Politecnico di Torino

Master of Science in Automotive Engineering

Master of Science Thesis

Modelling and Simulation of Hybrid Electric Vehicles

Comparison between Two Hybrid Electric Vehicle Configurations

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Abstract

Innovation is the most important driving force in engineering and the goal of reducing emissions and creating a greener environment is pushing companies hard to create new technologies or improve existing technologies to achieve higher efficiency values. Use of electric machines along with the standard powertrain of a vehicle is defined as hybridization. Vehicle hybridization can be achieved in various levels, starting with the use of electric machines which aid starting and stopping of the vehicle all the way up to being able to drive the wheels. This master thesis deals with modeling of a hybrid vehicle as a parallel hybrid one in two different configurations.in order to achieve the best result, in the first step a hand calculation is done for finding the required power and torque for Electric motor and internal combustion Engine in continuous and transient performances as well as on cycle analysis. With applying the obtained results and given data on model, a lot of comparisons will be available between two configurations regarding fuel consumption and mechanical characteristics.

Keywords: Modeling, Parallel Hybrid vehicles, on cycle analysis, Fuel consumption

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Abbreviation

GFE: government furnished equipment

HEV: hybrid electric vehicle

FCS: fuel cell systems

CVT: continuous variable transmission

ICE: Internal combustion engine

EM: Electric motor

UDC: urban driving cycle

GVM: gross vehicle mass

NEDC: new European driving cycle

LVH: lowest value heating

FAER: fuel air equivalence ratio

BMEP: brake mean effective pressure

FMEP: friction mean effective pressure

SOC: state of charge

DOD: depth of discharge

ECU: engine control unit

1

Introduction

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

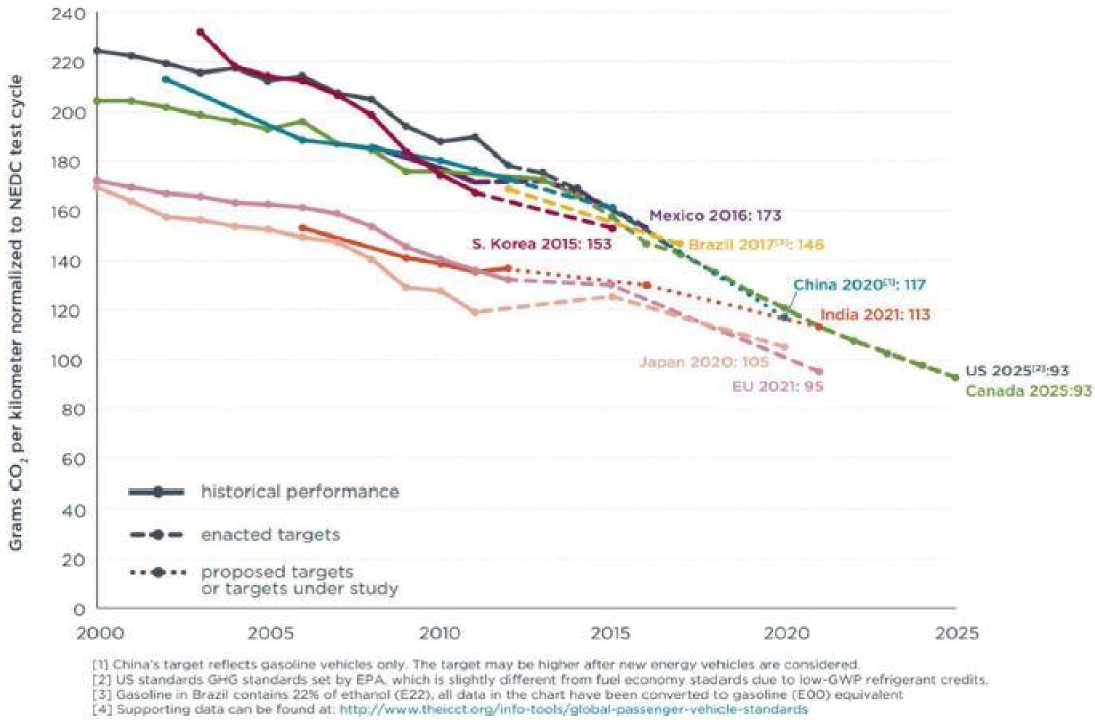


Figure1.1: *CO2* regulations for passenger cars [1]

In order to meet regulation requirements, the usage of alternate sources of energy to propel vehicles is increasing. These alternate sources can be used as a standalone form of energy for propulsion or be combined with existing propulsion systems to decrease the harmful effects on the environment. The use of these two systems combined for propulsion of the vehicle can be defined as hybridization. The most common sources of energy in such systems are the use of an internal combustion engine and an electric motor. ICE, EM, Battery pack or super-capacitor and gearboxes form the crucial components of a hybrid powertrain system. Sizing of these components is essential in order to achieve high levels of efficiency of each of the subsystem individually and when combined.

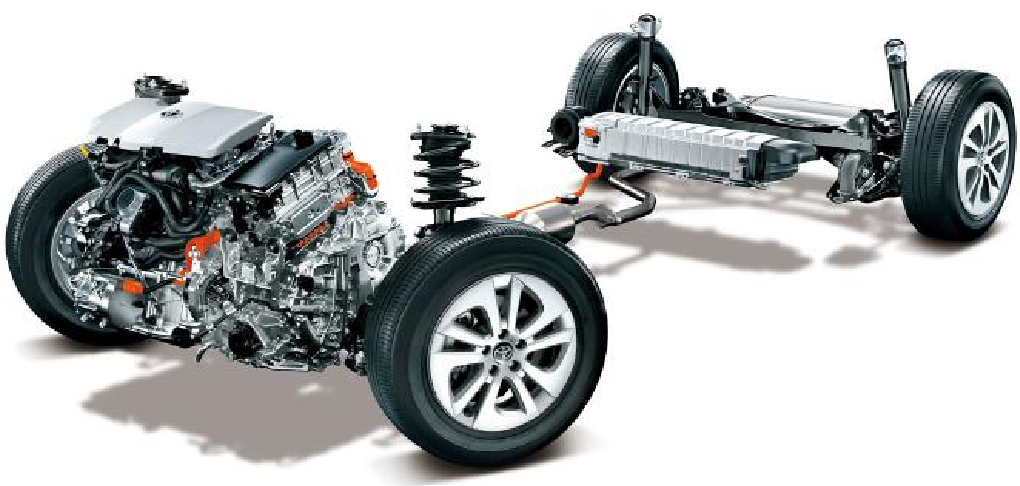


Figure 1.2: Example of a Hybrid powertrain - Toyota Prius [2]

The simulation platform chosen for this study is the new version of LMS Imagine. Lab Amesim software which is called Simcenter Amesim. The software package is included proper tools in order to model, analyze and predict the performance of various systems.

This software with using of a set of libraries for different physical domains is a pioneer for a complete 1D simulation suits to model and analyze multi-domain, intelligent systems and predict multi-disciplinary performance. The modeling of each system is done in four steps:

- Sketch mode: it links the different components.
- Sub model mode: it chooses the physical sub model associated with each component
- Parameter mode: it sets parameters for each sub-model.
- Run mode: it starts the simulation and gets the results.

1.1 Methodology

Work was primarily divided into two stages.in the first step all given data by the main client and all assumed data by the consulting company are considered in order to do hand calculation for finding the target of main vehicle component with respect to primary preconditions. And the second step is making the model for two configurations regarding all obtained results and making a comparison between the two models.

1.2 Deliverables

The deliverables of this thesis are listed below:

- Obtaining the results of continuous and transient performances for ICE and E-motor through the hand calculations.
- Performing on cycle range and on cycle UDC analysis.
- Making vehicle modelling for P2 and P3 hybrid configurations, using applying all results obtained with hand calculations.
- Making comparisons between the results of two configurations regarding fuel consumption and other component's outputs.

1.3 Limitations

During the course of the project there might be several limitations to achieving the set goals and deliverables. Some of them are discussed in this section.

Key limitations were listed as mentioned below:

• After reviewing some pieces of literature we found that there is a lack of standard drive cycle for analysis, which makes it difficult to judge technologies and understand how the military can benefit from a hybrid vehicle. This could be the fact that military threats are constantly changing and it is generally unknown where a military vehicle would be needed. [4]

• The concept of an Electrical duty cycle is completely omitted, whereas Military vehicles are equipped with government furnished equipment (GFE), defined as communication devices, weapons systems or any other military-specific item. [4]

• Since the vehicle in our case of the study was a real project under research phase, except some known input parameters others are considered as an assumption by the company.

2

Theory

2.1 Classification of hybrid vehicles

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

2.1.1 Based on level of hybridization

Micro Hybrids

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

Mild Hybrids

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

Full Hybrids

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

Plug-In HEV (PHEV)

A plug-in hybrid vehicle is much like a conventional hybrid, but it has the capability of being plugged in to recharge the battery.

Plug-In hybrids are designed to travel relatively-long distances without help or little from the ICE (all-electric range). Even before the charge is completely used up, the engine may provide additional power for recharging the battery, accelerating, or in order to climb a hill.

The main difference between the Plug-In hybrid and conventional hybrid is that the Plug-In can potentially use the electric motor as the primary power source, and the ICE to provide additional /needed power.

2.1.2 Based on powertrain design/architecture

Series Hybrid Vehicle

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

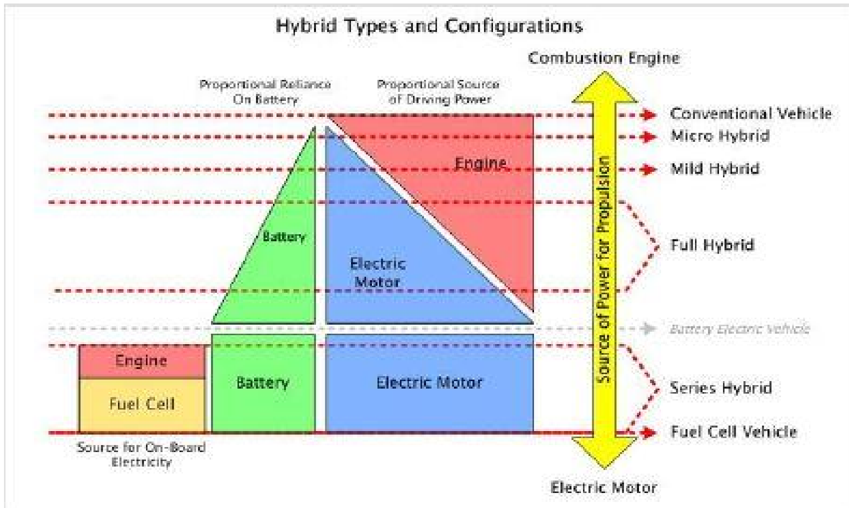


Figure1.1: HEV classification based on level of hybridization [3]

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

Also based on hybridization ratio for series Hybrid we have this classification:

- **RANGE EXTENDER**

low degree of hybridization.it is a sort of thermally assisted electric vehicle ,in which the ICE works at a fixed point (max.efficiency) and it is used to charge the batteries .the ICE (and the electric machines connected to the ICE) is designed in order to provide the average power during the desire driving cycle. The range is related to the tank size.
Reduction of battery pack since the necessity to have a sufficiently long range in pure electric conditions.

Drawbacks of the range extender HEV:

1) Since the whole vehicle dynamic is managed by the batteries, problems might arise when a long driving range is also required in pure electric mode, due to the well-known trade-off between energy and power capabilities of battery packs.

2) Battery charge cycles have efficiency lower than unity, thus further reducing efficiency of energy transfer process from ICE to wheels.

- **LOAD FOLLOWER**

ICE+generator are designed to produce maximum steady-state power. The ICE does not work at a fixed operating point but follows the time history during the cycle .during transient ,i.e. When peak power is requested ,the battery pack produce the power gap .the system is characterized by higher efficiencies (reduce charge /discharge cycles of the batteries)and performance.

FULL PERFORMANCE

ICE+generator are designed to produce maximum peak power.it is usually not an interesting solution for ICE application, but can be used with HEV in which ICE is replaced by FCs.

Parallel Hybrid Vehicle

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

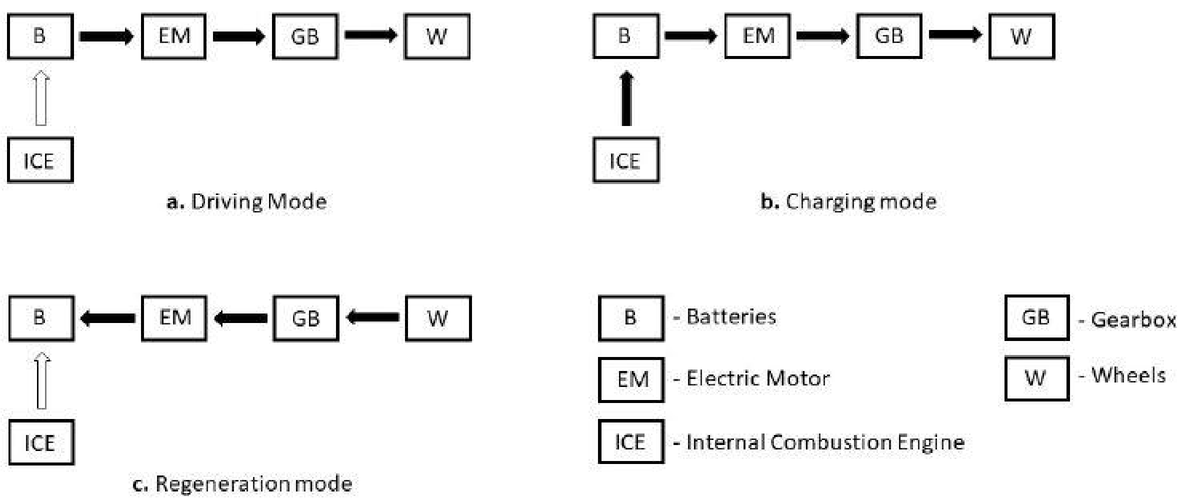


Figure 2.2: Architecture and Power-flow in a series hybrid vehicle

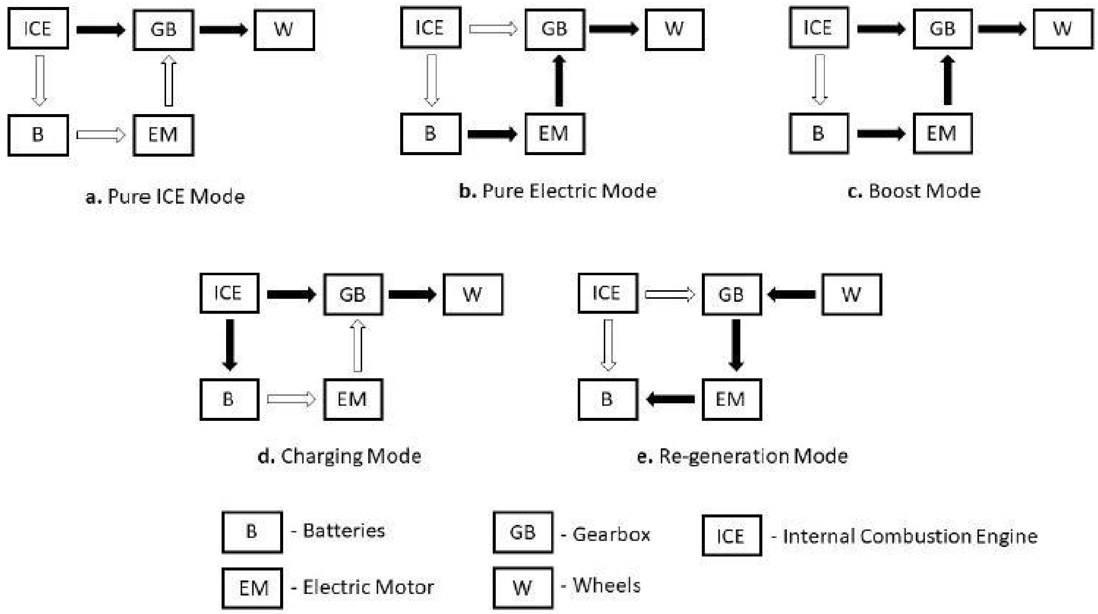


Figure 2.3: Power-Flow in a parallel hybrid vehicle

At low speeds or initial acceleration conditions, the vehicle can function on pure EV mode given that the ICE operates at less efficient regions and the torque capacity of the EM is very high. At high power demand conditions, can power the wheel simultaneously to compensate for the lower power output of a downsized engine.

Under normal running conditions, the vehicle can operate under pure ICE mode as it operates under a better efficiency region when compared to that of an EM.

Series-Parallel Hybrid Vehicle

Commonly referred to as 'Split Hybrids', this system as the name suggests contains elements of both series and parallel hybrid systems. The primary difference between a split hybrid and the conventional hybrid systems is the presence of two motors/generators compared to the single motor/generator in a regular series and parallel hybrid vehicles. The power flow is managed via a planetary gearbox and belt driven Continuously Variable Transmission (CVT). Figure 2.4 represents the generic architecture of a split hybrid system.

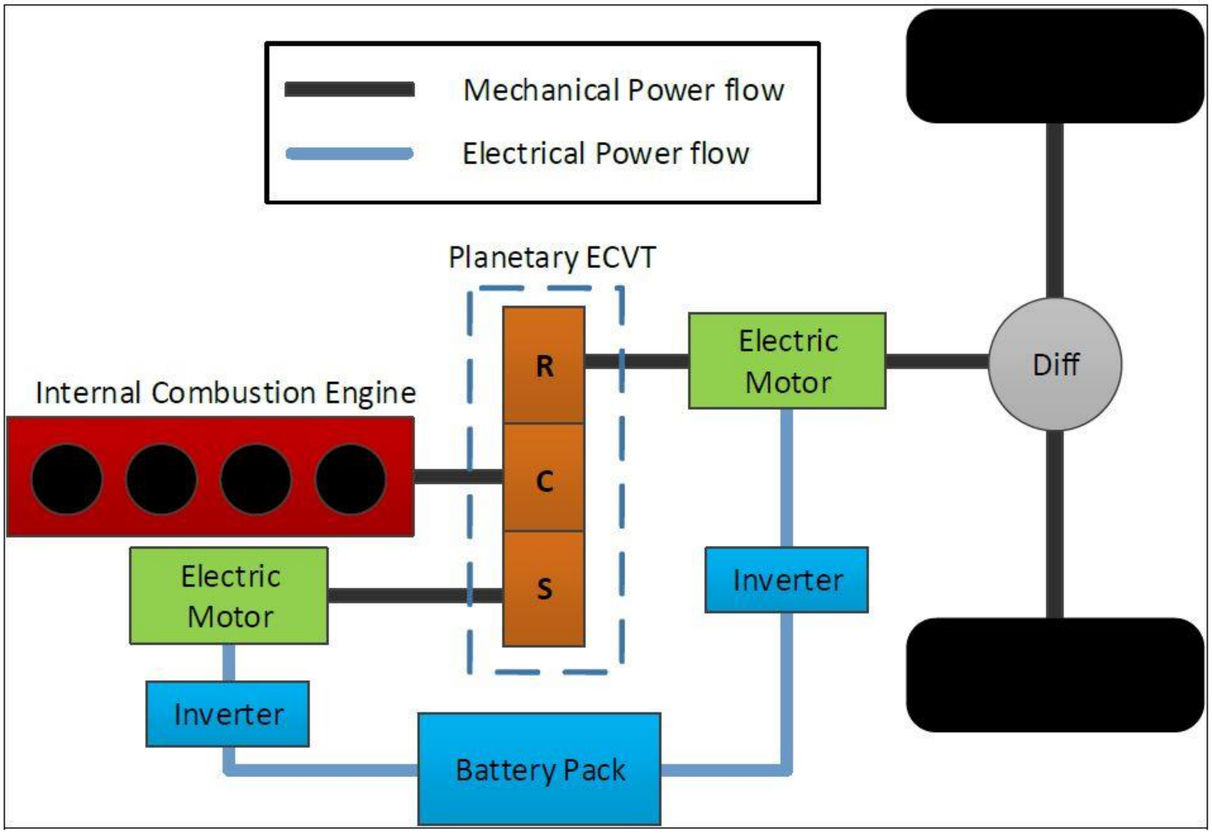


Figure 2.4: Power-Split Hybrid Powertrain Architecture

Also depends on position of electric motor, we have another category of hybridization architecture.

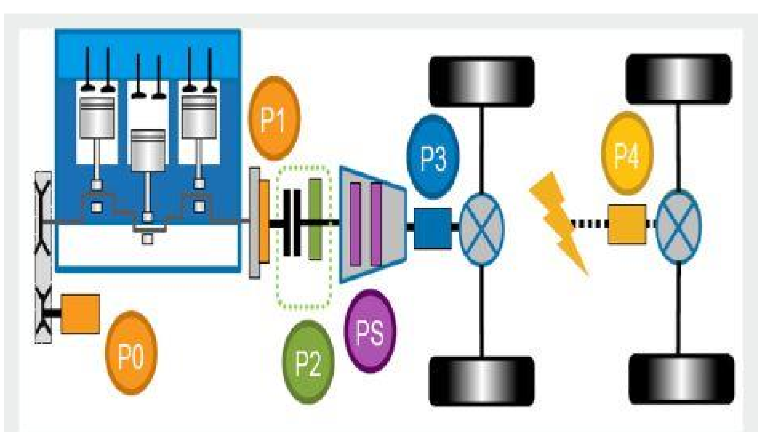


Figure 2.5: hybridization architecture based on electric motor position

P0	With a belt, the electric machine is linked with internal combustion engine
P1	The electric machine is link with the crank shaft of internal combustion engine directly.
P2	With a belt or integrated between ICE and transmission, the electric machine is side-attached and it is decoupled from ICE with a clutch.
Ps	Both on primary or/and secondary shaft, The electric machine can be installed inside of gearbox.
P3	After gearbox on final drive, The electric machine is installed.
P4	The electric motor supply the torque to an axle or wheels hub directly.

Table 2.1: architecture explanation based on the electric motor position

P0: Micro Hybrid

P1: Mild Hybrid

P2, Ps (power split), P3: Full Hybrid .Plug-in Hybrid

P4: BEV

2.2 Advantages and Disadvantages

Advantages of a series HEV are:

1. The optimization of engine operation and efficiency are done in Series hybrid systems. The ICE can be run at its most efficient point and shut off when it is not needed, since it is not connected directly to the wheels. The systems also remove any need to clutches and conventional transmissions.
2. The location of engine-generator set can be flexible
3. Being suppleness of drivetrain
4. Compatibility for short trips

The disadvantages of a series HEV are:

1. It requirements to have three propulsion components: ICE, generator, and motor.

2. It needs to design the motor for the maximum power in sustain condition which the vehicle may require, such as when rising a high grade. However, the vehicle works below the maximum power most of the time.

3. Require to size of all three drivetrain components for maximum power for long-distance, sustained, high-speed driving. This is required since the batteries will exhaust quickly, which force the ICE to supply all the power with the generator.

The following are advantages of a parallel HEV:

1. Only two propulsion components is needed: ICE and motor/generator. In parallel HEV, the motor can be used as a generator and vice versa.

2. We can use a smaller engine and a smaller motor with the same level of performance until batteries are depleted. For short-trip distance, both can have the rating half of the maximum power to provide the total power, with the assumption that the batteries are never depleted. For long-distance trips, the engine would be graded for the maximum power, while the motor/generator may still be graded to half the maximum power or smaller.

3. There is no necessity to have Multi-conversion of the power from the engine to the driven wheels.

4. Higher Overall efficiency.

The following are disadvantages of a parallel HEV:

1. Increasing the complexity of the control, since power flow has to be organized and mixed from two parallel sources.

2. Needing the complex mechanical device due to the blending power from the ICE and the motor.

2.3 Engine and Motor Operation in each system

The figure below shows difference the ratio of use between engine and motor which is depending on the hybrid system.

Since in a series hybrid, engine is used to generate electricity for the motor to drive the wheels, the engine and motor have more or less the same amount of work.

But in a parallel hybrid, the engine is used as the main power source, and motor is used only to provide assistance during acceleration. So, the engine is used much more than the motor.

In a series/parallel hybrid (THS in the Prius), the power from the engine is divided by a power split device, so there is continuously variable in the ratio of power which is going to the wheels directly and to the generator. Since the motor can run with generated electrical power, the motor is used more than in a system of parallel.

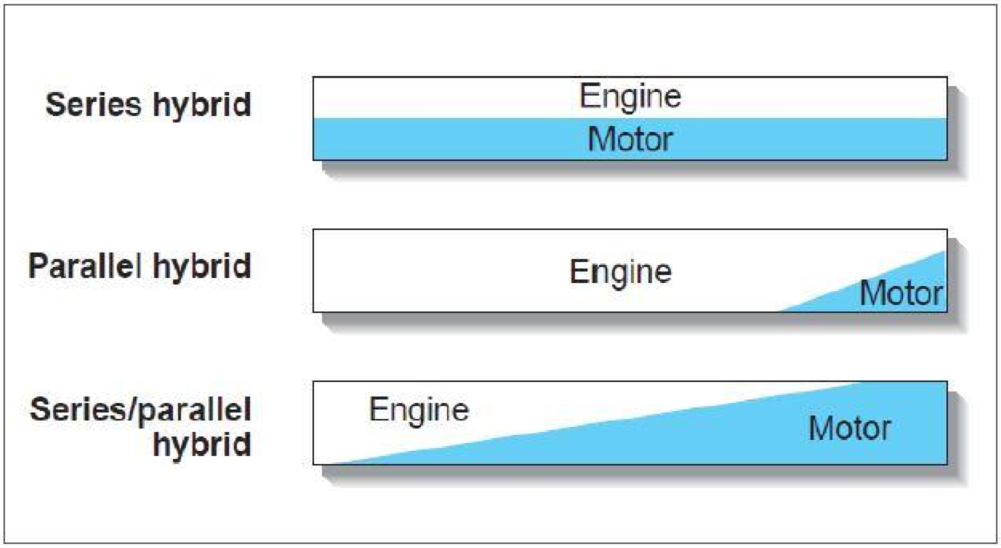


Figure 2.6: ratio of engine and motor operation in hybrid systems

2.4 Characteristics of Hybrid Systems

Hybrid systems have the following four characteristics:

1) ENERGY-LOSS REDUCTION

The system automatically stops the idling of the engine (idling stop), thus reducing the energy that would be wasted.

2) ENERGY RECOVERY AND REUSE

Wasting energy as a heat during deceleration and braking is recovered as electrical energy, then provided to power the starter and the electric motor.

3) MOTOR ASSIST

The engine is supported by electric motor during acceleration.

4) HIGH-EFFICIENCY OPERATION CONTROL

The vehicle’s overall efficiency will be maximized by using the electric motor in order to run the automobile under operating conditions in which the efficiency of engine is low and by generating electricity under operating conditions in which the efficiency of engine is high.

All of these characteristics are included in the series/parallel hybrid system and therefore provides both fuel efficiency and driving performance.

	Fuel economy improvement				Driving performance	
	Idling stop	Energy recovery	High-efficiency operation control	Total efficiency	Acceleration	Continuous high output
Series	●	◎	●	●	○	○
Parallel	●	●	○	●	●	○
Series/ parallel	◎	◎	◎	◎	●	●

◎ Excellent ● Superior ○ Somewhat unfavorable

Table 2.2: hybrid system comparison

3

Review on military vehicle classifications

In worldwide operations, many different vehicles are used but there are only three different military vehicles used for all of the publications: High Mobility Multipurpose Wheeled Vehicle (HMMWV), shown in Figure 3.1, Family Medium Tactical Vehicle (FMTV), shown in Figure 3.2, and Heavy Mobility Expanded Tactical Truck (HEMMTT), shown in Figure 3.3. These three vehicles include a wide range of weights from 4,536 kg to 14,970 +kg, indicative of class III through class VII vehicles. Moreover, the data related to these vehicles for design specifications and performance is readily available. [4]

Figure 3.1: Class III HMMWV [4]

Figure 3.2: Class VI - VII FMTV [4]

Figure 3.3: Class VIII HEMMTT [4]

Depending on power system design and drive cycles, parallel hybrid configurations (a class III HMMWV) can realize between 4.3-45.2% fuel economy improvements.
The results of this reference indicate that for parallel hybrid powertrains, in smaller class vehicles there exists more opportunity for fuel efficiency improvement. The series hybrid

shows more possible opportunity for improvement in the very large class VII-VIII vehicles than a parallel one. [5]

After reviewing of kinds of publications for military hybrid vehicles and mission of our vehicle in this thesis with a structure which is shown in figure 3.4, the parallel hybrid configuration is chosen for this project.

Figure 3.4: the vehicle which is considered for this project

4

Methods

The approach to vehicle modeling, the key components during each of the modeling process are all explained in this section. During the modelling, all mechanical components are extracted in IFP-DRIVE library in Simcenter.

4.1 Given data

All main given data by the main client are listed below:

- Kerb vehicle weight(the vehicle weight without occupants or baggage): 2,550 kg
- Gross vehicle mass-GVM(maximum operating mass of the vehicle): 6,000 kg
- Maximum speed : 140 km/h
- Gradient capability: 60% fully laden from static
- Engine type/Model: Ford 3.2L I5 Engine, common rail direct injection with turbocharger. All technical specification shown in table 4.1.
- Transmission: ZF 6-speed automatic 1revers gear. All technical specification shown in table 4.2.
- Transfer unit : open differential

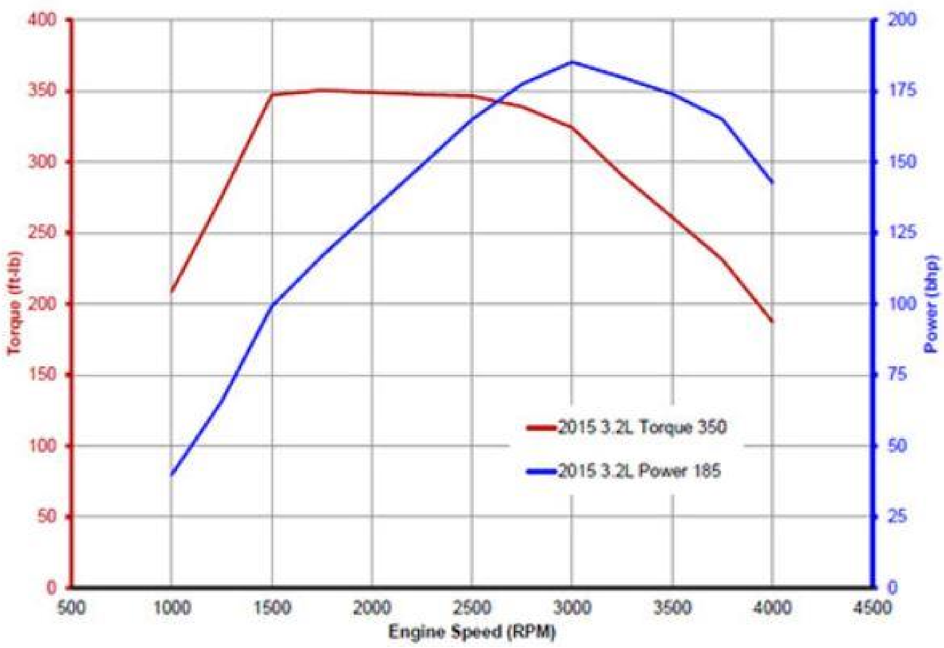


Figure 4.1: 3.2L POWER STROKE HORSEPOWER/TORQUE CURVES [6]

Engine:	Ford 3.2L Power Stroke Inline 5 diesel
Applications:	2015 - current Ford Transit
Displacement:	3.2 liters, 195 cubic inches
Block Material:	Cast iron
Cyl. Head Material:	Aluminum
Firing Order:	1-2-4-5-3
Compression Ratio:	15.8 : 1
Bore:	3.54 inches (89.9 mm)
Stroke:	3.96 inches (100.76 mm)
Aspiration:	Electrically actuated single variable geometry turbocharger (VGT), air-to-air intercooler (CAC, charge-air-cooler), composite intake manifold
Injection:	Direct injection, high pressure common rail (26,100 psi), Piezo electric injectors
Valvetrain:	OHV, dual overhead camshafts, 4 valves per cylinder
Emissions Equipment:	EGR, SCR, SBS (single brick system, combination DPF and DOC)
Engine Weight:	514 lbs w/ oil
Oil Capacity:	12 qts w/ filter
Fuel:	ULSD, B20 biodiesel compatible
DEF Tank Capacity:	5.5 gallons
Peak Horsepower:	185 hp @ 3,000 rpm
Peak Torque:	350 lb-ft @ 1,500 -2,500 rpm

Table 4.1: 3.2L POWER STROKE SPECIFICATIONS [6]

Figure 4.2: 6HP28 Automatic Transmission [7]

Transmission type	6HP28		
Type of drive	Standard drive		
Input torque	Max. 440 Nm	Max. 600 Nm	Max. 650 Nm
Torque converter	W255RH-4GWK TTD	W270RH-4GWK TTD	ZDW260RH-4GWK
Standard ratios /Gears			
1	4.17		
2	2.34		
3	1.52		
4	1.14		
5	0.87		
6	0.69		
R	3.40		
powered axle	3.73		
weight	84 kg	89 kg	92.5 kg
Oil capacity	10 dm^3		
Transmission oil	Lifetime oil fill		

Table 4.2: 6HP28 Automatic Transmission Specifications [7]

4.2 Hand Calculations [8]

In this work, hand calculations are done based on the given data and all assumptions which are listed below. This task is done in order to find continuous and transient performance for ICE and EM considering the preliminary conditions. As NEDC cycle is chosen for mission profile, also on cycle UDC analysis is computed during this work as to find the energy at battery terminals and number of cycle with/without regenerative braking.

NOTE: all calculations are based on P2 configuration but for having same level of comparison, all obtained results are considered also for modelling of P3 configuration.

All available data which are deal during calculations are listed in Table 4.3.

Kerb weight	2,550 kg
Payload capacity	3,450 kg
Vehicle translating apparent mass(M_{at})	5% more than the kerb weight
Rolling resistance coefficient (Kr)	13 kg/ton
Air density (ρ)	1.23 kg/m^3
Gravity(g)	9.81 m/s^2
Aerodynamic coefficient (Cx)	0.4
Frontal Area(Af)	3.24 m^2
Wheel rolling radius(Rd)	0.35 m
Vehicle auxiliaries power	200 W
Base speed	3000 RPM
Max speed	9000 RPM
Transmission efficiency	95%
E-motor efficiency	90%
inverter efficiency	95%
Battery round trip efficiency	78%
The fixed speed ratio for E-motor	2
The first gear ratio of gearbox	4.17
Final drive ratio	3.73

Table 4.3: input data for calculations

Hypothesis: 2/3 of breakable kinetic energy is electrically regenerated.

The condition considering obtaining desired results are listed in Table 4.4.

EM	Maximum speed	50 km/h
	slope	35 %
	EV range	75 km
ICE	Maximum speed	140 km/h
	slope	60 %

Table 4.4: given condition for calculation

Note: since the maximum speed for E-motor is 50 km/h so we can consider just one UDC as our cycle.

- Duration: 195 s
- Distance: 994.03 m
- Average speed: 18.35 km/h

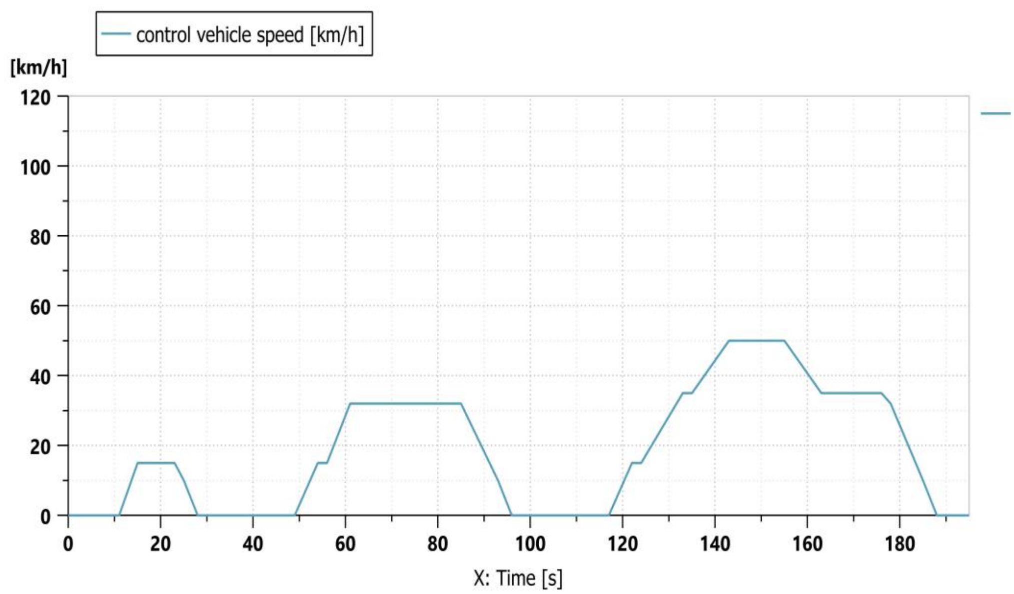


Figure 4.3: one UDC considered as our cycle

4.2.1 E-Motor computations

- **Continuous performance**

1) Considering maximum continuous speed on level road is equal to 50 km/h:

$P_{rol@Vmax}$=M.g. Kr.Vr.cos(α)=10.63 kw (4.1)

$P_{aer@Vmax}=\frac{1}{2}.\ \rho.\ C_x.\ A_f.Vr^3=2.1$ kW (4.2)

$P_{r\text{-}total}=12.76$ kW (4.3)

$P_{continuous}=\frac{Pr-total}{transmission\ efficiency}=13.43$ kW (4.4)

Where:

$P_{rol@Vmax}$: rolling resistance power at maximum speed at wheels [W]

$P_{aer@Vmax}$: aerodynamic power at maximum speed at wheels [W]

$P_{r\text{-}total}$: total resistance power [W]

$P_{continuous}$: continuous power of electric motor [W]

M: Gross vehicle mass [kg]

2) Considering 15% continuous gradeability at 10 km/h:

$P_{rol}=M.g.\ K_r.V_r.\cos(\alpha)$

$P_{aer}=\frac{1}{2}.\ \rho.\ C_x.\ A_f.Vr^3$

$P_{slop}=M.g.V_r.\sin(\alpha)$ (4.5)

$P_{tot}=27760.8$ W

$T_{continuous}=\frac{P-total}{\omega}=112.4$ N.m (4.6)

Where:

P_{slop}: slope power at wheels [W]

$T_{continuous}$: continuous torque of electric motor [W]

$\omega=\frac{(Vr/3.6)}{Rd}*\text{transmission ratio}$ (4.7)

transmission ratio=2*4.17*3.73

- **transient performance**

Acceleration from 0 speed on 35% slop with an acceleration a=3 m/s^2:

$T_{rol}=\frac{M.g.Kr.Rd.\cos(\alpha)}{\text{transmission ratio}*\text{transmission efficiency}}$ (4.8)

$T_{slop} = \frac{\text{M.g.Rd.sin}(\alpha)}{\text{transmission ratio}*\text{transmission efficiency}}$ (4.9)

$T_{dyn} = \frac{M_{at}\ \text{.a.Rd}}{\text{transmission ratio}*\text{transmission efficiency}}$ (4.10)

$T_{transient=}$ 456.5 Nm

Where:

$T_{rol:}$ rolling resistance torque [Nm]

$T_{slop:}$ slope resistance torque [Nm]

$T_{dyn:}$ dynamic torque [Nm]

$T_{transient:}$ transient torque of electric motor

M_{at}: Vehicle translating apparent mass under test conditions [kg]

- **on cycle range**

Considering power auxiliaries with average consumption 200 W:

On cycle range=200*195=39 kj =10.83 wh (4.11)

4.2.2 ICE computations

- **Continuous performance**

1) Considering maximum continuous speed on level road is equal to 140 km/h:

$P_{r\text{-}total}$=76.63 kW

$P_{continuous} = \frac{\text{Pr}-\text{total}}{\text{transmission efficiency}}$=80.67 kW

2) Considering 15% continuous gradeability at 20 km/h:

P_{tot} =27760.8 W

$T_{continuous}=\frac{P-total}{\omega}$=225.3 N.m

Where:

$\omega=\frac{(Vr/3.6)}{Rd} * \text{transmission ratio}$

transmission ratio=4.17*3.73

- **transient performance**

Acceleration from 0 speed on 60% slop with an acceleration a=0.2 m/s^2:

$T_{transient}$= 761.9 Nm

4.2.3 on cycle UDC analysis

With applying all formula for the power and obtaining the energy subsequently for each different phase of UDC cycle, resulting in finding requested energy for traction mode and regenerative braking.

Numbers at table 4.5 in black colors are dedicated to zero-speed phase and in blue, green, red are set to constant, acceleration and deceleration phases respectively.

Duration(s)	Speed(km/h)	Requested total power(kw)	Requested total energy(Wh)
0÷11	V=0	0	0
11÷15	V=0÷15	5.019	2.772
15÷23	V=15	3.246	7.213
23÷28	V=15÷0	1.473	1.003
28÷49	V=0	0	0
49÷61	V=0÷32	15.431	25.251
61÷85	V=32	7.361	49.076
85÷96	V=32÷0	-0.708	-1.509
96÷117	V=0	0	0
117÷143	V=0÷50	32.463	113.372
143÷155	V=50	12.763	42.543
155÷163	V=50÷35	-6.937	-8.894
163÷178	V=35	8.172	34.049
178÷188	V=35÷0	-1.481	-2.566
188÷195	V=0	0	0

Table 4.5: UDC cycle analysis

Following energy results are shown below:

- ✓ for acceleration and constant speed (traction mode)= 274.276 Wh (4.12)
- ✓ for regenerative braking= -11.966 Wh (4.13)

- **Energy at battery terminals (for each cycle):**

✓ Traction mode ⟶ $\frac{274.276}{\text{trans.eff.} * \text{E}-\text{motor eff.} * \text{inverter eff.}}$+auxiliaries=348.53 Wh

(4.14)

✓ Regenerative raking ⟶ $\frac{2}{3}$*(-11.966)* $\frac{95}{100} * \frac{90}{100} * \frac{95}{100} * \frac{78}{100}$= -5.1 Wh

(4.15)

✓ Total=343.43 Wh

- **Considering the EV range is 75 km and specific energy for NIMH battery is 120 $[\frac{\mathbf{Wh}}{\mathbf{kg}}]$:**

✓ Number of cycle = $\frac{75*1000}{994.03}$=75 (4.16)

✓ Requested energy= Number of cycle*total energy=25757.25 Wh (4.17)

✓ Minimum battery weight=$\frac{\text{Requested energy[Wh]}}{\text{specific energy}[\frac{\text{Wh}}{\text{kg}}]}$=214.64 Kg (4.18)

✓ Number of cycle without regenerative braking=$\frac{\text{Minimum battery weight}*\text{speciifc energy}}{\text{energy for traction mode}}$=74 (4.19)

✓ Range without regenerative braking =$\frac{\text{Number of cycle}*\text{total lenght of cycle}}{1000}$=73.55 Km (4.20)

4.3 vehicle model

The vehicle which is modeled for this thesis work is a Parallel Hybrid Vehicle which consists of an ICE and EM installed after and before gearbox in two configurations. There are lots of components model with their sub-model help to make 1D-Modelling and simulation. The Main models to be considered in following.

4.3.1 Drive Cycle

Drive cycle is the most crucial part of the entire model when using quasi-static approach. The standard drive cycle consists of set of speed, acceleration, time and elevation profiles. The amount power required by the vehicle is calculated using these values of acceleration and velocity which is explained in the following section. The total distance driven, X_{tot} (4.21) is defined as the sum of all velocity steps v_i multiplied by step size h.

$$X_{tot}=\sum_{i=0}^{n} \mathrm{vi} * \mathrm{h} \qquad (4.21)$$

The various drive cycles used are briefly explained in following section.

1: **WLTP (Worldwide harmonized Light Vehicle Test Procedure)** - The drive cycle, in general is divided Into 3 classes with average and maximum speed achievable increases with increase in class. Each class is further divided into various parts namely low speed, medium speed, and high speed. Class 3 of the drive cycle however is divided into 4 parts with an extra high speed along with the standard three parts. The four parts of drive cycle can be observed clearly from the velocity profile shown in Figure 4.4.

2: **EUDC (Extra Urban Driving Cycle)** - The EUDC is a short driving cycle which was designed to represent aggressive, high speed driving modes. Figure 4.5 represents the velocity and acceleration profiles of the extra urban driving cycle.

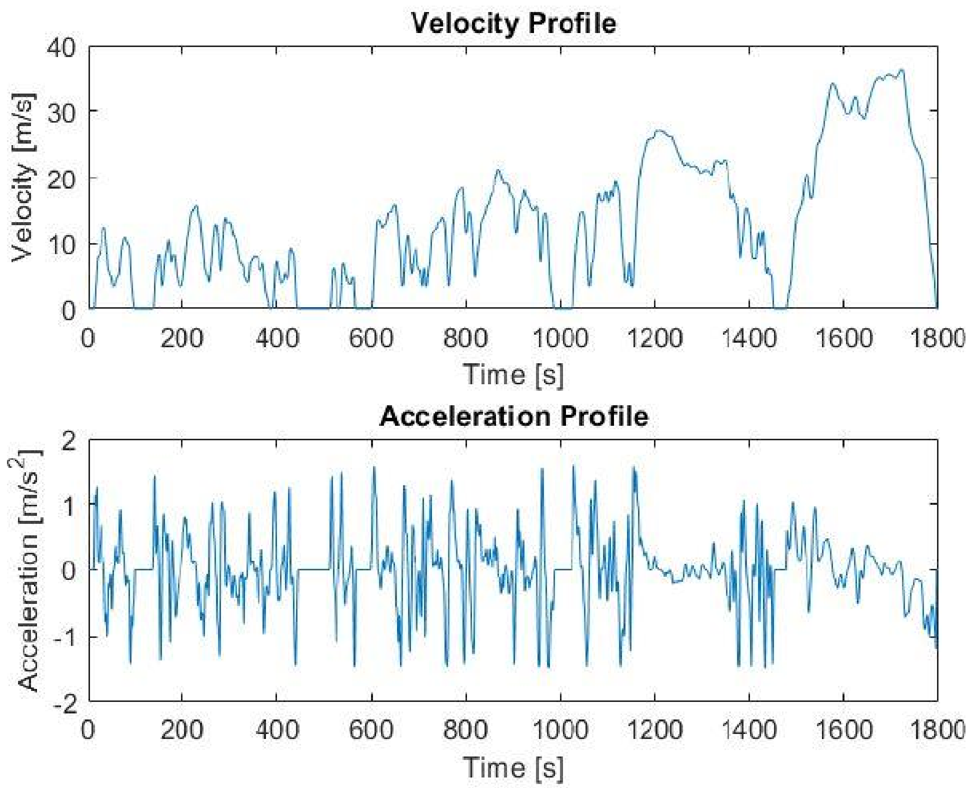


Figure 4.4: velocity and acceleration profiles in WLTP: Class 3

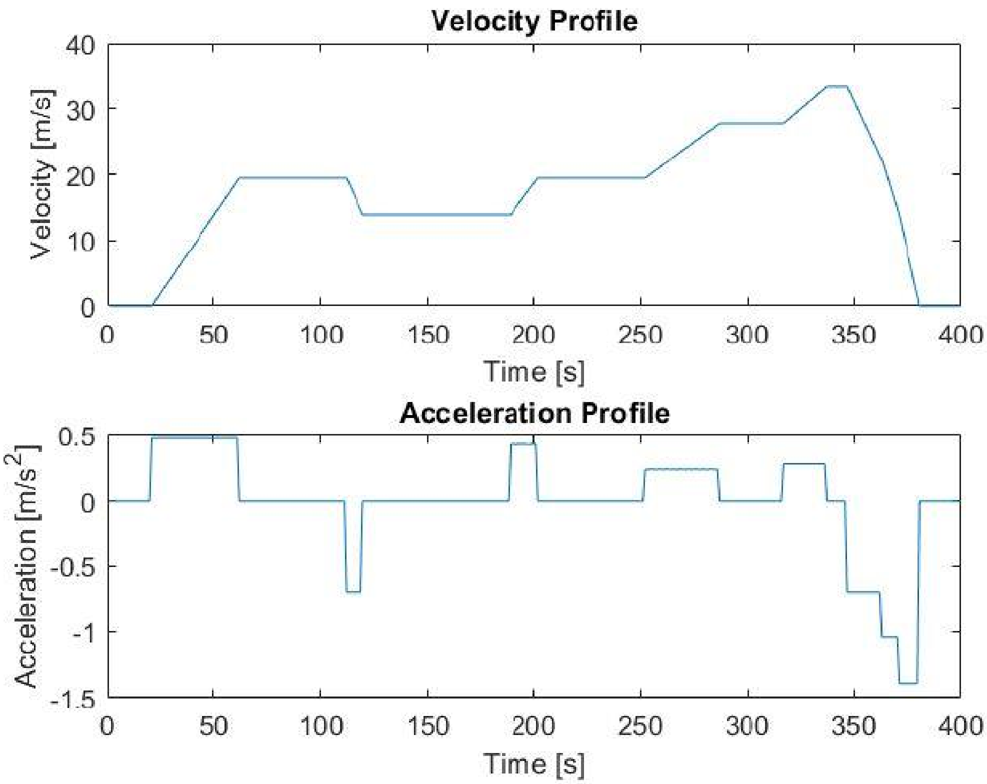


Figure 4.5: velocity and acceleration profiles in EUDC

3: **NEDC (New European Driving Cycle)** - The NEDC, which is supposed to represent the typical car usage in Europe consists of a repeated cycles of Urban Drive Cycle (ECE-15) as phase-1 and EUDC as phase-2.The two phases of the driving cycle can be viewed in Figure 4.6.

4**: FTP-75** - The Environmental Protection Agency (EPA) of the United States of America defined the drive cycle for analysis of fuel consumption and emission levels at the end of the tailpipe for cars. Figure 4.7 shows the velocity and acceleration profiles for FTP-75. This drive cycle represents the typical daily commute for passenger cars in the US.

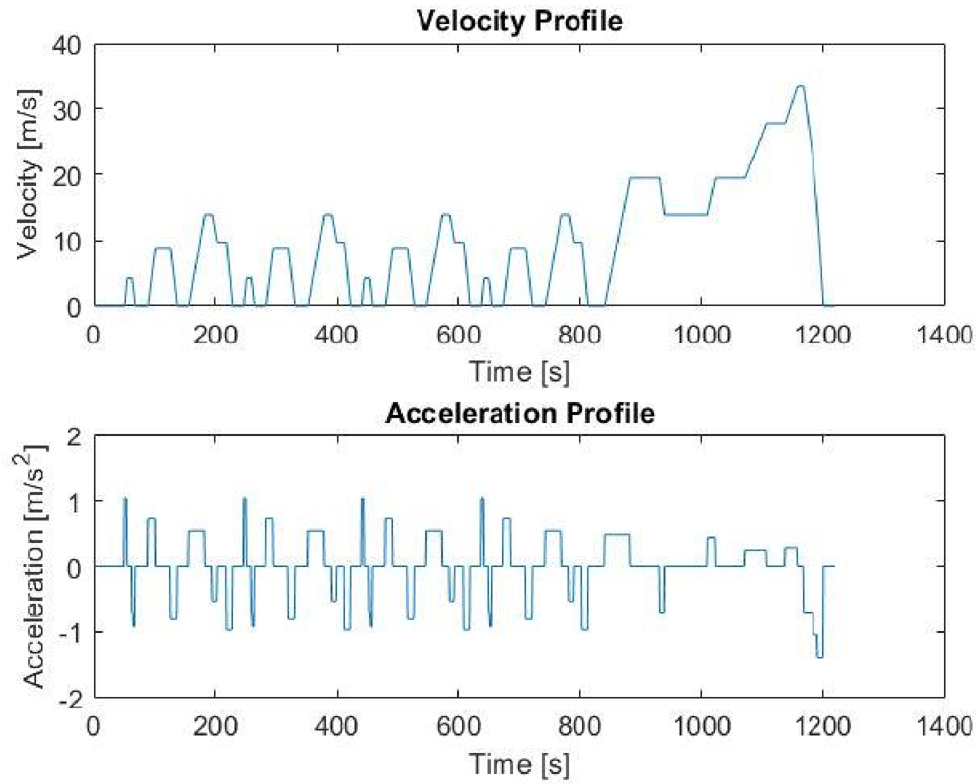


Figure 4.6: velocity and acceleration profiles in NEDC

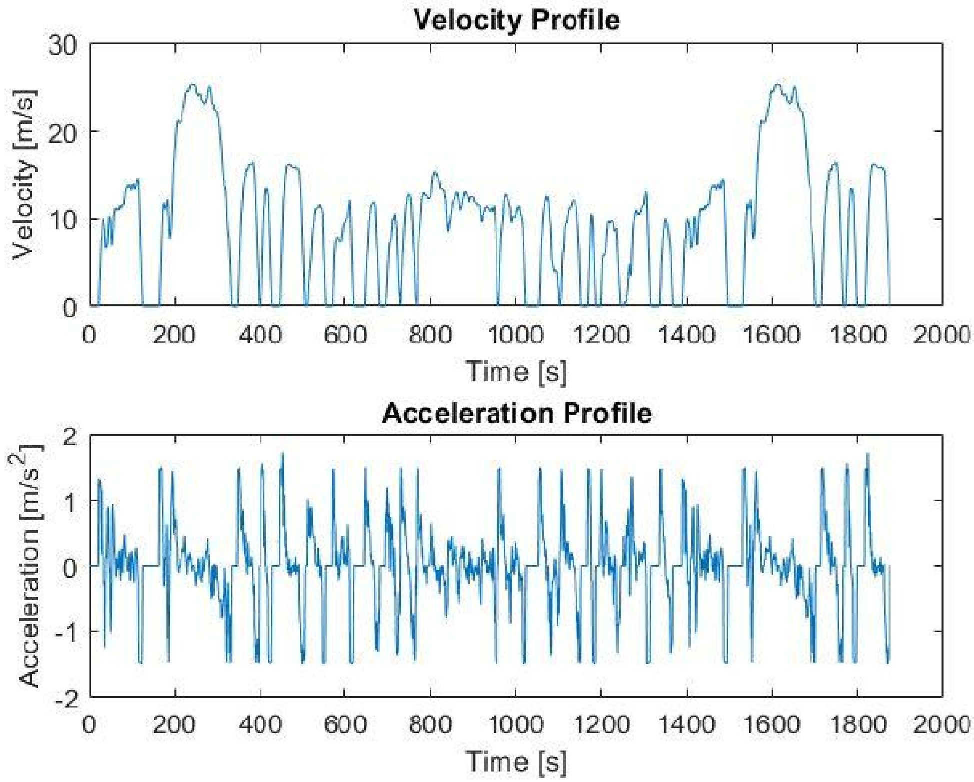


Figure 4.7: velocity and acceleration profiles in FTP-75

In this work, since the mention military hybrid vehicle is used just for patrolling inside the city, so NEDC driving cycle is chosen as the mission profile.

4.3.2 ICE [9]

Engine component should be used whenever an engine performance over a cycle is required. The prediction of the fuel consumption or emissions over driving cycles is accurate and has a low CPU cost (fixed time step compatible). Engine component should be used whenever an engine performance over a cycle is required. The prediction of the fuel consumption or emissions over driving cycles is accurate and has a low CPU cost (fixed time step compatible).

✓ Combustion mode

Depending on the control strategy, the engine performances may vary. Special modes can be related to consumption "fuel economy", "comfort/sport driving", related to emissions "low emissions", "DPF regeneration", "EGR variation" or any other needs.

✓ Data needed by the engine

In order to make the analysis for ICE we need to have the following data.

- Torque
- BMEP
- Fuel Consumption
- FMEP
- Equivalence Ratio
- exhaust temperature

The DRVICE Tables Creator tool is an interactive interface dedicated to the generation of data files necessary to use IFP-Drive Engine submodels. It allows to compute operating characteristics for a given engine considering its architecture and high end performances. It assists you to:

- Compute realistic operating characteristics for a given engine considering its architecture and high end performances
- Display plots in order to validate computed characteristics
- Create data files based on these computations, and necessary to operate IFP-Drive engine submodel.

You have to enter following parameters to compute these maps:

- Engine swept volume
- Engine stroke
- Engine number of cylinder

- Engine high-end performance, which can be either:
    - Engine maximum torque and speed at maximum torque, as well as engine maximum power and speed at maximum power
    - high end torque curve (as a function of engine speed)

All the above-mentioned parameter given in table 4.1.

The type of maximum load data is Scalar. Scalar mode should be used when only engine maximum torque and power are available. An extrapolation is made based on this data to generate a complete curve for high end torque similar to the one that should be defined in Vector mode. Maximum torque and maximum power characteristic are put in this creator same as below:

A. maximum torque 474.53 Nm @ 1850 Rev/min
B. maximum power 137.954 Kw @ 3000 Rev/min

Except for engine type, all parameters are predefined with a default value. You can use your values if necessary. Parameters default value depends on the Engine type parameter value:

For compression ignition engine all defaults value are shown in table 4.6.

Gross indicated efficiency	0.42
FAER Min. value	0
FAER max. value	0.8
Fuel Specific heating value	44000
Stoichiometric air/fuel ratio	14.5

Table 4.6: Combustion parameters default values

The fuel consumption/emissions maps used in engine can be defined in g/h or in g/kWh.

The generation process is based on an iterative algorithm illustrated below. Main principle of this algorithm is to compute the pumping losses for the different operating points of a generated {Engine Speed, BMEP} grid.

When Scalar Mode is used to set engine performances, a generic spacing of 500 rpm is applied between points from 1000 rpm until the first value higher than the max power speed defined by user. Three iso-speed value are added for idle (700 rpm), max torque speed, and max power speed. For each speed value, the grid are regularly disposed so as to have 40 points between 0.5 bar and the maximum BMEP defined by user for the given speed.

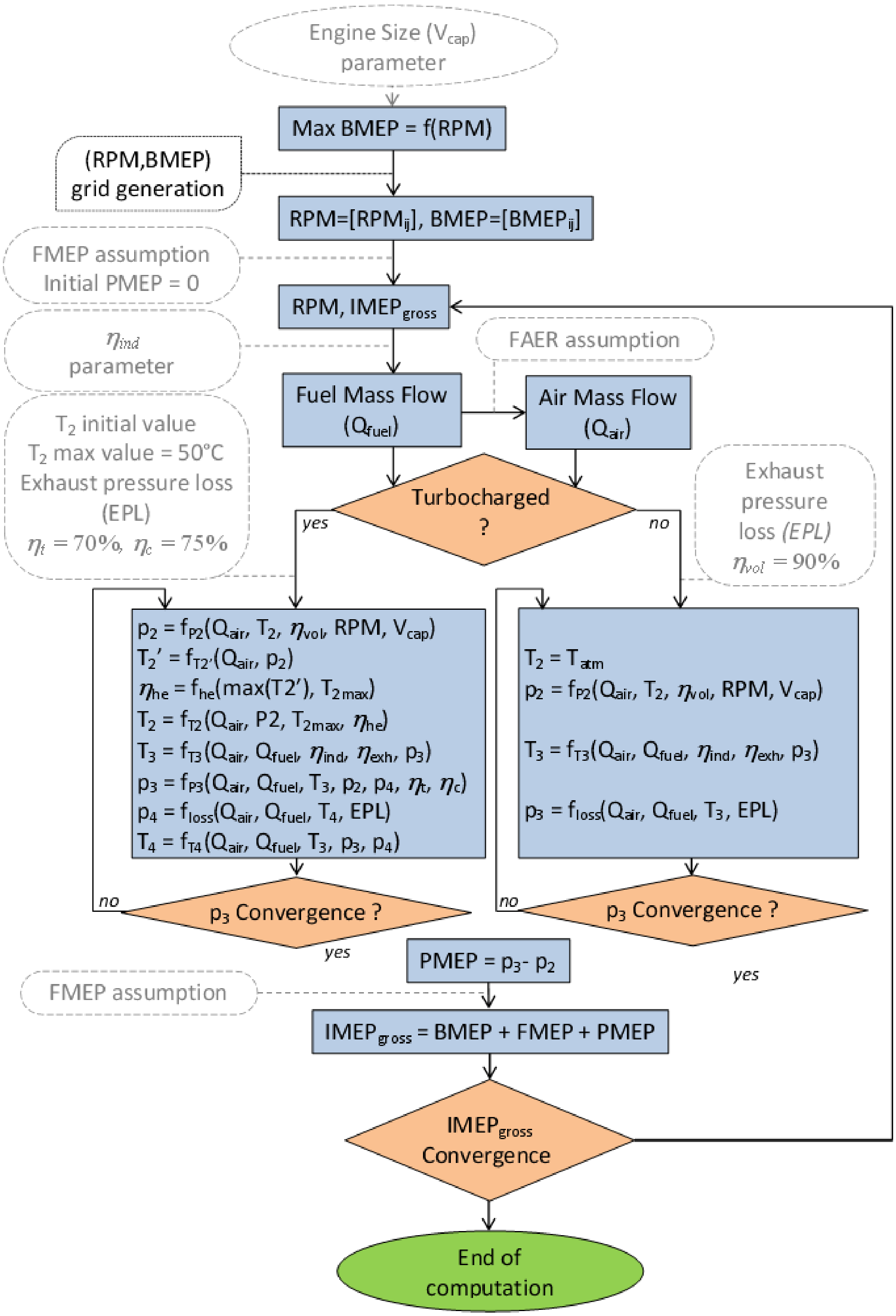


Figure 4.8: computation diagram for creating ICE data [9]

The BMEP matrix inherited from this grid will be converted in an initial gross indicated mean effective pressure (IMEPgross) matrix, considering a friction mean effective pressure (FMEP) assumption, and an initial pumping mean effective pressure (PMEP) value of 0. The computation algorithm will actualize the PMEP matrix until its value is converged.

FMEP matrix assumption is considered a linear function of engine speed, which basic formula is:

$$\text{FMEP}=\alpha\cdot\text{N}+\beta \tag{4.22}$$

β is assumed as a constant, while α may vary with engine architecture. Precisely, the value of α is adapted to take into account the influence of the engine architecture on bearings sizing, with a correction factor defined so that:

$$\alpha=\alpha ref\cdot\left[1-\sum pi\cdot\left(\frac{nb,i\cdot D^3b,i\cdot Lb,i}{nb,ref\cdot D^3b,ref\cdot Lb,ref}\cdot\frac{Vcap,ref}{Vcap}-1\right)\right] \tag{4.23}$$

Where:

- ref index refers to reference values that are to be corrected,
- i index refers to the two different sources of friction taken into account, namely cranckshaft and piston-ring assembly,
- p is the proportion of total friction taken by cranckshaft or piston-ring assembly,
- nb is the number of bearings,
- Db is the bearing diameter,
- Lb is the bearing length,
- Vcap is the engine total swept volume.

The reference values used for the FMEP computation can differ considering the combustion definition, and for compression ignition are presented in the following table.

αref [bar/rpm]	Low speed point
n*b*,*ref* (crankshaft)	5
nb,ref (piston-ring assembly)	8
D*b*,*ref*	54.1 mm
L*b*,*ref*	19.1 mm
V*cap*,*ref*	1.46 L
p (crankshaft)	21%
P(piston-ring assembly)	59 %

Table 4.7: Reference values used to determine FMEP correction

fuel mass flow is estimated considering gross indicated efficiency *ηi*,*gross* and fuel specific heating value *LHV* defined in combustion part for each point of the grid, so that:

$$Qfuel= \frac{Pi,gross}{\eta i,gross \cdot LHV} \tag{4.24}$$

Where *Pi*,*gross* is the gross indicated power associated with each operating point.

Air mass flow is deduced from fuel mass flow, based on operating fuel/air equivalence ratio (FAER) hypothesis, which depends on the chosen combustion mode.

In compression ignition engines, FAER is supposed to vary between two values (min and max defined in combustion part), thus allowing for different air mass flow possible values. The FAER value is chosen so as to minimize the difference between intake manifold pressure and atmospheric pressure, so that pumping losses can be reduced. Precisely, the choice of intake manifold pressure value for a given operating point is made considering naturally aspirated air mass flow value at atmospheric pressure:

$$Qair,atm=\eta vol\cdot\cdot Vcap\cdot \frac{RPM}{120} * \frac{patm}{Tatm} \tag{4.25}$$

Where $Vcap$ is the engine total swept volume (in $m3$), ηvol the engine volumetric efficiency (assumed to be 90%), and RPM the engine speed (in rpm).

For each point of the grid, this air mass flow, combined with previously determined fuel mass flow, allows to determine a reference FAER value:

$$FAER_{ref} = \frac{Qfuel \cdot AFRstoich}{Qair,atm} \tag{4.26}$$

- if this value is comprised between authorized min and max value, than FAER is fixed to this value and air mass flow is fixed to naturally aspirated air mass flow ($p2=patm$,$T2=Tatm$),
- if this value is below authorized min value, than FAER value is fixed to min value and air mass flow is deduced accordingly (with the same equation as spark ignition engine),
- If this value is above authorized max value, than FAER value is fixed to max value and air mass flow is deduced accordingly (with the same equation as spark ignition engine).

Once air mass flow is computed, air-path pressures and temperatures calculation is made with assumptions depending on engine architecture (turbocharged or naturally aspirated).

The mean effective pressures (BMEP, FMEP) and the torques are linked by the following relations:

For 4 stroke engine:

$$BMEP = 4 \cdot \pi \cdot Tout \cdot \frac{0.01}{V} \tag{4.27}$$

$$FMEP = 4 \cdot \pi \cdot Tfric \cdot \frac{0.01}{V} \tag{4.28}$$

Considering:

- *BMEP*: Brake Mean Effective Pressure [bar]
- *FMEP*: Friction Mean Effective Pressure [bar]
- T_{out}: engine output torque [Nm]
- T_{fric}: engine friction torque [Nm]
- *V*: engine swept volume [L]

Torque computation

The engine output torque is computed from the ECU load request as follow:

$$T_{out} = T_{maxc} \cdot load + T_{minc} \cdot (1 - load) \qquad (4.29)$$

Where T_{maxc} and T_{minc} are the corrected maximum and minimum torque.

Fuel consumption

The real fuel consumption is computed as follows:

$$Cons = cons_{file} \cdot (1 + kstart) \cdot expfcons \qquad (4.30)$$

With:

- *cons*: real fuel consumption
- $cons_{file}$: value read in fuel file
- *kstart*: overconsumption during engine start
- *expfcons*: cold temperature effect

4.3.3 Electric motor

The electric model is bidirectional (motor/generator) and independent from the technology of the motor and its converter.

2 curves are used in this component. The maximum positive torque and the maximum negative one.

Maximum torques can be set as:

- Constant
- Computed from simple data (maximum torque [Nm], maximum power [W] and maximum speed [rev/min])
- Read in file function of:
  - speed [rev/min]
  - voltage [V]
  - temperature [degC]

The negative torque can be:

- Reversed from positive torque: values are copied and sign is opposite
- Computed with same dependencies as the positive torque

If data are only available for positive speed, the same values will be used for negative speed. If data are specified in positive and in negative rotary velocity, values read will be kept as it is in the file.

In this component, peak torque should be used. Continuous maximum torques should be handled by the VCU component.

1) Torque

From the input torque request T_{set} , the torque T_{lim} is limited as follows:

$$Tmin \leq Tlim \leq Tmax$$

With T_{min} and T_{max} the negative and positive torque corresponding either to user-defined parameters or values read in tables as a function of the operating point.

The output torque T_m is determined from the limited torque T_{lim} by using a first order lag:

$$\mathrm{Tm} = \frac{1}{1+\mathrm{tr}\cdot s} \cdot \mathrm{Tlim} \tag{4.31}$$

With t_r the user-defined time constant [s].

2) Power Balance

The mechanical power P_{mec} [W] is calculated as:

$$Pmec = Tm \cdot \omega \tag{4.32}$$

Where T_m and ω are respectively the torque [Nm] and rotary velocity [rad/s] of the shaft.

The lost power P_{lost} [W] is computed either from:

- a table,
- or a user-defined efficiency η:

$$P_{lost} = (1-\eta) \cdot |P_{mec}| \tag{4.33}$$

Two modes can then be defined:

- $P_{elec} > P_{mec}$: motor mode,
- $P_{elec} < P_{mec}$: generator mode.

With P_{elec} the electric power [W].

The different operating modes of the electric motor/generator can be illustrated on the diagram:

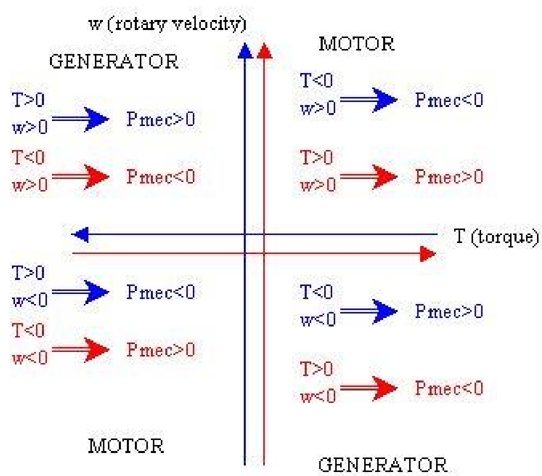


Figure 4.9: different operating modes of the electric motor/generator

So the relation between the mechanical and the electric power to take into account the Simcenter Amesim sign convention is the following:

$$Pelec = Pmec - Plost \tag{4.34}$$

With:

- $P_{mec} < 0$ in motor mode,
- $P_{mec} > 0$ in generator mode,
- $P_{lost} > 0$.

Either user-defined or deduced from P_{lost}, the motor/generator efficiency corresponds to:

- motor mode:

$$\eta = 2 - \frac{Pelec}{Pmec} \qquad (4.35)$$

- generator mode:

$$\eta = \frac{Pelec}{Pmec} \qquad (4.36)$$

3) Electrical current

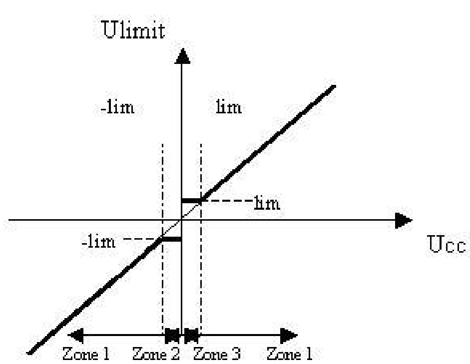
The output current I_5 [A] at port 5 is calculated as follows:

$$I5 = Pmec - PlostU \qquad (4.37)$$

Where U is the input voltage [V] given by:

$$U = V5 - V6$$

Note: to avoid division per 0, U_{lim} is used instead of U with:



- zone 1: $U_{lim} = U$
- zone 2: $U_{lim} = -10^{-3}$
- zone 3: $U_{lim} = 10^{-3}$

The Electric Motor Tables Creator tool is an interactive interface dedicated to the generation of data files necessary to use IFP-Drive motor submodels. It allows to compute operating characteristics for a given motor considering its architecture and high end performances. It assists to compute realistic operating characteristics for a given motor considering its architecture and high end performances.

Inputs

Motor architecture: buried permanent magnet synchronous motor

Continuous base power [W]: 21000 W

Maximum continuous torque [Nm]: 320 Nm

Maximum speed [rev/min]: 9000 RPM

Nominal voltage [V]: 500 V

Computation

The process is divided in several steps. The first step is the geometrical sizing of the machine, which is done to comply with the maximum peak torque.

The sizing of the motor is determined by a classical D2L sizing methodology.

The product D2L is determined from analytical expression of the torque.

- For synchronous machines:

$$Dg^2 \cdot L = \frac{4 \cdot C \cdot T}{\pi \cdot Al \cdot Bg} \qquad (4.38)$$

Considering

- D_g: the air gap diameter
- C: ratio between synchronous torque and reluctance torque
- T: the maximum peak torque
- A_l: the peak linear current density
- B_g: the peak air gap induction

- For asynchronous machines:

$$Dg^2 \cdot L = \frac{4 \cdot T}{\pi \cdot Al \cdot Bg \cdot p \cdot cos\phi} \qquad (4.39)$$

Considering

- p: pole pairs number
- $cos\Phi$: power factor

Using the ratio of the length of the machine to the air-gap diameter (χ) which is estimated by an empirical formula based on pole pairs number, the inner rotor diameter D_{in} and length of electric machine (L) can be estimated thanks to the following equations:

$$\chi = \frac{\pi}{4 \cdot p} \cdot p0.5 \qquad (4.40)$$

$$D_{in} = \left(\frac{Dg^2 . L}{\chi}\right)^{0.33} \qquad (4.41)$$

$$L=\chi \cdot D_{in} \tag{4.42}$$

Sizing of the different machines continues in different ways.

For the synchronous motors, diameters of the stator and rotor, with the number of slot per phase, are then calculated. Slot sizing is evaluated considering a trapezoidal shape. Sizes of the magnets are then calculated. Finally the number of conductors in one slot is evaluated. Mode details are presented in references [10 & 11].

For the asynchronous motors, diameters of the stator and the rotor, the sizes of the slots are then calculated. The conductor's number is evaluated.

Then, for all the machines, main electric and magnetic parameters such as inductances, flux and resistances, are calculated.

The second step is to represent the electromagnetic behavior in the d/q axis reference Park frame.

During the third step, a control strategy is developed to establish the relevant strategy at each operating point.

Finally the different losses occurring in the motor are calculated in the last step. Total losses maps and also efficiency maps are then available.

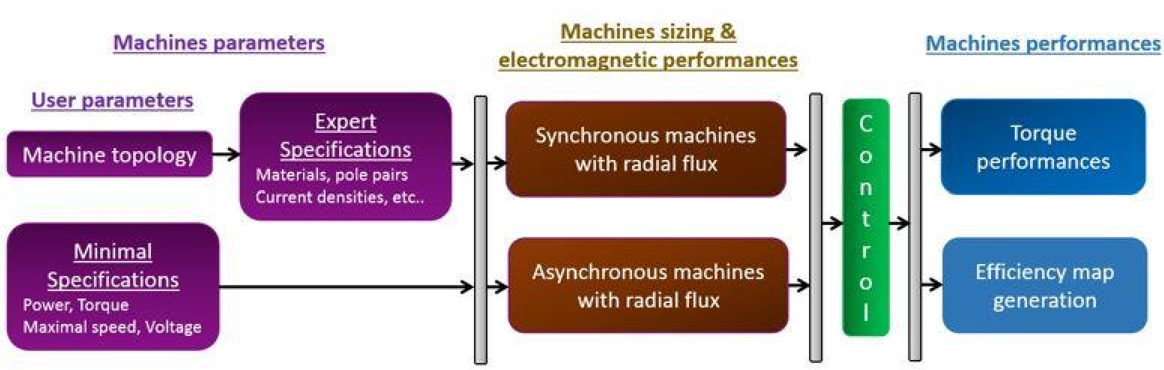


Figure 4.10: electric machine performances diagram

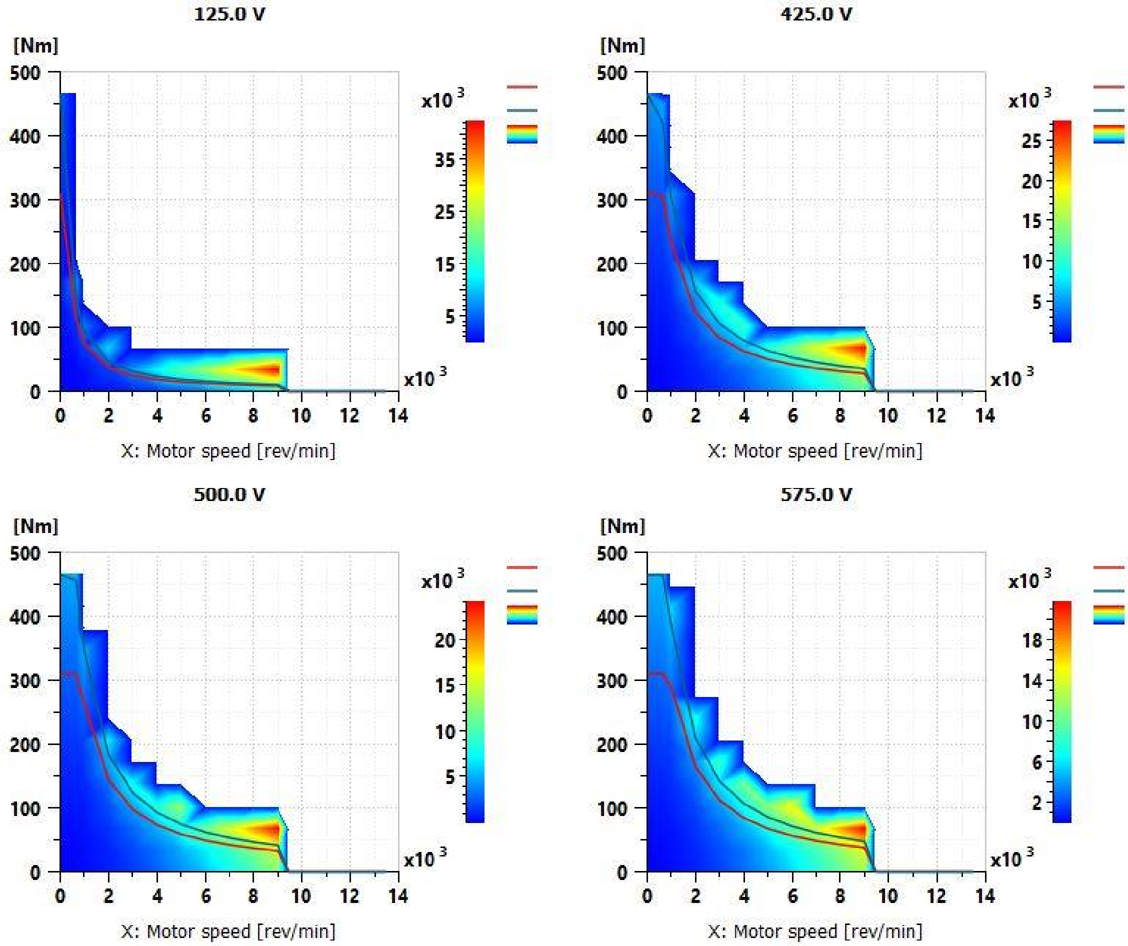


Figure 4.11: losses for considered electric motor

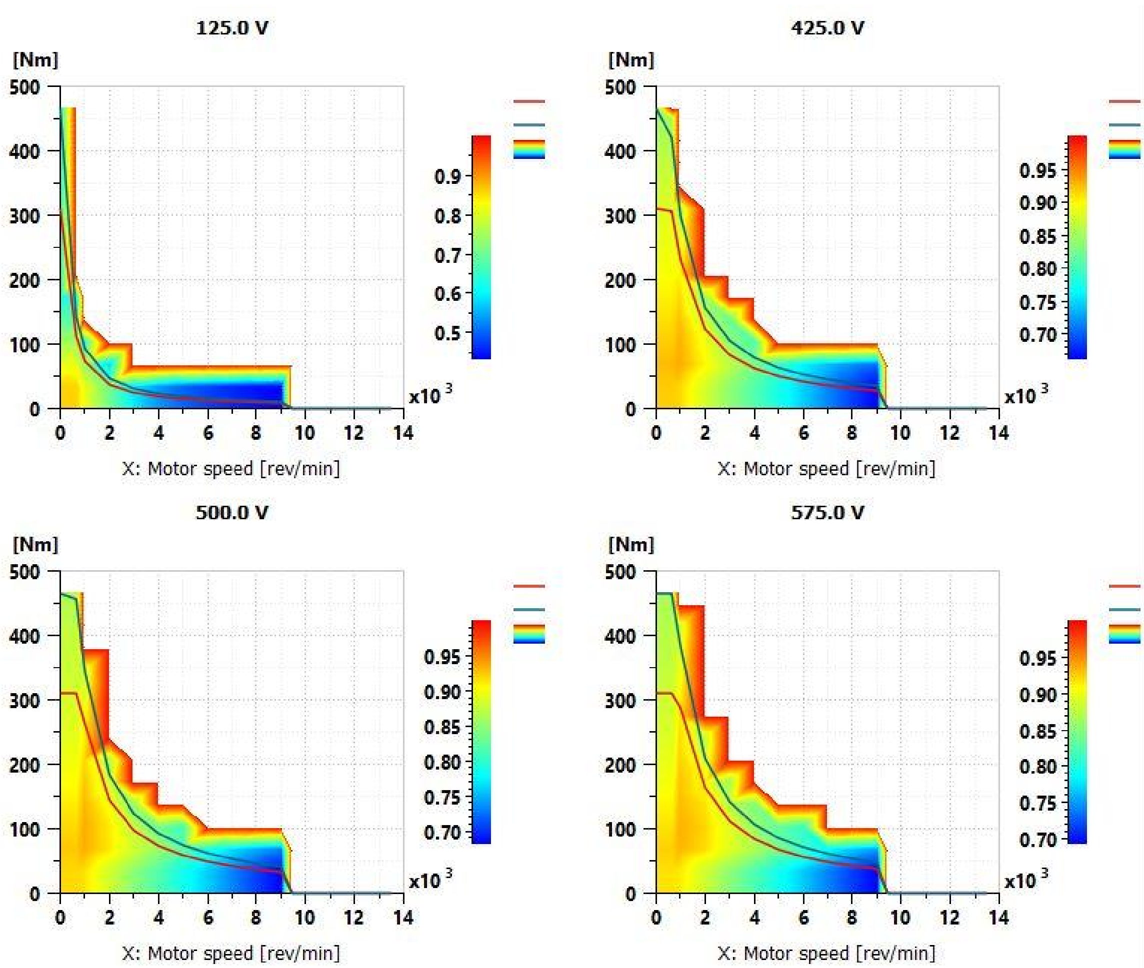


Figure 4.12: Efficiency for considered electric motor

5

Hybrid powertrain architecture modelling

After defining two configurations for this vehicle, P2 and P3 which were discussed in introduction, and knowing the required components and their data through the evaluation or assumption, now we can model architectures in main environment of Amesim.

The vehicle is modeled in P2 configuration shown in figure 5.1 and P3 configuration shown in figure 5.2.as can be seen in P2 the electric motor in installed before the gearbox whereas in P3 the electric motor is located after gearbox .

For both models a clutch (rotary Coulomb and/or stiction friction) is installed between the output shaft of engine and input shaft of gearbox.

In both cases, the gear ratio between engine and gearbox is set to 1 and also for gear ratio of electric motor is set to 2, but since in P3 configuration the electric motor is connected to axel without gearbox Interference, another gear set with ratio of 8 is added to this configure.

Beside the battery one electric signal as an auxiliary's power with 200 W is linked to the Electric motor.

The state of charge of battery is set to 65 % and the rated capacity of the battery is 6.5 Ah.

The state of charge *SOC* [%] of the battery is a state variable which derivative is calculated as follows:

$$\frac{dSOC}{dt} = \frac{-dq}{dt} \cdot \frac{100}{Cnom} \tag{5.1}$$

Where C_{nom} is the rated capacity [As]. This derivative is limited so that the state of charge remains in a [0; 100%] range.

In following, the depth of discharge *DOD* [%] is used as an input to read the open circuit voltage and the internal resistance data files. It is deduced as follows:

$$DOD = 100 - SOC \tag{5.2}$$

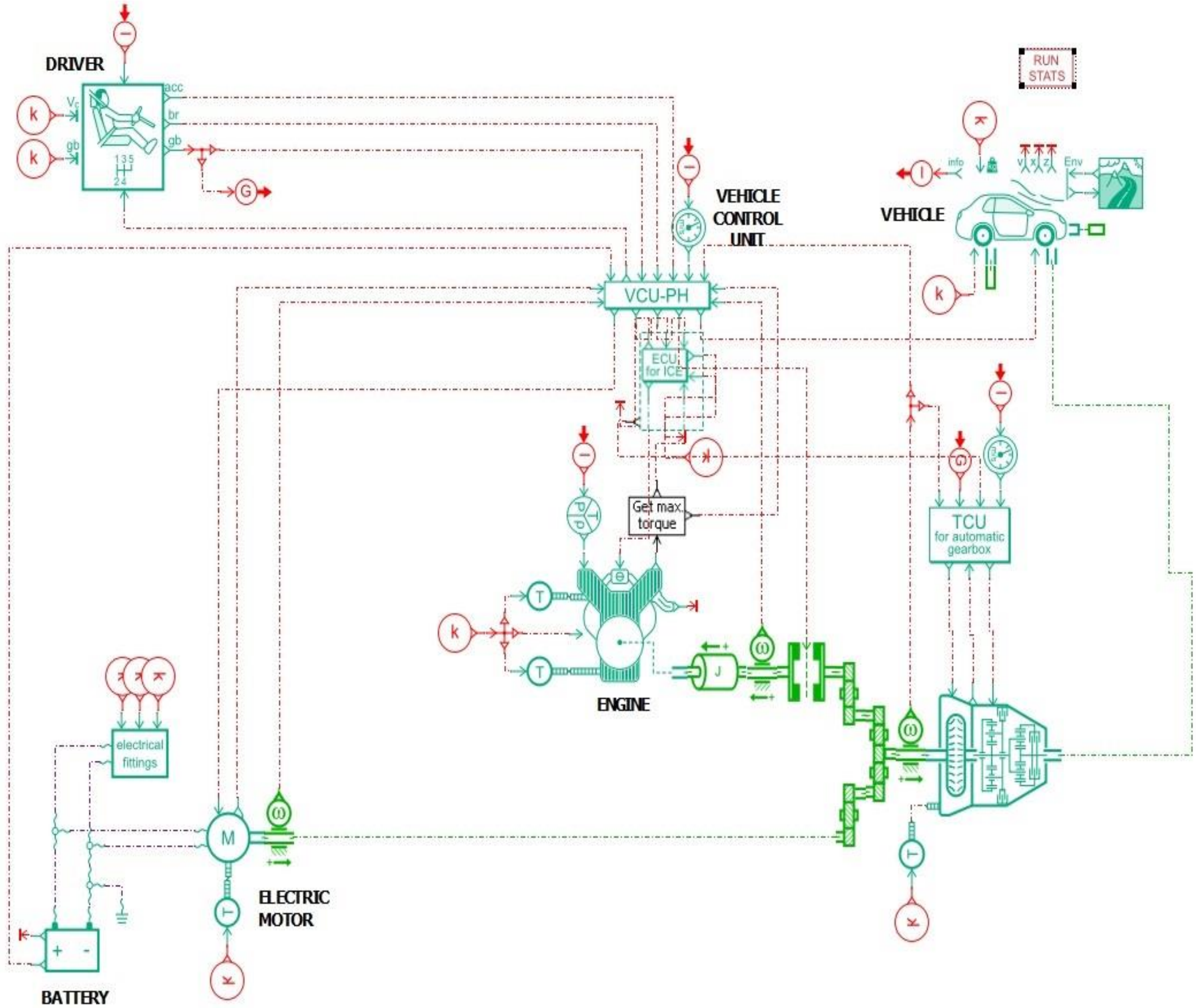


Figure 5.1: P2 hybrid configuration

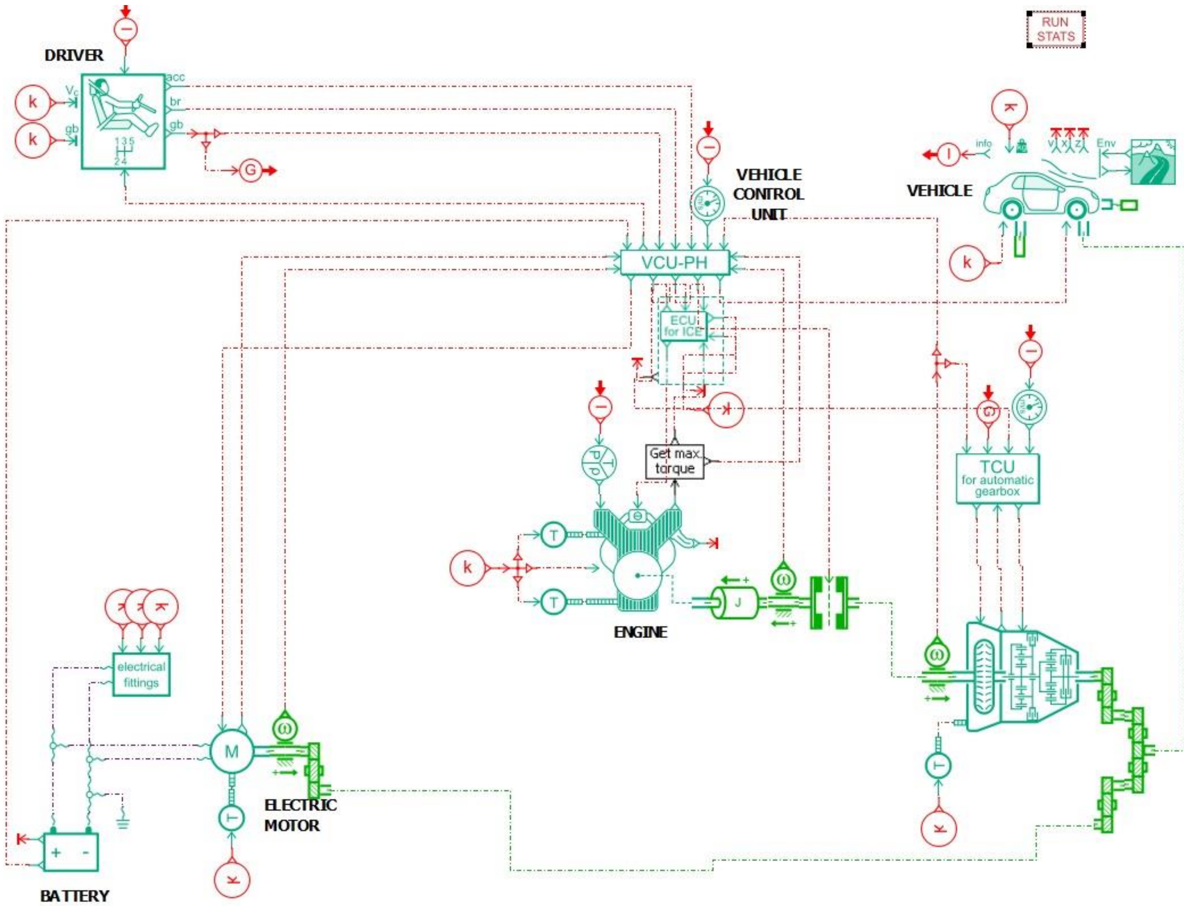


Figure 5.2: P3 hybrid configuration

In modelling three control units are used, control unit for parallel hybrid vehicle, control unit for ICE and transmission control unit for automatic gearbox.

1) <u>ECU for ICE</u>

This ECU component is an Engine control Unit. It ensures the right communication between the driver load request and the engine control signals (combustion mode, idle speed regulation, maximum speed regulation, fuel resume speed...).

Several regulations are performed by the ECU:

- idle speed
- maximum speed
- fuel resume speed

The control laws implemented in the ECU can be represented as figure 5.3.

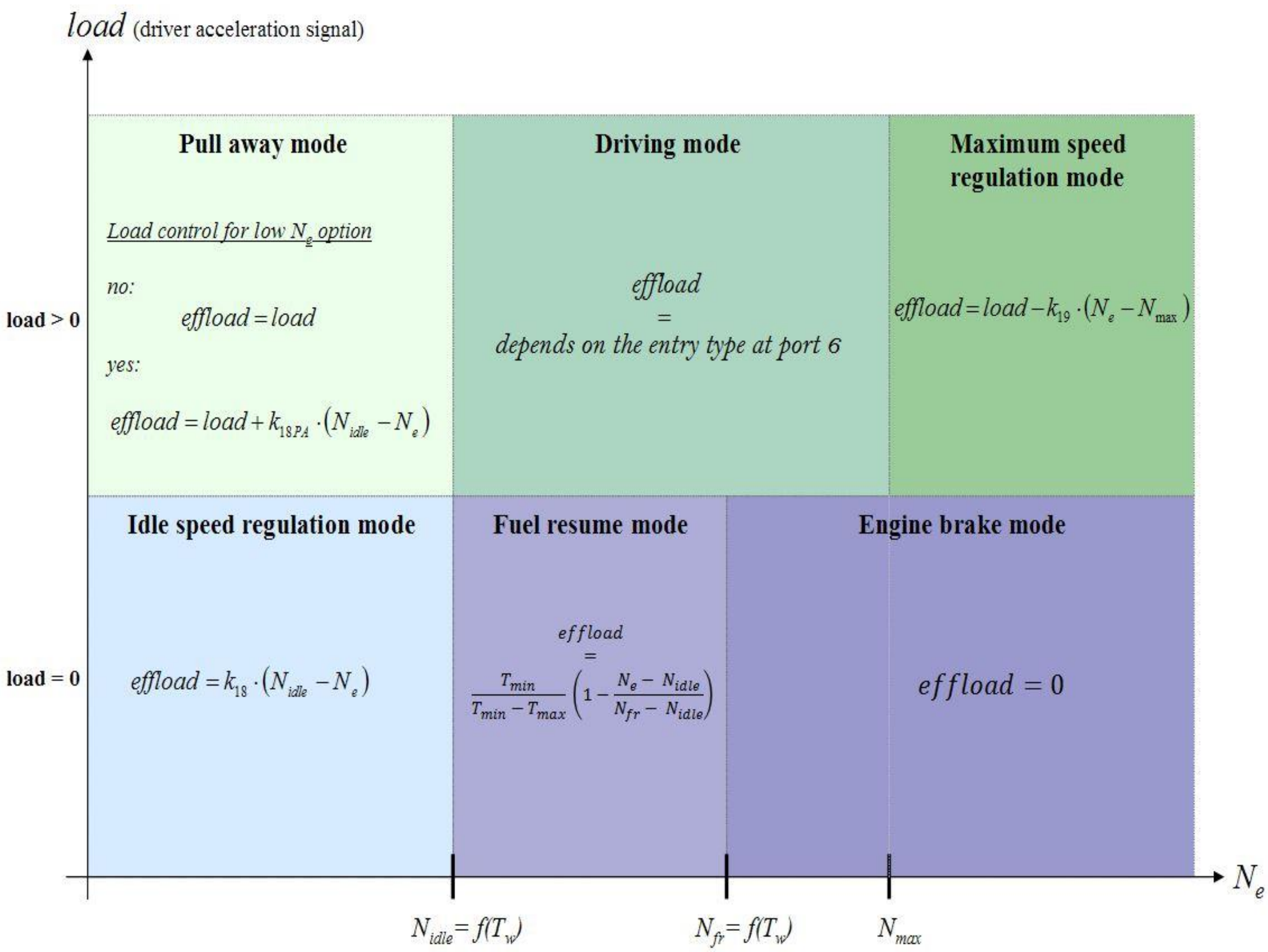


Figure 5.3: control laws in the ECU [13]

With:

- N_e: input engine speed [rev/min] at port 2
- *load*: input driver acceleration signal [null] at port 6

- N_{idle}: user-defined controlled idle speed [rev/min]
- N_{fr}: user-defined fuel resume speed [rev/min]
- N_{max}: user-defined maximum engine speed [rev/min]
- k_{18}: user-defined gain for idle speed regulation [null]
- k_{18PA}: user-defined gain for idle speed regulation during pull away [null]
- k_{19}: user-defined gain for maximum speed regulation [null]
- T_{min}: minimum engine torque [Nm]
- T_{max}: maximum engine torque [Nm]

In this work the kind of effload is s signal between 0 and 1 .

$$effload=load \tag{5.3}$$

Considering the load is driver load [null, W, kW or Nm].

According to ECU algorithm, the variable "regulation mode" indicates the current mode used for regulation.

- -1: engine brake mode
- 0: engine stopped
- 1: fuel resume mode
- 2: idle speed regulation mode
- 3: pull away mode
- 4: driving mode
- 5: maximum speed regulation mode

2) <u>Transmission control unit for automatic gearbox</u>

Several inputs are used by gear ratio computation:

- the engine rotary velocity,
- the vehicle speed,
- the load,
- The engaged gear ratio.

Lockup clutch control can be function of:

- the engine rotary velocity,
- the vehicle speed,
- the impeller/turbine relative speed,
- the load,
- The engaged gear ratio.

The ECU will compute 2 values:

- Engine/vehicle speed for downshifting,
- Engine/vehicle speed for upshifting.

If engine/vehicle speed is lower than the first value, the ECU will try to engage the previous gear, if engine/vehicle speed is higher than the second value, the ECU will try to engage the next gear.

In this work the strategy to compute these 2 values (and thus to control gear shifting) is ‘’ gear shifting function of engine speed only’’

Only 2 fixed values of engine speed will be used (2 parameters). If engine speed reach nominal upshift engine rotary velocity, next gear will be engaged. If engine speed reach nominal downshift engine rotary velocity, previous gear will be engaged.

Lockup clutch strategy

The lockup clutch control can be deactivated by using the "use lockup clutch" enumeration.

The parameter gearbox ratio above which the lockup clutch can be used gives the possibility to avoid the use of the lockup clutch with some gear ratio.

The ECU will compute 2 values:

- ✓ Engine/vehicle speed for disengaging lockup clutch,
- ✓ Engine/vehicle speed for engaging lockup clutch.

In this work the strategy to compute these 2 values (and thus to control the lockup clutch) is a function of impeller/turbine relative rotary velocity.

A simple parameter *slip* is used:

$$\text{If } (W_{imp} - W_{turb}) \leq \frac{slip}{100} \cdot W_{imp} \quad lckctrl = 1 \text{(engaged lockup clutch)} \qquad (5.4)$$

$$\text{If } (W_{imp} - W_{turb}) > \frac{slip}{100} \cdot W_{imp} \quad lckctrl = 0 \text{(disengaged lockup clutch)}$$

Where:

- W_{imp} is the impeller rotary velocity.
- W_{turb} is the turbine rotary velocity.
- *Slip* is the impeller/turbine slip threshold (in %) for lockup clutch control calculation.

<u>Gear shifting</u>

The ECU computes 2 values:

- ✓ Engine/vehicle speed for downshifting,
- ✓ Engine/vehicle speed for upshifting.

If engine/vehicle speed is lower than the first value, the ECU will try to engage the previous gear, if engine/vehicle speed is higher than the second value, the ECU will try to engage the next gear.

The gear lever can be set to:

"Drive" (value at port = 1): the TCU will use forward gears.

"Neutral" (value at port = 0): the TCU will not use gears.

"Reverse" (value at port = -1): the TCU will use reverse gears.

Lockup clutch

The ECU computes 2 values:

- ✓ Engine/vehicle speed for disengaging lockup clutch,
- ✓ Engine/vehicle speed for engaging lockup clutch.

If engine/vehicle speed is lower than the first value, the ECU will disengage the lockup clutch, if engine/vehicle speed is higher than the second value, the ECU will engage the lockup clutch.

While the gear lever is put on "neutral", the lockup clutch is not used.

3) Control unit for a parallel hybrid vehicle

In this approach, the electric motor and the engine are connected to the manual gearbox. The control unit manages the power requested to the engine and the electric motor. If the battery needs to be regenerated, the engine is used to drive the vehicle, and if the power requested is lower than its optimum power (according to its rotary velocity), the difference is send to the electric motor to charge the battery.

Inputs management

Two integer parameters are used to set driver input command type:

- Acceleration command type: it should be set accordingly with driver acceleration type.

- Brake command type: it should be set accordingly with driver braking type.

Driver commands are modified by two gains

- one for the acceleration: gain on the acceleration command
- one for the braking: gain on the braking command

<u>System parameters</u>

Three parameters are used to describe the system

- maximum braking torque for the vehicle
- idle speed of the engine
- filename for gear ratio between the electric motor and the vehicle

The strategy is composed of 4 modes:

- Mode 1: battery should not be charged, engine is not used
- Mode 2: battery should not be charged, engine is used
- Mode 3: battery should be charged, engine is not used
- Mode 4: battery should be charged, engine is used

There are 2 transient modes when engine is starting:

- If the engine speed is lower than idle speed / 2, the clutch is engaged and the engine is not started.
- When the engine reaches idle speed / 2, the clutch stays closed and the engine is switched on.

Information about powertrain are sent to the driver through this port:

- Engine speed [rev/min]
- Powertrain maximum power [W]: $P=Tmax \cdot N$ of engine or motor depending on the mode.

- Powertrain minimum power [W]: $P = Tmin \cdot N$ of engine or motor depending on the mode.
- Powertrain inertia equivalent mass [kg]: 0

6

Results

All results in table 6.1 are extracted from Method discussion which is explained in chapter 4 using the hand calculations.

EM	Required Pc (continuous power)	13.43 kw
	Required Tc (continuous torque)	112.4 Nm
	Required Ttrans (transient torque)	456.5 Nm
ICE	Required Pc (continuous power)	80.67 kw
	Required Tc (continuous torque)	225.3 Nm
	Required Ttrans (transient torque)	761.9 Nm
ON CYCLE UDC ANALYSIS	Required energy for traction mode	274.276 Wh
	Regenerated energy in regenerative braking phase	-11.966 Wh
	Required number of cycle	75
	Minimum battery weight	214.64 Kg
	Number of cycle without regenerative braking	74
	Range without regenerative braking	73.55 Km

Table 6.1: hand calculations results

Also after making model and doing analysis on that, we can extract output power and torque for each mechanical components, also the instantaneous fuel consumption and total fuel consumption are obtained.

In the following figures are shown all considered parameters for both configurations.

▪ P2 configuration

In figure 6.1 the vehicle speed and control speed are illustrated. A comparison between them shows that vehicle speed profile follow the NEDC cycle in a suitable tolerance. Changing some control parameters such as anticipative, proportional and integral gains in acceleration control loop lead to almost match between vehicle speed and control speed profiles. Also in figure 6.2 the error between two speeds is illustrated which shows a suitable range between 0 to 1 m/s at most of the times.

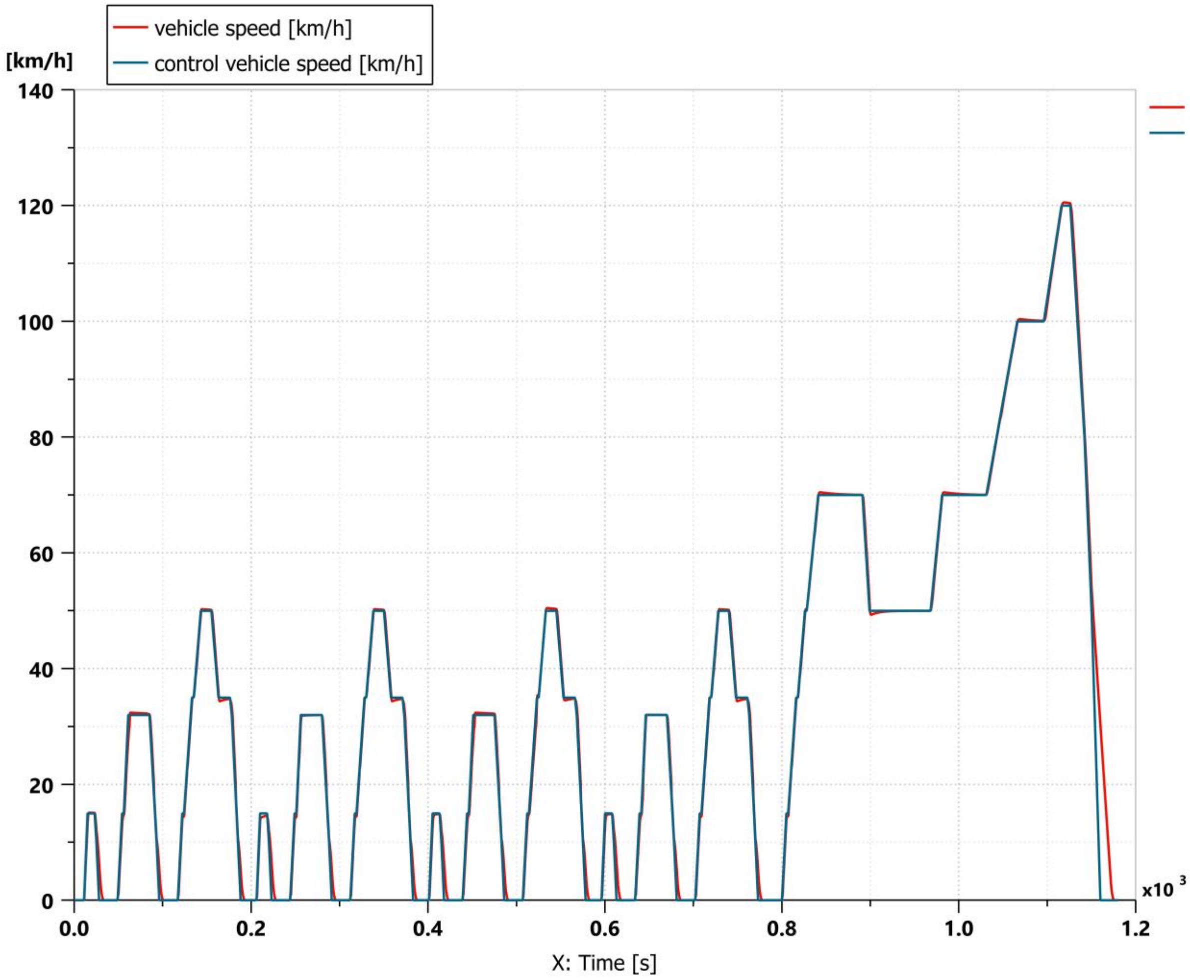


Figure 6.1: vehicle speed and control speed for P2 configuration.

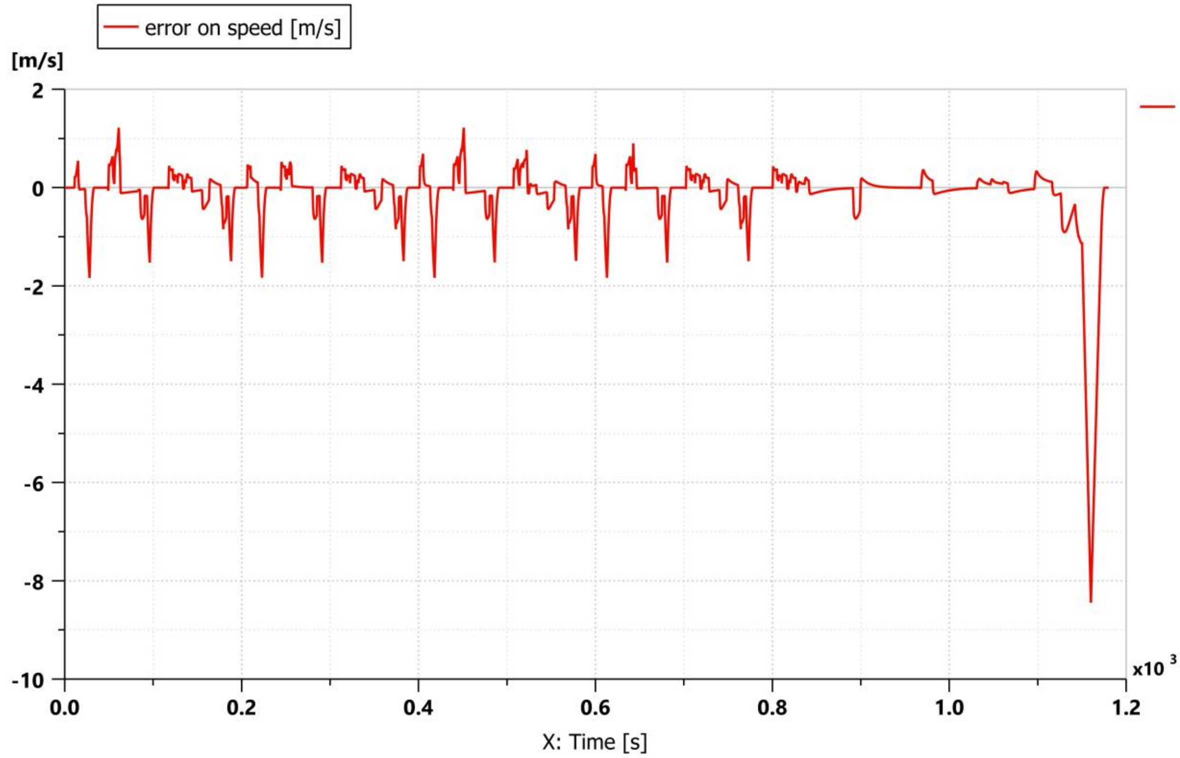


Figure 6.2: error on speed for P2 configuration.

Regarding the fuel consumption, both instantaneous and total fuel consumption [L/100km] are shown in figure 6.3. Also the final fuel consumption as it is known is set to 16.4 [L/100km]

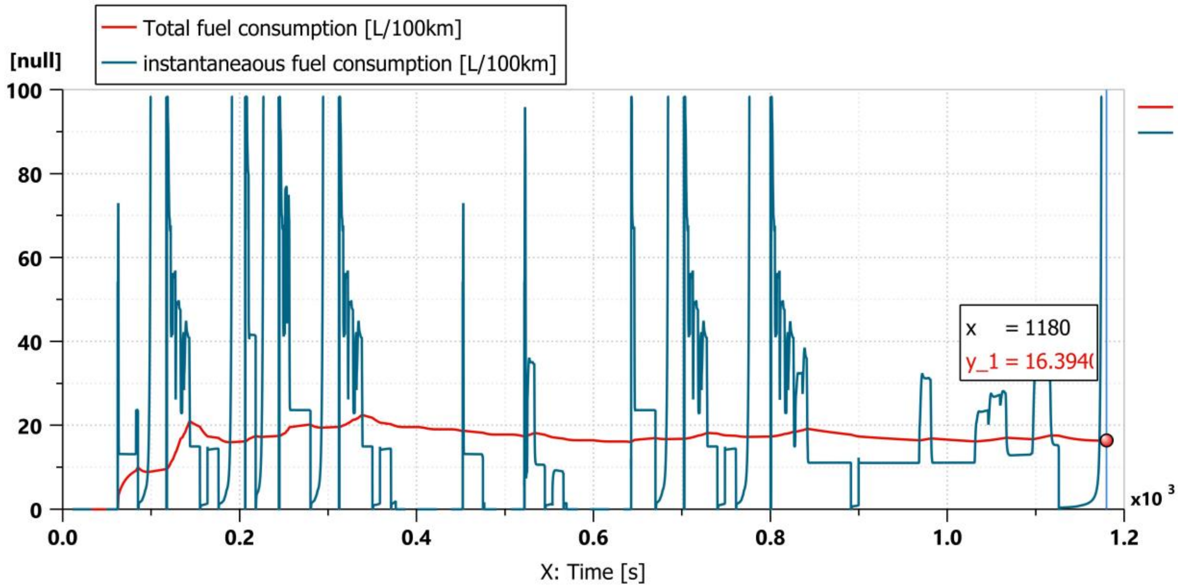


Figure 6.3: total and instantaneous fuel consumption for P2 configuration

- ## P3 configuration

Same as the explanation for P2 configuration the vehicle speed and control speed are illustrated in figure 6.4.also the error between two speeds is illustrated in figure 6.5 which shows a suitable range between 0 to 1 m/s at most of the times as well as P2 configuration.

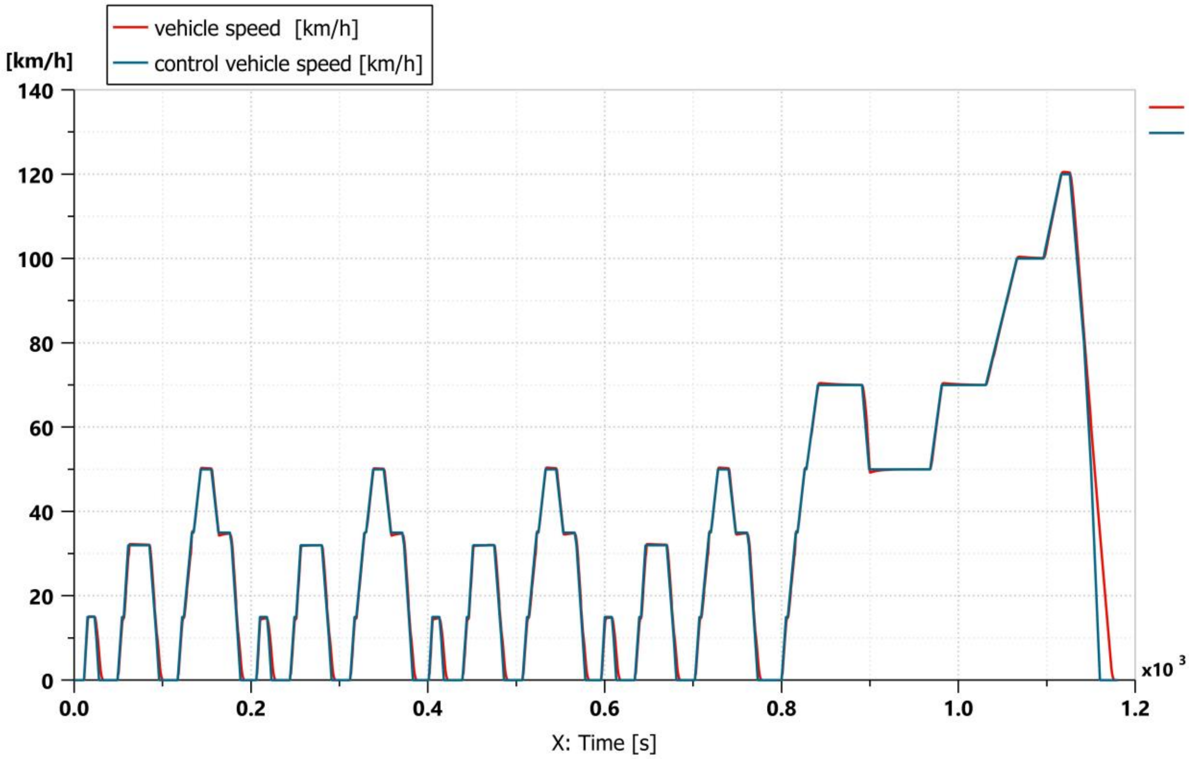


Figure 6.4: vehicle speed and control speed for P3 configuration.

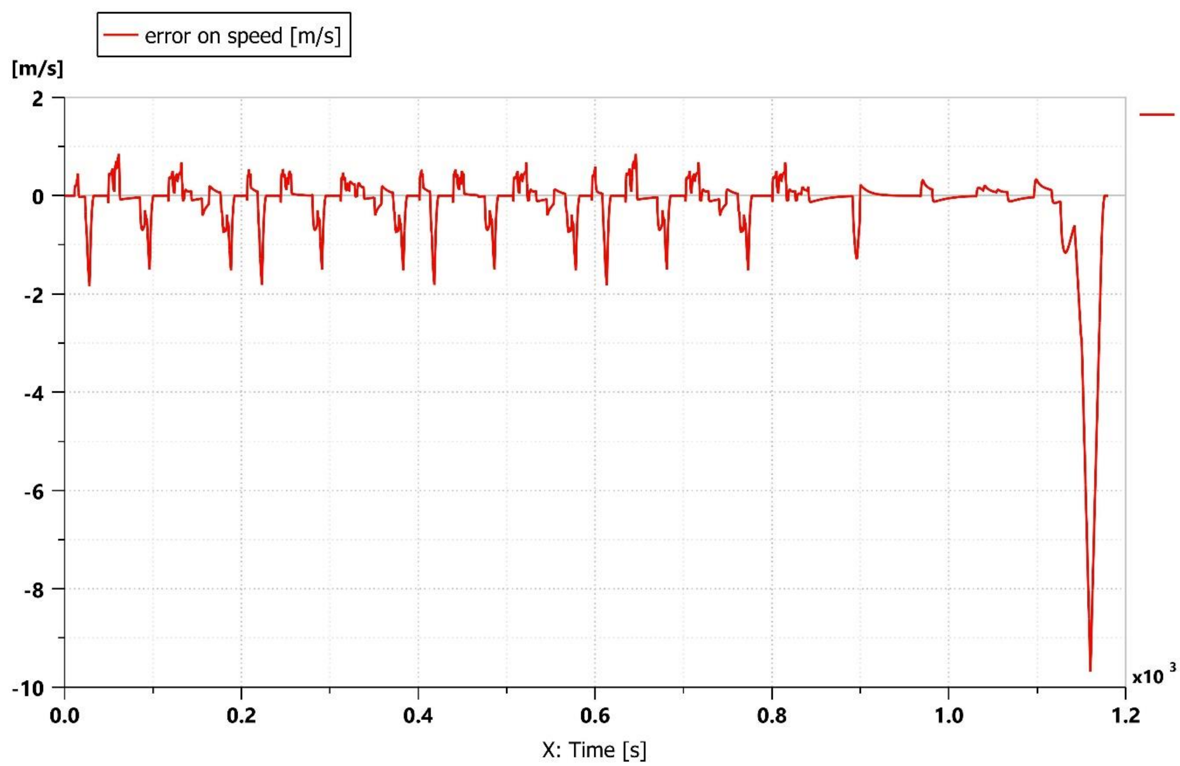


Figure 6.5: error on speed for P3 configuration

The fuel consumption, both instantaneous and total fuel consumption [L/100km] are shown in figure 6.6. Also the final fuel consumption as it is known is set to 15.6 [L/100km]

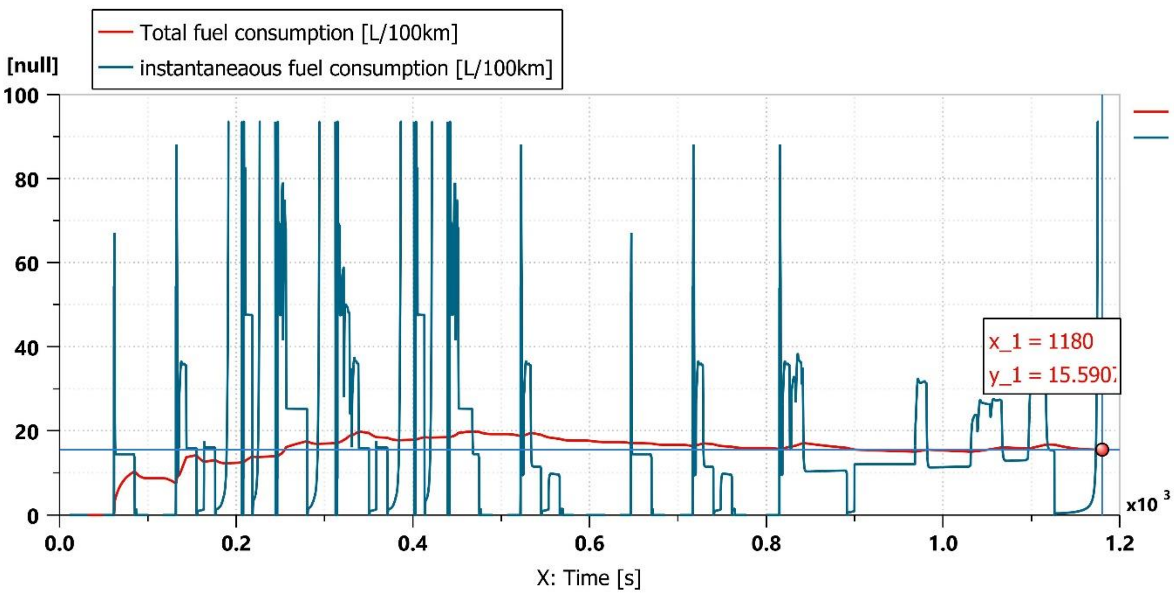


Figure 6.6: total and instantaneous fuel consumption for P3 configuration

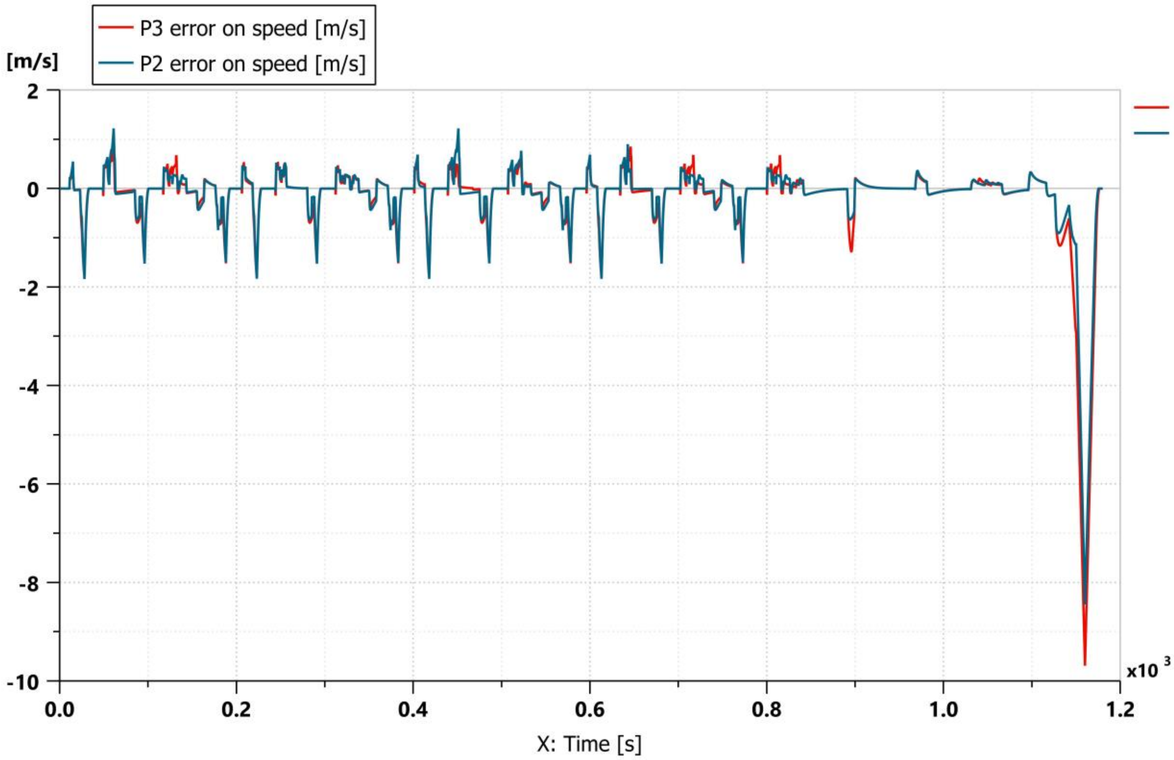


Figure 6.7: comparison error on speed between P2 and P3.

7

Conclusion and future works

As the main goal of this thesis work was the comparison of fuel consumption between two configuration as well as modeling, in figure 6.8 is shown the P3 configuration has better fuel economy with less consumption.

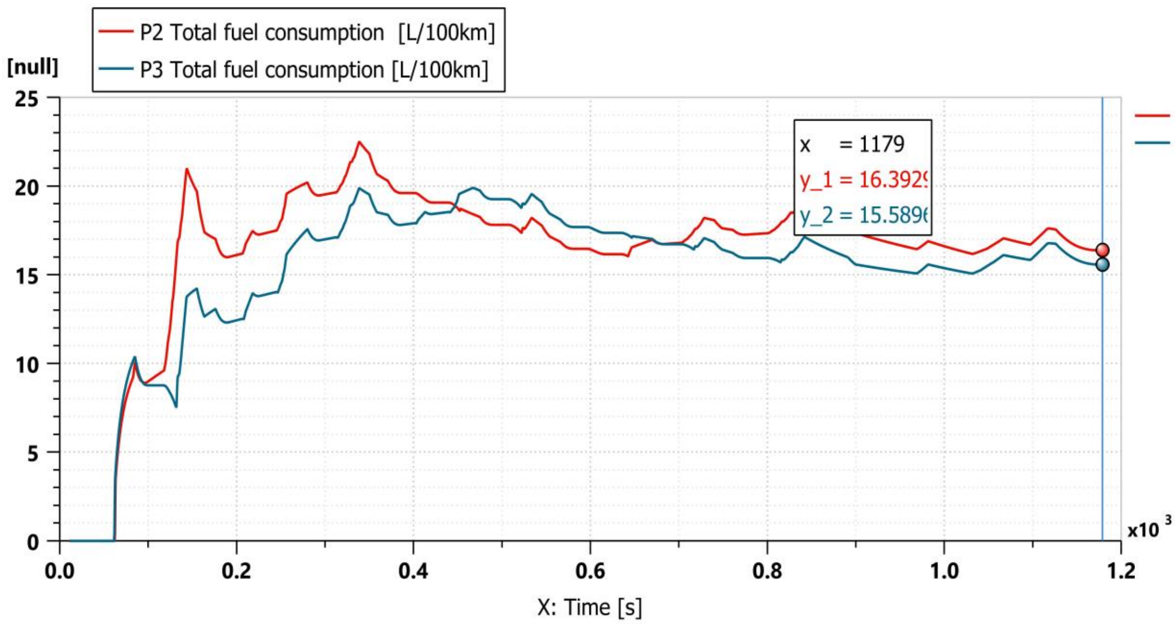


Figure 6.8: total fuel consumption for both configurations

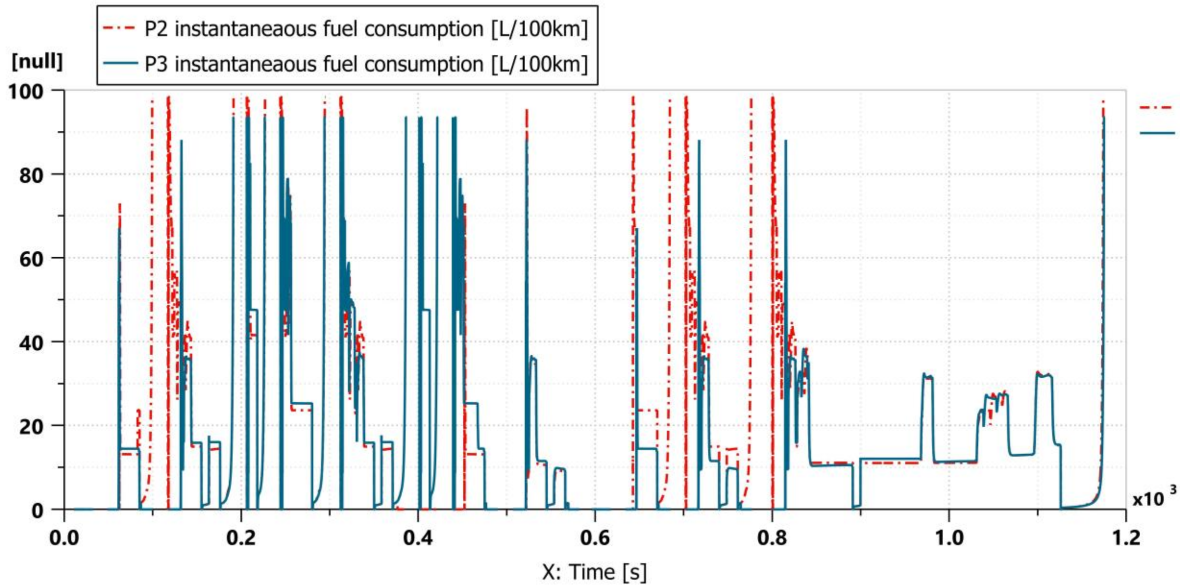


Figure 6.9: instantaneous fuel consumption for both configurations

Also as it is clear in figure 6.10 the state of charge at battery output, which is used to describe how full a battery is, for P3 configuration is lower the P2 one in most times of the cycle. Therefore, the electric motor consumes more battery potential to assist more the internal combustion engine especially in EUDC cycle which leads to less fuel consumption. Moreover, in figure 6.11 is understandable the electric motor in P3 configuration, supply more torque with respect to P2 configuration during the cycle.

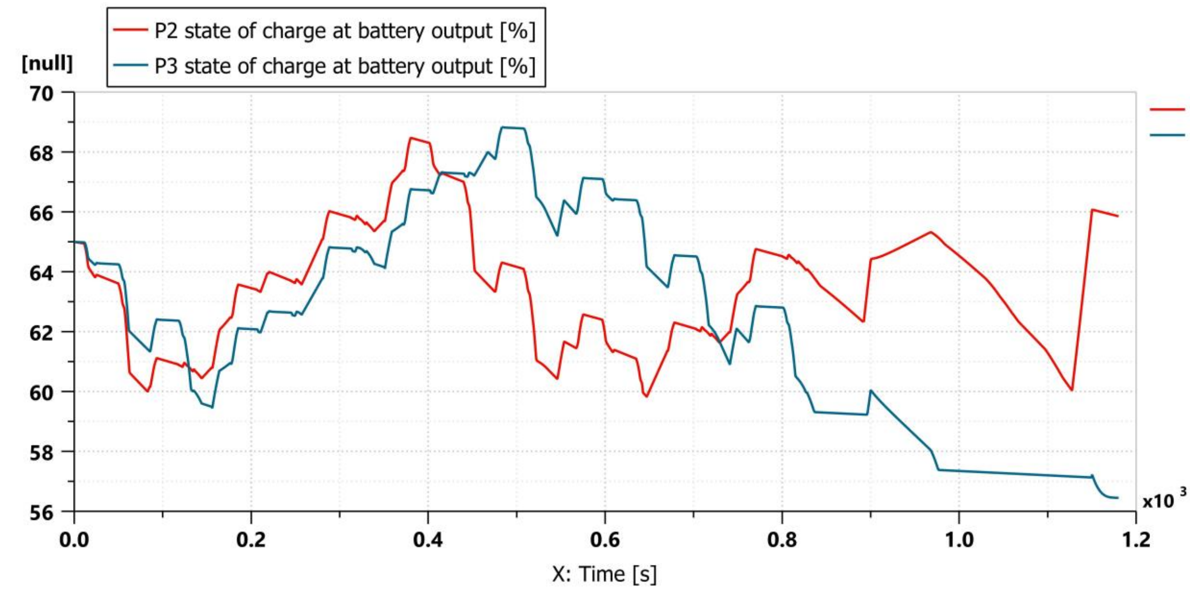


Figure 6.10: state of charge at battery output for both configuration

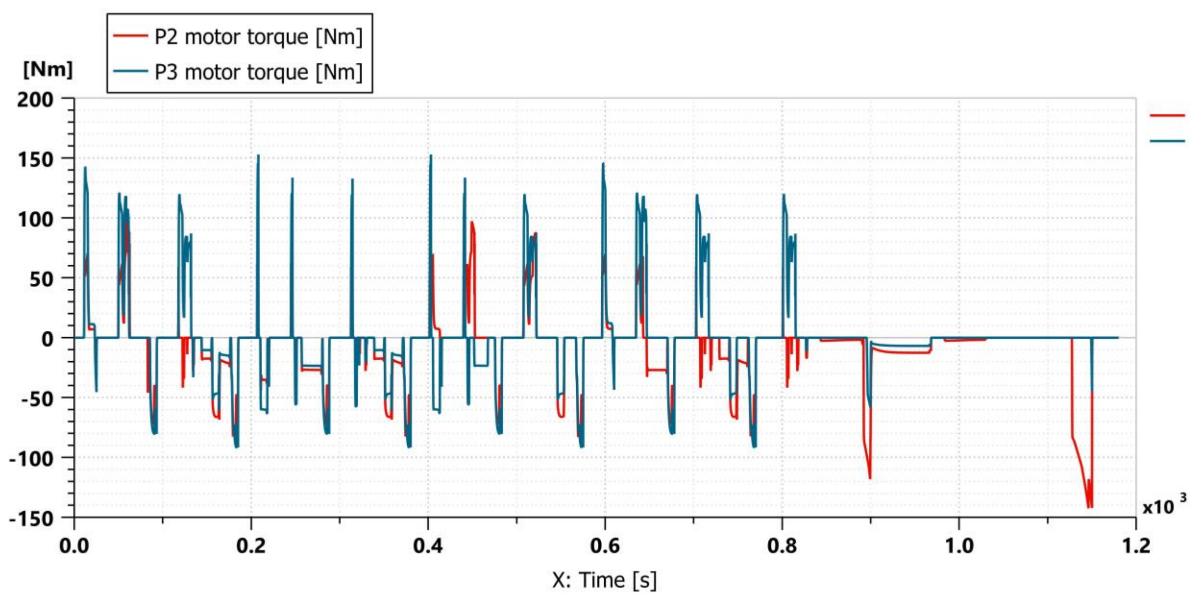


Figure 6.11: output motor torque for both configuration

Future works

This model can be developed with adding some after treatment systems in order to make a comparison between their emissions.

As well as this regarding the control field, a suitable hybrid control unit can be used in combination working phases.

Moreover, a more accurate optimization control strategy for driveline, as well as utilization a battery power management system, resulting in proper sizing of the mechanical component to reduce the weight of vehicle and fuel consumption subsequently.

Bibliography

[1] Wisdom Enang & Chris Bannister. Modelling and control of hybrid electric vehicles (a comprehensive Review), www.elsevier.com/locate/rser. 2017.

[2] Prius hybrid powertrain, https://newsroom.toyota.co.jp/en/download/15138467.

[3] Digging deeper: The road map for savings with hybrid cars, http://ecoadvice.stanford.edu/digging_deeper/dd_cars.html.

[4] MILITARY VEHICLE OPTIMIZATION AND CONTROL by Denise M. Rizzo, 2014

[5] D. Kramer and G. Parker, "Current state of military hybrid vehicle development," Int. J. Electric and Hybrid Vehicles, vol. 3, pp. 369–387, 2011.

[6] http://www.powerstrokehub.com/3.2-power-stroke.html

[7]https://www.zf.com/products/media/product_media/cars_5/cars_driveline_6_speed_automatic_transmission/6HP28_DataSheet.pdf

[8] Electric and hybrid propulsion systems course in Politecnico di Torino.

[9] Alix, G., Dabadie, J., and Font, G., "An ICE Map Generation Tool Applied to the Evaluation of the Impact of Downsizing on Hybrid Vehicle Consumption," SAE Technical Paper 2015-24-2385, 2015, doi:10.4271/2015-24-2385.

[10]A. Abdelli, Optimal Design of a n Interior Permanent Magnet Synchronous Motor for Wide Constant-Power region Operation: Considering Thermal and Electromagnetic aspects SAE Int. J. Alt. Power. 3(1):2014.

[11]F. Le Berr, A. Abdelli, D.-M. Postariu and R. Benlamine, Design and Optimization of Future Hybrid and Electric Propulsion Systems: An Advanced Tool Integrated in a Complete Workflow to Study Electric Devices, OGST Journal, Vol. 67, No. 4, pp. 539-645.

[12]Dabadie, J., Sciarretta, A., Font, G., and Le Berr, F., Automatic Generation of Online Optimal Energy Management Strategies for Hybrid Powertrain Simulation, SAE Technical Paper 2017-24-0173, 2017, DOI: 10.4271/2017-24-0173.

[13] https://www.plm.automation.siemens.com/global/en/products/simcenter/simcenter-amesim.html