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Real-world Fuel Economy and Electric Range for a Plug-in Hybrid Electric Vehicle

Master's thesis in Mechanics and Maritime Sciences

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Abstract

One of the key facts which lets the customer decide when purchasing a vehicle is after seeing the facts and figures proclaimed by the manufacturer pertaining to Fuel consumption and/or Electric range. The grounds on which the manufacturer declares these figures are through conducting tests under standardized laboratory conditions. Yet, there are a lot of limitations when conducting such tests under closed conditions which results in a value, may differ from real driving conditions. This is perhaps leading to dissatisfaction of the end user due to the discrepancy in the value stated by the manufacturer and the actual figures achieved by the customer when driving on road. A fact to be acknowledged that several real-world factors which affects the fuel consumption and/or electric range are not being captured under laboratory conditions, which in itself is a limitation. The purpose of this master's thesis work is to map such real-world factors to study their influence on fuel consumption and electric range for a plug-in hybrid electric vehicle.
The study was conducted at CEVT AB, Gothenburg which is an engineering innovation centre within the automotive sector. The primary objective was to list down the factors covered under NEDC, WLTP and RDE driving conditions, and later create a virtual road network using the "CarMaker" tool to replicate a route identified by CEVT which conforms RDE regulation. Further, a PHEV simulation model was developed which represented RDE driving scenario, and a post processing script was written in Python to generate results from the simulation. It was found that the fuel consumption and electric range does vary when the vehicle is driven on real roads due to the influence of factors such as road gradients, electric load from auxiliary devices, driver behavior etc. The impact on electric range was significantly higher during the conditions, (i) When the auxiliary load was increased representing the demand of electrical power from the cabin climate control system at different ambient temperatures, (ii) When the test mass of the vehicle was increased to the maximum recommended limit, (iii) When the vehicle reached higher speeds, $90<V<120$ km/h. Also, the fuel consumption was considerably higher when the vehicle was driven starting with an empty battery(Min. SoC level), since it could not take the advantage of electric powertrain at lower efficiency regions of the combustion engine.

Keywords: Real-world factors, Fuel Consumption, Electric Range, Real Driving Emissions, NEDC, WLTP, Plug-in Hybrid Electric Vehicle

Nomenclature

PHEV:	Plug-in Hybrid Electric Vehicle
FC:	Fuel Consumption
ER:	Electric Range
RDE:	Real Driving Emissions
NEDC:	New European Driving Cycle
WLTP:	Worldwide Harmonized Light-duty Vehicle Test Procedure
SOC:	State of Charge
MT:	Manual Transmission
HV:	High Voltage
LV:	Low Voltage
GPS:	Global Positioning System
F_{aero}:	Aerodynamic drag force [N]
F_{acc}:	Force of acceleration [N]
F_{roll}:	Rolling resistance force [N]
F_{grade}:	Gradient force [N]
P_{tot}:	Total power consumption [W]
ρ_{air} :	Air density $[kg/m^2]$
C_x:	Coefficient of aerodynamic resistance
A:	Vehicle effective frontal area $[m^2]$
v_{car}:	Velocity of the vehicle $[m/s^2]$
$v_{headwind}$:	Velocity at the head wind $[m/s^2]$
a:	Acceleration $[m/s^2]$
C_r:	Rolling resistance coefficient
α :	Inclination angle [degree]
m:	Vehicle operating mass [kg]
g:	Gravitational acceleration $[m/s^2]$

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1
Introduction

1.1 Background

Every car before being introduced to the market undergoes tests on a chassis dynamometer under standardized conditions, for example NEDC (New European Driving Cycle) and WLTP (Worldwide harmonized Light-duty Vehicles Test Procedure), to determine the fuel consumption and electric driving range. However, due to many factors, such as driving style, ambient conditions, road, traffic etc, the fuel consumption and range may significantly vary when a customer is driving his/her car on the road. The motive behind the thesis work is to map the “real world factors” to understand their importance and analyse the impact on fuel consumption and electric range through model build, simulation work, and theoretical studies.

1.2 Purpose & Aim

The purpose of the study is to identify various factors affecting fuel consumption and electric range when the customer is driving on a real road, and emphasize on conducting further research to be in accordance with EU Real Driving Emissions (RDE) driving conditions.

The aim of the thesis work is to assess the increase in fuel Consumption and decrease in the electric Range when these real-world factors are applied to the PHEV simulation model.

1.3 Scope

The scope was well defined and clear right from the commencement of the thesis work which aided in creating a good work flow and develop a time plan accordingly. The scope included, identifying various factors covered under NEDC, WLTP, RDE and other real-world conditions, creating a virtual road network of the RDE route in "CarMaker" tool, and to build a PHEV and traffic model (Pedestrians, lead vehicles) representing a driving scenario according to RDE regulation. Further, a post processing script to be written in "Python" to extract the results from simulation, followed by analyzing the impact from each factor on Fuel Consumption(FC) & Electric Range(ER). Finally, draw conclusions from the obtained results and make some recommendations towards potential area of work in the future.

1.3.1 Factors excluded in the study

Some of the real-world factors which has an effect on fuel consumption and electric range of the vehicle were first listed on the paper. 40 different factors were tabulated and categorized based on, (i) Ambient temperature conditions (Summer>20; Winter<15 Degree Celsius), (ii) Driver dependence, based on On-road usage and Off-road maintenance, (iii) External factors, dependent on road conditions and other factors such as traffic density, Power-steering load etc. Nevertheless, the factors had to be filtered out depending on simulation possibility and model accuracy, the availability of working models, degree of impacts on FC and ER and the factors not covered under RDE driving conditions. So, the following factors mentioned below are the factors excluded from the study.

- **Air density**: The change in air density has an impact on air to fuel ratio (AFR) which consequently impacts on an engine performance[8]. Higher the atmospheric temperature, lesser is the density of air and vice-versa. Both, high and low air density have impact on fuel consumption in an engine since lower air density contains less oxygen and result in incomplete combustion, leading to more fuel consumption per unit power output. Whereas on the other hand with higher air density, having AFR that is too high on the fuel might water down the combustion process creating less heat, and less ideal power. The possibility to simulate this factor at different air densities was the reason for it be excluded in our study.
- **Inlet air temperature** : The density of air varies with temperature as explained before, and hence this factor plays a vital role in the engine performance. The reason for excluding this factor is similar to that of air density.
- **Viscosity of lubricant oil** : It has an indirect effect on FC & ER caused by variation in temperature and also by its ageing. High viscosity of lubricant oil at lower atmospheric temperatures offers less lubrication and creates more friction between sliding parts, which in turn reduces engine performance [9]. On the other hand, very low viscosity of oil offers only a thin lubricating film, thereby creating friction between sliding parts. This study did not consider the ageing of oil and its specification was also not varied.
- **Cold engine**: Fuel consumption is dependent on the operating temperature of an engine. During winter conditions the engine is usually warmed up for achieving a better start, which if not, would result in heat losses and thereby lead to higher FC. An engine model valid for low initial temperatures was necessary to investigate the impact on FC, which unfortunately was not available, therefore excluding this parameter. All the simulations are with an engine initial temperature of 23 degree celsius.
- **Timely replacement of filters(oil, fuel, air)** : Impurities in Fuel, air and lubricant oil affects the performance and life of an engine, thereby having an indirect impact on FC. Hence, filters play an important role in enhancing the performance of an engine by ensuring cleaner air, oil and fuel is entered into the system[10]. The performance of filters at different stages was not considered in our study.
- **Power-steering load**: There are different types of power steering systems such as Hydraulic Power-Assisted Steering (HPAS) and Electric Power-Assisted

Steering. But, HPAS consumes more fuel as the hydraulic pump is constantly driven by the engine, even at times when the vehicle is not steered. Recent studies have shown that EPAS consumes 90% less fuel when compared to HPAS since the electrical energy is demanded from the electric motor only during steering conditions. It was also considered to be negligible since the steering input accounts to a very small part of the total driving time. In an event of parking maneuvers, the steering loads are observed to be highest with high steering wheel input at low vehicle speeds, which does not include in our work. Therefore, it was decided to exclude this parameter from our study.

- **Driving with windows open**: Although driving with windows open increase the aerodynamic drag on the vehicle reducing its ER and increase in FC [11], it is quite uncommon with the drivers in the European region. This is due to the presence of cabin climate control system. Hence it was decided to exclude this parameter from the study.
- **Windy conditions**: The aerodynamic drag has a significant impact on FC & ER since it offers resistance to the vehicle motion, and it increases with increase in vehicle speed. Although it was found that the wind speed in the Gothenburg region is between 1.5 - 7.6 m/s, there were challenges in finding the data related to wind direction and wind distribution at different road segments. Though it was possible to be modeled in the simulation, the level of accuracy was still questioned which leaded to exclusion of this factor.
- **Fuel type (Quality and energy content)** : Quality of fuel refers to a degree of contaminants found in the liquid, and therefore has an influence on engine performance. The energy content may also vary depending on the change in temperature and the content of commercial fuel (Example: Ethanol Blend), since it has an affect on amount of fuel per unit volume. In this work, the variation in the quality of fuel at different gas stations and its energy content at varying temperatures were not considered. So, this parameter was disregarded.
- **Trailer load**: Any additional load on the vehicle leads to higher demand of torque on the wheel, thereby increasing the fuel consumption or decrease in electric range. This factor was not included in the study as it is a rare scenario and the model was not developed for this particular case.
- **Battery charging habits** : It is a driver dependent factor which leads to a large scope of work, and hence this was not considered to be a part of the study.

1.3.2 Factors included in the study

Depending on importance for FC and ER, simulation possibility, model accuracy and the availability of working models, a final selection of the factors were made. A detailed explanation on the final list of factors is found in Chapter 3, under the methodology section. Parameters which has been focused in the work are:

- Increased vehicle mass
- Speed of the vehicle
- Road gradient

- Traffic density
- Speed limits
- Low range of tire pressure
- Driving modes (pure electric, hybrid)
- Cabin Climate Control System
- Road surfaces
- Driver aggressiveness

1.4 Research Questions

There are three research questions needed to be answered in the thesis work.

- What are the factors that have an impact on fuel economy and electric range for a plug-in hybrid electric vehicles (PHEVs), that makes them deviate from the value proclaimed by Type Approval (TA) tests?
- How much influence does the real-world factors have on FC & ER for a PHEV?
- Which of these factors are most important to be focused in future work?

1.5 Disposition

The following section, Chapter 2 in the thesis discusses about the theory on Driving cycles, various energy losses experienced when the vehicle is driven on road, different powertrain systems, and auxiliary devices. Further, the different steps/procedures followed during our work has been furnished in Chapter 3. Later, the results from the simulation has been analyzed and discussed in detail under Chapter 4. Finally, conclusions and Recommendations are provided in Chapter 5, followed by references to the study.

2
Theory

2.1 Driving Cycles

A driving cycle is a certain set of data points indicating the speed of the vehicle over time. They aid in reducing the expense of on-road tests, testing time and the efforts required by the test engineer. The main intent behind is to bring the road to the test lab(chassis dynamometer) or to the computer simulation environment. There are different types of driving cycles which are followed by different countries to assess the performance of the vehicle, like FC, ER and polluting emissions. They are usually derived theoretically or through direct measurements of a driving pattern which are deemed representative. The two types are, "Transient driving cycle" which represents continuous speed changes over time, typical of on-road driving, and "Modal driving cycle" which involves prolonged periods at constant speed. The commonly used driving cycles are the European NEDC, and Globally harmonized WLTP driving cycles, the later striving to represent more of a real-world driving behaviour[1]. Following sections will discuss more in detail on the aforementioned driving cycles and their test procedures.

2.1.1 NEDC

It is designed to assess the FC and emission levels of passenger cars (excludes Trucks and Commercial vehicles) and is believed to represent typical usage of a car in Europe. Nevertheless, it has received a lot of criticism for indicating economy figures which is practically not feasible in reality, due to long idle time and low accelerations which is unrealistic. It consists of four repetitive urban part, which is known as Urban driving cycle (UDC), and an extra urban part called EUDC. The distance covered over the entire cycle is 10,932 meters accounting to 1180 seconds with an average speed of 33 km/h. The cycle is illustrated as in Figure 2.3. Further weaknesses noted in the drive cycle are (i) Tests are performed using optional economy settings which is ideally not chosen by the drivers (ii) No auxiliary load since cabin climate control and heated windows/seats are switched off[1]. Due to many such drawbacks, the United Nations Economic Commission for Europe (UNECE) has developed a new Global harmonized drive cycle WLTP, which is discussed in the following section.

Figure 2.1: UDC Cycle [1]

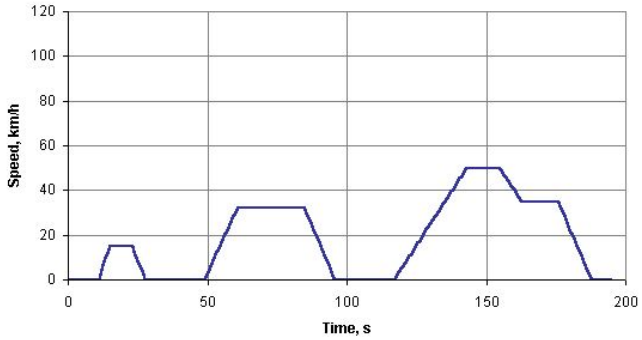


Figure 2.2: EUDC Cycle [1]

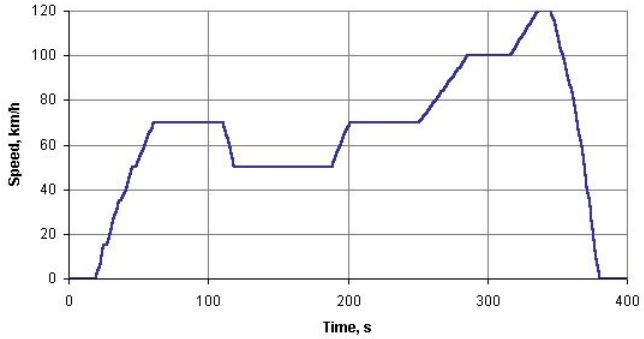
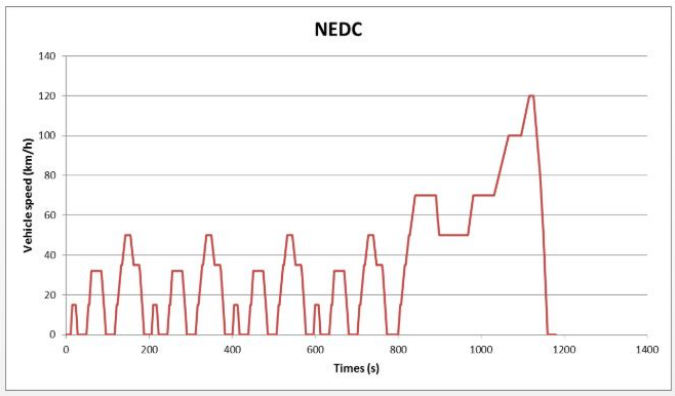


Figure 2.3: NEDC Driving Cycle [1]



2.1.2 WLTP

The Worldwide Harmonized Light Vehicles Test Procedure is a global harmonized laboratory test standard for assessing the level of pollutants, FC and ER for light duty vehicles (Passenger cars and light commercial vans). It is a much improved version of NEDC which provides stricter guidance concerning the conditions of road load, total car weight(Cargo and Passengers), ambient temperature etc. Different cycles are followed depending on the vehicle class based on Power/Weight ratio in

kW/Tonne. The classification of vehicle class is furnished in Table 2.1 and drive cycles corresponding to those vehicle class is shown in Figure 2.4-2.6. Although there is a significant improvement from NEDC test procedure, the WLTP is still criticized for low acceleration levels, and missing of road gradients which actually increases the engine load 2 to 3 times [1], subsequently increasing the pollutants. Hence, the EU legislation for emissions has put-forth a new test measure called Real Driving Emissions (RDE) which quantifies the pollutants, FC and ER while driving on real roads.

Table 2.1: WLTC test cycles for vehicle categories with different power-to-mass ratio(PMR) [1]

Category	PMR[W/kg]	Maximum Velocity[km/h]	Speed Phase Sequence
Class 3b	PMR 34	$V_{max} \geq 120$	Low 3 + Medium 3-2 + High 3-2 + Extra High 3
Class 3a	PMR 34	$V_{max}<120$	Low 3 + Medium 3-1 + High 3-1 + Extra High 3
Class 2	$34 \geq PMR22$	-	Low 2 + Medium 2 + High 2 + Extra High 2
Class 1	PMR ≤ 22	-	Low 1 + Medium 1 + Low 1

Figure 2.4: WLTC Cycle for Class 3b vehicles [1]

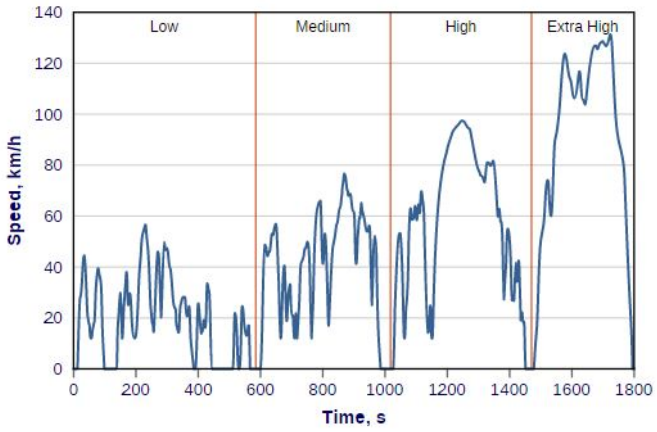


Figure 2.5: WLTC Cycle for Class 2 vehicles [1]

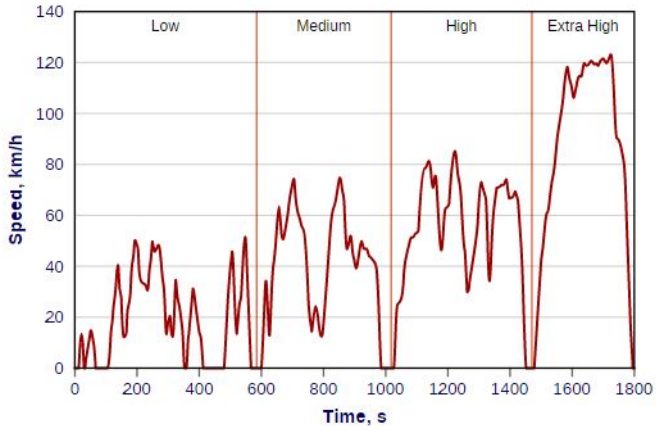
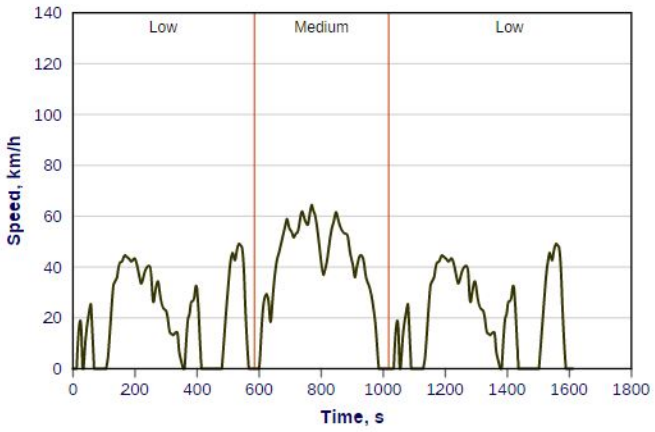


Figure 2.6: WLTC Cycle for Class 1 vehicles [1]



2.1.3 Real Driving Emissions (RDE)

Compared to the other types of test procedure which are designed for reproducibility and free from external influences, driving a vehicle on road under real-life scenarios is never reproducible. RDE test measures the pollutants, such as NOx emitted by cars when driving on real roads and the influence of ambient conditions, traffic situation, road profiles and driver behaviour which will impact the results. Europe, the first region in the world to introduce such an on-road testing procedure which marks a major leap in emission testing for light duty vehicles. It does not replace WLTP, but rather augments it. To evaluate the tailpipes emissions, a special equipment named Portable Emission Measuring System (PEMS) is fitted on the vehicle for real-time monitoring of key pollutants [12]. The driving conditions according to the regulations stipulated are mentioned below.

- Low and High Altitudes
- Varying temperatures
- Additional Payload
- Up and Downhill driving
- Urban roads where the speed must be <60 km/h
- Rural roads where the speed must be between 60 and 90 km/h
- Motorway where the speed must be between 90 and 140 km/h

2.2 Energy Losses

There are a lot of energy losses associated with the vehicle when driving on road. Not all of the fuel input to the engine is utilized for propelling the car down the road, but instead only 12-30% of the input energy is used for this purpose [13]. Depending on type of driving environment - City, Highway, combined city and highway, the extent of energy loss is varied. For an example, the engine losses incurred when driving under city conditions include idling, power-steering load, rolling resistance etc. Whereas, higher aerodynamic drag is experienced during motorway driving, when compared to other losses in city conditions. Hence there is a great potential to

address these losses by using advanced engine technologies and through hybridization, of which the latter one is discussed in further chapters. All the resistive forces, such as Aerodynamic drag, Rolling resistance, Steering load etc., and its influence on the energy consumption is explained in the following sections.

2.2.1 Aerodynamic drag

Aerodynamic drag is the opposing force to the relative motion of any object[14]. It is a force that acts in the same direction of the airflow and in parallel. It increases with square of vehicle speed and is therefore very crucial at higher speeds. Thus, manufacturers when designing the vehicle take into consideration the aerodynamic drag coefficient as an important performance characteristics in addition to other features. One such example is streamlining the frontal area of the vehicle. The drag coefficient is nothing but a dimensionless quantity which is used to quantify the resistance of an object in a fluid environment. Reducing the drag has a lot of benefits in terms of achieving higher fuel efficiencies and increasing the overall performance of the vehicle.

$$F_{aero} = 0.5 \times \rho \times C_d \times A \times v^2 \tag{2.1}$$

2.2.2 Rolling Resistance

When the gas pedal is pushed in a vehicle, energy is transferred from engine to the wheels which results in rotating the wheel and enough momentum being built up to propel the vehicle. To achieve this, the vehicle must overcome various factors that resists the forward movement, and one such factor is Rolling resistance. It is sometimes referred to as Rolling drag or Rolling friction, and is the force which resists the motion of a body (Such as Ball, or Tire) when rolling on a surface. It is the effort required to keep the tire rolling and is influenced by operating mass of a vehicle, rolling resistance coefficient $[C_r]$ and road grade $[\alpha]$. It is caused by a tire deflection when the wheel is rotated, a drag force on tire, friction between tire and road surface, etc.

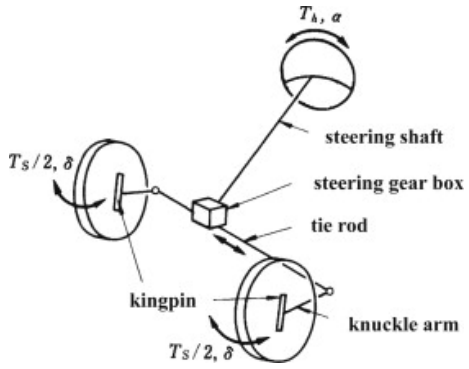
$$F_{roll} = m \times C_r \times \cos(\alpha) \tag{2.2}$$

2.2.3 Power Steering

The power steering system is installed in the vehicle in order to help the driver turn the wheels with minimal steering effort. The major difference which could be observed in cars of today when compared to cars 5 or 10 years ago will be the revolution in power steering system. Most of the power steering system will rely either on an electric motor or a hydraulic piston for power boost. The majority of the cars sold today come with Electric Power-Assisted Steering (EPAS). The other types of steering system are Hydraulic Power-Assisted Steeting System (HPAS) and combination of the latter two i.e., Electric-Hydraulic power-assisted steering system. Manufacturers have switched to EPAS to reap the benefits of fuel savings. Studies have shown that EPAS uses 90% less energy than HPAS [15], and results in 4% less fuel consumption. This is due to the fact that hydraulic system uses a pump driven

by the car's engine for pressurizing the fluid, and continuously sap energy from the engine irrespective of the wheel is turning or not. On the other hand, the EPAS uses the electric power generated by the engine and needs energy only when the wheel is steered. The common configuration of the steering system is shown in Figure 2.7

Figure 2.7: Vehicle steering system [2]



2.3 Powertrain System

In a vehicle, the powertrain consists of the key components that generate power and deliver it to the road surface. This includes both engine and transmission, with more recently battery and electric motor as well in case of hybrid powertrains. The classification of vehicles is generally based on the type of prime mover and conventional vehicles use Gasoline or Diesel engines as their source of propulsion. However, the hybrid vehicles too use Gasoline or Diesel engines as one of the source of propulsion together with battery and electric motor as the second source. There are different types of hybrid powertrains classified based on the mechanical and electrical linkage to the final drive and wheels, and also based on the overall architecture. Series, Parallel and Split hybrid are one such examples of hybrid powertrains offered in the market. Further information on the different types of hybrid systems are discussed in the following sections.

2.3.1 Hybrid Electric Vehicle(HEV)

Vehicles which have hybrid powertrain system i.e., a combination of an internal combustion engine (ICE) and an electric machine as their prime mover is termed as Hybrid Electric Vehicle (HEV). The presence of such a powertrain is primarily intended to achieve better fuel economy when compared to a conventional vehicle (Gasoline/Diesel). There are many degrees of electrification such as Micro HEV, Mild HEV, Full HEV, and Plug-in HEV, depending on the degree to which each functions as an electric vehicle. Table 2.2 shows their classification based on different features each type offer.

Table 2.2: Degree of electrification in vehicles

	Micro HEV	**Mild HEV**	**Full HEV**	**Plug-in HEV**
ICE Auto stop/start	**X**	**X**	**X**	**X**
Brake energy recovery		**X**	**X**	**X**
Electric motor assist		**X**	**X**	**X**
Pure electric drive			**X**	**X**

Out of the four types, Micro HEV is the lowest level of hybridization which can only offer a Auto Start/Stop feature. The electric energy stored in the auxiliary battery is used to quickly start the engine at a traffic signal and it does not provide any other feature which a typical HEV possess. Hence, a Micro HEV is usually not called as an Hybrid vehicle.
Whereas, a Mild HEV is a ICE powered vehicle along with an electric machine which is used for start/stop functionality and some levels of power assist to the combustion engine. Even Mild HEV's does not provide an exclusive electric-drive only mode like that of a Full HEV, and Plug-in HEV.
A full hybrid and Plug-in hybrid vehicle can both run only on a combustion engine, or only on an electric motor, or a combination of both. A major difference from full hybrid vehicle to plug-in hybrid is that the batteries in a plug-in hybrid vehicle can be recharged from an external source, and offers a much larger all-electric range.

Usually in a HEV, the idle emissions are reduced with the help of Auto Stop/Start function which completely turns off the engine when the vehicle comes to rest (Example: At a traffic light). The ICE is turned on again when the the driver takes off his/her foot from the brake pedal, providing a hassle free drive. HEV also reduces tailpipe emissions since the engine used is comparably smaller than that of a Gasoline/Diesel powered vehicle. Technologies such as Regenerative braking system make use of the vehicle's kinetic energy during downhill/braking conditions to convert into electric energy which is then stored in a battery.
Depending on the way in which the power is supplied to the drivetrain, the HEV's are classified into:

- Series Hybrid
- Parallel Hybrid
- Power-split Hybrid

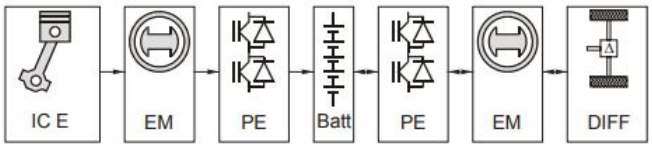
A parallel hybrid type of configuration has been used in our vehicle model which will be further discussed in the following sections.

2.3.2 Series Hybrid

Generally, also referred to as Extended-Range Electric Vehicle (EREV). Only the electric motor drives the drivetrain and the ICE which is used as a range extender powers the electric motor by acting like a generator. So, the ICE is mechanically not connected to the wheels making it to operate independently at its efficient region. Energy is being lost due to several stages of conversion which makes this type of hybrid configuration, uncommon in passenger cars. Thermal energy is being converted to mechanical energy in the ICE and this mechanical energy is later converted to

electric energy by running the generator. The electrical energy from the generator is used to either recharge the batteries or directly power the electric motor when the battery is empty. The wheels are only driven by the electric motor which is powered by the battery or through the generator directly. The major advantage of this configuration is that the ICE is made to run at its most efficient operating region which offers greater flexibility, higher efficiency and lower emissions. But, on that other hand it usually has a larger battery pack making it more expensive when compared to Parallel hybrids.

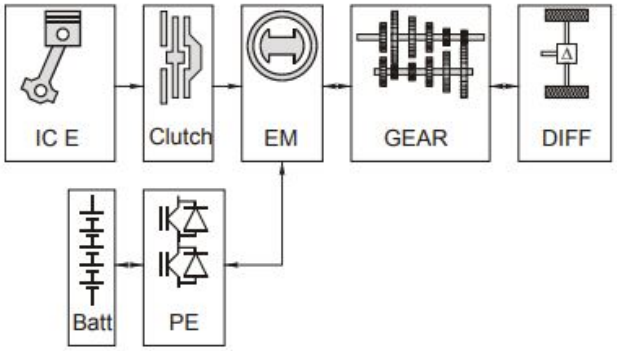
Figure 2.8: Series hybrid configuration [3]



2.3.3 Parallel Hybrid

A system having a ICE and an electric motor that can individually drive the wheels, or both coupled up together to drive the wheels. The ICE has a mechanical connection to the wheels through gearbox, and so do the electric motor. There are three forms of operating mode which are pure electric, pure ICE and power-assist, where the latter has power both from the ICE and EM. Parallel hybrids are more efficient in urban stop and go conditions since it takes the advantage of running EM at low speed/loads, where the ICE is not efficient. But during highway operation, the ICE is made use of, along with some levels of assist from the EM when needed. They also have a smaller battery pack when compared to other hybrids.

Figure 2.9: Parallel hybrid configuration [3]



2.4 Transmissions

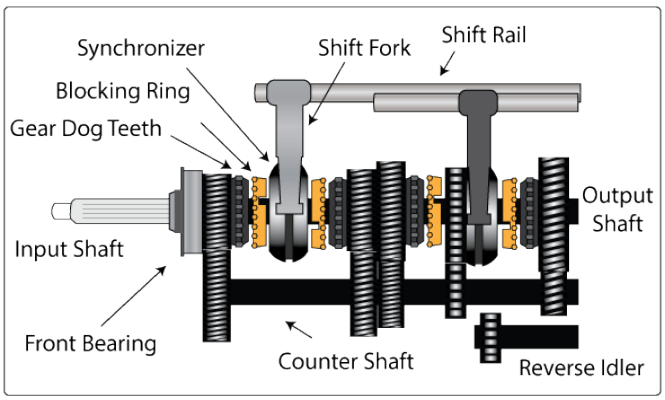
The term transmission often refers to a gearbox that simply uses a gear and gear trains to provide torque and speed conversions from a rotating power source to another. It usually has multiple gear ratios and switches between different gears as speed changes. The switching is done manually (By the driver) or automatically

with the directional control (Forward and Reverse) also being provided. In general, the transmission is either connected via a flywheel, fluid coupling, or a clutch to the engine crankshaft, and the output of the transmission drive the wheels via driveshaft to one or more differentials. Though the differential provide a further gear reduction, its objective is to rotate the wheels at different speeds which is essential to avoid slippage during a turn. Different types of transmission has been discussed below along with their advantages and disadvantages. The vehicle model focused in this work has a dual-clutch transmission type which is briefly explained in following sections.

2.4.1 Manual Shift Transmission

The manual shift transmission consists of three different shafts. The input shaft which is connected to the combustion engine via clutch/flywheel. The lay shaft or counter shaft holds different gears, and are meshed with the gears on the output shaft. Finally, The output shaft which is connected to the wheels via a differential. The configuration is shown in Figure 2.10. The different gear ratios is accomplished by locking and unlocking different sets of gears to the output shaft with the help of shifting forks and rail. The losses in the system can be influenced by the friction when the gears rotate relative to each other.
One of the main disadvantages of using manual shift transmission is that, it requires high work load on clutch and frequent gear shifts by the driver during heavy traffic. Due to this frequent gear shifts, the clutch is eventually damaged over time [16]. But, manual transmissions are less complex, cheaper, lighter and rugged, which makes it a choice amongst many users. In recent times, most of the conventional cars employ automatic transmissions which is gradually reducing the popularity of the manual transmissions.

Figure 2.10: Configuration of manual shift transmission gearbox [4]

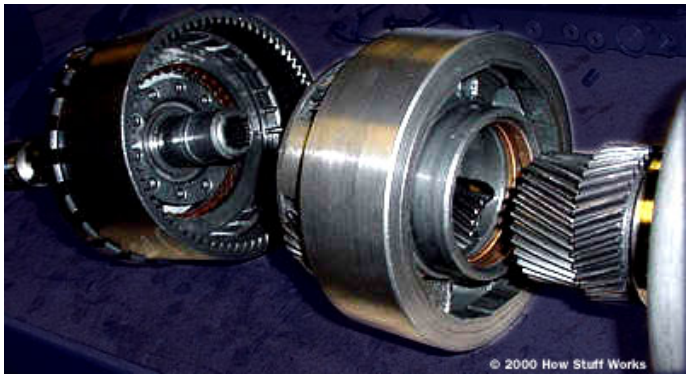


2.4.2 Automatic Transmission

A major advantage and a difference from the manual transmission is that there is no clutch pedal and gear lever included in this type of transmission, which directly

eliminates the efforts required by the driver. The gear shifts and engaging/disengaging of clutch is carried out automatically. Different gear ratios are achieved by the same set of gears with the support from bands and clutches. A typical planetary gear set in automatic transmission is shown in Figure 2.11. The planetary gear set consists of a Sun, Ring and planet gears which are meshed to each other. [17].

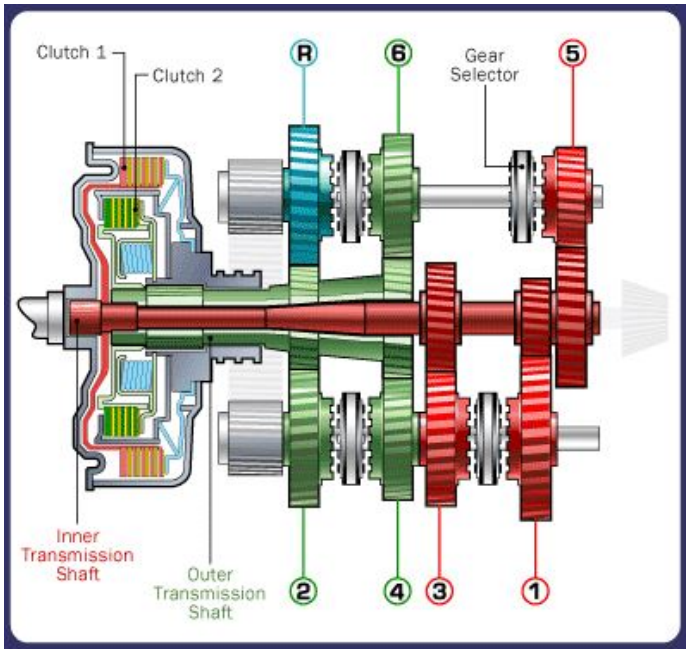
Figure 2.11: The planetary gear set [5]



Compared to manual shift transmission, automatic transmissions are more expensive, heavier and complex. It is also less fuel efficient due to the power loss in transmission fluid and requires more maintenance due to its complexity

2.4.3 Dual-clutch Transmission

Figure 2.12: An example of the dual-clutch transmission, 6-speed [6]



This kind of arrangement is also sometimes known as Powershift or direct shift gearbox. It possesses the advantages of a manual shift transmission together with

the qualities of an automatic transmission by providing different clutches for even and odd speed selector gears. The odd and even gears are placed on two different shafts which are engaged by two different clutches, clutch 1 & 2 as seen in the figure below. During a gear change, the engine torque is transferred from one gear to another without much interruption, providing a smooth and a gentle gear change. There is no much loss of power nor a jerk in the vehicle during this gear shifting operation. The selection of gears is usually done automatically.

2.5 Auxiliary Systems

Auxiliary systems are the ones that provide comfort and convenience in a vehicle, which includes cabin climate control, heating of seats/mirrors, infotainment systems, etc. The auxiliary systems are generally driven by electric power and consumes significant energy at different conditions. In particular, the cabin climate control system is the one which consumes highest amount of electrical energy. An understanding of few auxiliary systems has been furnished below.

2.5.1 Battery Thermal Management System

The operating temperature of a battery has to be maintained at a desired temperature for maintaining energy storage capacity, cell longevity, driving range and system safety. Hence, a thermal management system for a battery is very critical. The system should be equipped with four essential functions to ensure the right operation of a battery pack, and they are:

- **Cooling**
  When the battery temperature increases and reaches a certain point, the heat needs to be removed which is done by a cooling function.
- **Heating**
  During winter or cold climatic conditions, the battery pack temperature will be decreased to a limit which is not acceptable. Heating function in the system is thus needed to keep the temperature within a suitable range.
- **Insulation**
  When there is a large difference between ambient temperature and the temperature inside the battery pack, the temperature in the battery pack can dramatically rise or fall. To prevent this rapid change in temperature, an insulator is used to slow down the process.
- **Ventilation**
  There are exhaust gases within the battery pack which requires to be expelled out of the system. This is performed by a ventilation function in the thermal management system.

2.5.2 Pneumatic/Hydraulic System

This system is used for reducing the driver's force at situations such as opening/-closing of a trunk door, brake systems etc.Some portion of the electric energy is utilized to drive the actuators or compressors in these systems.

2.5.3 Air Treatment System

Incoming air can cause freezing and corrosion inside the vehicle components. Thus, the air has to be treated to increase the life of the compressor and maintain its regular function. An air dryer is thus implemented to remove humidity from the incoming air, and this requires some amount of continuous electrical energy to keep the system up and running.

2.5.4 Cabin Climate System

Cabin heating or cooling system is considered to consume the highest amount of energy amongst all the other auxiliary systems. It can also have a significant energy consumption when compared to total energy consumption from the vehicle. Cabin cooling system mainly comprises of a refrigerant, AC compressor, a blower fan etc., and heating coils in case of cabin heating. Within the cabin climate system, the compressor is the one that consumes high energy. Thus, the performance of a compressor plays an important roles on the total energy consumption.

3
Methods

3.1 Prioritization of Real-world Factors

The real-world factors having effects on either or both FC and ER were identified. The findings revealed 40 different parameters which were then categorized into groups based on (i) Ambient temperature conditions (Summer>20; Winter<15 Degree Celsius), (ii) Driver dependence, based on On-road usage and Off-road maintenance, (iii) External factors, dependent on road conditions and other factors. From literature study, the real-world factors that only had high impacts on FC and ER were selected amongst the listed parameters, which were later finalized based on different criteria.

The final selection of parameters were made by using four main criteria based on (i) Degree of importance on FC and ER (ii)Possibility for the parameter to be simulated (iii) Accuracy from the simulation, and (iv) Accordance to RDE regulation. The parameters was later ranked based on the formerly mentioned criteria and the one's which had high total scores were included in the scope of work. With maximum of 3 points each for degree of importance & simulation accuracy, and 0 or 1 point each for the other two criteria, the final scores for each factor were awarded collectively with the help of different subgroups at the company. The results of final selection is tabulated in Table 3.1 while the parameters excluded in the study is also shown in Table 3.2. The reasons behind the exclusion of parameters has been explained in Chapter 1, under the scope section. The parameters included in the simulation model are explained below.

3.1.1 Operating mass

Operating mass is defined as the total weight of a vehicle which might include passengers and cargo, but excluding a trailer. This is categorized as a driver dependent factor which has significant impacts on both FC and ER. Number of occupants in a vehicle is one of the possible drastic changes on the vehicle mass. An average passenger weight was assumed to be 75 kg based upon a study [18]. Other than the passengers, cargo weight is also considered to be important which can increase the overall operating mass.

3.1.2 Ambient Temperature

The temperature has a significant influence on the energy consumption from a auxiliary system such as cabin climate control (Cabin cooling and Heating), heating of seats/mirrors etc. During extreme cold temperatures, a need for cabin heating, heating of seats, mirrors and steering wheel arises which leads to high energy consumption from the auxiliary system. This in turn decreases the electric range of a vehicle. The energy consumption from these systems are seen when the customer is driving on real road, and the WLTP test procedure doesn't take this into account which makes a huge difference.Therefore, in this study the electrical load demand from cabin climate control system at initial temperatures of 0, 14, 23 & 30 degree Celsius are considered to analyze the impact on ER.

3.1.3 Vehicle Speed

An increment in speed increases the aerodynamic drag on the vehicle and consumes more power from the ICE and/or electric motor as a consequence [19]. Basically, an increase in speed is not considered to be a loss, but instead it is the braking event which is followed after reaching higher speeds is considered to be a loss of energy.

3.1.4 Speed limits

Speed limits are one of the external factors having impacts on a speed profile of a vehicle. The velocity, acceleration and deceleration of a vehicle are continuously changed which in turn affects the FC ER.

3.1.5 Road Gradient

A road inclination can dramatically affect FC by up to 20% compared to a flat road [20]. A vehicle driven along an uphill consumes more power in order to overcome the force from gravity, while a vehicle driven on a downhill consumes less. The energy consumption of a vehicle going through inclination is higher than that driven on a zero gradient road. In vehicles that have regenerative braking, the road gradients help in regaining some energy back from the vehicle's kinetic energy during a downhill condition. The energy thus regained is stored in a battery which can be used later for electric drive.

3.1.6 Road surfaces

Various type of road materials has an influence on the tire rolling resistance. It is likely that more the roughness of a road surface results in a higher rolling resistance, which is then needed to overcome by the vehicle propulsion system [14]. Thus, it leads to more demand of power from engine or electric motor for every distance travelled. In our study, the value of rolling resistance coefficient is increased by 15% from that of a value considered during WLTP test procedure, to depict a rough road surface. This is because the road surface is considered to be perfect, flat and smooth

for WLTP test procedure, and it may be higher when the vehicle is driven on real roads. The value is set at 15% after discussing with the internal team at CEVT.

3.1.7 Low Tire Pressure

During winter conditions, the density of air increases as the ambient temperature is decreased. The air pressure inside the tires reduce as the temperature drops since the air gets denser at lower temperatures. Low tire pressure is also possibly caused due to a lack of regular pressure check. By not inflating the tires regularly, people tend to drive with lower pressure than recommended which leads to increased resistance to vehicle motion and faster wearing of tires [11]. It is found that the tire pressure drops between 1-2 Psi(Pound per square inch) for every 10-degree Fahrenheit decrease in temperature [21]. Our study includes tire pressure <25% from the recommended limit, where a warning is usually triggered on the driver's infotainment system.

3.1.8 Driving mode (Pure electric, Hybrid)

In PHEVs, some variants may offer different driving modes for the driver to select. Running on pure electric mode at all times has its own advantages and disadvantages. The advantages include fuel savings, zero emissions, and a silent drive. But, after the battery reaches the minimum SoC (State of Charge) where there is no further possibility of pure electric range until it is recharged, the ICE is forced to run at all conditions. This doesn't take the advantage of electric motor at low speed/load regions where the EM is more efficient when compared to ICE.
Whereas in the hybrid mode, there is a frequent switch between EM and ICE, and a control strategy is developed in such a way that both the prime movers are operated in their best efficiency regions.

3.1.9 Traffic Density

Traffic density refers to a number of vehicles occupying a given length of road in a traffic lane. Traffic condition can change a driving behavior and vehicle performance since it affects vehicle speed, acceleration, start and stop condition of an engine. Hence, the energy consumption is influenced by the number of vehicles plying on road.

3.1.10 Aggressiveness of a driver

Driver aggressiveness correlates to the accelerator and break pedal position of a driver. The change in pedal position over time influences the way the energy is consumed by the electric motor or ICE. Sudden requirement on acceleration followed by harsh braking leads to a great loss of power since the energy required to accelerate the vehicle is more, than what it could be regained during braking conditions. The importance of pedal position over time is analyzed with this study and the impact it has on FC and ER is provided in the result section. A defensive driver is also considered in this study to observe the variation in ER and FC when compared to an aggressive driver.

Table 3.1: Real-world factors that were included in the simulation

Groups of factors	Parameters
Environmental conditions Summer(>20deg)	· Air Condition
Environmental conditions (Winter, <15deg)	· Cabin heating · Headlamps · Low tire pressure
Driver dependent(on-road)	· Aggressivness of a driver · Luggage · No. of occupants · Speed · Driving modes
External factors	· Inclination/Declination · Curves, intersections · Road surfaces · Traffic density · Speed limits

Table 3.2: Real-world factors that were not selected in the simulation

Groups of factors	Parameters
Environmental conditions Summer(>20deg)	· Tire wear-out due to excessive heat · Engine cooling · Lower air density · Low viscosity of oil · Battery cooling
Environmental conditions (Winter, <15deg)	· Battery characteristics · High viscosity of oil · Inlet air temperature · Engine warm up · Battery warm up
Driver dependent(on-road)	· Driving with windows open · Trailer load
Driver dependent (Maintenance)	· Wheel alignment · Timely replacement of filters(oil, fuel, air) · Battery charging habits
External factors	· Windy conditions · Fuel type (Quality & Energy content) · Power-steering load

3.2 Creating the Identified Route in CarMaker

"CarMaker" tool was used to build a virtual road network of the “CEVT RDE Route”, which was identified in Gothenburg. The road network was developed by importing GPS data from Google Maps into .kml file. Although the file could be

opened in Scenario/Road tab in CarMaker as in Figure 3.1, it did not allow us to split the road into multiple segments or edit it in order to add intersections, roundabouts and junctions. This meant that only roads from .rd5 file, which was a CarMaker format were allowed to be edited. Thus, the route in .kml file was imported into CarMaker and a replica of the same was created by tracing and building roads manually over the route, to yield the exact same road network. Post creating a newly built road network in CarMaker format, intersections, additional lanes, roundabouts and junctions were able to be added to look alike as the real route. Some parts of the work has been shown in Figure 3.2.

The new route consisted of three types of road segments which were sub-urban, city and highway. One of the important reasons that different types of roads were included in the test was because the model needed to be consistent with RDE regulation.

Figure 3.1: The road network obtained from GPS data

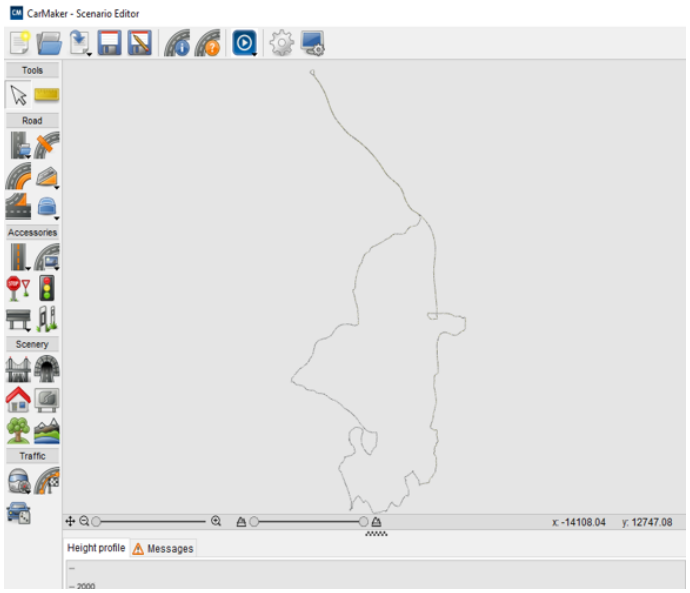
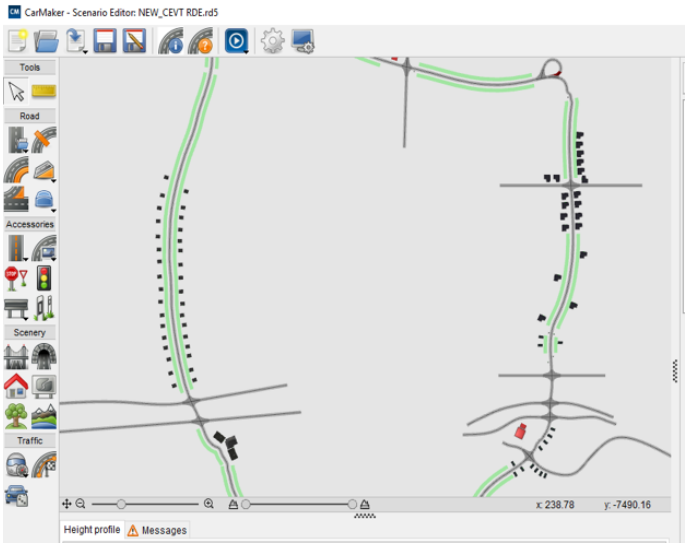


Figure 3.2: The road network with multiple lanes, intersections, roundabouts and junctions



3.3 RDE Driving Scenarios

Because the external factors on roads had lots of influence on FC and ER of a vehicle, the driving scenarios were defined to be as same as that of a real route. For example, the presence of road surfaces, intersections, curves and altitude of roads which had impacts on a driver's response. Therefore, these driving constraints were added into a model to create a realistic situation. The traffic density, driving behavior and other external factors were also included in the program settings.

3.3.1 Altitude Profile

One of the important parameters in the road network was the altitude profile. The height data was recorded from GPS by CEVT team while performing real driving on the RDE route. However, the height data was not so accurate enough, even if the data was interpolated. Therefore, the height above sea level of each road section was taken from Trafikverket[22] as seen in Figure 3.3. The height data of each position in the road network were recorded from the Trafikverket page and added them manually into ¨Elevation Profile¨ in CarMaker as shown in Figure 3.4. Although the data from Trafikverket was considered reliable, the accuracy of the data had to be validated. In order to visually confirm the accuracy of the height profiles on each road, a test drive was carried out on the real route to observe and compare the characteristics of road gradients, with the elevation profile adjusted in the model.

Figure 3.3: The altitude profile from Trafikverket

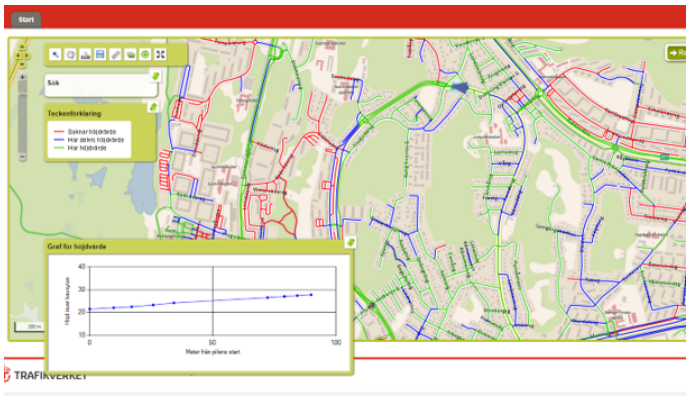
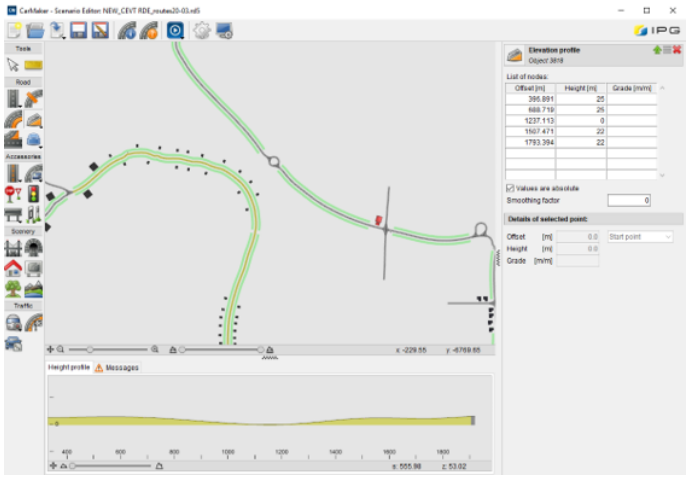


Figure 3.4: The elevation profile of roads in CarMaker



3.3.2 Road Network

Several details were added into the driving scenarios which had significant effects on vehicle driving performance and the reaction of a driver in the program. Some of these details were considered to be a driving constraint (Speed limits, speed breaker etc.,) and the rest were added in the model for the purpose of beautification. Most of the detailing, such as speed limits, buildings and trees were observed in Google maps on every road, to feed them into the model. The details which could not be figured from Google Maps were later observed during the test drive on real route. If a road quality was bad, a "friction strip" command was used in the CarMaker to add it to the road model. The timing of traffic lights were collected from the real driving observation and was fed into the traffic light settings. Some parts of the finished driving scenarios are shown in Figure 3.5, 3.6 and 3.7. The road network includes:

- Speed limits
- Traffic lights
- Bus stops
- Roundabout

- Speed Breakers
- Road surface
- Buildings and trees

Figure 3.5: Driving scenario with a speed breaker

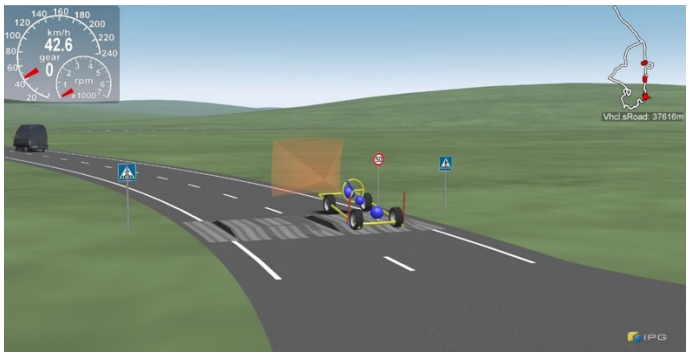


Figure 3.6: Driving scenario with a traffic light

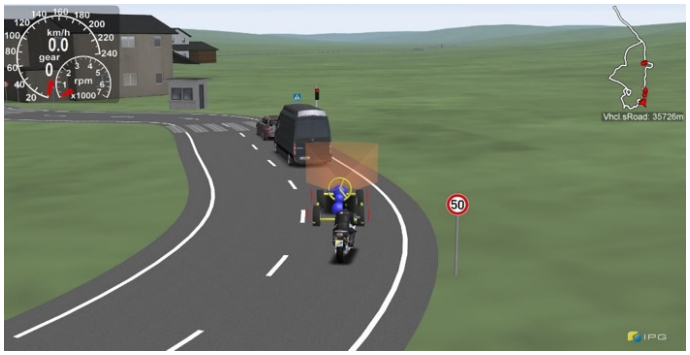
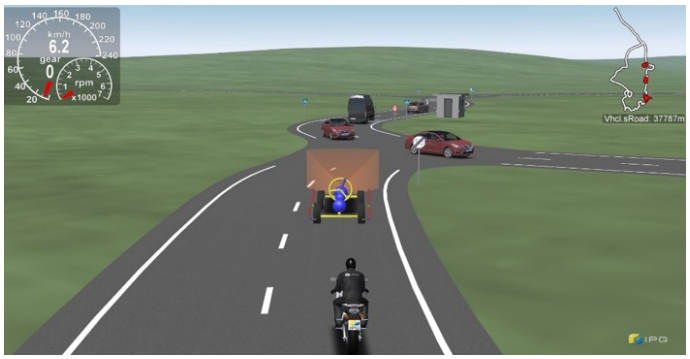


Figure 3.7: Driving scenario with cars passing at an intersection



3.3.3 Pedestrians

The number of pedestrians crossing the street were observed during the test drive, and was imitated. During the observation it was found that the vehicle stopped for a group of pedestrians only once, accounting to 20 seconds. So, a traffic light which

lasted 20 seconds was added to the road model at the observed position, to imitate the same as that experienced during test drive. Though it was possible to include a pedestrian model itself in CarMaker, there were few errors noticed which made the simulation to suddenly stop, and hence was decided to include a traffic light instead.

3.3.4 Traffic Density

The number of vehicles on road were added into the simulation to correspond to the traffic density in reality. Bus routes were also identified, but it was however observed that the vehicle did not follow any buses during the test drive on real route. There were special lanes for buses and trams in many roads and as a consequence, the vehicle did not follow any buses or trams. Additional vehicles on roads were added using traffic commands from 'Traffic' tab in CarMaker. Desired route path and start position could be selected according to Figure 3.8. Later, the maneuver for traffic objects was adjusted by writing a command for start condition and the time of appearance in the section as shown in Figure 3.9. By using this method, the start point and the action time of the traffic object were able to be controlled.

The traffic density was varied based on the data extracted from the number of vehicles on roads per day. According to the report informed by ÅF [7], the number of vehicles on road in Gothenburg during 2010 is shown in Figure 3.10. The traffic model that represented the observed conditions was considered to be approximately 0.1% of the vehicles informed in this report. In order to estimate the suitable number of vehicles in each driving scenario, different levels of traffic density were initially simulated to see the outcome of the scenarios. The appropriate scenarios were chosen as a representative of medium traffic density and heavy traffic density. Further, the number of cars in each scenario were calculated back to be a percentage of vehicles on roads within 24 hours, based on the report. Since different roads have varying number of cars, the traffic model was adjusted to be consistent considering the popularity of the roads by using the statistic data as a reference. Finally, the traffic density was chosen to be varied as 0.25% and 0.5% of the vehicles on the road per day for the case of medium and heavy traffic respectively. The assumptions made for vehicles in the traffic model.

- The specific number of vehicles which were created on each road based on traffic data from the report.
- The additional vehicles on road starts to drive as soon as the ego-vehicle arrived at a particular position.
- Each additional vehicle was 6 – 10 meters apart from one another at the start position.
- When additional vehicles arrived at the end of a road, they were disappeared if the next road segment had lower number of vehicles.
- If the following road had higher number of vehicles, the previous additional vehicles remained on the road, combining with more vehicles on a new road section.

Figure 3.8: Traffic command for additional vehicles

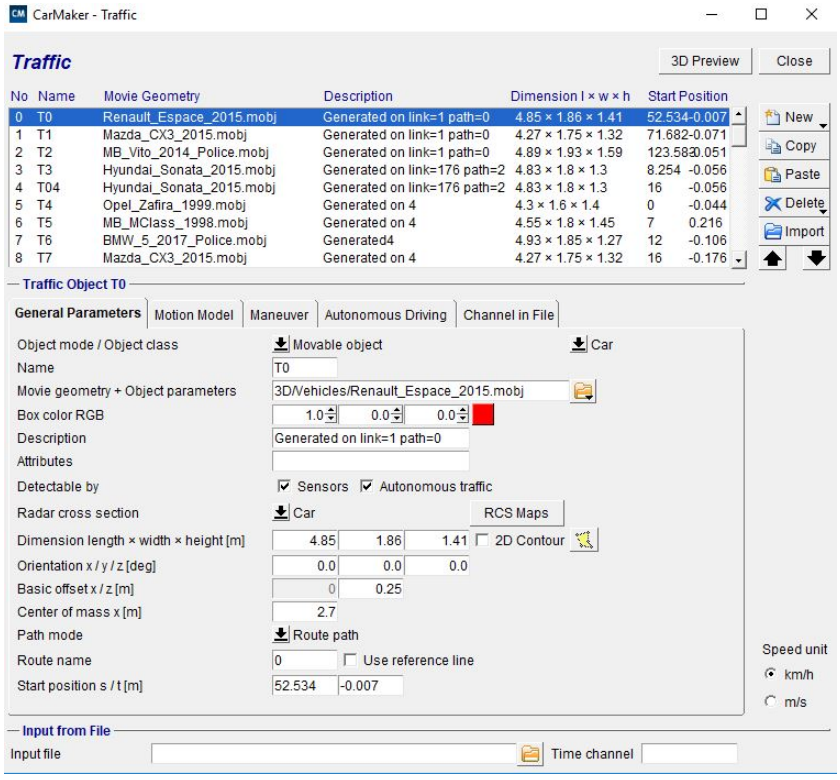


Figure 3.9: Maneuver settings for additional vehicles

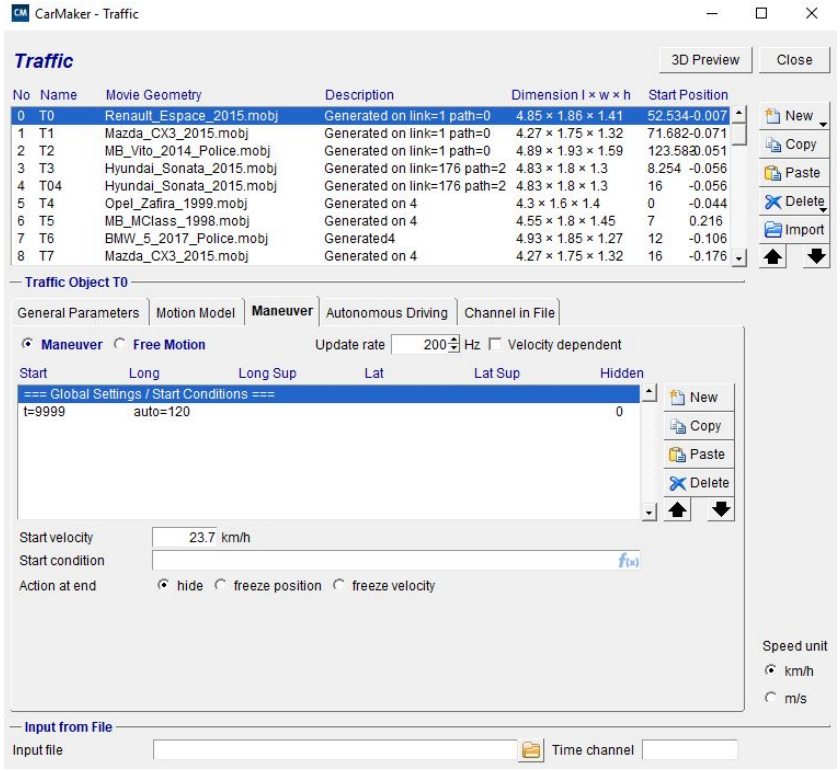
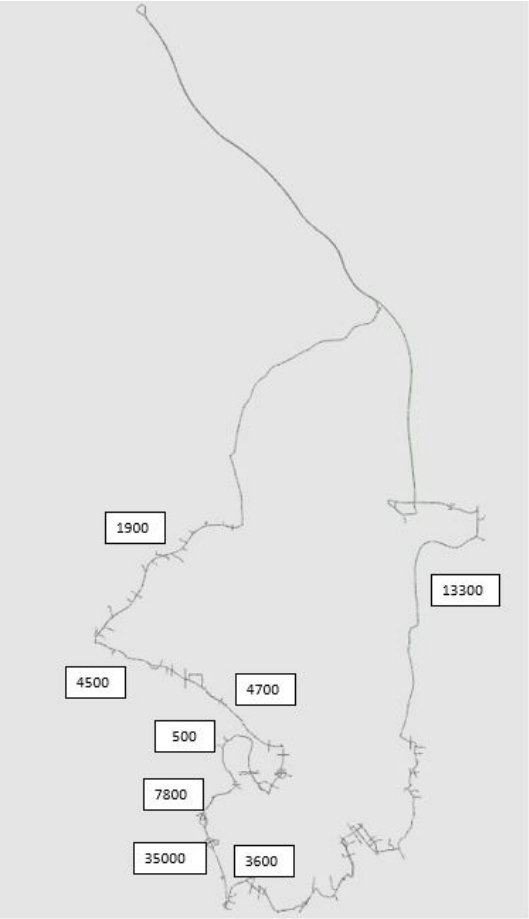


Figure 3.10: The number of vehicles per day in 2010 [7]



3.4 Vehicle Model

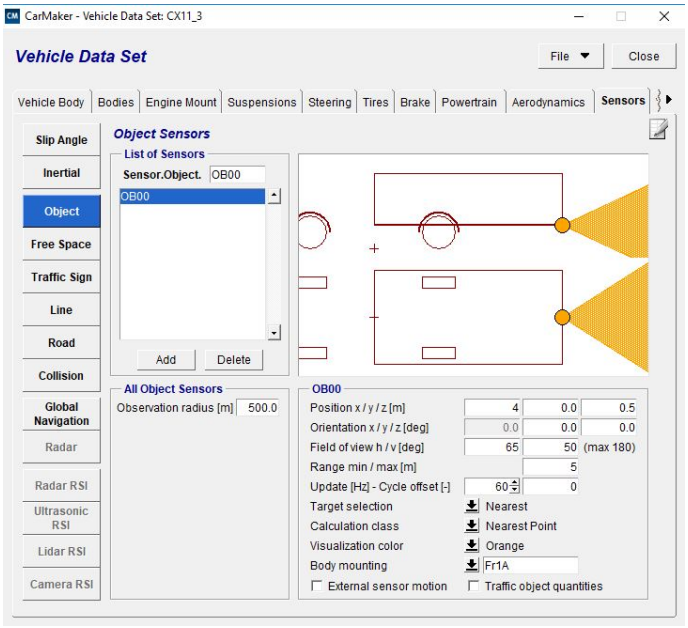
The finished model composed of engine, transmission, suspension, battery and brake which were imported into CarMaker. The vehicle performance was influenced by the parameters being varied in each test run. The details related to the vehicle model are listed below.

- Model : PHEV
- Hybrid configuration: Parallel type
- Engine: Gasoline
- Transmission : 7 speed, Dual-clutch transmission
- Brake : Regenerative

3.4.1 Vehicle sensor

To be able to detect traffic objects on road, such as pedestrians and other cars, the vehicle has a sensor located in front. The detection range of the sensor was adjusted to be 5 meters. According to Figure 3.11, if the detection range of the sensor was increased, the sensor also detected the cars driving in opposite lane due to its heading angle, which made the vehicle stop unnecessarily.

Figure 3.11: A sensor to detect traffic objects on roads



3.5 Driver Settings

The driver settings provided in CarMaker had three types of driving behaviors which were normal, aggressive and defensive. Several parameter values could be varied which resulted in different driving responses.

Cruising speed [km/h] is the specified speed that the driver in the program tried to reach.
Corner cutting coefficient allowed the vehicle to be off the driving lane. Value of zero implied that the vehicle is exactly on the driving lane. The higher the value meant the more freedom for the vehicle to go off the driving lane.
dt. Change of pedals [s] is the time a driver move his/her foot from the throttle to the brake pedal.
Min. dt Accel./Decel [s] is the minimum time the driver used for certain acceleration or deceleration.
The exponent of g-g diagram indicates the dependency between the longitudinal and lateral acceleration and also those of deceleration. The red lines in the diagram connect the maximum longitudinal and lateral acceleration.

Different settings of normal, aggressive and defensive drivers are shown in Figure 3.12, Figure 3.13 and Figure 3.14, respectively. The default settings of an aggressive driving behavior and a normal driving behavior provided by CarMaker were implemented in the simulations. It was found that the default settings of a defensive driving behavior made the vehicle leave the driving lane at one of the roundabouts, which stopped the simulation. Therefore, the values in the settings were adjusted in order to make the vehicle run on the desired lane.

Figure 3.12: The parameter settings for normal driving behavior

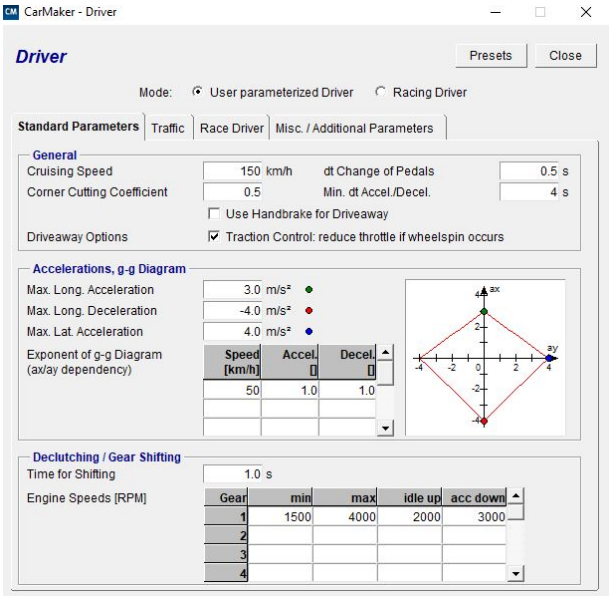


Figure 3.13: The parameter settings for aggressive driving behavior

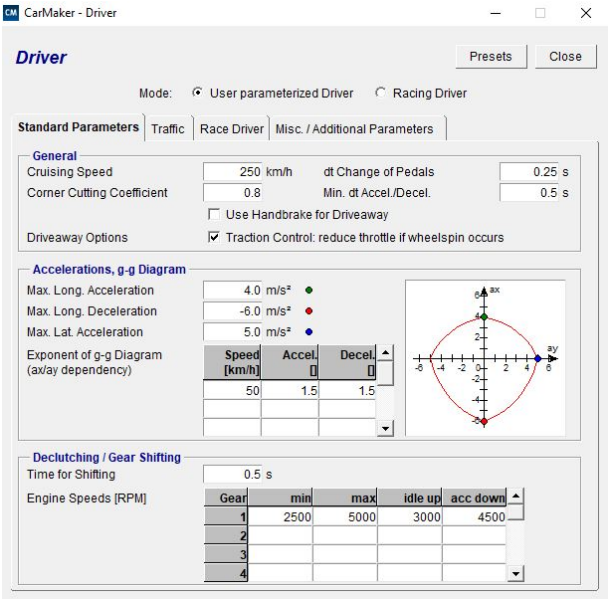
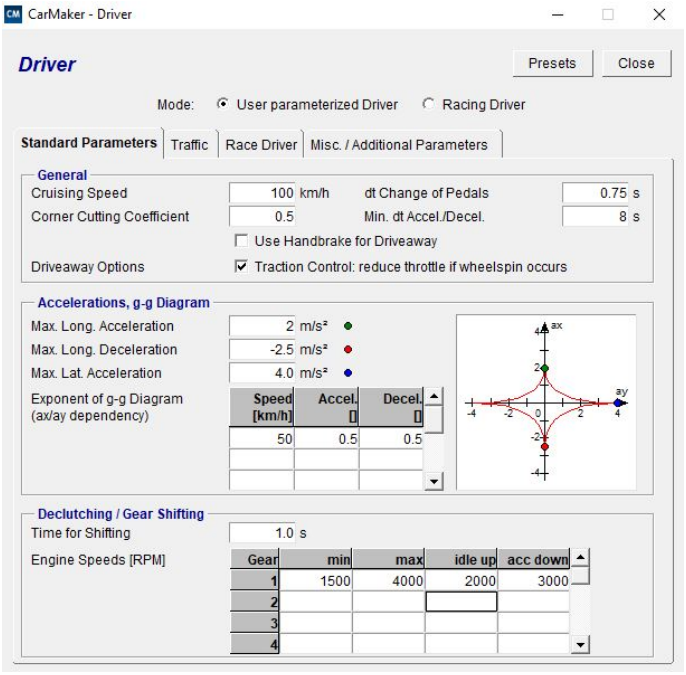


Figure 3.14: The parameter settings for defensive driving behavior



3.6 Parameter study

The simulation work was performed in CarMaker. The inhouse tool "AutoMaker" was used to effectively run batches of simulations with different parameter settings. The purpose was to see the impact on FC and ER when varying the factors that has been identified earlier in the thesis work. A total of 20 different test cases, including the benchmark case were created.The benchmark case was set according to Table 3.3. Each parameter was varied one at a time in every test case, while keeping others to be same as the benchmark case. The parameters considered to be varied are listed below. In the settings, a method to vary the tire pressure was by the changing rolling resistance coefficient.

- Test mass
- Rolling resistance coefficient
- Tire pressure
- Ambient temperature
- Road gradient
- Aggressiveness of a driver
- Speed profile
- speed limits
- Traffic density
- Driving mode (Pure electric/Hybrid)

Table 3.3: Settings of the RDE Base model

RDE Base model	
Test Mass	WLTP Test Mass
Road Gradient	No Elevation
Curves and Intersections	As per real route
Traffic Denisty	0.1%
Speed Limits	As per real route
Ambient Temperature	23 degree Celsius
Road Surfaces	As per real route
Driving Behavior	Normal

3.6.1 Test Cases

Case1: The test mass of the vehicle was reduced by 7.15% to represent one driver, and without any cargo.
Case2: The test mass of the vehicle was increased by 14.35% to represent a fully loaded vehicle.
Case3: The real altitude profile of the roads were added.
Case4: The road implemented in the simulation was a straight road, having the same distance as the real route. The speed profile from real vehicle measured on the real route was implemented in the test run.
Case5: The traffic density was increased to 0.25% which was considered as medium level.
Case6: The traffic density was increased to 0.5% which was considered as high level.
Case7: The traffic density was 0%, meaning that there were no additional cars on roads.
Case8: The speed limits were removed. However, the maximum cruising speed set in the driver model was 120 km/h.
Case9: The rolling resistance was increased by 19% to represent a reduction of tire pressure of 12%.
Case10: The rolling resistance was increased by 21.33% to represent a reduction of tire pressure of 25%.
Case11: The vehicle was made to run in hybrid mode.
Case12: The vehicle started with minimum SoC level i.e., with an empty battery.
Case13: The auxiliary load was increased by 300% to represent the electric energy consumption from the cabin climate system at 0 degree Celsius.
Case14: The auxiliary load was increased by 100% to represent the electric energy consumption from the cabin climate system at 14 degree Celsius.
Case15: The auxiliary load was increased by 100% to represent the electric energy consumption from the cabin climate system at 30 degree Celsius.
Case16: The rolling resistance coefficient was reduced by 6.5%.
Case17: The rolling resistance coefficient was reduced by 13.04%.
Case18: The driver behavior was aggressive.
Case19: The driver behavior was defensive.

4
Results and Discussion

4.1 Virtual Vs Real Driving Scenario

As mentioned earlier in the methodology section, a RDE driving scenario was created in CarMaker to perform virtual simulations for analyzing how each real-world factor affects FC and ER, when the vehicle is driven on road. Various scenarios as experienced by the driver when driving on real roads were put into thoughts, and a model was generated to replicate a realistic driving situation. There were few assumptions made while building the model for simplification purpose, and to verify these assumptions a test drive on the identified RDE route in Gothenburg was carried out. A difference of time taken was observed wherein the simulation was much faster than the real driving for 13.67%. This was due to the inaccuracy of the traffic model created in CarMaker where we could not replicate the exact behavior of other cars on road, allowing the IPG driver (CarMaker driver model) to drive much faster without any interruptions than reality.

4.1.1 Assumptions

The simulations were performed based on some assumptions which was made to reduce the complexity in the models. Although assumptions have an influence on the results outcome, it can be considered as a starting point for future work to improve the models further. Nevertheless, even after the assumptions being made, the results obtained from our study seemed to be logically correct which made us to proceed with the next steps. The list of assumptions which were made are:

- The vehicle is assumed to be parked in the garage and all the vehicle components are at 23 degree celsius ambient temperature
- The electrical load from cabin climate control system is assumed to be constant over the entire trip
- The friction from road surfaces is assumed to be constant along the entire route
- All the traffic objects created in the traffic model has identical behaviors

4.2 Fuel Economy and Electric Range

At first, the fuel consumption and electric range attained from the RDE base model (Benchmark case) was compared with results from WLTP test case. For confidentiality reasons, the FC & ER figures for the vehicle model considered in our study

has not been disclosed and the value is set to '100%' which will be a reference point to compare the results. Table 4.1 compares the value of all electric range in kilometers and the average speed (in km/h) attained during the test. It was necessary to compare the results of our base model with WLTP test case since the study involved in identifying the increase/decrease in FC and/or ER when the vehicle is driven on real roads, in contrast with tests on dynamometer. The modification which were made to the base model in comparison with WLTP included, (i) Maneuvering of the driver, (ii) Change in rolling resistance coefficient, (iii) Inclusion of speed brakers, speed limits, etc., into the road profile, (iv) Addition of traffic objects.
Hence, it was noticed that the electric range reduced significantly due to different factors influencing the energy consumption, and the break up of which factor had the highest impact on range has been tabulated in table 4.2.

The influence of traffic has been the least with 0.2% reduction in electric range, and was not true for the fact that the traffic model was inaccurate. The impact of such a factor is considerably high from what has been obtained. Stop and go conditions are quite obvious in a traffic situation and the demand of energy from the electric motor is slightly high as it needs to overcome the rolling resistance from tires, which usually has a higher percentage of the total load at lower speeds.
Rolling resistance stands second in the list with 4.2% and it is because of friction from road surfaces which offered resistance to vehicle motion. Different road surfaces offer varying resistance to motion, and in our study it was assumed that the rolling resistance coefficient is >15% than what the value is for WLTP, and was constant along the entire route. It's definitely not true that the road surface is the same along the entire route, but this assumption was for simplification and it might have a different influence on electric range when it is varied.

Lastly, the influence of vehicle speed on electric range was the highest with 9.4%. It can be observed that the average speed in WLTP test case was 46.5 km/h, whereas it was 57.2 km/h for our benchmark case. Higher the vehicle speed, the aerodynamic drag on the vehicle increases which resists the forward motion, leading to increased energy consumption. Also, some amount of energy might be lost during braking events when intersections or road curvature is encountered, as the vehicle would have reached higher speeds. Though a portion of energy is gained back through brake recuperation, the energy regenerated is less than what it is required to accelerate a vehicle.

Table 4.1: WLTP Vs RDE Base Model

Test case	**All electric range [km]**	**Average Speed [km/h]**
EU WLTP	**100%**	**46.5**
RDE Base model	**-13.8%**	**57.2**

Table 4.2: Factors influencing electric range

Factors	Impact on range (km)
Rolling resistance	-4.2%
Vehicle Speed	-9.4%
Traffic	-0.2%

Note: (-)sign indicates "Reduction", (+)sign indicates "Increase"

4.2.1 Variation in Operating Mass

Going forward, each test case was compared with the base model and the test cases were framed in such a way that one factor was changed at a time, while the rest of the other factors remained as it was in the base model. In the test case 1, the mass of the vehicle was decreased by approximately 150 kilos to observe the variation in fuel consumption and electric range. It represented only the curb weight plus one passenger with an average weight of 75 kg, and no additional cargo. The overall fuel consumption was reduced by 15.4% and the all-electric range was increased by 6.5%. Similarly, when the mass was increased in test case 2 to the maximum recommended limit representing a fully loaded vehicle, where the overall fuel consumption increased by 41%, while the all-electric range decreased by 12.3%. The overall fuel consumption denotes the quantity of fuel consumed from start to finish in l/100km. A significant increase in the overall fuel consumption is due to a decrease in the all-electric range and with the demand from the ICE starting quite early when compared to the base model as shown in Fig. 4.4

The fuel consumption after Min.SoC signifies the quantity of fuel consumed (l/100km) from the point of distance with empty battery, to the final point in the route. There is no much of a variation in these values since >60% of distance covered by the vehicle is through pure electric drive, and the remaining part of the route from the point of Min. SoC is a Highway, where the energy efficiency from ICE is high.
It is quite evident in the fuel consumption and electric range figures that the operating mass of the vehicle has a significant impact on vehicle performance. Increase in the car's payload will demand more torque on the wheels to keep it rolling, and hence more fuel consumption and reduced electric range per distance travelled. Figure 4.1 and 4.2 shows the Energy consumption vs Distance travelled for both the cases. The energy consumption from the HV battery over the distance is less with reduced mass case, whereas the energy consumption is more with increased vehicle mass. The latter is the case because of high energy demand from the electric motor for overcoming the resistance on wheels due to increased mass. Also from figure 4.3, it can be seen that for the case with reduced mass (Case 1) the fuel flow in ICE has started quite late over the distance when compared to the base model, which also signifies an increase in electric range. The straight line from the start until the first peak represents the all-electric range, which refers to a pure electric drive until the first point of fuel flow.

Table 4.3: Base Model vs Case 1 (Reduced Mass) and Case 2 (Max Load)

Test case	Modification from Base model	Overall Fuel consumption [l/100km]	Fuel Consumption after Min. SoC [l/100km]	All electric range [km]	Average Speed [km/h]
0	**Reference**	**100%**	**100%**	**100%**	**57.2**
1	**-150 kg**	**-15.4%**	**-4.4%**	**+6.5%**	**57.2**
2	**Max. load**	**+41%**	**+9%**	**-12.3%**	**57.0**

Figure 4.1: Plot between Energy consumption from the HV battery and Distance for case 1 (Reduced Mass) vs base model.

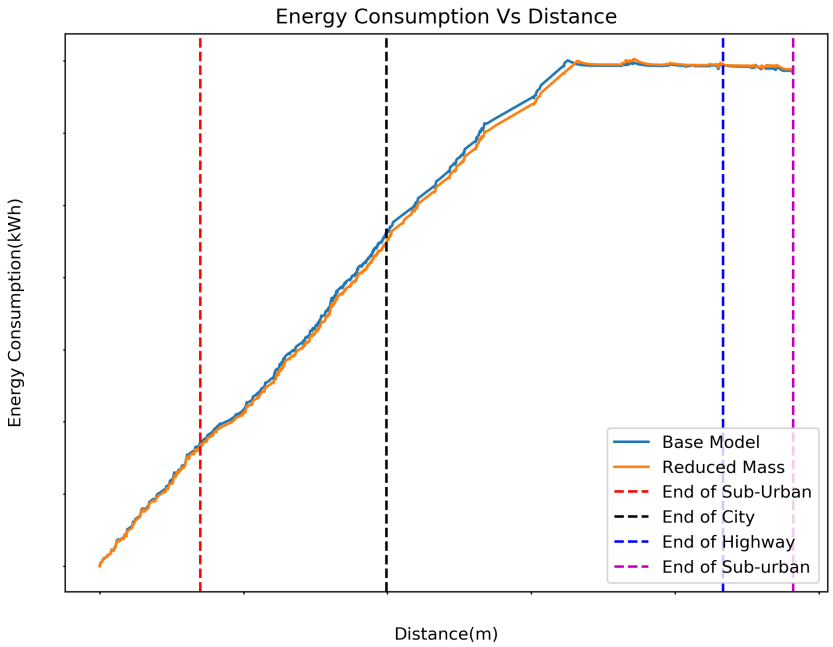


Figure 4.2: Plot between Energy consumption from the HV battery and Distance for Case 2 (Max Load) vs base model.

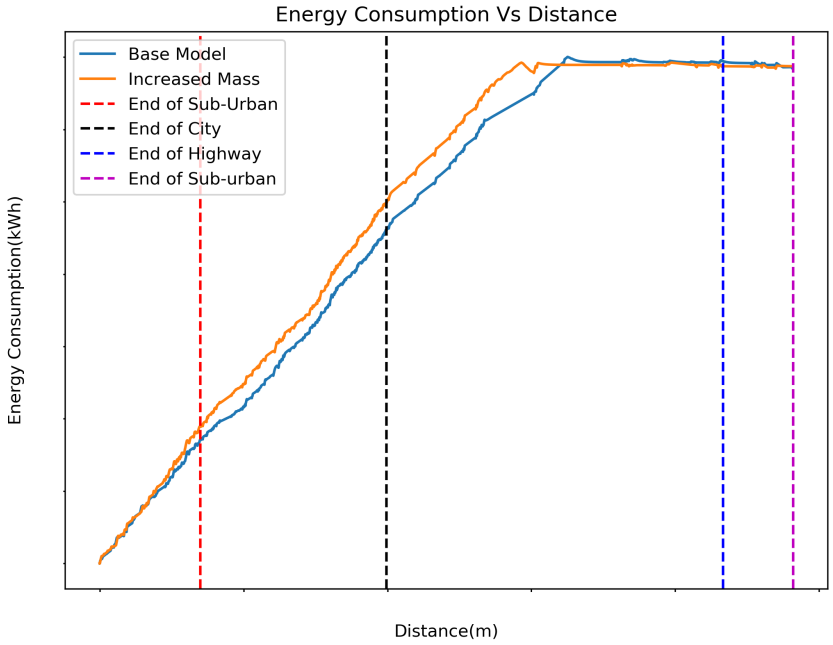


Figure 4.3: Plot between Fuel flow and Distance for Case 1 (Reduced Mass) vs Base model

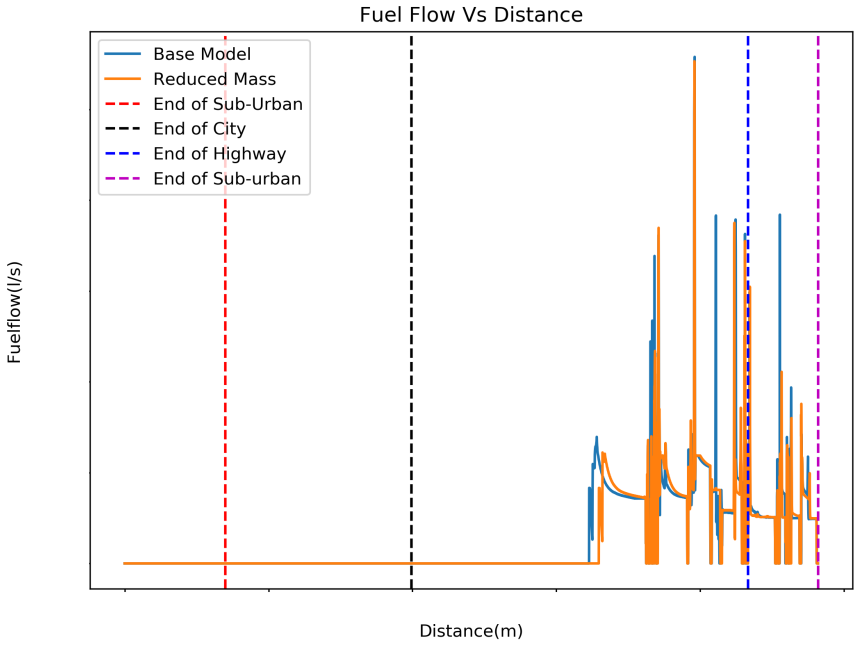
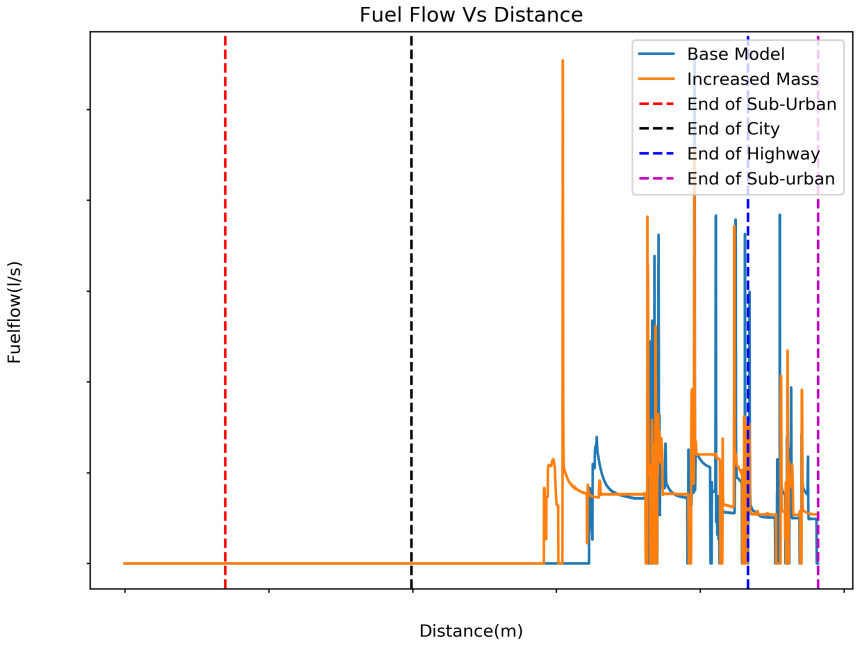


Figure 4.4: Plot between Fuel flow and Distance for Case 2 (Max Load) vs Base model



4.2.2 Road with Altitudes

The addition of altitudes to the road profile was the next factor considered to analyze the influence on FC & ER in test case 3. The road with gradients showed an increase in overall fuel consumption by 12.3% and decrease in the all-electric range by 6.5%. The fuel consumption after Min. SoC has increased but not significantly since there is a slight decrease in all-electric range, and the combustion engine has turned on early over the distance where the need for fuel flow high is high as seen in Figure 4.6. Although an increase in the gradient will request for more torque on the wheel, it is noticed that there is no much difference in the ER value since the electrical energy is regenerated during deceleration and downhill conditions through brake energy recuperation. The energy regained is then used to charge the batteries and in-turn drive the wheels.

Table 4.4: Base Model vs Case 3 (Road with Altitude)

Test case	Modification from Base model	Overall Fuel Consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	**Reference**	**100%**	**100%**	**100%**	**57.2**
3	**Road with Altitudes**	**+12.3%**	**+0.8%**	**-6.5%**	**57.2**

The battery SoC level is plotted along the distance as shown in Figure 4.5. Whenever the vehicle has encountered an elevation in the route, the energy in the battery has drained faster which can be seen by a sharp decline in the SoC curve. Also, the

electric energy regained through brake recuperation is indicated by small peaks on the SoC curve.

Figure 4.5: Plot between Battery SoC and Distance for case 3 (Road with Altitude) vs Base model

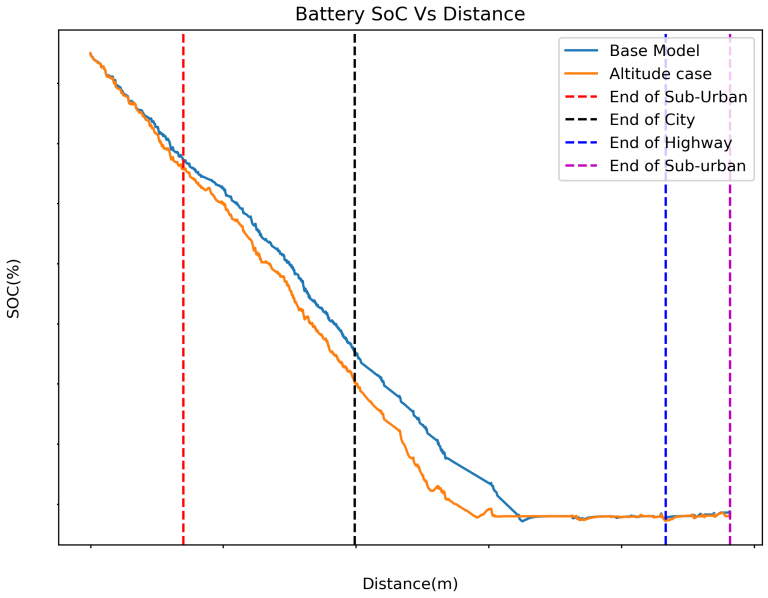
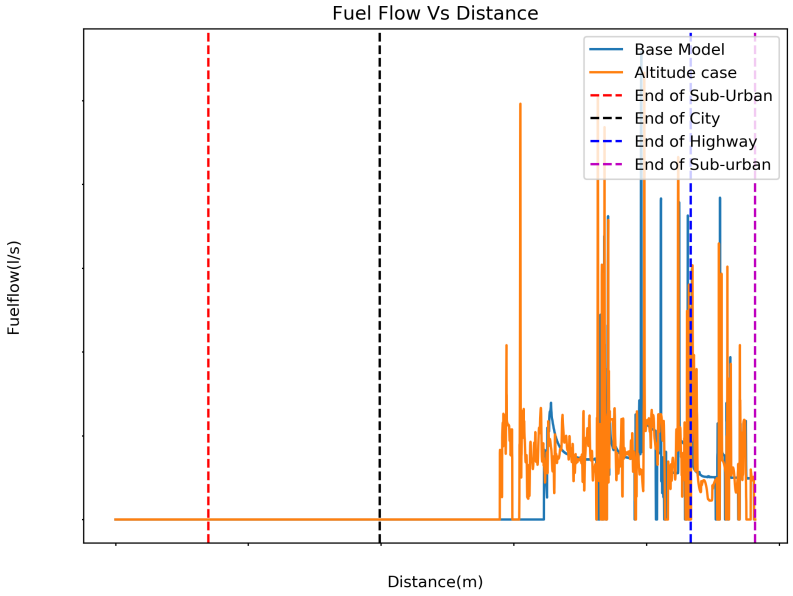


Figure 4.6: Plot between Fuel flow and Distance for case 3 (Road with Altitude) vs Base model.



4.2.3 Test vehicle speed profile

In this test case, the speed profile from the test vehicle which was driven on defined RDE route in Gothenburg was used. A straight road covering the length same as RDE route i.e., a length equal to that of the real route was created in CarMaker and the speed profile from the test vehicle was given as an input to the IPG driver. The vehicle was forced to follow this speed profile to compare the results of FC & ER to the base model. This was done to check if the simulation results from the RDE base model, match to the results from the real vehicle driven on the same RDE route. Unfortunately, this comparison did not yield us the result which was expected since the vehicle speed in simulation model was much higher when compared to the speed of the real vehicle. This can be observed from Figure 4.7 where the speed profile of both base model and real vehicle is compared. The vehicle speed from simulations are observed to be high in City and Suburban regions, and the speed from the test vehicle is comparatively low in those regions. This could be again because of inaccurate traffic models which is letting the vehicle to reach higher speeds, which is not the case with the test vehicle on real road. Hence, the all-electric range has increased by 24% and the overall fuel consumption has decreased by 56.1%. A huge difference in the fuel consumption over the complete distance (56.1%) is seen since the vehicle has almost driven pure electric.

Figure 4.7: Plot of speed profile for Case 4 (Test vehicle Speed Profile) vs Base model.

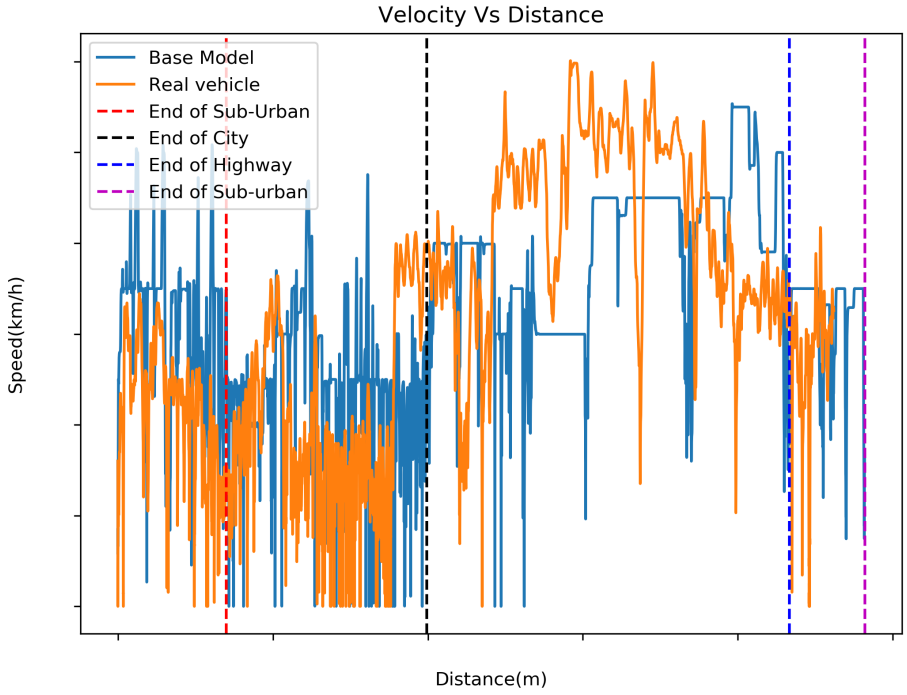


Table 4.5: Base Model vs Case 4 (Test vehicle Speed Profile)

Test case	Modification from Base model	Overall Fuel consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	Reference	100%	100%	100%	57.2
4	Defined vehicle speed profile	-56.1%	-8.3%	+24%	38.9

4.2.4 Variation in Traffic Density

The traffic density was varied across different road segments, City, Sub-urban, and Highway, and their influence on FC & ER was evaluated. Test case 5 and 6 represents medium and heavy traffic density respectively, and was compared to the base model which has normal traffic density. Please refer to section 3.3.4 for more information on traffic density. The route with medium traffic had no variation in overall fuel consumption i.e., 0%, and whereas with heavy traffic it was increased by 4.4%. A drop in the electric range was also noticed to be 1.9% and 1.7% for medium and heavy traffic respectively. The electric range for medium traffic is expected to be higher than the case with heavy traffic when compared to the base model. However, the electric range in the heavy traffic case was improved because the low average speed could save more energy used by the battery and the idling conditions had less impacts on the battery consumption. With increase in traffic density, there would be long idling conditions, low speed, and frequent braking & accelerating events which was expected to result in a significant increase in FC after Min SoC, but instead the results obtained were not evident. Hence, the traffic model needs more improvement which could predict better results with variation in traffic density, and this could be a scope for future work.

However, in this model there was not much of a variation in the ER values since the vehicle was not demanding energy from the battery during a standstill, except for the constant electric load from auxiliary devices. This could be the reason for the difference in ER due to increased traffic density when compared to the base model. Test case 7 represents "Zero traffic", and a slight variation in FC & ER values were observed. This was because the vehicle did not stop for any lead traffic, which led to an uninterrupted drive. The increase in the electric range was almost negligible, since the vehicle has reached higher speeds due to no traffic and the influence of aerodynamic drag has resulted in a compromise on ER, even though there was no/less stop and go conditions. The results for all the three test cases has been shown in Table 4.6.

Table 4.6: Base Model vs Case 5 (Medium Traffic), Case 6 (Heavy Traffic) and Case 7 (No Traffic)

Test case	Modification from Base model	Overall Fuel Consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	Reference	100%	100%	100%	57.2
5	Medium traffic	0%	0%	-1.9%	57.4
6	Heavy traffic	+4.4%	+1.6%	-1.7%	52.3
7	No traffic	-4.9%	-4.6%	+0.1%	65.2

4.2.5 Speed Limits

The scenario which had no speed limits, yet limited to a cruising speed of 120 km/h, was the test run that yielded the worst fuel economy amongst all the cases. As seen in Table 4.7, the overall fuel consumption rose to 129.4% and the electric range dropped by 40.7%. This was because the driver was aggressive during both acceleration and braking conditions and is very evident from the speed profile shown in Figure 4.8. A sharp increase in the overall fuel consumption was due to a significant drop in the electric range and the energy requirements from the combustion engine to reach the cruising speed is high, across the remaining distance. Though some of the energy would be regained during sudden or harsh braking conditions, the energy extraction from the battery/engine during acceleration is very high and cannot be compared with the energy regained during a braking event, as it is comparatively less. Also, at higher speeds the aerodynamic drag on the vehicle increases which could also cause a reduction in electric range and increase in fuel consumption. Nevertheless, the only advantage from having no speed limits was that the drive time reduced from the base model by 11.75%.
Although having the cruising speed at 120 km/h, Figure 4.8 however shows that the speed profile was not dramatically higher than that of the base model, because there were other cars in front.

Figure 4.8: Plot of speed profile for Case 8 (No Speed Limits) vs Base model.

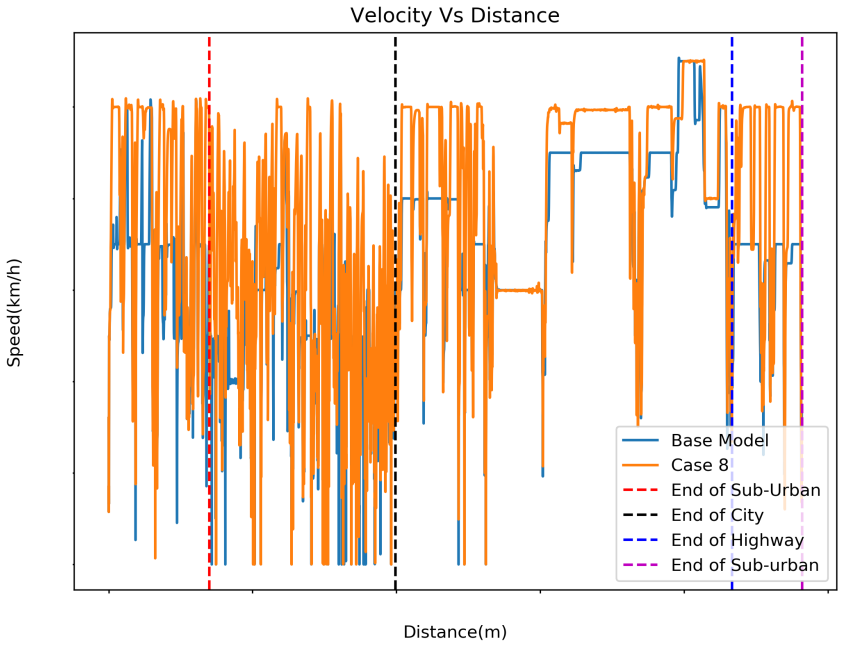


Table 4.7: Base Model vs Case 8 (No Speed Limits)

Test case	A Change from the	Overall Fuel Consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	Reference	100%	100%	100%	57.2
8	No speed limits	+129.4%	+33.3%	-40.7%	65.1

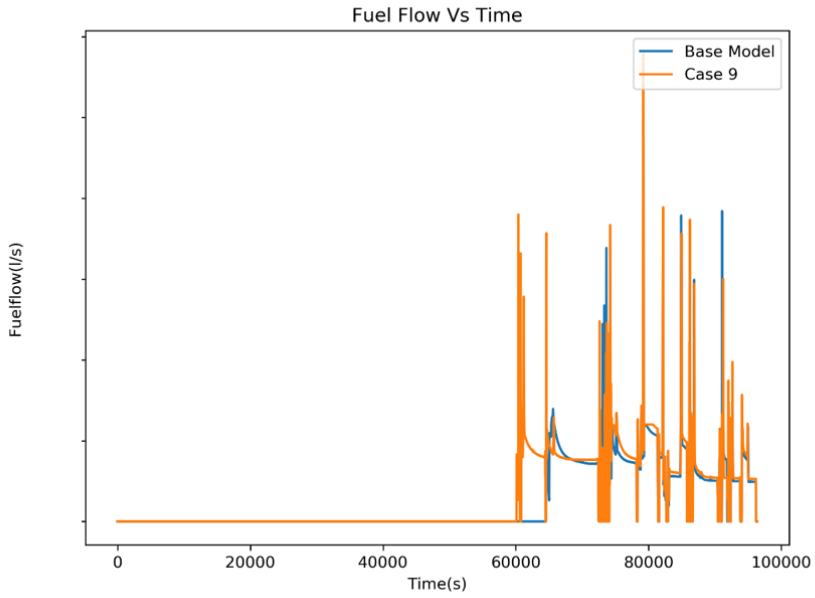
4.2.6 Tire Pressures

Having right tire pressures not only enhances the life of the tire, but also plays a vital role in reducing the fuel consumption per distance travelled and vice versa. This was clear in the results obtained in Table 4.8, where reducing the tire pressure by 12%, the overall fuel consumption increased by 7% and electric range dropped by 2.9%. When the tire pressure is low, the contact area between the tire and road surface is high which creates more friction and offers increased resistance to motion. Figure 4.9 clearly shows the decrease in electric range when compared to the base model, where the demand for fuel input from the ICE has started a bit early. Hence, it is very important to inflate the tires regularly to get the most out of it.

Table 4.8: Base Model vs Case 9 (Reduced Tire Pressure)

Test case	A Change from the Base Case	Overall Fuel Consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	Reference	100%	100%	100%	57.2
9	Lower tire pressure	+7%	+1.8%	-2.9%	57.2

Figure 4.9: Plot between Fuelflow and distance for Case 9 (Reduced Tire Pressure) vs base model.



4.2.7 Driving Mode

As observed in Table 4.9, when the vehicle was driven in hybrid mode (Test Case 11), the overall fuel consumption was increased by 7.7%. The reason for an in increase in fuel consumption is that the ICE is now also driven in some parts of the city, while it is only Highway in the base model. As observed in the figure 4.10, there is frequent switch between ICE and EM and there is no continuous operation from the EM for a longer distance as seen in the base model. There are quite a few advantages in such a mode since the EM is operated at lower loads and low speed conditions to take advantage over low efficiency from the ICE, and the combustion engine being operated at a point of higher loads/speeds where the efficiency is high. The value of the fuel consumption after Min. SoC has reduced dramatically since, 100% use of combustion engine is only during the remaining 18% of the route, while it is 34% from the base model. On the other hand, the all-electric range has shortened by 97.5% which means that the demand for fuel flow input has commenced soon after initial few kilometers of pure electric range even though the battery SoC is high. The horizontal straight lines in between the fuel flow inputs i.e., the line with zero fuel flow inputs are the times with pure electric drive which is considered to be the equivalent electric range. Thus, the way the FC and ER is calculated is quite different from other test cases.
With respect to test case 12, where the vehicle was driven starting from an empty battery, the overall fuel consumption has sharply elevated by 237.7%, and the fuel consumption after Min. SoC has increased to 21.7%. This was because the use of combustion engine is right from the start and the advantages of EM at different conditions could not be taken. All the energy comes from the fuel and nothing from the battery. Hence, even at regions where the efficiency of ICE is low, it was forced to run due to no storage of energy in the battery to perform a pure electric drive. However, some portion of energy is regained through regenerative braking and the energy is then stored in a battery which might be used to for engine start/stop, auxiliary devices or some amount of pure electric drive based on the percentage of SoC level.

Table 4.9: Base Model vs Case 11 (Hybrid Mode) and Case 12 (Start with Min SoC level)

Test case	Modification from Base model	Overall Fuel Consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	**Reference**	**100%**	**100%**	**100%**	**57.2**
11	**Hybrid mode**	**+7.7%**	**-60.8%**	**-97.5%**	**57.2**
12	**Empty Battery**	**+237.7%**	**+21.7%**	**NA**	**57.2**

Figure 4.10: Plot between Fuelflow and Distance for Case 11 (Hybrid Mode) vs Base model

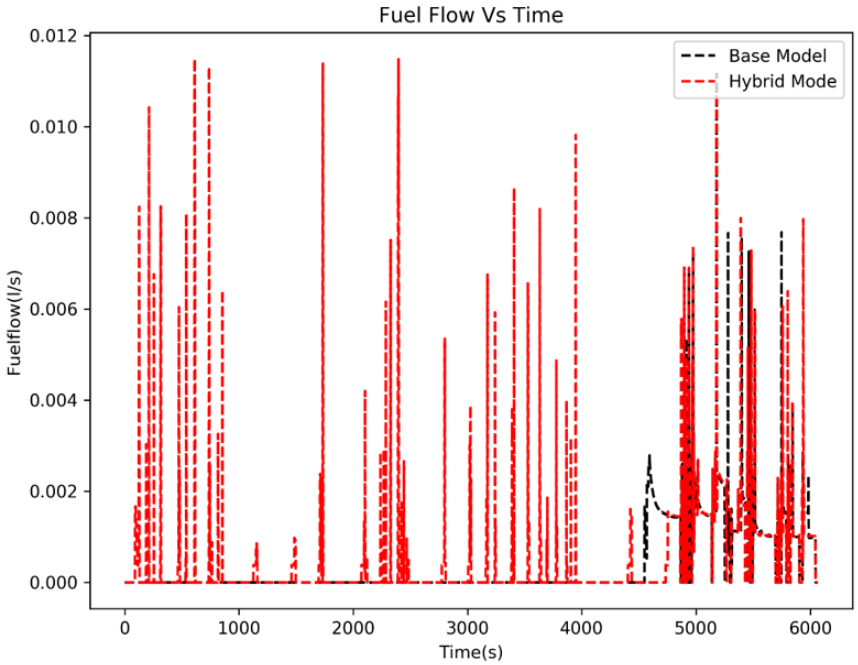
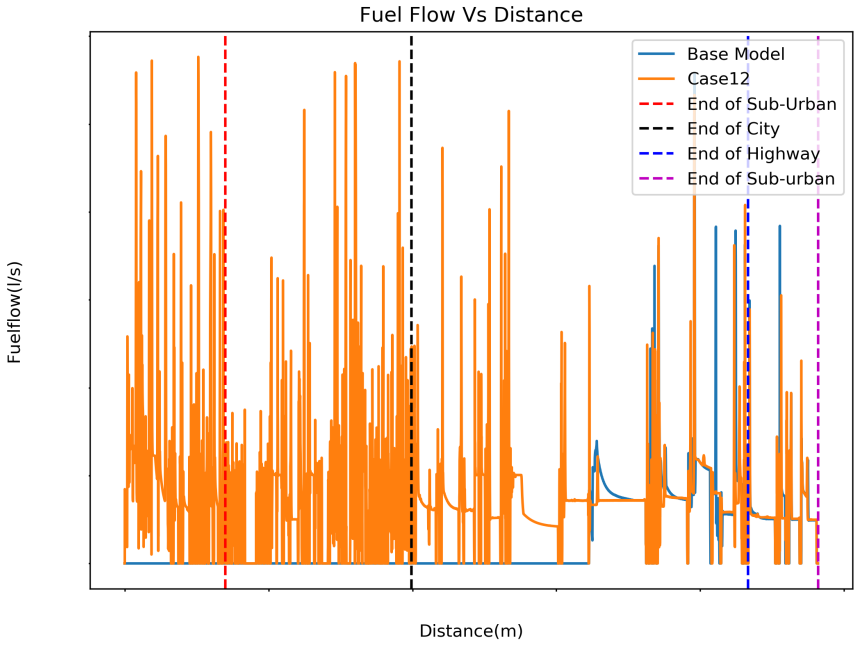


Figure 4.11: Plot between Fuelflow and Distance for Case 12 (Start with Min. SoC level) vs Base model.



4.2.8 Change in Ambient Temperature

Changes in ambient temperature influences the demand of auxiliary load from a cabin climate control system, among other things. In the test case 13,14 & 15, the auxiliary load from a cabin climate control system at 0, 14, & 30 degree Celsius were varied to analyze the effect on FC & ER. In case 13, the auxiliary load was increased by 300% from that of WLTP test case, to represent the electric energy consumption from the cabin climate system at 0 deg Celsius. The overall FC rose to 29.5% due to a decrease in the all-electric range by 14.3% , and the requirement on the ICE to be turned on for a longer period of time. The decrease in electric range is due to the demand of high electric energy from the auxiliary device which was being constantly sapped along the entire route. With the test case 14 & 15 at ambient temperature of 14 and 30 degree Celsius respectively, the auxiliary load was increased by 150%. This resulted a drop in electric range by 3.2% and an increase in overall fuel consumption by 6.3% which shows the same trend that an increase in auxiliary load would decrease the ER, and consequently increase in FC. The results for all the three case has been shown in Table 4.10
Figure 4.12 indicates the electrical energy consumption from the HV battery along the distance. With ambient temperature of 14 and 30 degree Celsius, the energy consumption was a bit higher than that of the base model which was set at 23 degree Celsius. When the temperature was at 0 degree Celsius, the energy consumption was much higher which made the electric range decrease significantly.

Figure 4.12: Plot between Energy consumption of HV battery and Distance for case 13 (0 degree), Case 14 (14 degree) and Case 15 (30 degree) vs Base model.

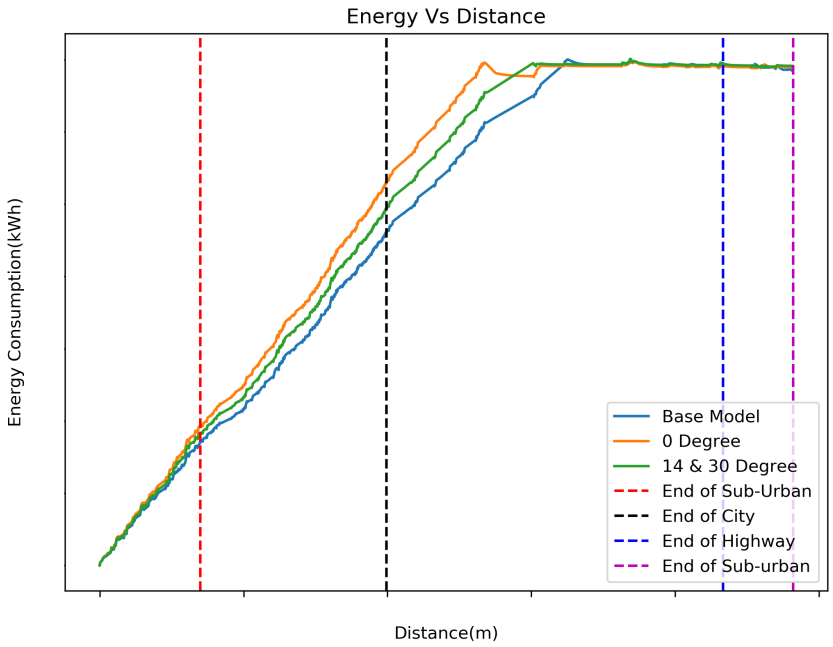


Table 4.10: Base Model vs Case 13(0 degree) Case 14(14 degree) and Case 15 (30 degree)

Test case	Modification from Base model	Overall Fuel Consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	Reference	100%	100%	100%	57.2
13	+300% Aux. load at 0 degree	+29.5%	+3.3%	-14.3%	57.2
14, 15	+150% Aux. load at 14& 15 degree	+6.3%	+0.7%	-3.2%	57.2

4.2.9 Change in Rolling Resistance Coefficient(RRC)

The results in the earlier section discussed about increased rolling resistance through decrease in the tire pressure which had a negative impact on both fuel consumption and electric range. To observe the influence of this parameter on the other side, the Rolling Resistance Coefficient (RRC) was decreased, which offered less resistance to vehicle motion. As shown in Table 4.11, it was obvious that the overall FC value decreased by 6.9% and the electric range increased upto 1.6% when the rolling resistance coefficient was decreased by 6.5% in test case 16 . Further decrease in the RRC value by 13% in case 17, resulted in a reduction in FC by 11.6%, and increase in ER upto 4.3%. This is quite straightforward that a decrease in rolling resistance results in lower fuel consumption and higher electric range.

Table 4.11: Base Model vs Case 16 (Reduced RRC by 6.5%) and Case 17 (Reduced RRC by 13%)

Test case	Modification from Base model	Overall Fuel Consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	Reference	100%	100%	100%	57.2
16	Reduced RRC by 6.5%	-6.9%	-4.2%	+1.6%	57.2
17	Reduced RRC by 13%	-11.6%	-4.2%	+4.3%	57.2

4.2.10 Change in Driving Behavior

The main differences in driving behavior were the rate of change in pedal position of both accelerator and brake pedal and the cruising speed from the driver. With case 18 where the driver was aggressive, the overall fuel consumption elevated by 14.6%, while the all-electric range dropped by 5.4% as shown in Table 4.12. This was due to sudden acceleration and high deceleration levels as seen in figure 4.13 where the driver frequently braked to avoid collision with the lead traffic. The energy was lost mainly due to frequent braking events, although some amount of energy was gained through regenerative braking.

Table 4.12: Base Model vs Case 18 (Aggressive Driver) and Case 19 (Defensive Driver)

Test case	Modification from Base model	Overall Fuel Consumption [l/100km]	Fuel Consumption after Min SOC [l/100km]	All electric range [km]	Average Speed [km/h]
0	**Reference**	**100%**	**100%**	**100%**	**57.2**
18	**Aggressive driver**	**+14.6%**	**+4.7%**	**-5.4%**	**57.0**
19	**Defensive driver**	**-19.7%**	**-2.2%**	**+10%**	**57.1**

In case 19, the driver was set to defensive mode which made the overall fuel consumption reduce by 19.7% and the all-electric range was increased by 10%. In this driver setting, the rate of change in pedal position and the cruising speed is much slower than the normal driver setting seen in the base model which resulted in a decrease in FC and increase in ER. It is evident from the figure 4.14 that the acceleration levels are lower than the base model and hence the energy is drained from the battery at a slower rate leading to increased all-electric range.

Figure 4.13: Plot of acceleration profile for Case 18 (Aggressive Driver) vs Base model.

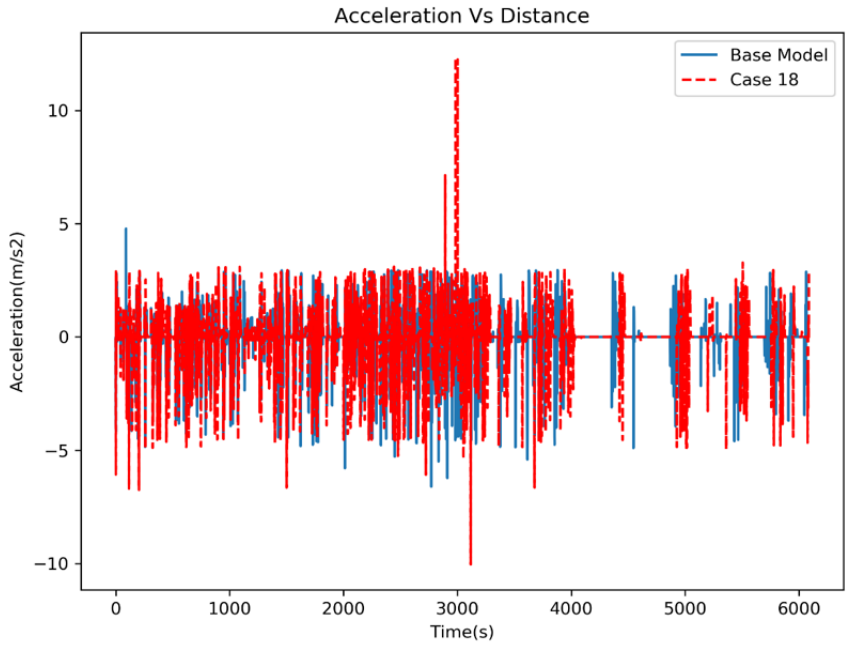
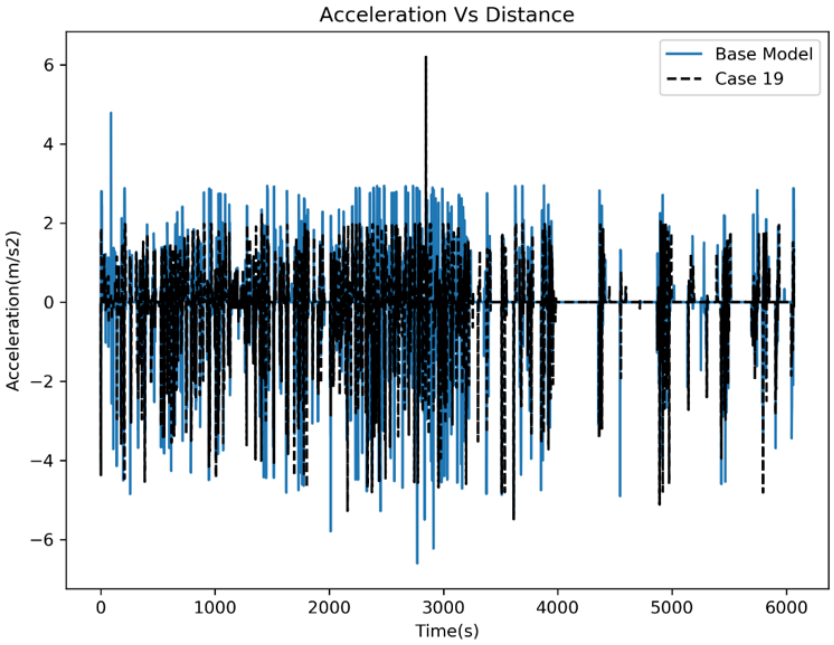


Figure 4.14: Plot of acceleration profile for Case 19 (Defensive Driver) vs Base model..

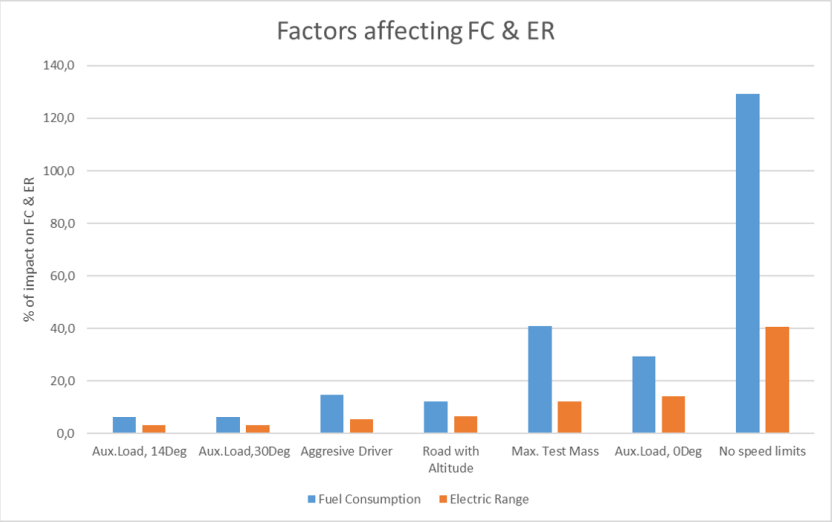


5
Conclusion

5.1 Conclusion

During the work, a RDE route in CarMaker has been developed for CEVT which has different driving scenarios. FC and ER for a plug-in hybrid electric vehicle in real driving conditions varied from tests on chassis dynamometer due to the influences of several factors. The results have shown that the factors which had a significant impact were vehicle speed, operating mass, road gradient, Auxiliary load, and aggressiveness of a driver. Out of all the factors Figure 5.1 depicted a trend on how much the real-world factors could have a negative effect on vehicle's fuel economy and electric range. Out of all the formerly mentioned factors, it was found that speed limits had the most influence on both FC abd ER. Also the auxiliary load at different ambient temperature too, had a lot of influence on electric range. Thus making the cabin climate control model more interesting to be studied further at different ambient temperatures. Other than these factors, the traffic density also has influence on FC & ER and a more accurate model during our study would have outlined its extent of impact.
The trend illustrates that the major impact is on Fuel consumption and this is because that even a slighter effect on electric range would consequently impact on FC as the combustion engine would be the only major source of propulsion after the battery SoC reaches a minimum.

Figure 5.1: Percentage of impact on FC and ER from real-world factors



6
Recommendations

There are a few areas in the thesis work which can be further improved or developed. A potential scope of work in the future which accurately predicts the impact on FC and ER includes (i) Detailed modeling of varying loads from auxiliary devices at different ambient temperatures, (ii) A model which predicts the behavior of an Engine and the Battery at different initial temperatures, since we had assumed the vehicle was parked in the garage, (iii) A detailed battery model which takes battery ageing into account, (iv) An improved traffic model.

6.1 Dynamic behaviour of Auxiliary devices

The auxiliary load applied in the vehicle settings was constant along the whole trip, and represented only the electrical load from cabin climate control along with other standard devices required during type approval tests(Eg: cooling fan, day-time running lights.,etc). A constant load is not realistic, and in addition the driver may switch on more electric consumers. Hence, a more accurate model can be developed which predicts the dynamic load from auxiliary devices at different ambient temperatures.

6.2 Parking environment

The initial temperature of all the vehicle components was 23 degree Celsius since we had assumed the vehicle was parked in the garage, which may not be true in all cases. Different initial temperatures of vehicle components such as Engine and Battery have significant effects on the overall performance and thus it is recommended to study the effects with varying initial temperatures.

6.3 Battery model

Battery ageing is an important factor which was not considered in our scope of work. The cell longevity and rate of charge/discharge capability eventually decreases with increased number of operating cycles in a battery. Hence it is important to consider this in the future scope of work which might indicate a variation in the electric range due to battery ageing.

6.4 Traffic model

Driving behavior of all other cars in the traffic model behaved in an identical manner. They had the similar reactions in every road segment which is not the case in a real driving scenario, thus making it unrealistic. The accuracy of the model can be improved by varying the driving behavior of all other cars to make the model more realistic.

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