for vehicle model simulations. Subsequently, a comparison of different layouts of powertrain technologies used in hybrid electric vehicles is observed from a research paper [3]. The paper concluded with fair comparison of different hybrid concepts to assess the fuel consumption rates, power and energy losses for different driving cycles. This paper is similar to this thesis which examines the different hybrid architectures within a hybrid concept. Furthermore, the benefits and drawbacks of the 48V P2 hybrid technology is studied from a presentation report published by Continental AG [4]. The 48V battery technology has surprisingly picked up over the last few years with all the OEMs researching on different hybrid architectures with these voltage batteries.

The objective of estimating fuel consumption benefits offered by different hybrid technologies is published by the US department of transportation. This report provides valuable insights on the benefits of electric drive powertrains and in particular, the benefits of crank integrated starter generator on the fuel consumption.

1.6 Concept review

Hybrid electric vehicles are understood as vehicles which have a combination of two different sources of energy for propulsion, one of which is electrical energy and the other through fuel energy. Fuel and electrical energy has been the most common hybrid configuration in the automotive industry since many years. To be more precise, HEV is a combination of a conventional Internal Combustion (IC) engine with a battery connected to an electric machine which are both used for propulsion. HEVs can be further divided into different structures which are simplified as will be discussed in the next section.

1.6.1 Hybrid vehicle concepts

1.6.1.1 Series Hybrid Electric Vehicles (SHEV)

In SHEVs, the vehicle is driven by an electric machine directly and not by a conventional combustion engine. The IC engine is used to drive the electric generator which in turn charges the battery that powers an electric motor that propels the vehicle. Under high load requirements, the motor draws energy from the battery as well as the generator. The general structure of series hybrid vehicles with energy flow is shown in Figure 1.2. The electric machine connected to the wheels can generate regenerative energy during braking which is used to charge the battery.

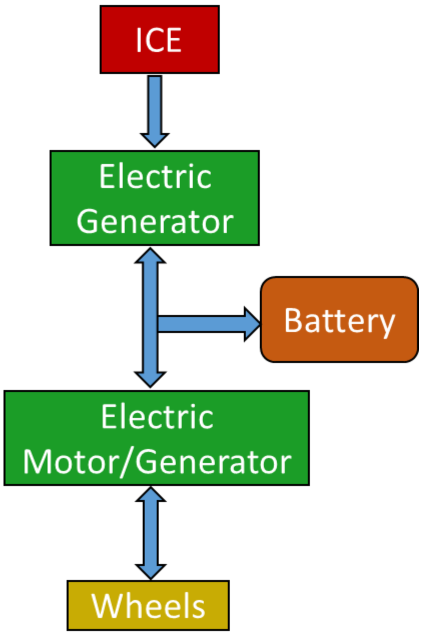


Figure 1.2 Schematic representation of a series hybrid electric vehicle

1.6.1.2 Parallel Hybrid Electric Vehicles

In a parallel hybrid electric vehicle, an IC engine and an electric motor are installed to deliver power in parallel to drive the wheels through a common transmission as shown in Figure 1.3. Since they are connected to a common coupling, they can propel the vehicle using an engine, motor or both together depending on the load demand. Furthermore, the electric machine can be used as a generator to charge the battery by regeneration through braking. This system is a compact system as it requires only two propulsion devices instead of three as in SHEV.

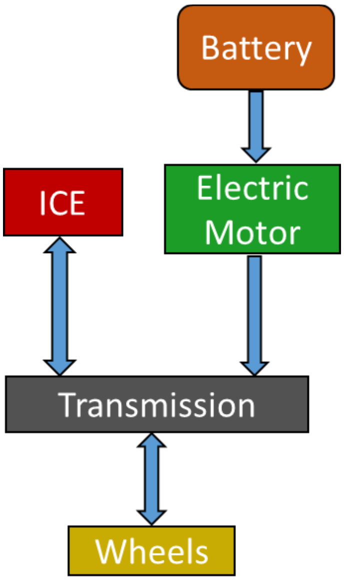


Figure 1.3 Schematic representation of a parallel hybrid electric vehicle.

1.6.1.3 Split hybrid electric vehicles

A split hybrid electric vehicle has both parallel and series features of hybrid electric vehicles. Since series and parallel hybrids tend to be more efficient at low and high speeds, respectively, a combined/split hybrid was introduced to incorporate the best features of both. The vehicle uses a planetary gear set to connect the two drive systems with each having its own controller. An efficient supervisory controller is required for this arrangement to ensure proper functionality of all the subsystems to meet the driver torque demand in the most efficient way. The arrangement of subsystem and their energy flow is shown in Figure 1.4.

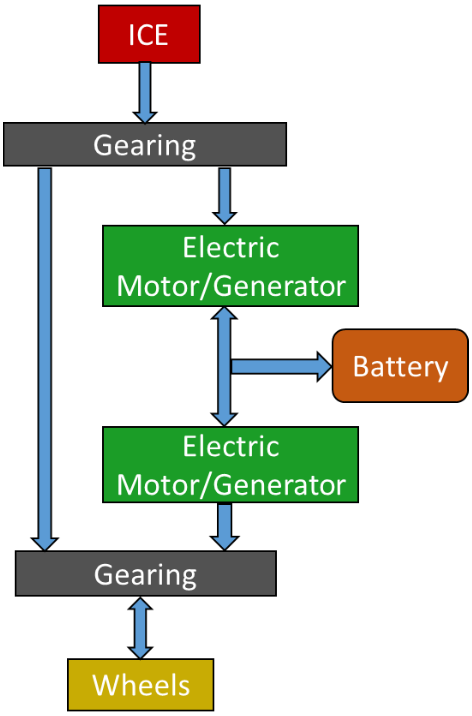


Figure 1.4 Schematic representation of a split hybrid electric vehicle.

1.6.2 Hybrid electric vehicle configuration

Hybrid vehicle configuration, architecture or topology gives us an understanding of the positioning of main components of the hybrid electric system on the vehicle. Figure 1.5 shows the different hybrid electric vehicle configurations arranged on a vehicle layout. Each architecture has its own advantages and disadvantages in terms of fuel economy benefit among other properties. Here, a brief description of the HEV architectures is provided:

- In P0 configuration, the EM is integrated to the crank shaft of the ICE through a belt arrangement. It was most commonly used as a starter generator and to charge the 12V battery system. However, with improved technology, higher power on the P0 is now used to provide stop-start and electric assist features along with 48V battery system. This system is also known as the front end accessory drive (FEAD).
- In P1 configuration, the EM is directly connected to the crank shaft of the ICE which is known as Crank Integrated Starter Generator (CISG).
- In case of P2 configuration, the EM is side-attached between the ICE and the transmission through a belt, chain or gear drive. A clutch is provided between

the motor and the EM, as seen in Figure 1.5, to decouple it from the engine when required.

- In P3, the EM is connected through a gear drive integrated into the transmission to reduce the energy loss to the wheels due to transmission.
- In case of P4 configuration, the EM is connected to the rear axle of the vehicle which is completely decoupled from the engine and transmission.
- In P5 configuration, EM is integrated to the wheel hub to directly drive individual wheels. The EM is also known as hub motors in this case.

In this thesis, evaluation on P0 and P2 configurations of HEV is carried out.

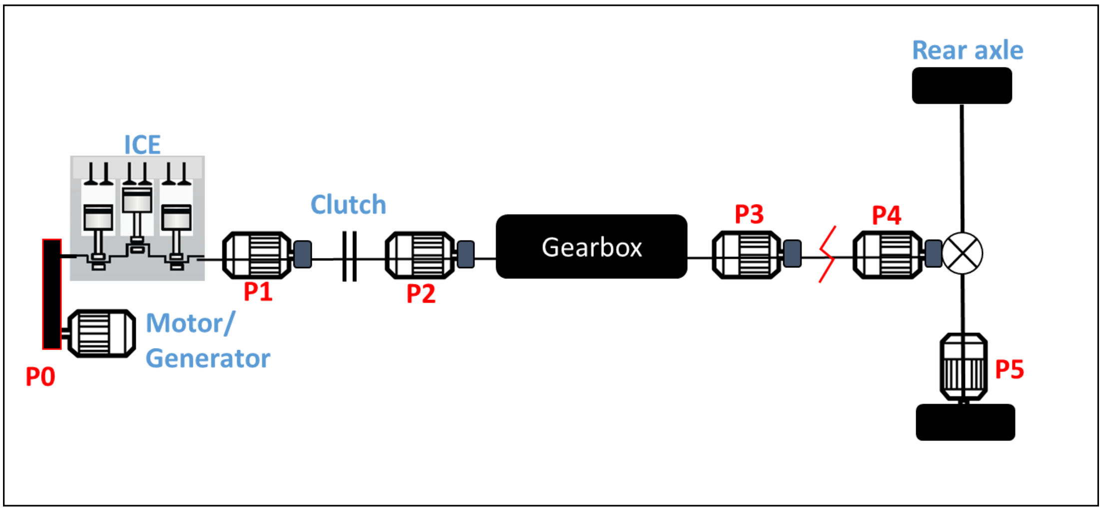


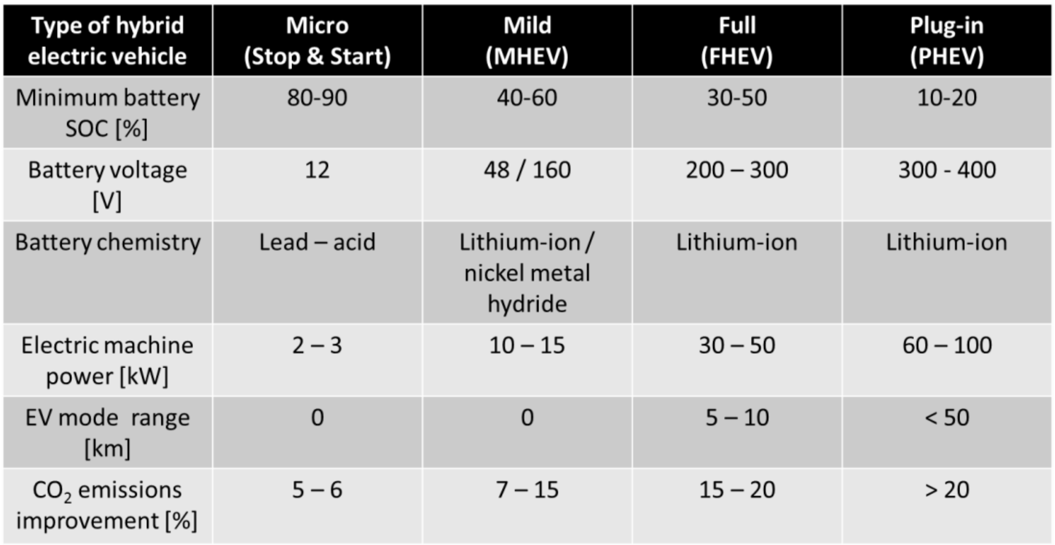
Figure 1.5 Positions of different hybrid vehicle configurations.

1.6.3 Types of hybrid electric vehicle

Hybrid electric vehicles can be divided to four types considering the degree of electrification used as energy source:

- Micro hybrid (Stop/Start)
- Mild Hybrid Electric Vehicle (MHEV)
- Full Hybrid Electric Vehicle (FHEV)
- Plug-in Hybrid Electric Vehicle (PHEV)

Table 1.1 Different types of hybrid electric vehicles and their properties [5]



Type of hybrid electric vehicle	Micro (Stop & Start)	Mild (MHEV)	Full (FHEV)	Plug-in (PHEV)
Minimum battery SOC [%]	80-90	40-60	30-50	10-20
Battery voltage [V]	12	48 / 160	200 – 300	300 - 400
Battery chemistry	Lead – acid	Lithium-ion / nickel metal hydride	Lithium-ion	Lithium-ion
Electric machine power [kW]	2 – 3	10 – 15	30 – 50	60 – 100
EV mode range [km]	0	0	5 – 10	< 50
CO_2 emissions improvement [%]	5 – 6	7 – 15	15 – 20	> 20

In this thesis, the topic of concern is the MHEV in the P2 configuration. The properties of MHEV can be seen from the Table 1.1. Hence, it can be defined as a vehicle with an internal combustion engine, a motor/generator of about 10 to 20 kW, a higher voltage battery of 48V and fuel consumption/CO_2 saving of around 10 to 20%. Along with this definition, MHEV can also be characterised by the position of the EM and the modes (control functions) that the vehicle can be operated. Table 1.2 shows the operating modes of three different types of MHEV. In the table, BISG (Belt Integrated Starter Generator), CISG (Crank Integrated Starter Generator) and TIMG (Transmission Integrated Motor Generator) in a MHEV is displayed with different control functions. The positioning of the electric machine will yield to different possible control functions. TIMG and BISG is reviewed and compared in this thesis. Furthermore, the 48V battery system will be used in this thesis because of its advantages over the 12V battery technology such as, simple integration into an existing vehicle architecture and its ability to deliver power to additional components makes it most cost efficient hybridization solution.

Table 1.2 Different technologies available under MHEVs

Control functions	BISG	CISG	TIMG
Cold engine cranking	No	Yes	Yes
Idle Stop & Start	Yes	Yes	Yes
Moving Stop & Start	Optional	Yes	Yes
Engine load shift	Yes	Yes	Yes
Torque assist (fill)	Yes	Yes	Yes
Torque boost	Yes	Yes	Yes
Sailing / Coasting	Optional	Yes	Yes
Energy recuperation	Yes	Yes	Yes
Brake regeneration	Optional	Yes	Yes
Electric driving / creep	No	No	Optional
External charging	No	No	No

1.7 Vehicle under investigation

The vehicle under consideration with all the subsystems are presented in Table 1.3.

Table 1.3 Vehicle specifications

VEHICLE	**XC60 T5, AWD**
ENGINE	**2.0 Litre, 4-Cylinder** **Gasoline Direct Injection**
TRANSMISSION	**8-Speed Automatic Transmission**
ELECTRIC MACHINE	**TIMG, 21kW**
HYBRID TECHNOLOGY	**MHEV, P2 Configuration**
BATTERY	**48 Volt System**
DRIVER / DRIVE CYCLE	**NEDC, WLTC, US06 & RTS95**

1.8 Drive cycles

As mentioned in the previous subsection, the engine-vehicle model will be run in different driving cycles to assess the difference in engine operation along with the vehicle. Consequently, four driving cycles were used to analyse the vehicle's average fuel consumption i.e. NEDC, WLTC, US06 and RTS95. In this report, results on WLTC and RTS95 drive cycles are used for explanation. However, the results of all drive cycles are also tabulated for comparison.

1.8.1 New European Driving Cycle (NEDC)

NEDC is a driving cycle that represents the typical usage of a light duty passenger vehicles in Europe, which last updated in 1997 and designed to evaluate the fuel economy and emission levels. Conversely, this drive cycle is slowly fading away from the automotive industry due to its unrealistic fuel economy figures. Table 1.4 provides the details of the drive cycle and Figure 1.6 shows the plot of velocity profile.

Table 1.4 Parameters of NEDC [6, 7]

Distance [km]	Duration [s]	Average speed[km/h]	Maximum acceleration [m/s^2]
11.02	1180	33.6	1.04

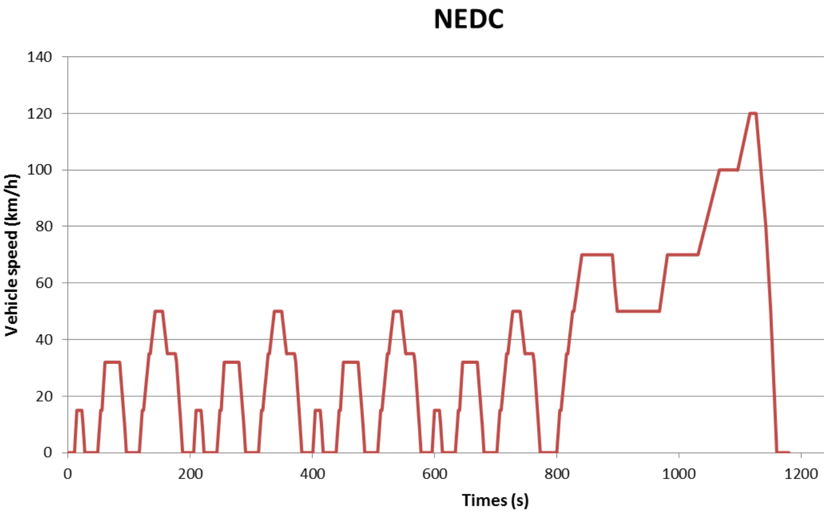


Figure 1.6 Velocity profile of NEDC [7]

1.8.2 Worldwide harmonized Light vehicles Test Cycle (WLTC)

WLTC is a part of World harmonized Light vehicles Test Procedure (WLTP) which was published by the global technical regulation [8]. WLTP outlines many WLTC test cycles which is characterised by different vehicle categories operating in different contrived. NEDC is slowly being replaced by the newly updated driving cycles under WLTP. WLTC class 3 cycle, which is used for vehicles with high power to weight ratios, is used in this thesis. This cycles is widely used in Europe as well as in Japan. Table 1.5 shows the details while Figure 1.7 shows the velocity profile of this drive cycle.

Table 1.5 Parameters of WLTC [8]

Distance [km]	Duration [s]	Average speed[km/h]	Maximum acceleration [m/s^2]
23.26	1800	46.5	1.66

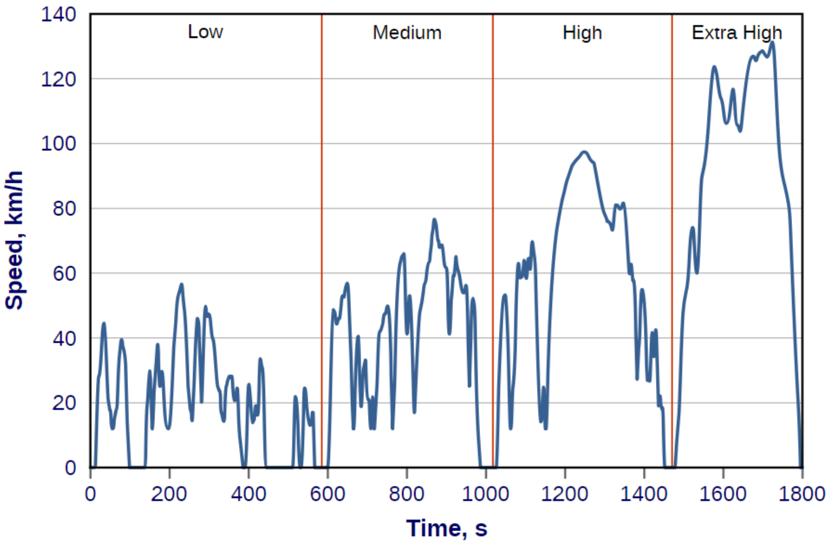


Figure 1.7 Velocity profile of WLTC [8]

1.8.3 US06 Supplemental Federal Test Procedure (S-FTP)

US06 driving cycle, a supplement to the FTP-75, represents high speeds and accelerations. It includes aggressive and rapid speed fluctuations and driving manners immediately post start up. Also, this cycle represents highway driving in the United States of America. Table 1.6 shows the properties of this drive cycle and Figure 1.8 shows the velocity profile.

Table 1.6 Parameters of US06 [9]

Distance [km]	Duration [s]	Average speed[km/h]	Maximum acceleration [m/s^2]
12.86	600	77	3.78

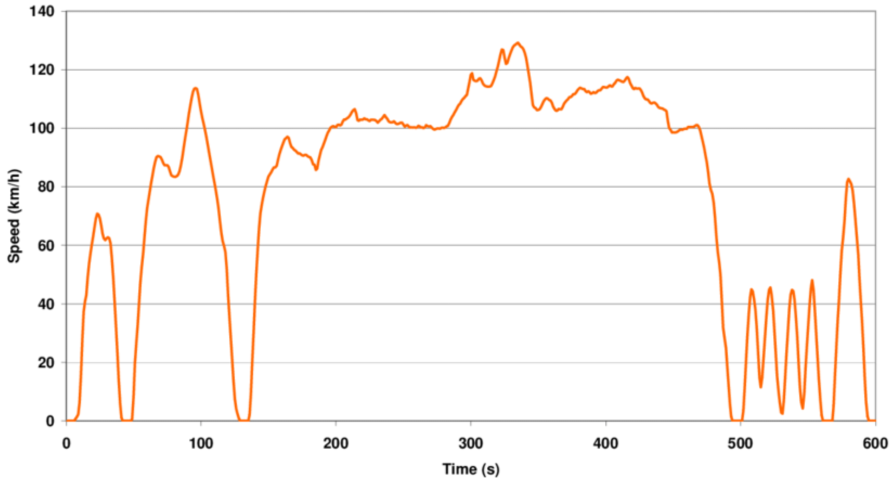


Figure 1.8 Velocity profile of US06 [10]

1.8.4 Standardized Random Test Sequence (RTS95 Aggressive)

RTS95 represents an aggressive driving cycle which includes city, rural and highway driving sections which is mainly used for European real driving emissions (RDE) development. This cycle has been developed completely on WLTP database which demands high acceleration and load on the engine [11]. Table 1.7 provides the properties of this drive cycle and Figure 1.9 shows the velocity profile.

Table 1.7 Parameters of RTS95 [8]

Distance [km]	Duration [s]	Average speed[km/h]	Maximum acceleration [m/s^2]
12.92	886	52.52	2.62

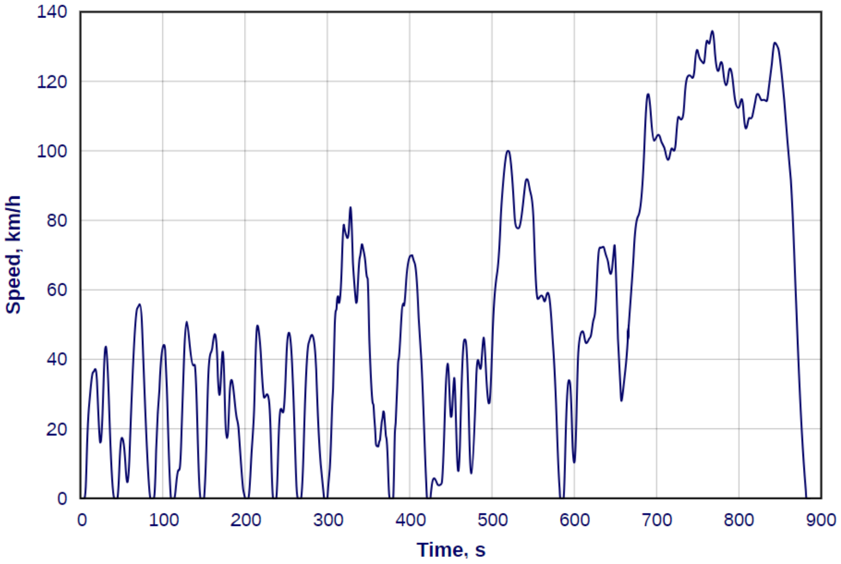


Figure 1.9 Velocity profile of RTS95 [11]

2 METHODOLOGY

2.1 GT-SUITE & GT-POWER

GT-SUITE is a leading software tool developed by Gamma Technologies that allows the user to model and simulate different automotive systems. GT-SUITE, according to Gamma Technologies, is a leading Model Based System Engineering (MBSE) tool which can be used in development and calibration of each subsystem or the entire vehicle development process [12]. It uses a graphical user interface called GT-ISE (Integrated Simulation Environment) that is component/object based modelling methodology. Template of various subsystems are readily available in the software under template library that can be used in the project map. Attributes and specifications corresponding to the vehicle subsystem can be then filled into each template. Hence, by creating all the parts required, one can create any automotive system that can be simulated for various conditions. This software is capable of handling 1D and 3D simulations along with the possibility of fusion of 1D and 3D simulations in one tool.

Furthermore, GT-POWER is a part of GT-SUITE applications under propulsion systems. This software is an engine performance simulation tool used by major engine manufacturers and vehicle OEMs. It also includes highly accurate wave dynamics using Navier-Stokes equations to estimate engine properties such as power, torque, airflow, fuel consumption and turbocharger performance. The method of modelling in GT-POWER remains the same in GT-SUITE using GT-ISE user interface.

2.2 Engine model calibration

A GT-POWER engine model of the 2 litre, 4-cylinder GDI engine having a turbocharger with waste gate was provided by Volvo Cars. The engine model consists of the following subsystems.

- Four cylinders with specific combustion & knock models
- Engine crank train
- Intake & exhaust manifolds
- Intake and exhaust valve train
- Turbo charger with waste gate
- Catalytic converter
- Air induction system and exhaust system

Engine model calibration was carried out from measurement data from the test rig. The reason for calibrating the GT-POWER model is to be able to deliver reliable results for investigations of full load performance and part load fuel consumption with corresponding valve lift profiles, variable cam phaser (VVT) settings, etc. GT-POWER engine model consisted of predictive combustion and knock models in all 4 cylinders at steady state operation. The combustion and knock models are predictive quasi-dimensional models (QDM). These models simulate homogeneous Otto combustion based on energy conservation equations.

The calibration of the entire engine model was carried out for part load as well as full load (Wide Opened Throttle-WOT) conditions. The procedure carried out for each condition is explained in detail in the following subsections.

2.2.1 Full load (WOT)

In case of full load simulation of the engine, the throttle is completely opened (WOT). The focus in this section is to control lambda and waste-gate to match the measurement data. The lambda controller is over ridden by the values from the measurement to assess the resultant torque and Break Specific Mean Effective Pressure (BSFC) values. The waste gate controller is fed with the desired target torque (full load curve from test rig) vs engine speed map for its operation. Along with this, inlet and exhaust valve timings are fixed according to the measurement data in terms of crank angel degree and Friction Mean Effective Pressure (FMEP). Furthermore, the combustion and knock related details are not imposed as it is handled by the predictive combustion and knock models. The values of turbo speed & exhaust temperatures are monitored to lie within their upper limits. Once the model is ready, simulations can be performed to check the difference in resultant torque curve against the measurement data. Additionally, BSFC values from the simulations can also be compared against measurement data to check the engine model's validity.

2.2.2 Part load

Precise modelling of an engine at part load is vital. This can be attributed to making the assumptions for modelling an engine simpler at WOT that may not be binding at part load. The task of simulating many different load/speed points on the engine is discussed in this section. To operate the engine at part load points, the amount of air that is inducted into the engine, i.e. a throttle, is used as a regulator. There are two possibilities for throttled operation in GT-POWER. An orifice is used where the diameter can be controlled or a throttle model which can be used to vary the throttle angle.

For this application, "ControllerThrottle" template (PI controller) is used to adjust the orifice diameter. With this template, the desired throttle angle/orifice diameter based on several physical quantities of the engine including upstream density, pressure and engine speeds is calculated. The engine model is then simulated for specific target BMEP values which is achieved by varying the orifice diameter. Along with the throttle controller, lambda controller (PID controller) is modified to yield fixed measurement data values. "ControllerTurboWG", template is used to target various engine performance parameters in turbocharged applications. At every time step, this controller computes the required waste gate diameter based on the engine and turbocharger system properties. Furthermore, the verification at part load is carried out for all the 4 cylinders by imposing the inlet and exhaust valve timings and FMEP values to achieve the target BMEP. BSFC results from post-processing is tabulated against measurement data from the test bench for verification.

Additionally, for the case of engine with cylinder deactivation, various control templates are used to switch off the fuel supply and retain the inlet and exhaust valves in closed position for two cylinders. The fuel supply through the two functioning fuel injectors are monitored to supply the fuel according to the measurement data from test rig. However, the friction component is considered to remain the same in the model as all other operations inside the engine remains the same.

2.2.3 Engine performance & fuel consumption map

To create map of engine maps, two approaches can be used. The first method is to make calculated guess of some initial throttle diameters that will give the desired Break Mean Effective Pressure (BMEP) in bar. BMEP results can be checked and the throttle can be further varied if necessary. The second method is to use the throttle controller as described in the earlier section. The target BMEP can be set in the controller and accordingly, it determines the required throttle diameter. An arrangement of BMEP target cases can be kept running at every engine speed. Once the throttle diameter values are determined, the controller can be disabled in order to avoid additional simulation time by the controller.

In this thesis, the throttle controller is used to achieve targeted BMEP. Henceforth, the engine model is simulated for different engine speeds and load points. The engine performance & fuel consumption maps that are required by the engine state template in the vehicle model are as follows:

- Map of engine speed (RPM), throttle position and corresponding BMEP (bar) values
- Map of engine speed (RPM), BMEP (bar) and corresponding FMEP (bar) values
- Map of engine speed (RPM), BMEP (bar) and corresponding Break Specific Fuel Consumption - BSFC (g/kW-h) values

2.3 Vehicle modelling in GT-SUITE

In this segment, a complete vehicle is modelled to run in different driving cycles to determine the fuel consumption and performance characteristics of a known vehicle. The vehicle model in GT-SUITE can be seen in Figure 2.1. The vehicle under investigation is Volvo XC60 T5 AWD with 2.0 litre inline 4-cylinder GDI engine. The vehicle modelling in GT-SUITE involves feeding details/values for all the components included in the vehicle. A lot of the data required for various components were found from an online catalogue on Volvo XC60. However, some key information on the gearbox, torque converter, clutch and brakes were acquired from their corresponding departments at Volvo Cars to accurately model the vehicle. The required templates and inputs for the modelling are briefly explained.

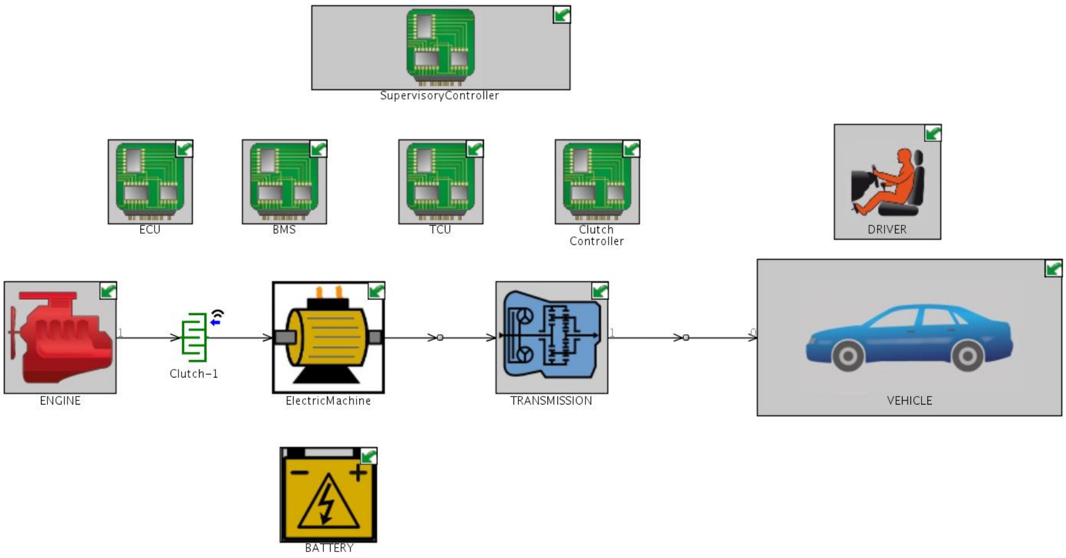


Figure 2.1 Vehicle model in GT-SUITE environment

2.3.1 Engine

The engine block in the vehicle model is a map-based model which requires several engine maps along with engine and fuel specifications. The required engine maps are as follows.

- *Mechanical Output Map:* A map of mechanical output (torque, BMEP or power) as a function of engine speed (RPM) and percent accelerator position (0 - 100%).
- *Engine Friction Map:* A map of engine friction (FMEP) as a function of engine speed (RPM) and engine load (BMEP or torque)
- *Fuel Consumption Map:* A map of brake specific fuel consumption (BSFC) as a function of engine speed (RPM) and engine load (BMEP or torque)

2.3.2 Vehicle

The vehicle template includes a collection of subsystems such as axle, tire, suspension, brakes, differential, propeller shafts, environment and road template. Figure 2.2 shows inside of a vehicle template clearly with all the subsystems.

- ***Vehicle body:*** Includes vehicle mass, cargo mass, vehicle dimensions, axle geometry, drag coefficient and frontal area (aerodynamic drag specification). Furthermore, trailer geometry and mass can be included if the user wishes to analyse such conditions. Inputs for this template was obtained from the vehicle catalogue with the dimensions as seen in Figure 2.3.
- ***Tires:*** Consists of tire traction, rolling resistance and rolling effective radius used in tire connections.
- ***Differentials:*** A locked differential with gear ratio, efficiency and inertia are given as input. Additionally, clutch engagement and initial speed passing conditions for the default on-demand AWD system strategies can be changed depending on the application

- ***Brakes:*** Is a friction model object, which specifies the brake friction characteristics that can generate a friction torque to stop the vehicle

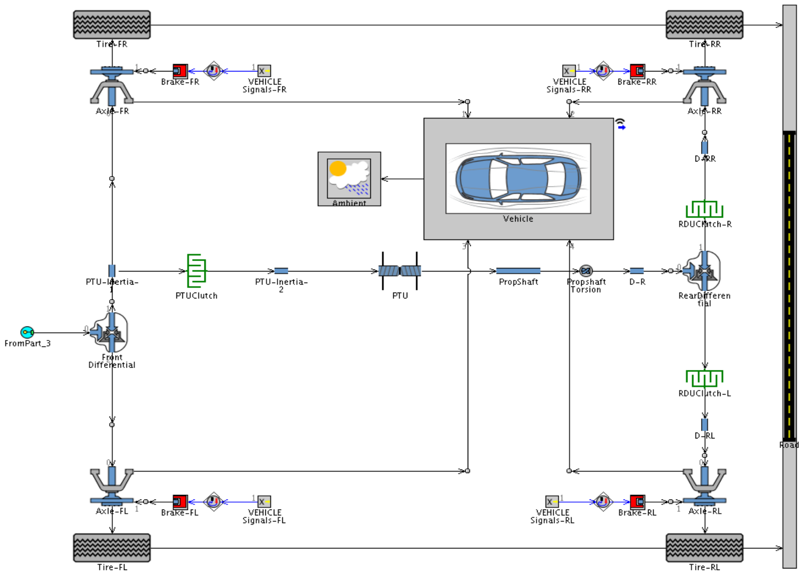


Figure 2.2 Vehicle template in GT-SUITE

- ***Axles:*** Axle moment of inertia including the wheel and tire is given as an input
- ***Road:*** Attributes such as road grade, road traction and other road characteristics can be implemented
- ***Environment/Ambient:*** Environmental characteristics such as air density and climatic conditions can be applied

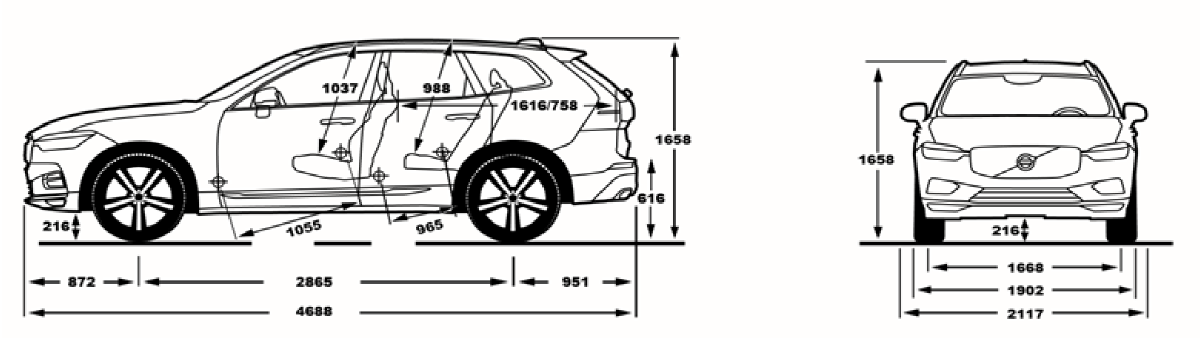


Figure 2.3 External dimensions of Volvo XC60

2.3.3 Driver

The driver template is a speed targeting PID controller that calculates the engine load torque required to target vehicle speed from the driving cycle. The driver template is shown in Figure 2.4. The speed is targeted by controlling the accelerator and brake pedal along with information on engine speed, gear number and evidently the vehicle speed. Driving cycles such as WLTP, NEDC, US06 etc., which have predefined vehicle speed with respect to time, are given as input attributes to the vehicle to follow.

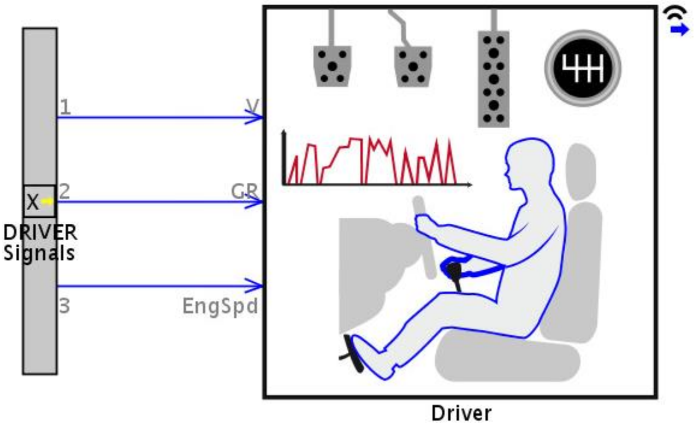


Figure 2.4 Driver template in GT-SUITE

2.3.4 Transmission

The internals of the torque converter includes the gear arrangement, torque converter with lockup and control signals for the gear shifts of the vehicle. Figure 2.5 shows the arrangements of these components. Data on 8-speed automatic transmission were obtained from the transmissions department at Volvo Cars. Gear ratios, in-gear efficiency, friction torque and moments of inertias are given as inputs in the transmission block.

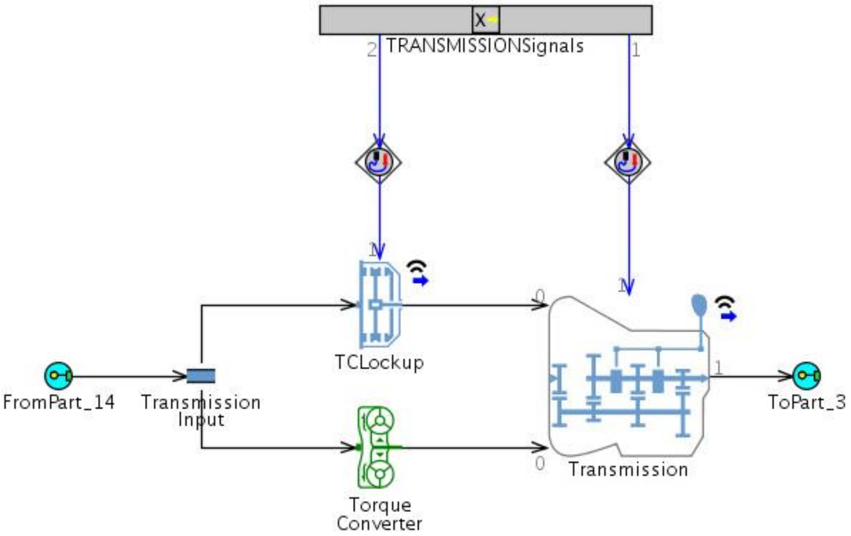


Figure 2.5 Automatic transmission template in GT-SUITE

The torque converter requires few characteristic tables to obtain desired accuracy in the result. The required tables are as follows.

- ***Coefficient of Performance Table:*** This table specifies the converter coefficient of performance as a function of speed ratio. Coefficient of performance is defined as the ratio of the impeller torque to the square of impeller speed of the torque converter. Furthermore, speed ratio is the ratio of turbine speed to impeller speed.
- ***Torque Ratio Table:*** This table specifies the torque ratio of the converter as a function of speed ratio. The torque ratio is the ratio of turbine torque to impeller torque and the speed ratio is as defined in latter section.

Torque converter lockup block is used in parallel with the torque converter to represent the clutch engagement and disengagement during gear shifts. In this work, the maximum static clutch torque and the effective radius of the clutch are entered from the received data.

2.3.5 Electric Machine (EM)

To model electric machines typically used in HEVs, this map-based motor/generator template is used. The model requires maps of electrical-to-mechanical power conversion efficiency and mechanical torque values against different motor speeds. The electrical machine is placed in the P2 configuration (Section 1.6.2) in the driveline and connected to the engine output shaft after the clutch through a chain drive. The chain drive ratio is entered in a simple gear connection template. This simple template requires the ratio shared between the two shafts as well as the efficiency of the system. Figure 2.6 shows the electric machine template along with the gear connection which mimics the chain drive system.

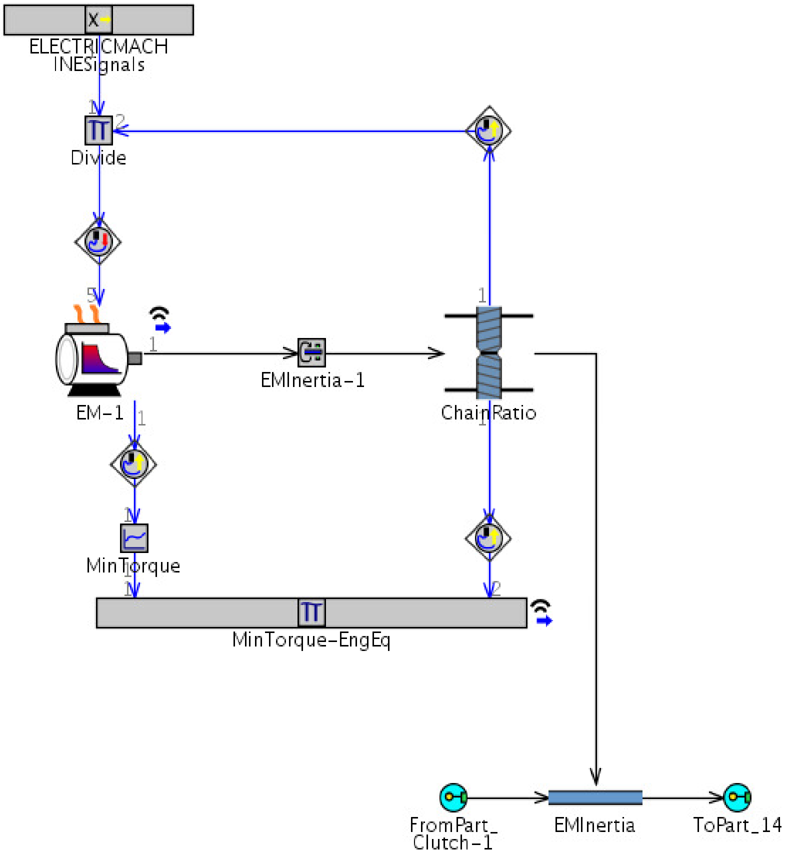


Figure 2.6 Electric machine template in GT-SUITE

2.3.6 Battery

The battery object, as seen in Figure 2.7, defines the parts which can be used to model the electrical battery at a system level without connections to an electrical circuit model. This model works on the principle of State of Charge (SOC). The SOC model includes the following maps of each cell:

- Open circuit voltage map, Charge
- Open circuit voltage map, Discharge
- Internal resistance map, Charge
- Internal resistance map, Discharge

Along with these maps, the number of cells stacked in series as well as in parallel are entered for calculating the full battery capacity. The SOC is calculated based on the power being drawn from the motor or supplied from the generator to the battery. Additionally, the predicted temperature is also used as an independent variable in the maps representing the properties of the battery. Data obtained from the battery manufacturer is used to model this template for accuracy.

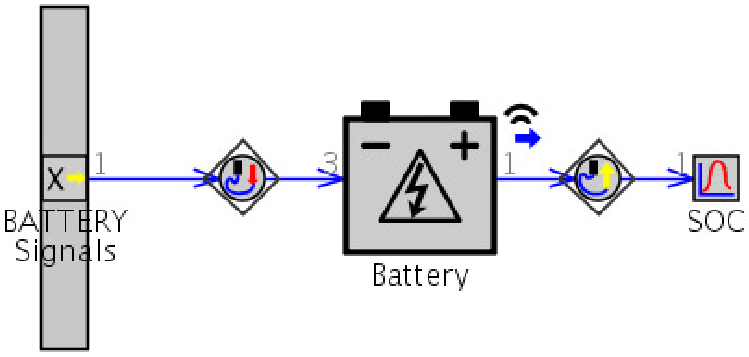


Figure 2.7 Battery template in GT-SUITE

2.3.7 Controllers

Supervisory control is a common term that is used for a controller governing over many individual controllers or control loops. This controller observers over the different controllers' processes at a higher level and helps to control them as intended. It also allows for integration of operations between different controllers and control loops to function in harmony with each other. In GT-SUITE, "FiniteStateManager" (FSM) template is used to supplement with finite state logic to control algorithms. According to Gamma Technologies, FSM is a logic based tool where pre-set modes of vehicle operation can be developed through control algorithms. FSM consists of states, where the different modes of the vehicle at any given time can be entered, and transitions, where conditions for moving from one state to another is set. These transitions are defined using conditional logical operator syntax (e.g. equal to, greater than etc.). In this thesis, along with FSM, a conditional programming model is also used. Multiple conditional statements can be created using 'if', 'then' and 'else' logics. Furthermore, logical operators such as logical "or" and logical "and" are used to set apart the Boolean expressions. Figure 2.8 shows the use of FSM and If-Then-Else templates used to create the control strategy for the MHEV. Within this control strategy, the following control functions/modes are included.

- Idle stop & start
- Idle charging
- Torque boost & assist/fill
- Energy recuperation
- Brake regeneration
- Electric driving/creep
- Charging while driving

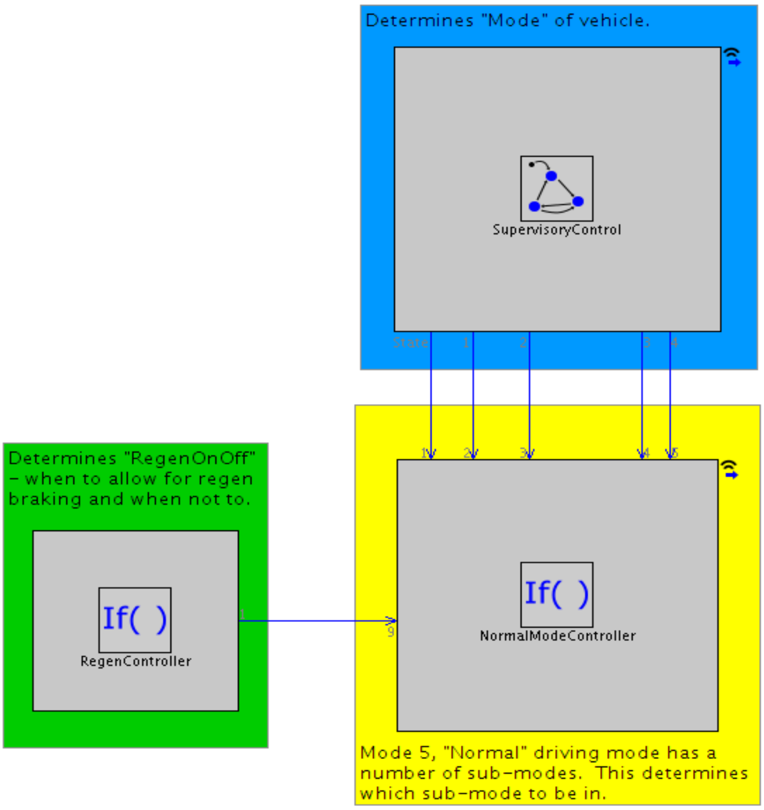


Figure 2.8 Supervisory controller in GT-SUITE

Along with its individual operations, the supervisory controller monitors and integrates the following controllers.

1. ***Engine Control Unit (ECU):*** The ECU is a set of signals that is sent and received from the engine to help manage the combustion process optimally and as required. In the ECU template, driver accelerator pedal position and engine speed control signals are used to govern the engine operation. Also, the ICE controller has basic details such as idle controller and engine shut off speeds for varied applications.
2. ***Transmission Control Unit (TCU):*** The transmission controller is created to provide the shift strategy for upshifting and downshifting of the automatic transmission at different speeds. The shift strategies for Electric Vehicle (EV) mode and Hybrid Electric Vehicle (HEV) modes are created according to the specifications of issue under investigation. Depending on the mode of operation of the vehicle, the final gear number is sent to the transmission template for gear

shift. Additionally, a torque converter lock up controller is used for the lockup strategy that determines the clutch actuator position based on transmission gear number drivetrain speed and lockup state. The internals of the TCU is shown in Figure 2.9.

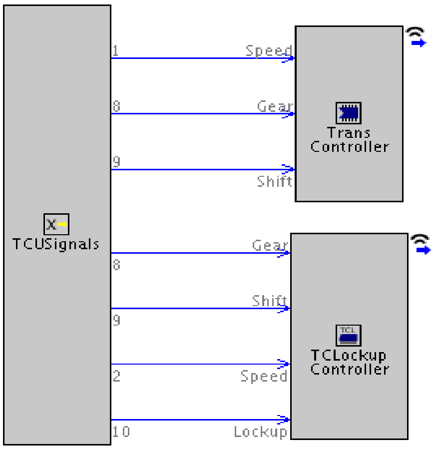


Figure 2.9 Transmission control template

3. ***Battery Controller / Battery Management System (BMS):*** BMS, as seen in Figure 2.10, is a simple PID controller that is modelled to request/deliver power from/to electrical machine based on the State of Charge (SOC) level readings. The SOC level is obtained from the battery template as explained in section 2.3.6. Also, a hysteresis component is used to switch from one value to another depending on the specific threshold. A lower and upper threshold of the battery SOC is specified for its operation. Hence, this component helps in maintaining the battery SOC within the required bracket.

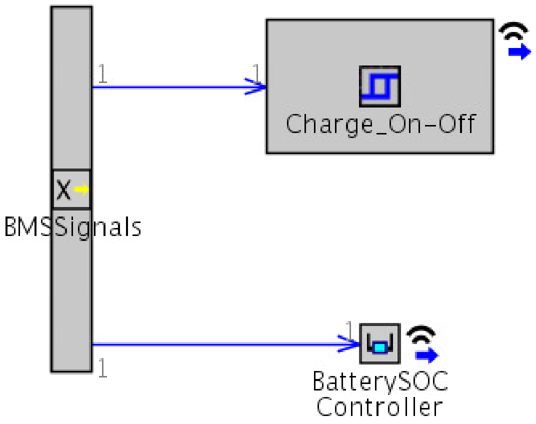


Figure 2.10 Battery management system in GT-SUITE

4. ***Clutch Controller:*** The controller is used to control the engagement and disengagement of the clutch that is located between the engine and motor. This controller consists of a basic logic that assists the clutch to engage during the operation of engine and disengage when the motor alone is running the vehicle. The clutch can also be disengaged during deceleration (regeneration phase) to

eliminate friction of the engine slowing down the engine. Instead, the energy is used by the motor/generator to charge the battery.

3 Results & Discussion

3.1 Engine calibration results

Results of engine calibration and simulations are presented in this section.

3.1.1 Full load comparison

In the case of full load (WOT) condition, the given model was slightly modified with the required controllers to obtain the targeted full load torque. As seen in Figure 3.1, the simulation results match perfectly well with engine test runs from 1800 RPM upwards. At lower engine speeds, the knock model restricts the engine from achieving higher loads. This, however, can be resolved by calibrating the knock model which does not come under the scope of this thesis. Moreover, the disagreement between simulation and measurement data at low engine speed and full load would not critically influence the results of this study.

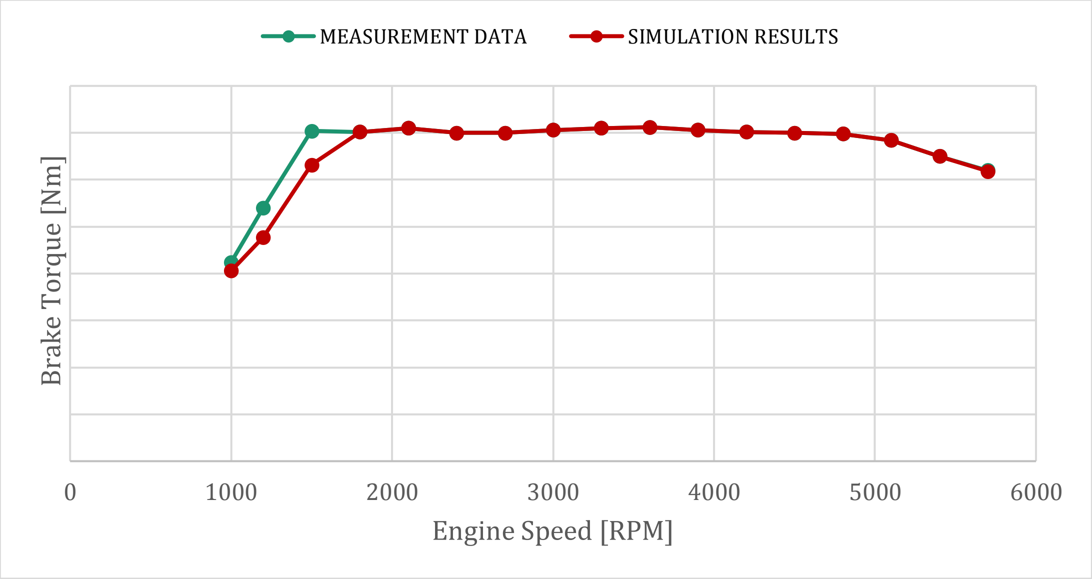


Figure 3.1 WOT torque comparison of simulation results against measurement data

3.1.2 Part load BSFC comparison

For the model to be calibrated in the part load condition, throttle, waste gate and lambda controllers had to be incorporated. The different load points at specific engine speeds from the measurement data are targeted in the waste gate and throttle controllers. Hence, these two controllers operate depending on the target load that is assigned at any particular engine speed. The latest measurement data is used to validate/calibrate lthe engine model for part load. The inlet and exhaust valve timings in terms of crank angel degrees is entered from the measurement data into the model.

The setting up of the model for part load condition is as explained in section 2.2.2. The engine is now simulated to extract the BSFC values in g/kWh. The values from the simulation and the experiment is compared in a chart to assess the level of calibration achieved on the engine model. Under part load condition, there are two discrete calibration processes that are carried out.

1. Part load *without* cylinder deactivation
2. Part load *with* cylinder deactivation

For the part load without cylinder deactivation, Figure 3.2 shows a chart of BSFC comparison of simulation results against measurement data. The equation used to calculate the difference is described below.

$$BSFC\ comparison\ [\%] = \frac{Simulation\ results - Measurement\ data}{Measurement\ data} * 100$$

As one would expect, the positive value in the chart denotes that the simulation results are overestimating the measurement value and vice versa. Among all the points, we observe that the maximum discrepancy is 4.9% at 1000 rpm 4 bar and an averaged absolute discrepancy of about 1.2%. At this point, engine calibration with a discrepancy of less than 2% represents a decently calibrated engine model. Moreover, this thesis does not demand for a calibration with least discrepancy. With this engine calibration at full load, the next step is to calibrate the model at part load with cylinder deactivation.

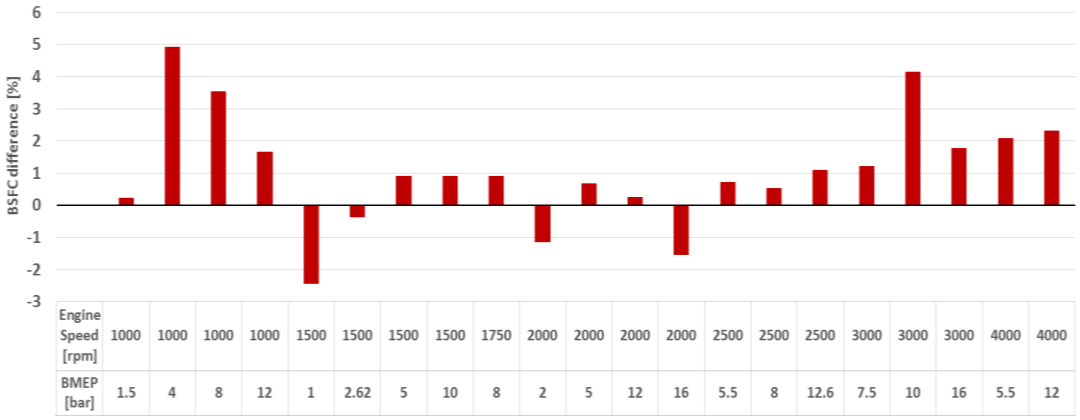


Figure 3.2 BSFC comparison of engine <u>without</u> cylinder deactivation of simulation results against measurement data

Part load with cylinder deactivation requires the model to be modified as explained in section 2.2.2. This modified engine model is simulated for its corresponding measurement data. Figure 3.3 shows the chart of BSFC comparison of simulation results against measurement data for the engine in cylinder deactivation condition. The calculation of difference is performed using the equation mentioned above. Hence, a positive discrepancy indicates that simulation results are higher than measurement data. In this analysis, a maximum discrepancy of 4.2% at 1000 rpm 1.5 bar and an averaged absolute discrepancy of 1.8% can be observed. Similar to the latter, the averaged absolute discrepancy is within the 2% limit and the engine model is said to be well-calibrated against the measurement data.

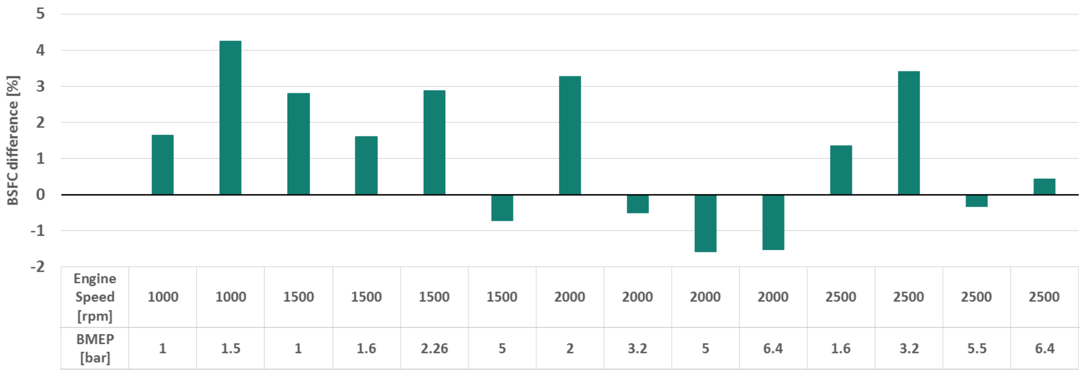


Figure 3.3 BSFC comparison of engine with cylinder deactivation of simulation results against measurement data

3.2 Map based engine with vehicle model

In the previous section, the engine is calibrated and ready for simulations to create the required engine maps to be entered in map based on the engine template in the vehicle model. The engine maps were created by simulating the GT-POWER engine model for multiple load points as explained in section 2.2.3. A total of 120 different engine speed and load points were chosen to extract the BSFC map. The throttle and waste gate controllers were made to target the different engine load points. Hence, they operated depending on the engine loads at different engine speeds. The lambda was entered manually for full load and part load conditions from the measurement data. Furthermore, a map of valve timings is created using the full load and part load measurement data from the test bench.

The next step is to simulate the unified model of engine with vehicle for different conditions to record and assess the results. Thus, in this section, the results from all the different vehicle simulations are explained along with their results.

3.2.1 Reference vehicle

Initially, a reference vehicle is chosen to perform a primary simulation and extract fuel consumption values that can be used to all other simulations and cases. The selected reference vehicle is Volvo XC60, AWD, 2.0 litre, 4 cylinder, GDI engine with cylinder deactivation and no electrification (i.e. no Stop-Start)

Once the simulation is completed, a new graphical interphase called GT-POST is used to view and handle the results. Figure 3.4 shows the map of BMEP vs. engine speed along with BSFC contours to represent a typical engine map. The blue colour indicates minimum BSFC values whereas red colour represents highest BSFC values of the engine as seen in the figure. Furthermore, the red dotted line in this figure indicates the minimum BSFC for the spread of engine speeds. The points that can be seen in the figure is the vehicle operating points imposed on this engine map in WLTC driving cycle. These points show the operation of the engine along with the load from the vehicle. To better conceptualisation these points, one can attribute these values to the load that is being calculated at the flywheel of the engine. Whereas the engine load is looked up from the mechanical output map of BMEP vs. engine speed that was entered in the engine state template as explained in section 2.2.3.

Figure 3.5 shows the time distribution of operation of the engine in percentage. The figure depicts the duration of operation and the area of operation of the engine on the engine load map for the unchanged driving cycle, i.e. WLTC. In this figure, for the sake of better perception, BSFC sweet spot of the engine and the full load BMEP curve of the engine are imposed. These are correspondingly indicated in all the subsequent plots of time distribution of engine operation. The colour code represents the time spent in percentage by the engine in that section. Similar to previous figure, blue colour indicates minimum time duration whereas red colour represents highest time duration of engine operation. The reference vehicle in WLTC driving cycle yielded an average fuel consumption of 7.5 l/100 km. With this as a reference value, different parameters are altered to assess the effects on average fuel consumption.

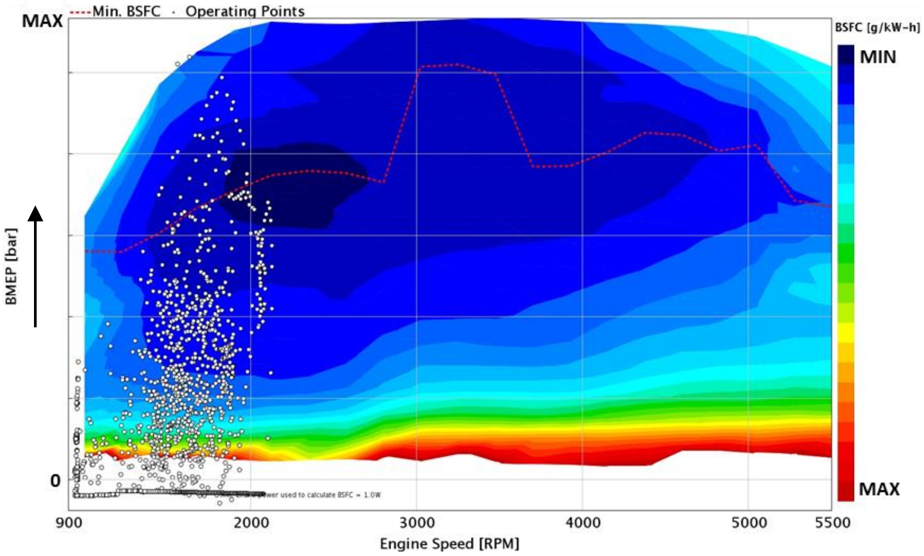


Figure 3.4 Vehicle operating points on engine fuel consumption map in WLTC

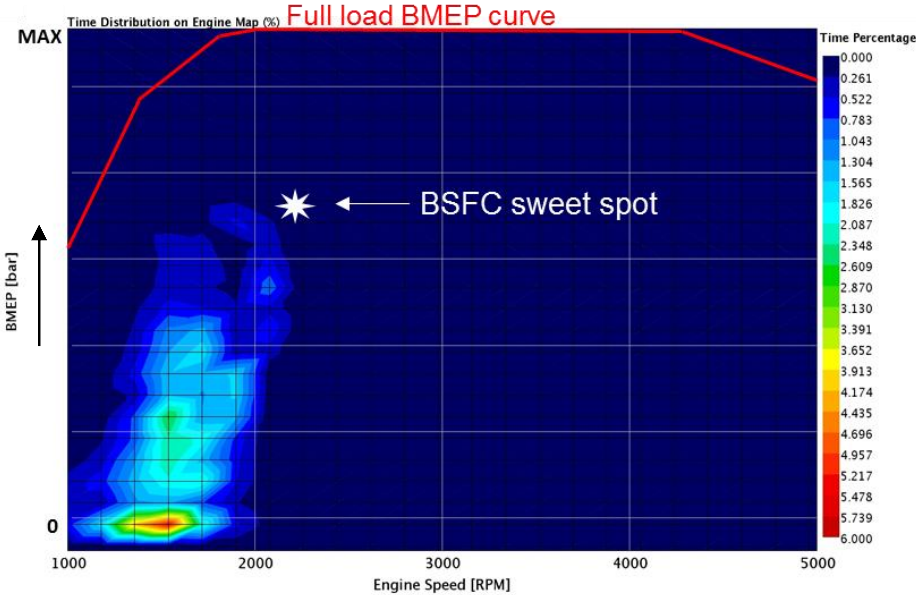
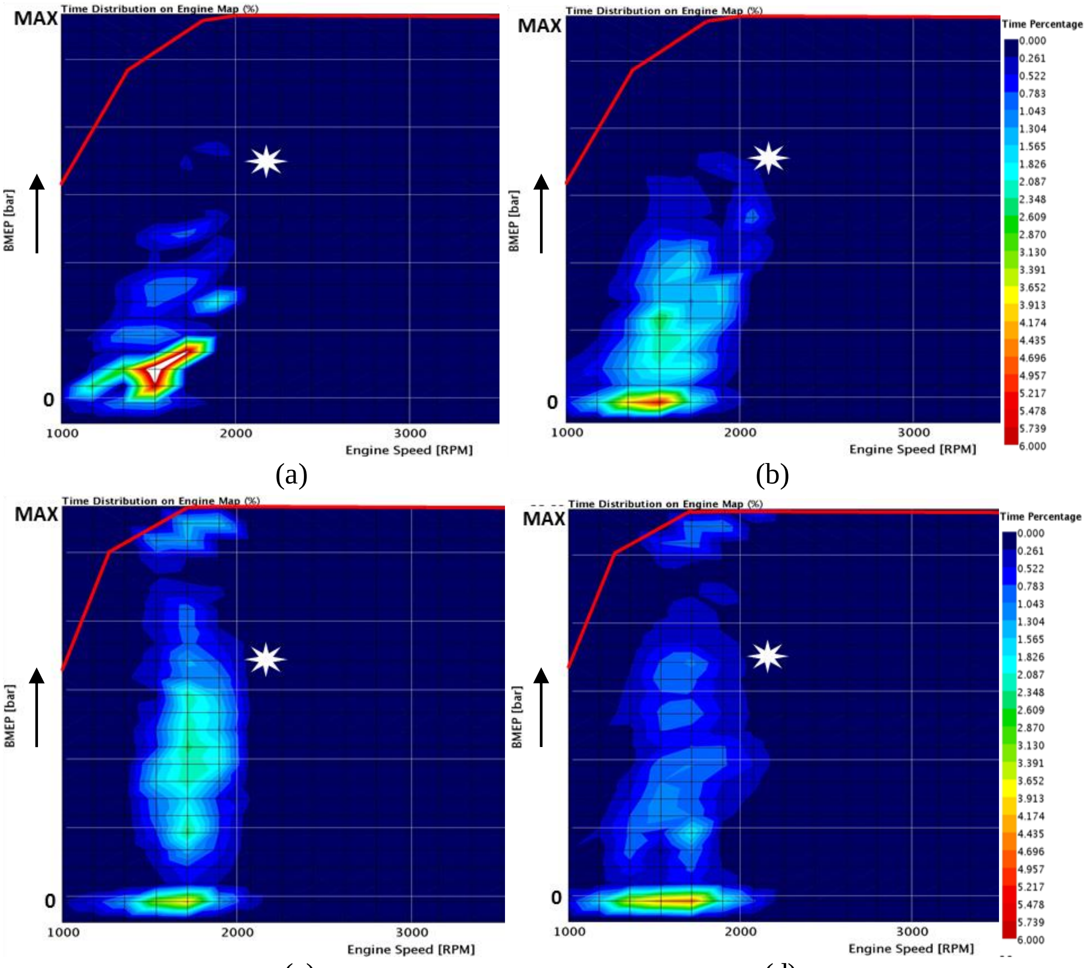


Figure 3.5 Time distribution of engine operation [%]

3.2.2 Reference vehicle in different driving cycles

With the reference average fuel consumption value set, the next step is to vary the driving cycles to evaluate the variations in the average fuel consumption of the vehicle. Figure 3.6 illustrates the time distribution of engine operation (%) for different driving cycles. The image is cropped until 3500 rpm of engine speed for the sake of clear comparison among different driving cycles. The engine operation, as we can see in the figure, lies at low engine speed due to the transmission shifting strategy and hence allows for the images to be cropped. The average fuel consumption values of the vehicle varies for each of these driving strategies as follows.

a) NEDC: 7.7 l/100 km
b) WLTC: 7.5 l/100 km
c) US06: 8.8 l/100 km
d) RTS95: 10 l/100 km



(a) (b)

(c) (d)

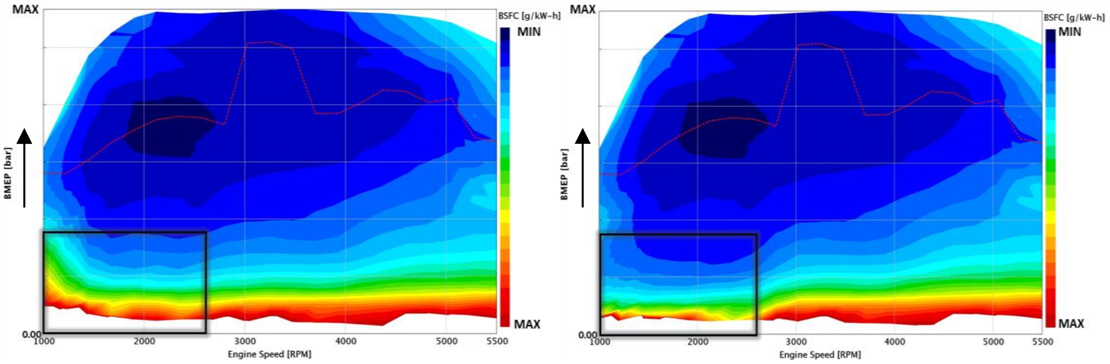
Figure 3.6 Time distribution of engine operation (%) in different driving cycles. (a) NEDC (b) WLTC (c) US06 (d) RTS95 Sensitivity analysis

With the reference vehicle simulated for different driving cycles, the values for each condition are recorded. In this study, the aim is to analyse the sensitivity of the model to different sub-system models in the vehicle. The cylinder deactivation on the engine, electric machine and transmission are evaluated in this section.

3.2.3 Cylinder deactivation

In this section, the impact of cylinder deactivation in the engine block on the fuel economy of the vehicle is analysed. Figure 3.7 shows the BSFC contour map of the engine without and with cylinder deactivation feature. As one can observe, the map more or less remains the same for both the conditions. However, in the area of low engine speed and low load condition (i.e. the highlighted region) there is a shift in the BSFC values, which leads to higher engine efficiency. It is quite clear from Figure 3.6 that there is a large portion of the engine operation points lying within the highlighted region as illustrated in Figure 3.7. However, please note that switching time and loss between these two modes are not considered; Additionally, there are some other limitation to utilize cylinder deactivation like NVH issue which are not included in the model. In this way, WLTC driving cycle is influenced meaningfully:

a) Engine <u>without</u> cylinder deactivation in WLTC: 8 l/100km
b) Engine <u>with</u> cylinder deactivation in WLTC: 7.5 l /100km



(a) (b)

Figure 3.7 BSFC contour map of the engine (a) without cylinder deactivation & (b) with cylinder deactivation

3.2.4 Electrical machine (EM)

The next step in the sensitivity analysis is to use the electric machine to assess its impact on the fuel consumption. Executing this leads to the requirement of a control strategy for the operation of the electric machine. Figure 3.8 depicts the control strategy of the electric machine. This has an electric launch/electric vehicle mode of the vehicle of up to 20 km/h and low torque demand condition. In steady state condition, the EM provides an electric torque assist. Additionally, in transient conditions of vehicle operation, the EM provides higher electric torque assist. This strategy is carefully incorporated into the supervisory controller as mentioned in section 2.3.7.

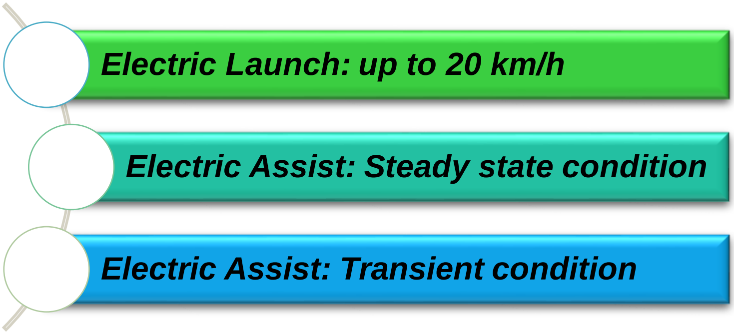


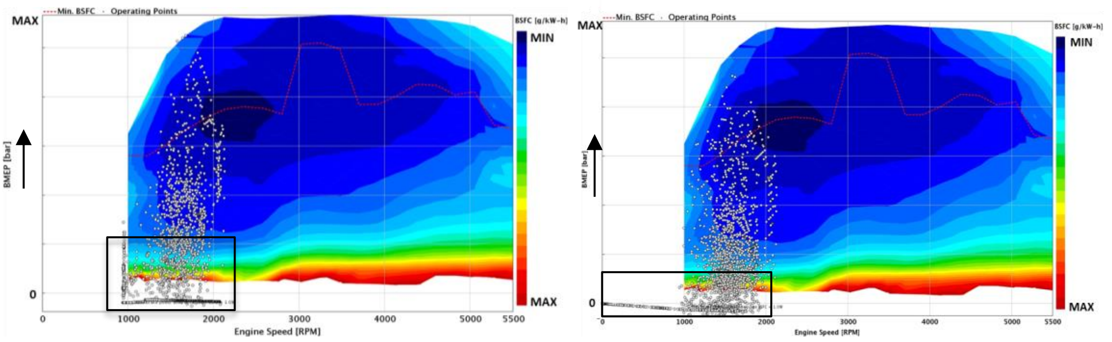
Figure 3.8 Control description of the electric machine

3.2.4.1 Observations in WLTC

To assess the impact of adding an electric machine with aforementioned control strategy, the vehicle was simulated in WLTC driving cycle and compared with the reference vehicle. In Figure 3.9 the vehicle operating points on the BSFC contour map of the engine without electrification in (a) and with electrification in (b) can be observed. The highlighted region in (a) represents the vehicle operation when the engine is idling. This, however, is completely removed in the presence of electric machine and pushed to engine off condition as seen in (b).

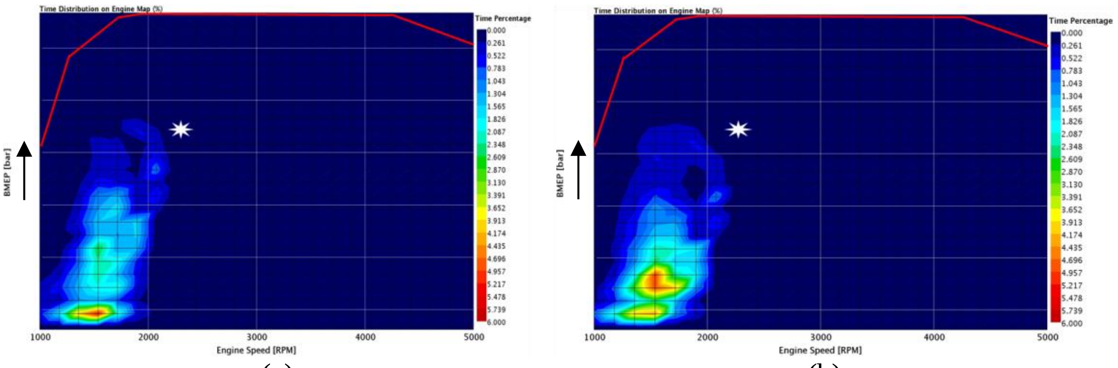
Figure 3.10 depicts the engine load & duration of operation in WLTC driving cycle with & without electrification. It can be seen in (b) that the engine operation is pushed up to a higher, more efficient region of the engine as compared to (a). This illustrates the use of electric machine at low load and low engine speeds for electric launch feature of up to 20km/h. The average fuel consumption is as follows,

a) Vehicle model without electrification in WLTC: 7.5 l/100 km
b) Vehicle model with electrification in WLTC: 6.9 l/100 km



(a) (b)

Figure 3.9 Vehicle operating points on the engine map in WLTC (a) without electrification (b) with electrification



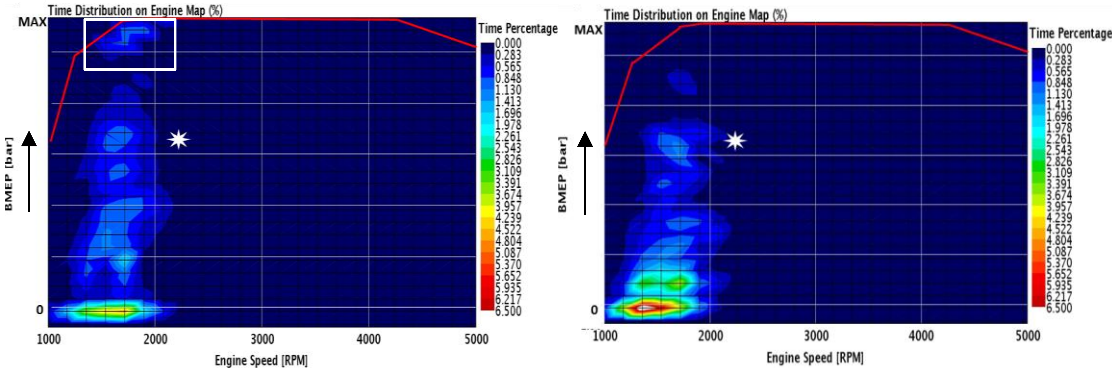
(a) (b)

Figure 3.10 Time distribution of engine operation (%) in WLTC (a) without electrification (b) with electrification

3.2.4.2 Observation in RTS95

An aggressive driving cycle is chosen to evaluate the function of transient assist feature of the electric machine. In an aggressive drive cycle, the engine tends to operate at high load region which is the area of poor BSFC. The region of high load operation of the engine is highlighted in figure 3.11 (a). However, with the addition of the electric machine, these high load region is being substituted by the motor and hence allows the engine to operate in a more efficient region on the engine map as seen in Figure 3.11 (b). This aids in reducing the fuel consumption as follows,

a) Vehicle model without electrification in RTS95: 10 l/100 km
b) Vehicle model with electrification in RTS95: 8.4 l/100 km



(a) (b)

Figure 3.11 Time distribution of engine operation (%) in RTS95 (a) without electrification (b) with electrification

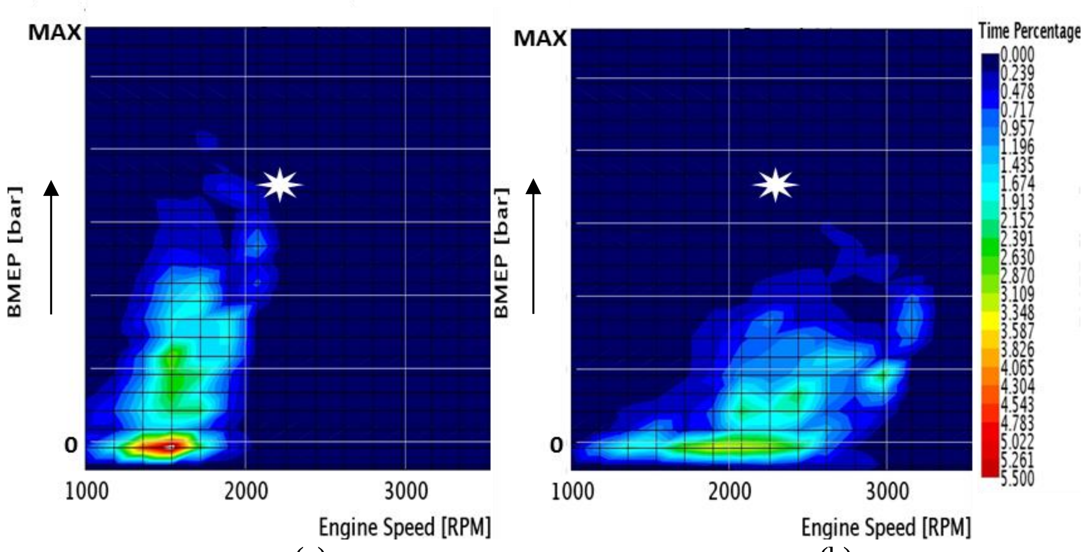
3.2.5 Transmission gear shift strategy

Next stage in sensitivity analysis is to vary the parameters in the transmission template. While retaining all the transmission model characteristics; the shifting strategy with respect to the vehicle speed is varied to assess the difference in fuel consumption of the vehicle. The preliminary shifting strategy was received from the transmission department at Volvo Cars. To study the sensitivity of the model to change in transmission shifting strategy, a rough estimate of an aggressive shifting strategy is implemented.

3.2.5.1 Observations in WLTC

In this section, the assessment of the vehicle model for the different shifting strategies in WLTC driving cycle is performed. Figure 3.12 shows the time distribution of engine operation (%) in WLTC driving cycle of the vehicle without electrification (reference vehicle). With the aggressive shifting strategy as seen in (b), the engine operates through higher engine speeds instead of using high load at low engine speeds as seen in (a). This aggressive shifting strategy leads to an increase in fuel consumption as follows,

a) Reference vehicle model with Volvo shifting strategy in WLTC: 7.5 l/100 km
b) Reference vehicle model with aggressive shifting strategy in WLTC: 8 l/100 km

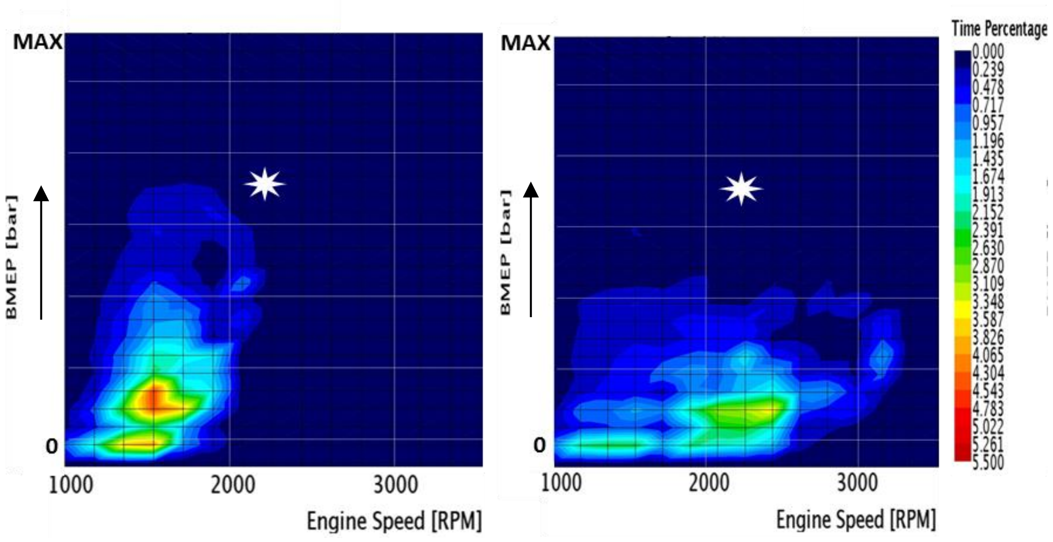


(a) (b)

Figure 3.12 Time distribution of engine operation (%) of vehicle without electrification (reference vehicle) in WLTC (a) with Volvo shifting strategy (b) with aggressive shifting strategy (rough estimate)

Figure 3.13 shows the time distribution of engine operation (%) in WLTC driving cycle of the vehicle with electrification. With the aggressive shifting strategy as seen in (b), the engine operates through higher engine speeds instead of using high load at low engine speeds as seen in (a). This study was to analyse if the electrification had an influence on the fuel consumption difference. However, it can be observed that this does not have any major impact. Aggressive shifting strategy once again leads to an increase in fuel consumption by the same amount shown below,

a) Vehicle model with electrification and Volvo shifting strategy in WLTC: 6.9 l/100 km
b) Vehicle model with electrification and aggressive shifting strategy in WLTC: 7.5 l/100km



(a) (b)

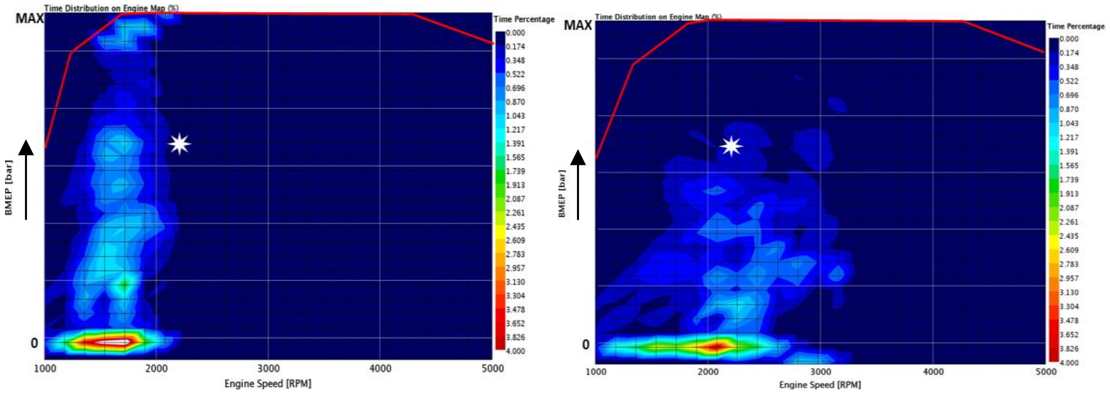
Figure 3.13 Time distribution of engine operation (%) of vehicle with electrification in WLTC (a) with Volvo shifting strategy (b) with aggressive shifting strategy (rough estimate)

3.2.5.2 Observations in RTS95

On the similar lines as the previous section, the model was simulated for an aggressive driving strategy. Figure 3.14 shows the time distribution of engine operation (%) in RTS95 driving cycle for the different transmission shifting strategies. As we can see in Figure 3.14 (b), the engine goes through a higher engine speed than the normal shifting strategy from Volvo. With this change in shifting strategy, the fuel consumption difference is as follows,

a) Reference vehicle model with Volvo shifting strategy in RTS95: 10 l/100 km
b) Reference vehicle model with aggressive shifting strategy in RTS95: 10.3 l/100 km

It can be observed that the difference between the two shifting strategies in RTS95 is 0.2 l/100 km. However, in section 3.2.5.1 we observe the difference between the two shifting strategies is 0.5 l/100 km in WLTC driving cycle. It can be inferred that the aggressive shifting strategy is better suited for an aggressive driving cycle as compared to a less aggressive urban driving cycle such as in WLTC driving cycle.

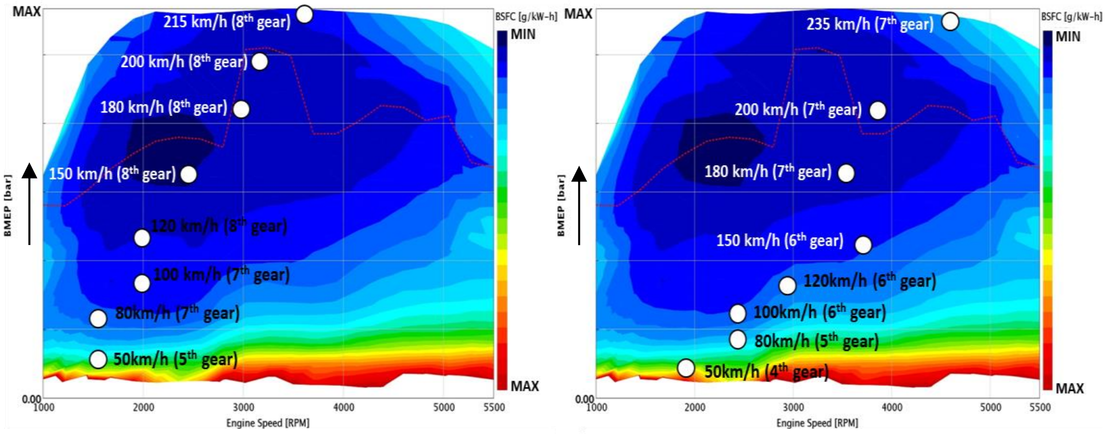


(a) (b)

Figure 3.14 Time distribution of engine operation (%) of vehicle without electrification (reference vehicle) in RTS95 (a) with Volvo shifting strategy (b) with aggressive shifting strategy (rough estimate)

3.3 Vehicle speed points on engine map

In this segment, the engine operation points during constant vehicle speeds are assessed. Various engine speeds ranging from everyday driving speeds to top speed of the vehicle for two different transmission strategy can be observed in Figure 3.15. These plots help in understanding the changes in the region of engine operation on the engine map due to transmission shifting strategy. In addition, this supports the early phase of engine development to optimise the engine operation in coordination with the transmission shift strategy. A table of all the vehicle speeds, transmission gear used and the fuel consumption is shown in Table 3.1 for better understanding.



(a) (b)

Figure 3.15 Constant vehicle speed on the engine map (a) in Volvo shifting strategy (b) in Aggressive shifting strategy (rough estimate)

Table 3.1 Fuel consumption for constant vehicle speeds in different transmission shifting strategy

Vehicle speed [km/h]		**Gear number**		**Fuel consumption [l/100km]**	
Volvo shifting strategy	Aggressive shifting (rough estimate)	Volvo shifting strategy	Aggressive shifting (rough estimate)	Volvo shifting strategy	Aggressive shifting (rough estimate)
50	50	5	4	3.7	4.5
80	80	7	5	4.7	5.6
100	100	7	6	5.9	6.2
120	120	8	6	7.4	8.3
150	150	8	6	10	11
180	180	8	7	13.7	13.7
200	200	8	7	16.2	16.5
215 (Top speed)	-	8	-	18.8	-
-	235 (Top speed)	-	7	-	25.5

3.4 Sensitivity analysis

To analyse variations of all the different parameters from the reference vehicle, a bar graph is plotted as shown in Figure 3.16. Different bar colours, as seen in the figure, represents the four driving cycles. The first category corresponds to reference vehicle without cylinder deactivation function. The second category represents the reference vehicle without cylinder deactivation function and in the presence of electric motor with the same aforementioned control strategy. The third category depicts the difference in fuel consumption of the reference vehicle with the addition of 21kW P2 electric machine with the control strategy explained in section 2.3.7. The fourth category shows the effect of including a 10 kW BISG in the P0 configuration on the fuel consumption. The fifth category displays the change in fuel consumption due to a reduction in the mass of the vehicle by 5%. Lastly, the change in fuel consumption due to change in the shape & mass of the vehicle. In this case, vehicle body dimensions is changed from Volvo XC60 to Volvo S60, i.e. from SUV to Sedan.

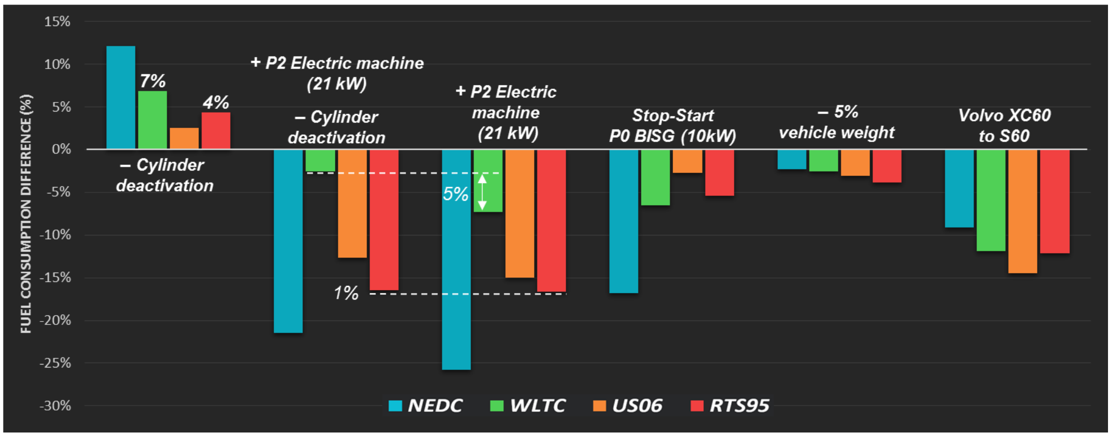


Figure 3.16 Sensitivity analysis to all the altered parameters

A critical observation that can be made is between the first three categories. Taking WLTC drive cycle as a reference cycle, in the third category, the application of electrification (electric machine) reduced the fuel consumption by 8%. Similarly, in the second category, the addition of electrification but removal of cylinder deactivation function from the reference vehicle causes the reduction in fuel consumption by 3%. This indicates that the effect of cylinder deactivation function of the engine in the presence of 21 kW EM (in P2 configuration) is 5% (8-3%). However, considering the first category (no electrification) the removal of cylinder deactivation function from the reference vehicle leads to an increase in fuel consumption by 7%. Hence, one can conclude that the effect of cylinder deactivation in the absence of electrification (7%) is more as compared to the vehicle with electrification (5%) in WLTC driving cycle. This critical observation can also be made for RTS95 driving cycle. Between second and third categories, the difference in fuel consumption is about 1%. This depicts the effect of cylinder deactivation in the presence of EM. Conversely, in the third category, the effect of cylinder deactivation on the fuel consumption is 4%. Once again it can be concluded that the effect of cylinder deactivation in the absence of electrification (4%) is more as compared to the vehicle in the presence of electrification (1%) in RTS95 driving cycle. A similar trend can also be observed in other driving cycles.

To the reference vehicle, a 10 kW 48 V BISG with a control strategy to provide stop-start feature is included in the model to evaluate its effect on fuel consumption. The impact of this feature is low in case of aggressive driving cycle such as US06 and RTS95 as we can see in Figure 3.16. However, the effect of assist feature in the 21kW EM plays a major role in reducing fuel consumption in aggressive driving cycles. Fuel saving in WLTC driving cycle is primarily due to stop-start feature. This can be noticed in the figure when compared to the third category. Lastly, the stop-start feature has a huge contribution in NEDC of about 12%. The higher fuel saving in NEDC is observed by the 21kW EM due to its electric launch feature which is well-matched to its low speed profile. Furthermore, the reduction of vehicle's weight by 5% leads to an improvement in fuel efficiency in all the driving cycle with a maximum contribution in RTS95.

As a last assessment, the vehicle is changed from the SUV to the sedan by retaining all the vehicle specifications but changing the vehicle's body shape and mass. Hence, this reduction in fuel consumption shows the effect of aerodynamic drag and weight of the vehicle on the average fuel consumption.

To finish, the fuel consumption and mass of CO_2 (g/km) values for different vehicle configurations are recorded. Table 3.2 describes the fuel consumption in L/100km and the mass of CO_2 g/km for different vehicle configurations that were explained in the latter subsections. The green highlight depicts the reference vehicle with cylinder deactivation feature of engine and 21kW EM connected in P2 configuration which produces least fuel consumption and CO_2 g/km emission.

Table 3.2 Fuel consumption in L/100 km and g CO_2/km for different vehicle configurations

Engine & vehicle / Driving cycle				NEDC		WLTC		US06		RTS95	
Engine (& vehicle)	Motor	Drive	Vehicle weight	L/100 km	g/km CO_2	L/100 km	g/km CO_2	L/100 km	g/km CO_2	L/100 km	g/km CO_2
With cylinder deactivation (reference vehicle)	No	AWD	1900	7.7	178.2	7.5	173.8	8.8	204.6	10.0	232.0
Without cylinder deactivation	No	AWD	1900	8.6	199.8	8	185.6	9.0	209.7	10.5	242.7
With Cylinder deactivation	21kW TIMG	AWD	1925	5.7	132.2	6.9	160.1	7.5	174.0	8.4	194.9
Without cylinder deactivation	21kW TIMG	AWD	1925	6	139.2	7.4	171.7	7.7	178.6	8.7	201.8
With Cylinder deactivation	10kW BISG	AWD	1915	6.4	148.3	7	162.4	8.6	199.1	9.5	220.9
With Cylinder deactivation	No	AWD	1800	7.5	174.0	7.3	169.4	8.5	198.4	9.7	226.0
With Cylinder deactivation, S60 (sedan)	No	FWD	1700	7.0	161.9	6.6	153.1	7.5	174.9	8.8	204.4
With Cylinder deactivation, Aggressive gear shifting	No	AWD	1900	8.1	188.9	8.1	187.0	9.1	210.2	10.3	238.3

3.5 Vehicle energy consumption

In GT-POST, the energy consumption of all the different components of the vehicle apart from the engine and electric machine can be extracted. Figure 3.17 shows the energy loss in each subsystem of the vehicle for different driving cycles in one of the vehicle configurations. In all the driving cycles, the aerodynamic drag, tires and brakes are the maximum contributors of the vehicle's total energy loss due to subsystems. Torque converter and differentials also play significant roles in the energy losses of the system.

To assess the energy loss of the engine and electric machine, Figure 3.18 can be observed. This bar graph displays the energy depletion due to fuel consumption by the engine and due to battery used by the motor for different driving cycles. The energy depletion is highest in WLTP/WLTC driving cycle because it is the longest driving cycle and least in NEDC due to its low speed profile.

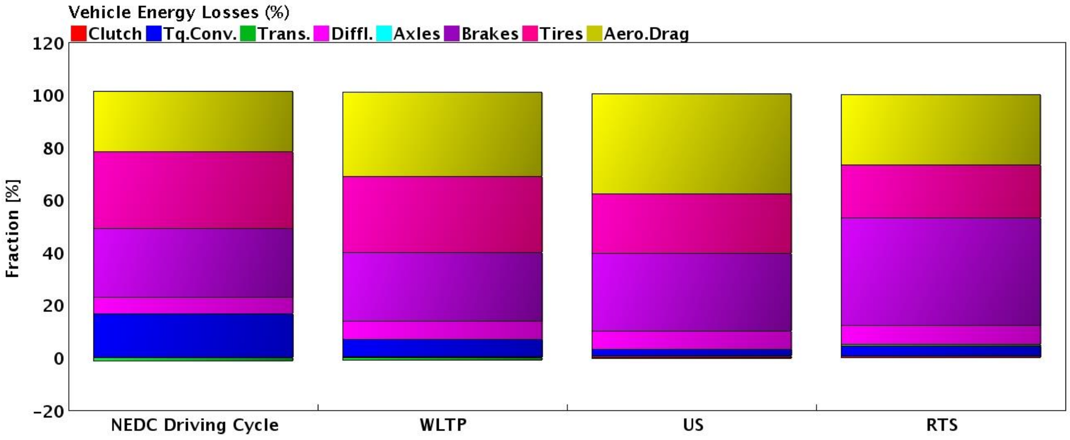


Figure 3.17 Vehicle components energy consumption

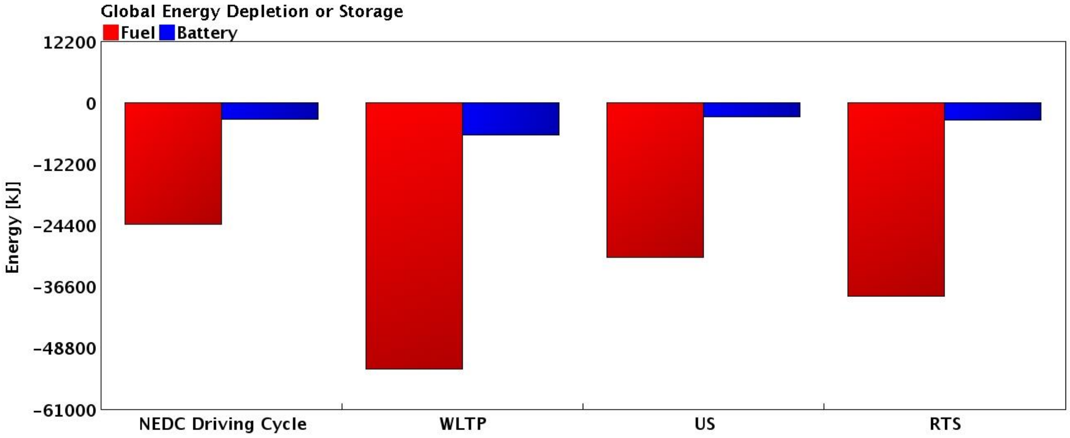
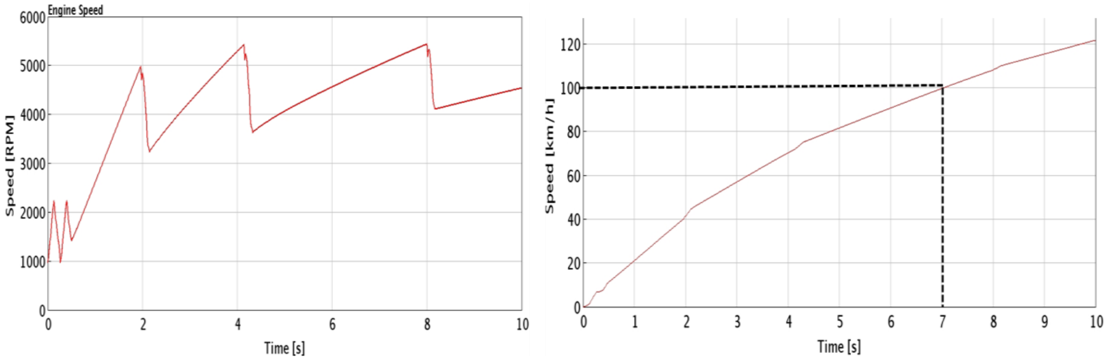


Figure 3.18 Energy consumption by engine and electric motor

3.6 Performance test

An acceleration test of the reference vehicle (i.e. without the EM) is performed. The simulation is conducted to check the performance of the map based engine-vehicle model against the measurement data. The result of the wide open throttle acceleration test is compared with the real world value to check the accuracy of the model. The map based engine-vehicle model completes from stand still to 100 km/h in 7.02 seconds as opposed to the measurement data of 6.95 seconds. Figure3.19 (a) shows the change in the engine speed as the gear shifting occurs throughout the acceleration test and (b) shows the time taken by the vehicle to reach 100km/h.



(a) (b)

Figure 3.19 Acceleration test (a) Engine speed vs. Time (b) Vehicle speed vs. Time

4 Discussion on high-fidelity engine model

GT-SUITE can model engines with different levels of fidelity for different computational times. High fidelity engine models are characterised by crank angel degrees which enable it to capture engine phenomena to a high extent. In an attempt to understand the difficulties and challenges faced in the unification of these two different models, a high-fidelity engine model with high level of discretisation is integrated to the low-fidelity vehicle model. An initial observation between the two models is the two different time steps used in each case. The detailed engine model is a periodic simulation with the model resolved based on crank angle degrees. However, the vehicle model is a continuous simulation with a time step specified in time i.e. seconds in this case. This indicates that upon including the high-fidelity engine model, the results are not tracked with respect to cyclic angles. This greatly reduces the accuracy of simulation. Thus, the high-fidelity engine model fails to keep up with the changes in the drive cycle as seen in Figure 4.1. The figure shows the engine speed comparison between map-based and high-fidelity engine models with the vehicle model simulated in NEDC driving cycle. The computationally demanding high-fidelity engine model may provide high accuracy in engine results, conversely, not suited for vehicle-level simulations with long transient actions.

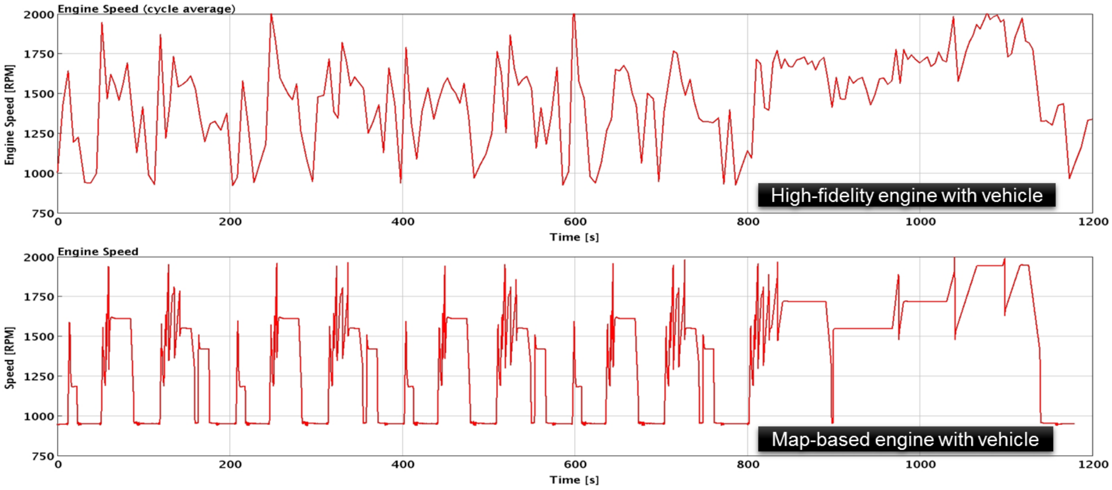


Figure 4.1Engine speed comparison of high-fidelity engine and map-based engine model integrated to vehicle model in NEDC driving cycle

While high-fidelity engine model is most commonly used in engine simulations, they are too slow to be incorporated into system level simulations as explained in the latter paragraph. For the model to run in real time, a Fast Running Model (FRM) of the engine needs to be created [13]. FRM is a fully-physical engine model that is designed to run fast. There is a possibility to convert the existing high-fidelity engine model to a FRM in GT-SUITE, see Figure 4.2. The process of converting high-fidelity to FRM engine model involves simplifying the control volumes to reduce the number of sub volumes and the level of discretisation. The time step for each calculation in simulation can also be increased which reduces the simulation time and also accuracy of the model. This relatively simplified model, however, was not evaluated in this thesis as the accuracy of the results was perceived to be unsatisfactory and the required measurement data were not available on temperature, thermal coefficients and pressure drops on all simplified control volumes.

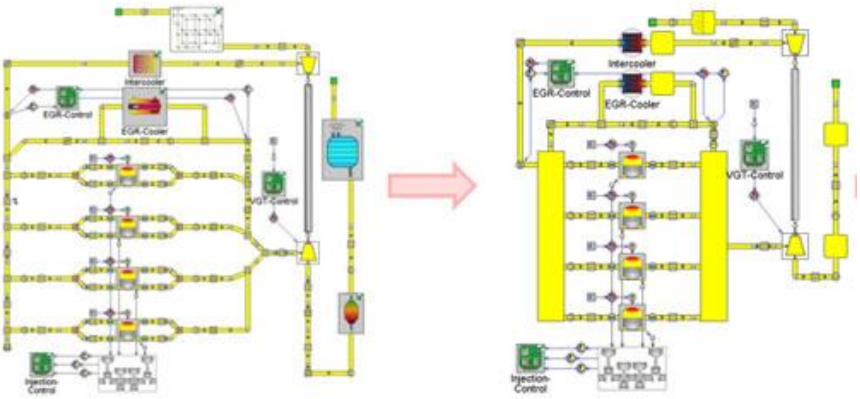


Figure 4.2 Conversion from a detailed to a FRM engine model [14]

Finally, as illustrated in this thesis, a series of engine performance maps that represent the characteristics of an engine were used in the map-based engine template. This template can be linked to other vehicle components and works similar to the latter explanation with the outputs generated as a consequence of speed-load map look-ups [13]. Hence, this allows for very low computational demand with simulations running faster than real time. For better accuracy, the engine maps can be made more detailed to capture all the speed and load values. Integrating this model with vehicle model helps capture vehicle or system level phenomena such as drive cycle analysis and fuel consumption studies as exemplified in this thesis.

5 Conclusions

In this thesis, a method was developed to enable us to integrate an engine with a vehicle with different electrification levels. This is to be used in early phases of engine development when the detailed information of all vehicle sub-systems are not defined. P0 and P2 MHEV concepts with different technologies are evaluated for fuel consumption and performance studies. According to the simulations in which some operating limitations and losses are not considered, the key results are listed as follows.

- On the reference vehicle, removing cylinder deactivation feature from the engine model deteriorates fuel economy in WLTC around 7%.
- Applying EM (21kW) with torque assist and electric launch feature to the reference engine-vehicle model would lead to 8% fuel saving in WLTC.
- Eliminating cylinder deactivation from the engine model while retaining the EM (21 kW) deteriorates fuel economy in WLTC around 5%.
- Hence, the effect of cylinder deactivation is reduced in the presence of the EM. This is due to operation engagement of both the EM and the cylinder deactivation at low load/speed region of the engine map.
- P0 with start-stop influences the fuel consumption meaningfully. The impact of this feature depends on the driving cycle type i.e. based on the speed profile in the cycle. Considering WLTC driving cycle, he 10kW BISG with Start-Stop feature alone results in 7% reduction in fuel consumption while the 21kW TIMG with electric assist and electric launch mode leads to a reduction in fuel consumption by 8%.
- In aggressive driving cycle like RTS95, the benefit of cylinder deactivation is less than that of an urban, less demanding driving cycle like WLTC (4%). However, the benefit of the 21kW TIMG with electric assist and launch modes is much more significant up to 17%.
- In terms of the impact of vehicle weight on fuel consumption, a 5% weight reduction would lead to 3% fuel saving in WLTC.
- Translation from SUV to sedan improves fuel economy by 12% in WLTC. This depicts the impact of aerodynamic drag coupled with vehicle weight on the average fuel consumption of the vehicle.
- The GT-SUITE vehicle model performs a 0 – 100 km/h vehicle acceleration test in 7.02s.

6 Future work

The following issues can be considered for further development of the engine-vehicle model:

- Time to torque (turbo lag) can be incorporated in the integrated engine-vehicle model.
- With the analysis of engine in the early phases of engine development made easy, the effect of other engine technologies can be studied in the integrated engine-vehicle models. The typical examples of possible studies are variable compression ratio (VCR), duel intake cam, variable cam profiles.
- Switching time of cylinder deactivation can be considered in the GT-SUITE engine-vehicle model.
- Fast Running Models (FRMs) of the engine can be included along with the vehicle model which has real time operation capability.
- The supervisory control strategy can be further improved and optimised in GT-SUITE. Additionally, a Simulink harness template can be used in GT-SUITE to directly link existing control functions from Simulink.
- Transient analysis of drive cycle simulations, thermal warm up, cold start and energy loss in the system due to lubrication can be included in the GT-SUITE engine-vehicle model.

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