

Vehicle Simulation for Powertrain System Testing

Master's thesis in Automotive Engineering

CONSTANTIN-FLORIN ANDRONE
SUDHIR BALAKRISHNA RAO

REPORT NO. 2017:74

Vehicle Simulation for Powertrain System Testing

CONSTANTIN-FLORIN ANDRONE
SUDHIR BALAKRISHNA RAO



Department of Applied Mechanics
Division of Combustion
Chalmers University of Technology
Gothenburg, Sweden 2017

Vehicle Simulation for Powertrain System Testing

CONSTANTIN-FLORIN ANDRONE

SUDHIR BALAKRISHNA RAO

© Constantin Florin Androne, Sudhir Balakrishna Rao, 2017.

Supervisors: Ulf Lind, Volvo Cars Corporation
Ronny Lindgren, Volvo Cars Corporation
Fredrik Axelsson, Volvo Car Corporation

Examiner: Sven B. Andersson, Chalmers University of Technology

Technical report no. 2017:74

ISSN 1652-8557

Department of Applied Mechanics

Division of Combustion

Chalmers University of Technology

SE-412 96 Gothenburg

Telephone +46 31 772 1000

Applied Mechanics/Chalmers

Göteborg, Sweden, 2017

Vehicle Simulation for Powertrain System Testing

CONSTANTIN-FLORIN ANDRONE

SUDHIR BALAKRISHNA RAO

Department of Applied Mechanics

Division of Combustion

Chalmers University of Technology

ABSTRACT

The increase in the extent of vehicles running on internal combustion engines has led to serious concern towards the harmful gasses emitted from them, which affects the balance of natural ecosystem. To reduce the amount of emissions emitted from vehicles, emission regulations are reinforced continuously; which all vehicle manufacturers must fulfil. To meet the emission regulations, powertrain testing has become more important right from the development process of a vehicle.

The Hardware-in-Loop is one of the powertrain testing approach which allows testing to be conducted on a test object. The test object can be an engine or any powertrain component without the need for a complete vehicle as in Chassis Dyno testing. Besides the test object which is physical hardware, software components containing all the models to replicate the complete vehicle testing are required. The correct functionality of the software component is vital; if one model produces unwanted behaviour, the whole test can be delayed for days.

The objective of the thesis is to create a tool that can be used to check the software components and inform the user if the behaviour of the models varies from what is expected. This testing approach is called Model-in-Loop testing.

Engine along with its Electronic Control Module (ECM) was regarded as test objects in our Hardware-in-Loop testing. To convert from Hardware-in-Loop to Model-in-Loop, two new models have been introduced: one for the internal combustion engine and another for the electronic control module of the engine. The remaining software components are retained from Hardware-in-Loop. After the introduction of these two models, the Model-in-Loop was fully functional and the simulation of the complete vehicle was made possible.

Once the simulation was possible, the next stage was to create a tool that would perform a check on the models. This tool is referred in this report as Unit Testing. In case the current models are further developed or new models are being introduced, the testing tool will analyse the output and inform the user about the reliability of the models. The user can also use this tool to have an in-depth analysis of the speed of the vehicle, distance travelled and how well it manages to follow the target speed trace, the fuel consumption and CO₂ emissions.

The final step was to compare the Model-in-Loop testing results across Chassis Dyno testing and Hardware-in-Loop testing to understand the feasibility of further development of the models to capture reliable results. The results obtained from Model-in-Loop was comparable with that of other two testing approaches. The complexity involved in obtaining accurate torque values were realised to implement more models to capture turbocharger, Exhaust Gas

Recirculation (EGR), mass airflow effects and possible future work in the development of this testing approach was studied.

The thesis is split into three parts; report, appendix and code. The report contains information about the reasoning, objective, methods and findings and is available for public. The appendix and the code, together with the data used in simulation are considered confidential and is only available within Volvo Car Corporation.

Keywords: Hardware-in-Loop, Model-in-Loop, Chassis Dyno, testing, simulation, Unit testing, fuel consumption, CO₂ emissions, EGR, turbocharger

Acknowledgement

We would like to thank Ulf Lind and Ronny Lindgren from Volvo Cars Corporation for providing us the opportunity to work on this exciting assignment. We would also like to thank our examiner Sven B. Andersson for guiding us in this project.

This thesis would not have been possible without the continued support from our supervisors Ronny Lindgren and Fredrik Axelsson. They kept track of our progress, helped us in understanding the vehicle model and intervened in a right manner to help us complete the thesis in due time.

Also, thanks to Daniel Ottosson for providing us with engine test and chassis dyno results and to Markus Grahm and Vijayakrishnan Venkateshmohan for helping us understand the engine model and the difference between the model and a real engine.

Table of contents

ABSTRACT.....	V
Acknowledgement.....	VII
Table of contents	VIII
Table of figures	IX
1. Introduction	1
1.1 Background	1
1.2 Emission Testing Methodology	1
1.2.1 Real-Driving-Emissions (RDE) testing	2
1.2.2 Complete vehicle/Chassis Dyno testing	3
1.2.3 Hardware-in-Loop (HiL) testing	3
1.2.4 Model-in-Loop (MiL) testing	4
1.3 Objective	5
1.4 Emission testing procedure	5
1.4.1. Road load determination.....	6
1.4.2 Emission Measurement	7
1.4.3 NEDC testing procedure.....	8
1.4.4 Worldwide harmonized Light Vehicles Testing Procedure (WLTP).....	9
1.5 Comparison of test procedures	10
2. Method	13
2.1 Hardware-in-Loop testing methodology	13
2.2 Hardware-in-Loop to Model-in-Loop transfer methodology	14
2.3 Model-in-Loop function strategy.....	16
3. Unit Testing.....	21
3.1 Sanity check	22
4. Results & Discussions.....	27
4.1 Driver comparison	27
4.1.1 Driver for NEDC cycle.....	27
4.1.2 Driver for WLTC cycle	28
4.2. Gear selection comparison	28
4.3. Test cycle comparison.....	29
5. Conclusions	33
6. Future work	35
References.....	37

Table of figures

Figure 1 Vehicle with a PEMS attached	2
Figure 2 Vehicle on chassis dynamometer.....	3
Figure 3 Engine on a Hardware-in-Loop test rig (University, 2017)	4
Figure 4 Emission measurement on Chassis Dyno.....	7
Figure 5 NEDC Velocity profile (Chen, 2016)	8
Figure 6 WLTC Velocity set points (Giakoumis & Zachiotis, 2017).....	9
Figure 7 NEDC vs WLTC class 3-2 (Giakoumis & Zachiotis, 2017).....	11
Figure 8 NEDC vs WLTC class 3-2 acceleration distribution (Giakoumis & Zachiotis, 2017)	11
Figure 9 Hardware-in-Loop components	13
Figure 10 Model-in-Loop components	14
Figure 11 Flow direction for driver model.....	15
Figure 12 Direction of information flow between the main models.....	16
Figure 13 Comparison between real engine and the modelled engine	18
Figure 14 ECM Functions	18
Figure 15 Transmission function.....	19
Figure 16 Velocity deviations	23
Figure 17 Information related to exceeding speed limits.....	24
Figure 18 Information related to the test mass and travelled distance	24
Figure 19 Information related to fuel, CO ₂ , engine speed and torque	25
Figure 20 WLTC driver behaviour	25
Figure 21 NEDC - Driver Selection	28
Figure 22 Selected gear comparison.....	29
Figure 23 Driver behaviour comparison of MiL, HiL and Chassis dyno	30
Figure 24 Engine speed comparison of MiL, HiL and Chassis dyno	30
Figure 25 Engine torque comparison of MiL, HiL and Chassis dyno	31
Figure 26 Fuel consumption comparison of MiL, HiL and Chassis dyno	32

1. Introduction

Testing is considered the backbone for any development activity; and the situation is indifferent in the automotive context. There has been a major push towards performing faster, reliable testing approaches to meet the current demands of the market. The advancement in software development has led to the rise of new virtual testing methodology called simulation.

Model based Simulation is one of the approach utilized currently by automotive manufacturers for testing of complete vehicle on a software platform

How reliable are simulation over actual traditional testing? What are the drawbacks? These questions remain unanswered and the thesis work throws light on this regard by focussing on emission.

1.1 Background

The number of vehicles sold worldwide increased from 39.2 million between 1990-1999 to 77 million vehicles sold in 2016 only [1], and reports suggest that this number will lead to a growth in the total number of vehicles on the road, reaching to more than 2 billion vehicles by 2040 [2].

The vast majority of vehicles on the road today are still using internal combustion engines, and the exhaust gases resulted from combustion process have a negative impact on environment and on the human health.

Due to greenhouse effect of carbon dioxide, and the impact of other exhaust gases components on environment and human health, a set of regulations have been developed to limit the amount of these harmful gasses that can be produced by vehicles.

1.2 Emission Testing Methodology

To ensure that the results for vehicles from different companies are comparable, the legislation not only states the maximum allowable values for different exhaust emissions (CO₂, NO_x, HC, particles), but also the testing methodology and procedure for measuring the vehicle fuel consumption and emissions.

The methodology specifies the drive cycle (speed profile), environmental conditions (ex. ambient temperature and pressure), vehicle parameters (added weight, fluids level etc.) and the procedures involved in preparation of the vehicle for testing (soak time, soak temperature etc.).

While developing or testing new vehicle technologies that influence fuel economy, there are four main ways of testing:

1. Real-Driving-Emissions (RDE) testing
2. Complete vehicle/Chassis Dyno testing
3. Hardware-in-Loop (HiL) testing
4. Model-in-Loop (MiL) testing

1.2.1 Real-Driving-Emissions (RDE) testing

Real-Driving-Emissions (RDE) will be the test implemented in near future. In this test, the vehicle is driven on a mix of rural, urban and motorway conditions, which are entirely dependent on speed and are evenly distributed. The vehicle travelling up to 60 km/h is considered to be in urban condition, between 60 to 90 km/h in rural condition and speeds above 90 km/h in motorway condition.

The emission measurement is performed real time through portable emission measurement system (PEMS). However, this testing is initially in its preliminary stage and due to differences between the cycle emissions and in real driving emissions, large developmental work has to be done for preparation of engine and powertrain components for this test. Traffic conditions, driver, temperature effects and various other factors including the errors within hardware and software components of the PEMS also influence the results of this test. A PEMS mounted on a vehicle can be seen in

Figure 1.



Figure 1 Vehicle with a PEMS attached

This way of testing has the advantage of showing the fuel consumption and emissions of the real vehicle driving on a real road, but due to uncontrollable factors (driving behaviour, traffic, weather etc.) each test is unique, and the results cannot be reproduced. Therefore, this method is used as a verification method, and not as a development tool. [3]

1.2.2 Complete vehicle/Chassis Dyno testing

In the complete vehicle testing, the ready to drive complete vehicle is being tested. For this test, the complete vehicle is put on a chassis dynamometer which is also called as rolling road. The rolling road is connected to electric machines capable of producing a road load. The road load corresponds to the resistances encountered by the vehicle at different speeds. As precise as it is, it is also very costly, as one needs the complete vehicle, and an extensive infrastructure to be able to run the tests (a chassis dynamometer, soaking rooms etc.), and it is difficult to make adjustments or test out different powertrain components.

Unlike RDE test, whose results are non-reproducible due to varying conditions, complete vehicle testing offers an advantage over it by ignoring traffic conditions, road conditions, and other influences. There are still many factors that can influence the test results (mainly because of the human operator), but the deviation between different runs are very small. An example of a test set-up can be seen in **Figure 2**.



Figure 2 Vehicle on chassis dynamometer

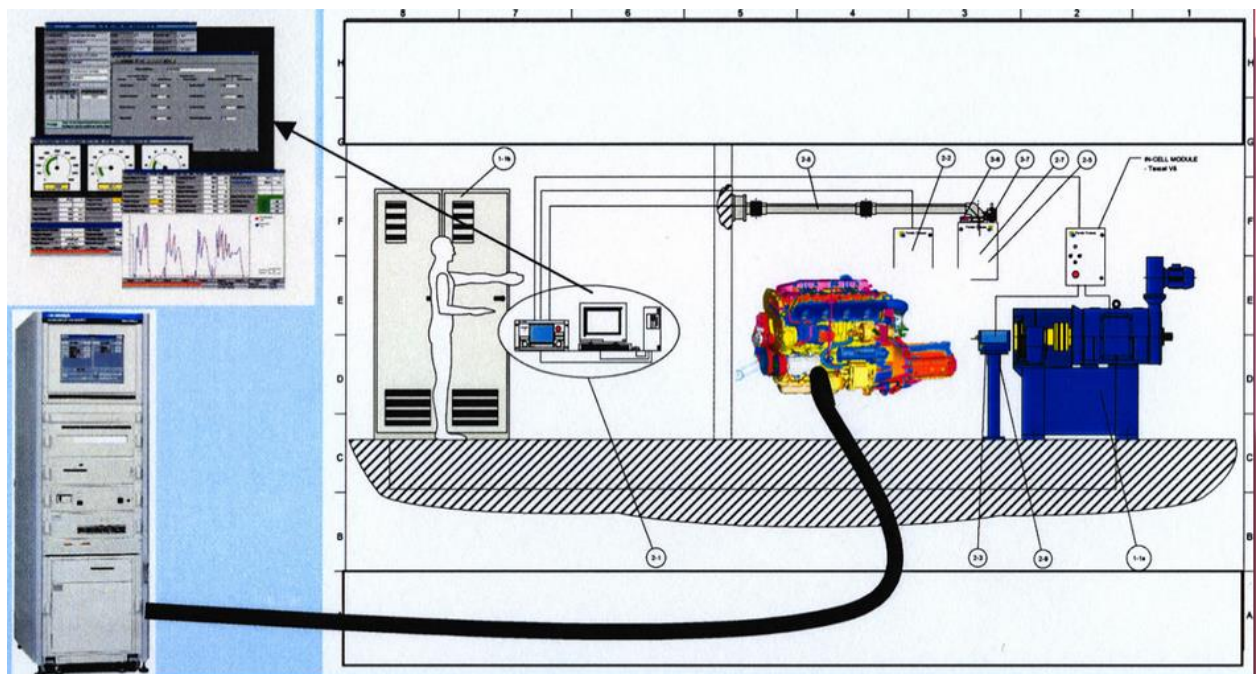
1.2.3 Hardware-in-Loop (HiL) testing

Hardware-in-Loop testing represents a cheaper, more flexible alternative to full vehicle testing. The main advantage comes from the fact that, the need for a complete vehicle is eliminated, to be able to test different scenarios on with the test object. For example, a test object can be an engine. The engine is mounted on a stand allowing better access to it, so it is easier to perform different tweaks or to replace components. Main advantage is that, tests performed through this method can be automated, and with one single engine, different vehicle set-ups can be tested (e.g., different gearboxes, different brake regeneration strategies etc.). Another advantage is represented by the fact that, deviations due to the human operator are removed, as this type of testing is using a model of a driver, instead of an actual human driver, thus eliminating the uncertainties induced by the human.

Even though the infrastructure required for one test cell is not as extensive as for full vehicle testing, it is still relatively expensive. In addition, it requires long time to replace the components. A picture of a test cell and a schematic of a test cell with an engine rig can be seen in **Figure 3** a and b.



a. Photograph



b. Schematic view

Figure 3 Engine on a Hardware-in-Loop test rig [4]

1.2.4 Model-in-Loop (MiL) testing

With exponential development in software and control strategies, it is now possible to replicate the complete vehicle testing through model based environment (e.g., Simulink/Matlab). This facilitates testing to be conducted in an offline computer based environment. It reduces the development time as well as the related expenses.

Model-in-Loop (MiL) testing contains the complete vehicle model involving various plant and control models of vehicular components (eg.: engine, transmission), that could be updated and interchanged

depending on various testing requirements which reduces the time involved in replacing the components as in HiL testing.

MiL testing is easy to set-up and fast to run on regular computers and it does not require any complex infrastructure as in HiL. It also offers flexibility to test different test cases such as different engines, transmission and vehicle configurations. The MiL can also be used to perform sanity/validation checks of new models before being implemented in HiL.

There are also disadvantages with this method. Even though the results are repeatable, that does not mean they are close to results obtained on a chassis dynamometer or even in HiL, especially in the early stages of the model development.

1.3 Objective

The quasi steady state emission cycle (New European Driving Cycle - NEDC) and transient emission cycle (World Harmonized Light Duty Test Cycle - WLTC) are reproducible sequence of events/test cycles on which the emission testing is conducted. The vehicle model in the HiL utilizes these test cycles to determine the fuel consumption and in turn the emission characteristics.

The existing vehicle model is based on the HiL testing conducted on the Engine at FPD test rig in Volvo Cars Corporation. The objective with this thesis is to create a tool for developing the existing vehicle model for HiL testing through MiL testing approach.

To achieve the emission-testing target, the developed vehicle model has to meet the compliance close to HiL testing. The Engine and the Electronic Control Module (ECM), which are the hardware/test objects under HiL testing, have to be modelled and transferred to capture the similar behaviour through MiL testing.

The sanity/validation check is performed in order to determine the reliability of the result from the MiL testing approach with the complete vehicle (Chassis Dyno) testing and the HiL (Engine Dyno) testing.

The MiL must also retain modularity, so that testing could be performed for different vehicle and powertrain configurations and facilitate module interchangeability. Another important reason for modularity is that the same model will be used for both MiL and for the simulated component of HiL which implies that, the input-output signals of the models used in MiL have to match the ones used in HiL.

Further, implementation of automated testing approach, referred as Unit testing, to facilitate testing on various test cases involving different vehicle and powertrain configurations for quicker result generation and ease of usage. Unit testing will be used to ensure the quality of the vehicle model.

1.4 Emission testing procedure

European emission norms (Euro-I) introduced in 1992 provided the emission standards involving the allowable limit of emissions which all the manufacturers in EU and EEA countries must adhere to, while rolling out their vehicles to the road. These norms have the role to force the vehicle manufacturers to reduce the amount of greenhouse gases released from the vehicle exhaust. These greenhouse gases affect the climate change, the environment and the human health. These Euro norms have been revised continuously to limit the amount of these harmful gases. [5]

This increase in awareness about effects of emission and enforcement of stringent emission regulations, initiated the necessity of developing various testing procedures. These procedures are means of communicating and comparing data about fuel consumption and emissions, between the vehicle manufacturers, in a standardized manner.

Since the RDE testing is still in its inception stage, the norms are being revised to facilitate this test in future. The manufacturer currently utilizes the laboratory based testing procedure of NEDC to provide fuel consumption and emission results. However, from September 2017 onwards, this NEDC testing procedure will be replaced by more realistic Worldwide harmonized Light vehicles Test Procedure (WLTP), which would result in significant changes for the current test procedure and in turn the fuel consumption and emission results. The results obtained from WLTP will then be compared with real world driving. There will be a conformity factor, meaning that the emissions in RDE will be allowed to exceed the results obtained in laboratory conditions, but only to some extent.

1.4.1. Road load determination

Vehicles drive on the principle of conversion of electrical or chemical/fuel energy into mechanical energy. In this paper, the accent is put on “classical” powertrain, without electrification. The useful work i.e. making the vehicle move is performed only by a part of the fuel energy and rest of them count as losses.

Suppose we have 100% of fuel Energy in the fuel tank, in highway usage, 69% of energy represents Engine losses. The remaining losses are as follows: 5% as drivetrain losses, 4% as idling losses, 2% as accessories losses, 11% as aerodynamic drag, 7% as Rolling resistance and 2% for braking are lost in the process. [6]

The road load can be calculated. It is a function of aerodynamic drag, rolling resistance, road grade and inertia force and is given by:

$F = \text{aerodynamic drag} + \text{rolling resistance} + \text{road grade} + \text{inertia force}$

$$F = \frac{1}{2} \rho C_d A v^2 + mg C_r + mg \sin \theta + m \frac{dv}{dt} \quad (1)$$

where C_d is drag coefficient, v is vehicle velocity, C_r is rolling coefficient, θ is road grade, m is mass of vehicle and g is acceleration due to gravity

Experimental data for road load is obtained through coast down testing. Prior to the testing, the vehicle is driven (usually more than 5000 km) to make sure the driveline components had a proper break in. The coast down test is performed on a flat road to eliminate the influence of the road grade and is desired to have no wind. The vehicle is accelerated to a desired speed. Once the desired speed is reached, the transmission is put in neutral and the vehicle is allowed to coast. The speed of the vehicle and the time are measured with high precision devices. Data such as ambient temperature and pressure are also recorded, as they influence the test. In dynamometer, this influence is considered by adjusting the resistance of the dynamometer rollers.

This makes the road load a function of aerodynamic drag, rolling resistance and inertia force which are majorly influenced by the vehicle velocity. Depending on the behaviour of the driver and the road conditions various test cycles called drive cycles are introduced which mimic the driving of the vehicle. The drive cycle consists of series of acceleration, braking, constant velocity and idling events. Depending on these drive cycles, the testing procedure of NEDC and WLTP are developed. The term

“test procedure” involve not only the test cycle but also the steps involved in vehicle preparation such as cold starting, soak time and temperature, conditioning and also emission measurement and analysis.

1.4.2 Emission Measurement

The method used for measuring fuel consumption and for analysing the exhaust gases composition in chassis dynamometer testing at laboratory conditions is shown in **Figure 4**. The vehicle is mounted on the rollers, secured in place and a gas collector is connected to the tailpipe.

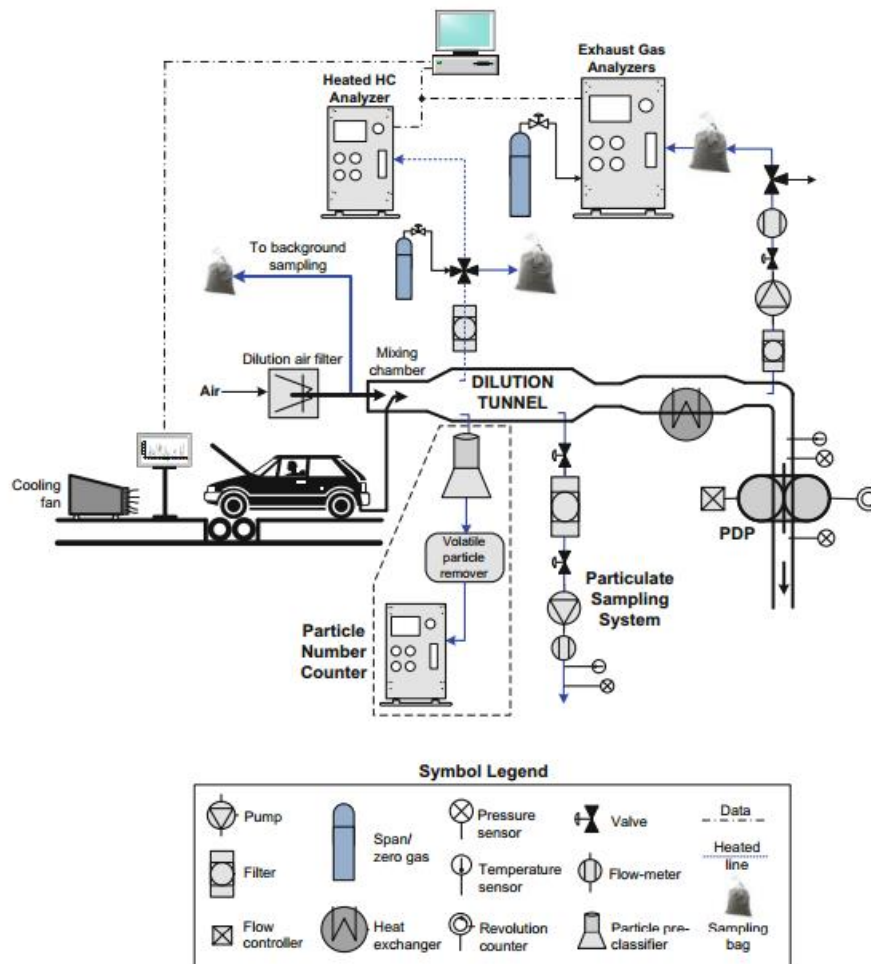


Figure 4 Emission measurement on Chassis Dyno [7]

In this testing, based on NEDC testing procedure or WLTP, the vehicle is pre-conditioned, the resistance of dynamometer rollers is set and the required procedures are followed. The driver's task is to follow the speed trace of the test cycle either NEDC or WLTC. The driver operates the gas pedal, braking pedal and gearshifts (in the case of manual gearbox) to follow the test cycle very closely.

The emissions are being sampled from the tailpipe to the dilution tunnel through Constant Volume Sampling (CVS). CVS is based on dilution of exhaust gases with the filtered ambient air. The dilution of exhaust gases is done in order to prevent condensation of water in the sampled exhaust gas and to study the mixing behaviour of the exhaust gas with atmospheric air. CVS should measure the total volume of the gas and air mixture and collect required amount of this sample for emission analysis. A positive displacement pump (PDP) on the other side of the dilution tunnel maintains the constant flow.

Required samples of total flow in the form of batches are collected at points in the dilution tunnel where there is homogeneous mixing of exhaust gas with ambient air and are collected in bags. Gas analysers are used immediately after the test to determine the concentration of the gases. Based on the type of pollutants to be detected various types of gas analysers are used. Non-Dispersive Infrared (NDIR) analyser is used to determine CO and CO₂ emissions, Flame ionization detector (FID) is used to determine HC's, non-dispersive ultraviolet resonance absorption method (NDUV) is used to determine NO_x and gravimetric method is used for particulates.

1.4.3 NEDC testing procedure

This testing procedure utilizes the New European Driving Cycle (NEDC) to determine the road load and in turn, the fuel consumption and emission results on a city driving conditions. The drive cycle can be seen in **Figure 5**. It consists of four urban cycles (four ECE-15 that form UDC) each taking 195 seconds, up to a total urban driving time of 780 seconds and one extra urban cycle (EUDC) of 400 seconds. UDC is characterized by low speed, low engine load and lower exhaust temperature, with a maximum speed of 50 km/h, which is considered similar to normal driving in cities. The extra urban component reaches speeds of up to 120 km/h, speed that is typical for highway driving. Before the vehicle is to be tested, it must undergo soak for at least 6 hours at a temperature of 20-30 degrees. [8]

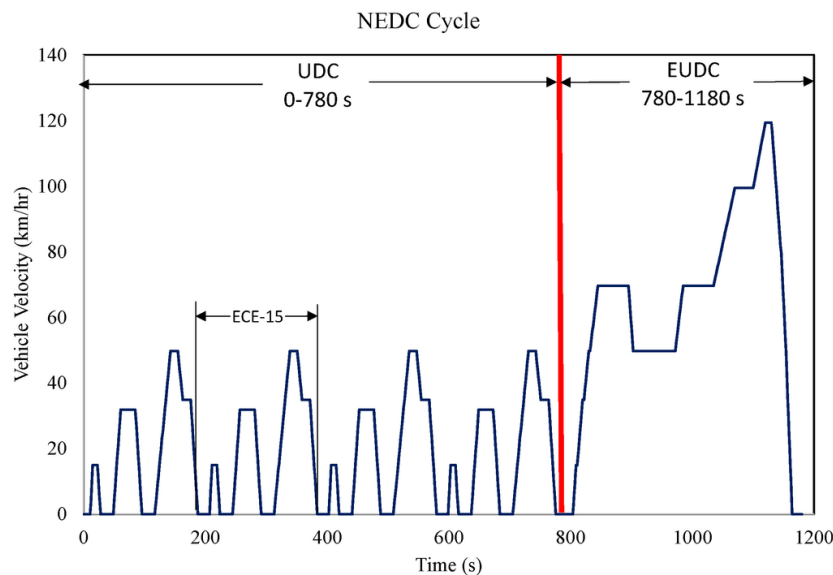


Figure 5 NEDC Velocity profile [9]

Lately, this testing procedure has received a lot of criticism due to the unrealistic fuel consumption and emission numbers. The NEDC drive cycle is quite outdated with a maximum acceleration of 1.042m/s^2 , unusual low vehicle average speed of 34 km/h and maximum speed of 120 km/h for only 3 seconds does not provide the actual representation of the present driving scenario. The vehicle manufacturers also found various loopholes to exploit the fuel consumption numbers. The vehicle would be fitted with low rolling resistance tyres while testing and would be changed when released into the market, the alternator could be disengaged to cancel out the electrical load on the engine, special lubricants that would reduce the friction losses in various components were used, etc. Due to fixed gearshift patterns, the gearbox ratios could be chosen so that the engine runs at speeds and loads that allow high efficiency. The test cycle is the same irrespective of power to mass ratio (PMR) which influences the vehicle speed. These limitations were fixed by introducing the standardized WLTP. [10]

1.4.4 Worldwide harmonized Light Vehicles Testing Procedure (WLTP)

This type approval testing procedure involves WLTC rather than the outdated NEDC. WLTC Driving cycle is more dynamic in nature and realistic, being constructed using data recorded from real world driving. When considered the fact that, the maximum acceleration is raised to 1.6m/s^2 with higher acceleration and deceleration phases throughout the cycle, higher average cycle speed of 46.5 km/h , maximum speed of 131 km/h and in turn the reduction in idle phase shows more aggressive driving behaviour when compared to NEDC. [10] [11]. Speed profile for different classes can be visualised in **Figure 6**. Classes are defined based on power to mass ratio (PMR).

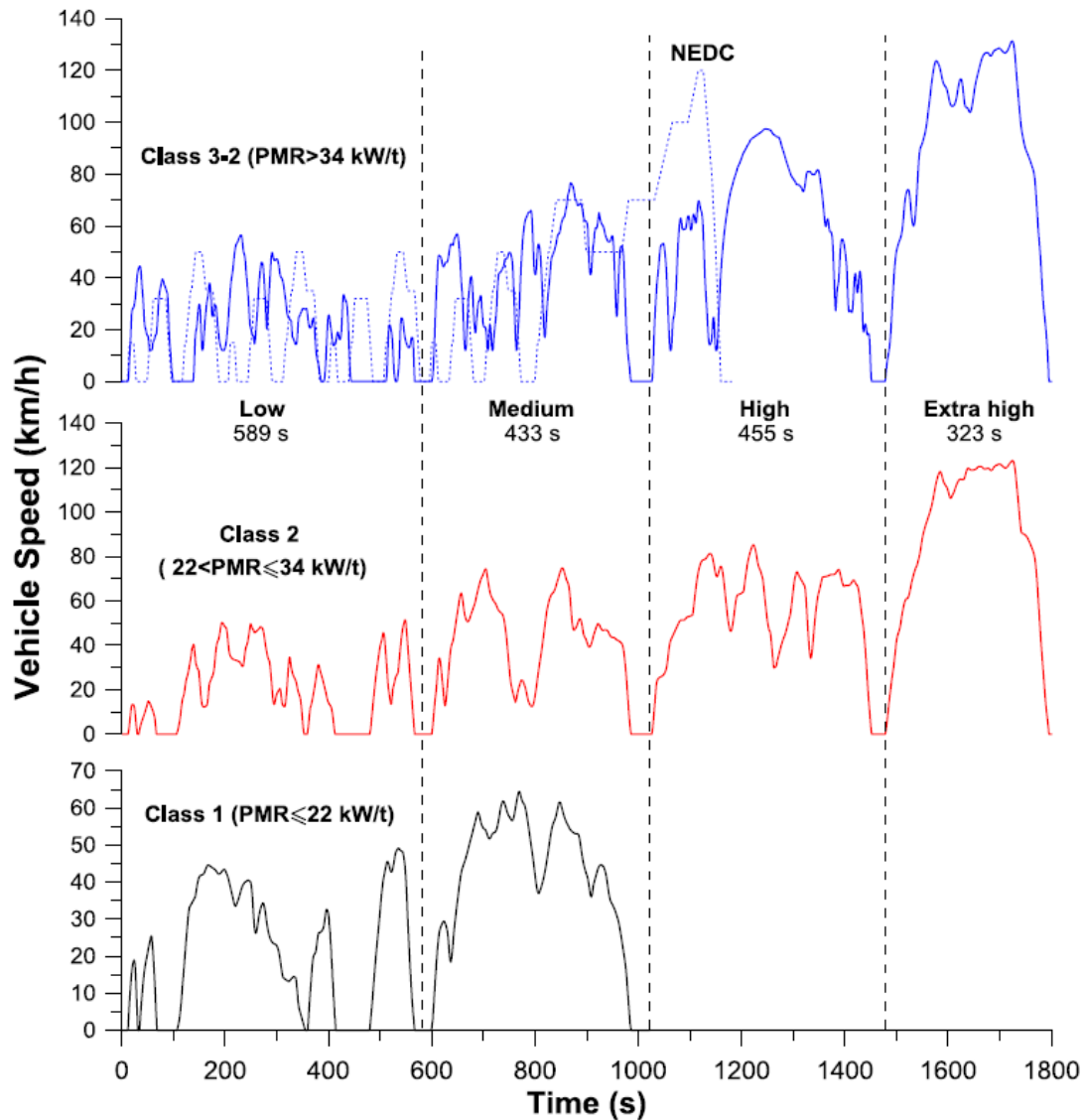


Figure 6 WLTC Velocity set points [12]

The testing procedure is more standardized and strict while considering the electrical load on the engine, same tires while testing and on the road, maintaining a constant soak temperature of 23°C , and various additional factor respective to each vehicle is considered for example: gear shift patterns, test cycle variations depending on the PMR ratio, electrical consumers, tires etc. [13].

Selection of WLTC Cycle

As presented in **Figure 6**, the WLTC Cycle is subdivided into various classes, which differs based on the velocity profiles. Suitable class of WLTC Cycle is determined based on the Power to mass (PMR) ratio and the vehicle maximum speed (V_{\max}). The table shows the classes based on these considerations. The vehicle with higher PMR ratio and V_{\max} are pushed towards utilizing their maximum velocity and abrupt changes in acceleration and deceleration is quite significant in this class of vehicles when compared with the vehicles with lower PMR and V_{\max} numbers. This difference in classes provides more reliability than NEDC cycle having a single cycle for all vehicles.

The methodology for choosing the correct class can be seen below:

For the test vehicle considered in the MiL simulation, the vehicle considered has a power of 231 HP and with the curb mass of 2040 kg.

$$PMR = \frac{\text{Power (W)}}{\text{Curb mass(kg)}}$$

$$PMR = \frac{231 * 745.7 \text{ (W)}}{2040 \text{ (kg)}}$$

$$PMR = 84.43 \text{ (W/kg)}$$

In **Table 1** the vehicle classes can be seen, based on maximum speed and PMR. Based on the value obtained for PMR and considering that the maximum speed is higher than 120km/h, class 3b is chosen for our evaluation.

Table 1 Vehicle classes for WLTC

PMR (W/kg)	V_{\max} (km/h)	Category
PMR > 34	$V_{\max} \geq 120$	Class 3b
	$V_{\max} < 120$	Class 3a
$34 \geq PMR > 22$	-	Class 2
$PMR \leq 22$	-	Class 1

1.5 Comparison of test procedures

For a better understanding of the need for switching from NEDC to WLTC, a direct comparison of the main changes has been made. The class used in this comparison is the one for class 3-2 (Class 3b), which is suitable for most light vehicles on the market. The first change that stands out is the speed profile, which can be seen in **Figure 7**. WLTC provides a more realistic driving scenario than NEDC, which should lead in turn to lab results for fuel consumption and emission testing closer to the real world. The increased number of speed variations also makes it more difficult for vehicle manufacturers to optimize the powertrain to obtain better results during the test.

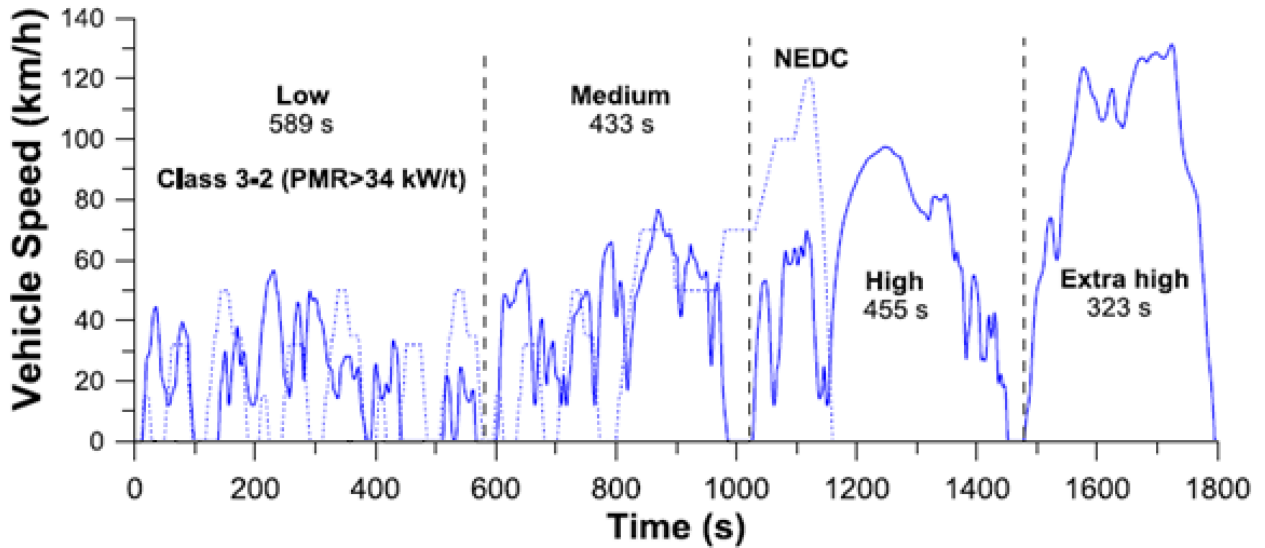


Figure 7 NEDC vs WLTC class 3b [12]

Another interesting characteristic is the acceleration distribution shown in **Figure 8**. While in NEDC both maximum and average accelerations have a low value, and are relatively constant, it is clear that in WLTC they are more chaotic, offering a better representation of the driver's behaviour in real driving scenarios. Apart from test cycle, the various other factors that influences the testing procedure can also be seen in **Table 2**.

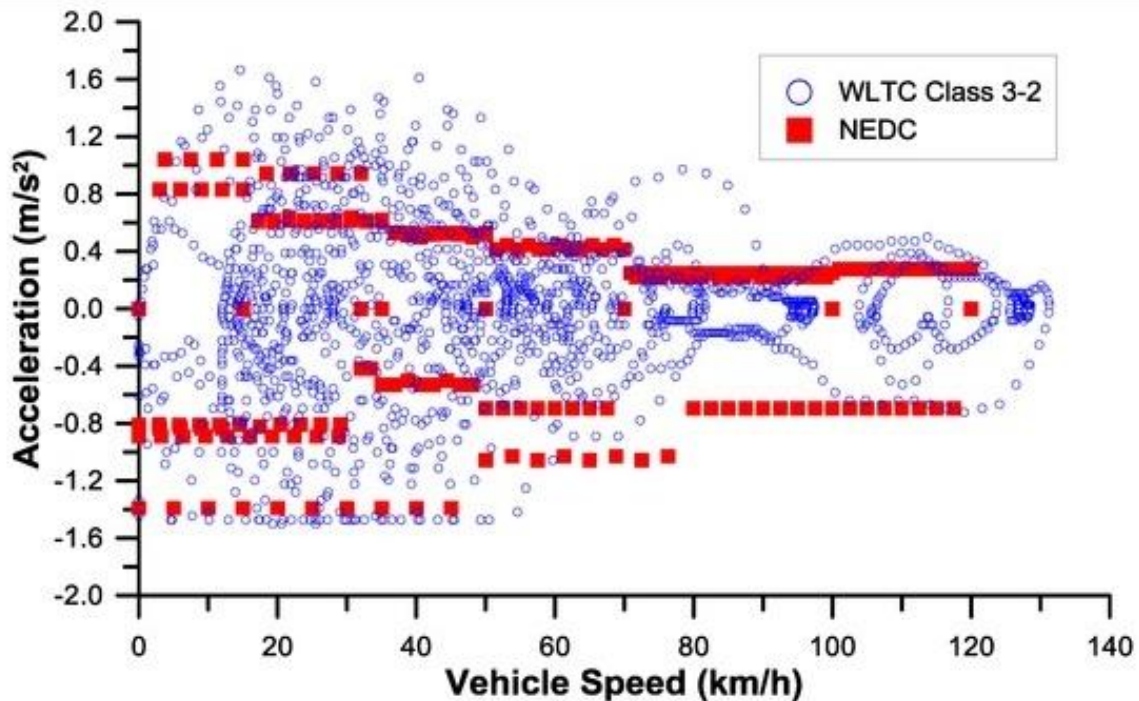


Figure 8 NEDC vs WLTC class 3b acceleration distribution [12]

Table 2 Testing procedures [14]

Parameters	NEDC	WLTP
Road types	2 (37% urban 63% extra-urban)	4 (13% urban 87% extra-urban)
Number of cycle versions	One for all vehicles	3 classes/subclasses/downscaling
Gear shift points *	fixed for all vehicles	specific to each vehicle
Total distance	11 km	23.25km
Average speed	34 km/h	46.5km/h
Max speed	120km/h	131km/h
Max acceleration	1.042 m/s ²	1.6 m/s ²
Influence of optional equipment	Not Considered	Considered
Accelerating/decelerating phase	36%	84%
Constant speed phase	40%	13%
Idle phase	24%	3%
Test temperature	20-30 ⁰ C	23 ⁰ C

*for vehicles with manual gearbox

2. Method

This section focusses on simulation tools to capture the emission testing behaviour of Chassis Dyno. The Hardware-in-Loop (HiL) emission testing eliminates complete vehicle testing instead requires only a component to be tested called as test object along with virtual components. A step further is the Model-in-Loop where the complete vehicle is modelled.

How is the HiL transferred to MiL? How does the MiL function? How do compare the test object in the HiL with the virtual object in MiL? The answer to these questions lies in this section

2.1 Hardware-in-Loop testing methodology

This testing methodology contains two major parts; HiL Real Time System and the Test Object. The Test Object is the hardware under test, which can be engine, transmission or other components. The HiL Real Time system contains all the remaining vehicular interaction, components, controller and plant models, which actively exchange information with the test cell object. If the engine is under test, it is also called Engine-in-Loop Testing (EiL). The **Figure 9** shows the typical EiL testing methodology.

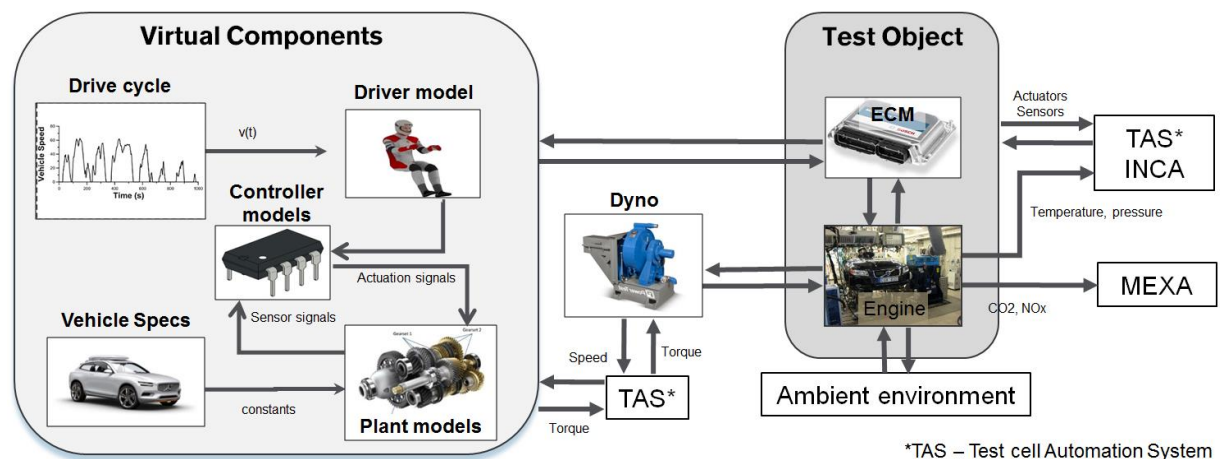


Figure 9 Hardware-in-Loop components

Unlike Chassis Dyno testing, where the human driver follows the drive cycle, the HiL testing involve velocity set points relative to the drive cycle sent to the driver model through CAN Signals. The Driver model captures the velocity set points and tries following it by changing acceleration and gear request over the drive cycle. This information is sent to the controller models. The controller model contains the control strategy for the plant models and sends actuation signals to the plant models. The plant model contains all the vehicular components that are not present in the test object for ex: transmission, tyres etc. The plant models capture all the function and losses, which are not included in the test object and in turn send out sensor signals back to the controller models. Based on the sensor signals, the controller models modify the actuation signals sent to the plant models. The plant models also exchange torque to Testcell Automation System.

Test cell Automation System (TAS) exchanges signals with the dyno. The dyno then transmits torque to the engine. The engine is in constant interaction with the ambient environment, dyno and the control action of the ECM. The ECM exchanges information with the HiL Real Time System and TAS for efficient engine controlling. The speed of the engine shaft is perceived by the dyno and sent back to TAS. The TAS in turn send the speed signal back to the plant models. Based on the sensed speed signal,

the plant models evaluate the necessary function and sends out sensor signal back to the controller models and the cycle continues. INCA along with TAS records and measures all the signal flows throughout the operation. The emissions are measured with Motor Exhaust gas Analyzer (MEXA).

2.2 Hardware-in-Loop to Model-in-Loop transfer methodology

The main purpose behind the MiL simulation is to reduce the development time and the expense by providing an interface to test the models in an offline environment. The MiL/vehicle model must be able to replicate the vehicle behaviour in the absence of a physical engine.

The TAS, which had a major role in transfer of signals across the plant models, dyno and the physical ECM, has been removed. The ECM has been modelled in the controller block which receives the control signals to actuate the modelled engine which is now modelled inside the plant model. There is continuous exchange of information within the controller block and the plant model block to follow the control signals obtained from the driver model throughout the drive cycle. The schematic representation of MiL information flow is shown in **Figure 10**.

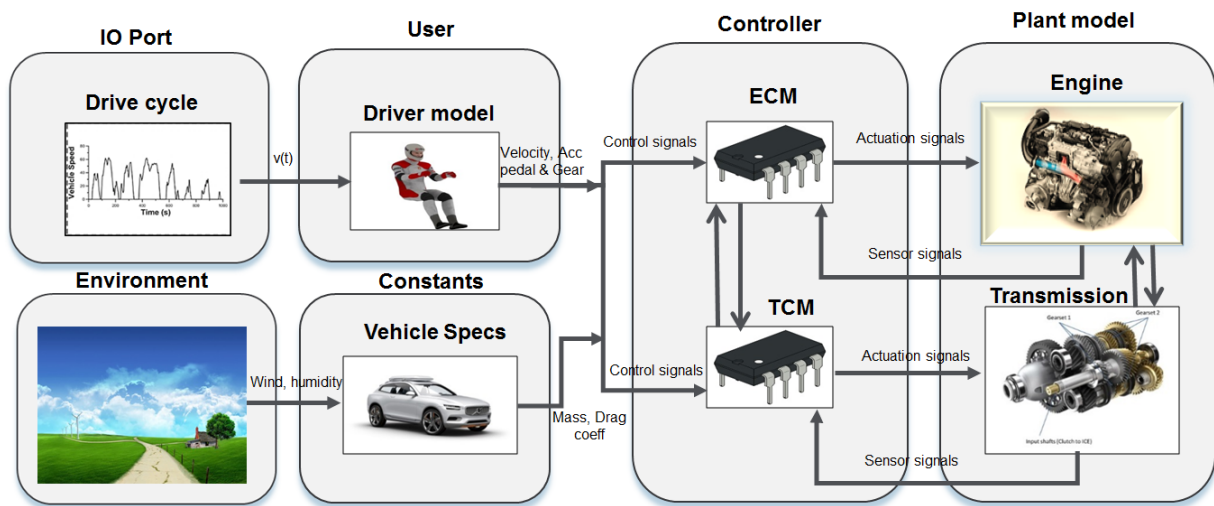


Figure 10 Model-in-Loop components

IO Port Block

In HiL, this block is used to connect the signals from the testing environment to the simulation environment of the HiL. It receives signals from TAS, process them, and then sends new signals to various blocks within the model. In the MiL environment, due to the absence of TAS, all the hardware signals have been removed. Due to the fact that the models have to keep their modularity, the signals with the same functionality still have to be processed and sent from this block. Therefore, the signals previously processed and sent by hardware have to be replicated in this block.

In MiL this block contains the status of the ignition, gear lever position and the drive cycle. Different drive cycles can be chosen. The most used cycles for this paper are NEDC and WLTC, therefore only these two options have been implemented, with the possibility to switch between them.

User Block

This block contains all the information related to the driver behaviour. It majorly contains two sub models, drive cycle and the driver.

Drive cycle

Drive cycle model majorly contains the target vehicle velocity signal taken from IO Block and the tolerance limits by which the driver follows the drive cycle. Based on the driver interaction, there can be two types. Strict driver who follows the driving cycle closely and normal driver who can deviate from the driving cycle within the tolerance limits.

Driver

Driver model functions based on the assumption that the currently observed vehicle acceleration will be kept if the pedals are not moved, and it consists of two core elements. The first element is a state machine that controls the actions of the driver. The second element is used to model the pedal pressing and controlling, using the information received from the state controller. This action flow is shown in **Figure 11**.

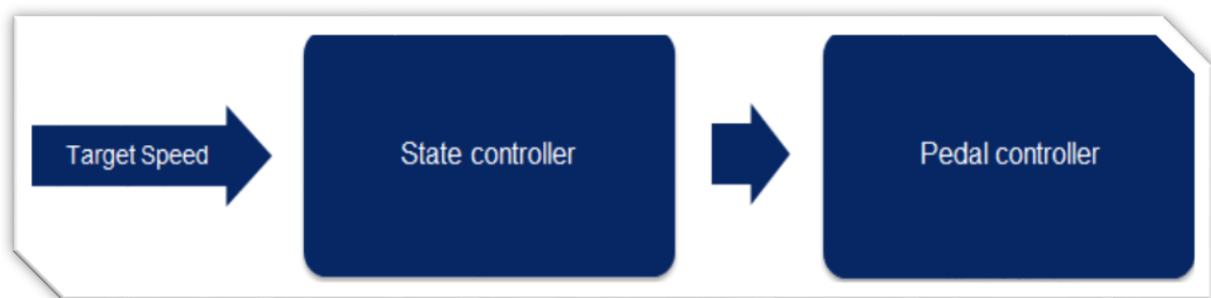


Figure 11 Flow direction for driver model

The way the driver works is, using the assumption made above, the speed of the vehicle is predicted at two moments in the future. The speeds can be obtained by integrating the acceleration. The two predicted speeds are compared to the target speed, and the speed deviation (error) is calculated. The sums of the two error values are multiplied by weights that are adjusted to depend on vehicle speed, control error and actual speed.

In the state controller, the pedals to be pressed are decided based on the speed profile. For an automatic gearbox, an example can be viewed in **Table 3**.

Table 3 State controller example

Gearbox	Stopping	Accelerating	Coasting	Braking	Take-off
Automatic	Brake pedal pressed.	Accelerator controls vehicle speed.	All pedals released.	Speed controlled using brake pedal.	Brake and accelerator control vehicle speed. Launch control presses accelerator.

Environment Block

This block contains the influence of environment such as climbing angle, road grade, wind velocity, ambient temperature and road friction which are considered constants throughout. The output from this block does not influence the engine model. However, during model upgradation to meet RDE legislation, it will definitely have a greater impact.

Controller Block

Similar to the HiL testing, this block contains all the control algorithms necessary for fully functioning

of the plant models. The main difference is that the ECM is now modelled within this block enabling actuation signal flow to the modelled engine unlike in the HiL testing where we had physical ECM sending control signals to the actual engine. It also contains all the controllers for plant models mainly the TCM for transmission and controllers for infotainment, chassis, driveline and so on. The controllers also exchange information between other controllers within the block.

Plant model Block

This block now contains an engine model which takes actuation signals from the modelled ECM in the controller block. Apart from that, it contains all the plant models of HiL testing. The plant model captures the required actuation signals from the controller block perform the requested function and sends the sensor signals back to the respective controller models within the controller block. The plant models also exchange information between other plant models as well.

2.3 Model-in-Loop function strategy

The purpose of the model is to follow a target speed. The target speed is set by the driving cycle, and that acts as an input for the driver.

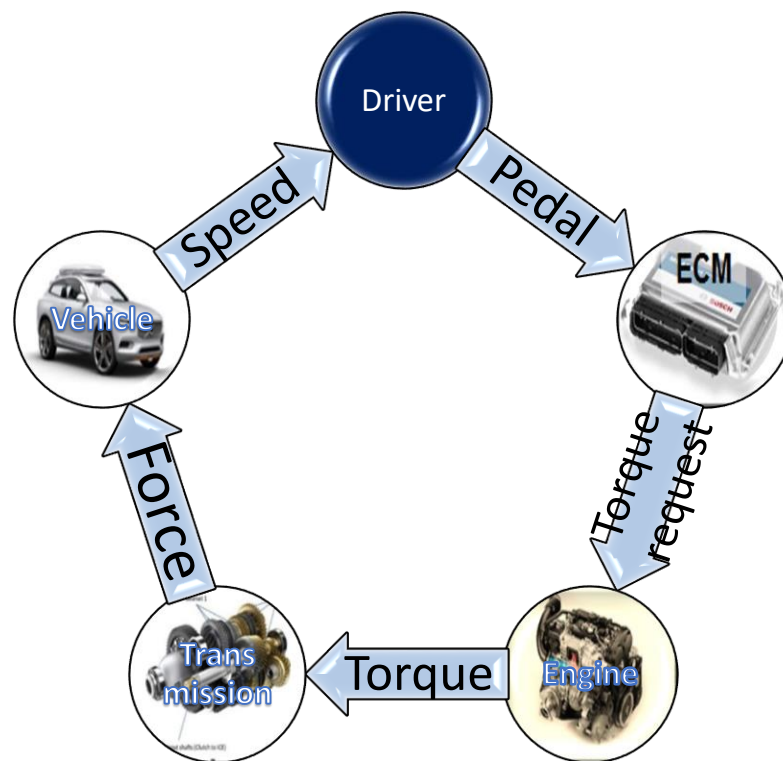


Figure 12 Direction of information flow between the main models

The Driver sub model in the user block compares the vehicle speed with the target speed of the test cycle either NEDC or WLTC. Based on the difference between the two speeds, the driver initiates the pedal command, which is transmitted to the ECM in the controller block. The ECM sends the corresponding torque request signal as the actuation signal to the engine in the plant model block. Based on the torque request and associated torque and gear limitations, the engine transmits the equivalent

torque which flows through the gearbox, driveline and to the wheels. The force at the wheels is calculated from the torque at the wheel and the corresponding tyre characteristics, and based on the vehicle specification the corresponding acceleration is obtained which is integrated to obtain the current vehicle speed which is transmitted to the Driver block and the cycle restarts as shown in **Figure 12**.

The torque request sent from the ECM is also influenced by engine speed and gear limitations sent from the TCM apart from velocity and pedal position. The ECM is in constant communication with the TCM and the torque obtained from the engine when it passes through the drivetrain, the corresponding controllers initiate the required limitations to send the demand request and the plant models perform the required action based on the received signal from the corresponding controllers.

Comparison between the Engine in HiL and MiL testing

In HiL testing, Propulsive Vehicle Control (PVC) is the torque management controller consisting of control modules which calculates the requested torque to be sent to the ECM. The torque request is based on the functioning of pedal maps calculated from the signals received from the driver model and the engine. Based on these signals, there can be two different functions by which the pedal map can be calibrated

Torque map

$T_q = T_q(\text{Accelerator Pedal, Engine Speed})$

This pedal map is calibrated in torque as a function of accelerator pedal position and engine speed. This is mainly used in manual transmissions.

Force map

$F = F(\text{Accelerator Pedal, Vehicle Speed})$

This pedal map is calibrated in traction force as a function of accelerator pedal position and vehicle speed and is used only in automatic transmissions.

Along with these pedal maps influencing the traction force request, the Propulsive Vehicle Control (PVC) also contains control modules influencing the torque request from Cruise control, Engine Speed control, Crankshaft torque control, Speed control, wheel torque control and idle control. The final torque request is sent to the ECM through CAN actuator signals, which controls the functioning of the engine, and the engine transmits the final torque and sends its state as the feedback signal to the PVC as shown in **Figure 13**.

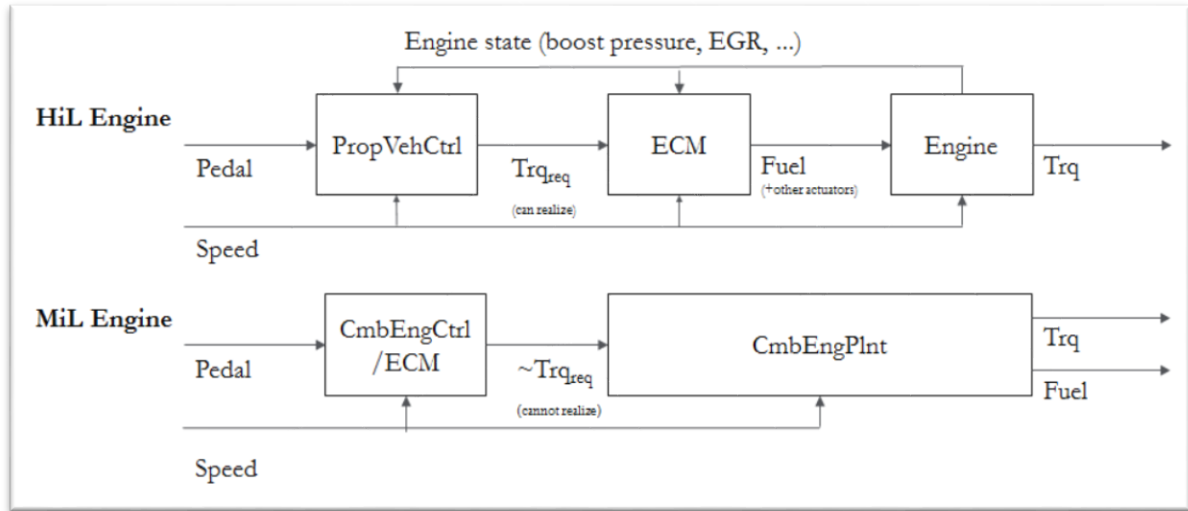


Figure 13 Comparison between real engine and the modelled engine

In MiL testing, the PVC is replaced by Combustion Engine Control/ECM, which serves the same purpose of transmitting the torque request to the Combustion Engine Plant model as shown in **Figure 13**. The torque request is calculated based on the inputs received from driver model and the limitations put forth by the Transmission Control Module (TCM). Apart from torque request function, the ECM also contains various sub functions as shown in **Figure 14**.

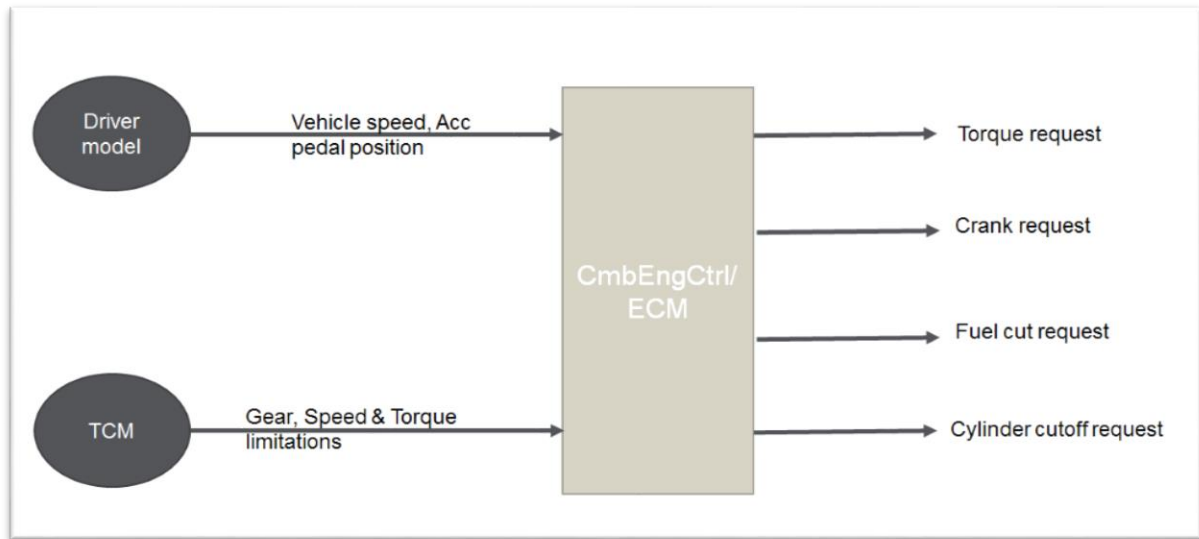


Figure 14 ECM Functions

Estimation of Engine Torque

All the request signals from ECM are coupled into a signal actuator bus which is transmitted to engine plant model.

The torque request is then compared with the calibrated torque maps within the engine plant model to transmit the actual engine torque. This torque is then subjected to torque limitations from TCM which limit the engine torque within the specified interval. Through model upgradation, basic traction control model is added which takes into account the engine torque along with vehicle speed and longitudinal speed to provide traction torque.

The torque at the crankshaft ($T_{crankshaft}$) is then calculated to determine the fuel consumption. It is given by

$$T_{crankshaft} = T_{motored} - T_{coldfriction} + T_{auxiliary}$$

where $T_{motored}$ is the motored torque calculated based on the product of engine speed and cylinder cut-off torque, $T_{coldfriction}$ is the cold friction torque calculated based on the product of engine speed with engine temperature and $T_{auxiliary}$ is the auxiliary torque which is the sum of mechanical torques exerted by the engine, power steering pump, alternator and climate control.

Estimation of Fuel Consumption and NOx

The torque at the crankshaft is compared against the engine speed on a calibrated fuel consumption map to determine the net instantaneous fuel consumption. With upgradation of the engine model to the latest VSim, it is now possible to determine the emissions majorly the NOx through a model called Engine Mode Manager within the ECM which switches the exhaust flow through the EGR. This control action is then transferred to the plant model which interpolates the calibrated NOx data with engine speed and engine torque to output the NOx emission result.

Influence of Transmission

The Transmission Control Module (TCM) receives the information related to vehicle speed and pedal positions from the driver model and compares it with the target gear received from the ECM to formulate the requested gear. This information is then transmitted to Automatic Transmission model which has the gear shift control strategy to output the actual gear which is then fed back to TCM as sensor signals as shown in **Figure 15**.

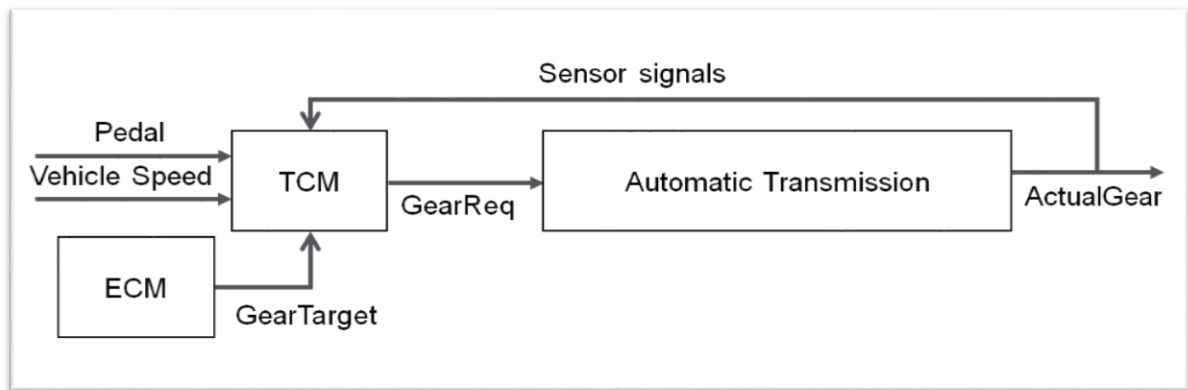


Figure 15 Transmission function

The target gear from the ECM has been tuned to output the same shifting strategy of the HiL testing, in order to compare the accuracy of the results from the MiL testing with HiL testing and Chassis Dyno testing.

3. Unit Testing

The automation of the tests is described in this section. To reduce the time required from a human operator, the process will be automated. The testing should be prepared by an operator and then proceed without any intervention. With this tool, new models can be tested before being implemented in Hardware-in-Loop system. Without this tool, if a new model is not behaving as expected, and if it is not discovered before being implemented in the software component of the HiL system, a lot of time is wasted, potentially delaying testing in multiple test cells until the problem is fixed. This being considered, it makes sense to have a tool that analyses the models, in a separate environment, without delaying the project.

Four main steps need to be carried out in order to test if, a new model performs in a right way:

1. Choose the simulation parameters

The operator selects the correct parameters for the simulation. Among other parameters, this includes choosing vehicle model, engine type and characteristics, transmission details; type of driver required and drive cycle desired.

2. Type the correct input files

Once the choice has been done, the operator can move on and input the correct file names into an excel file. Since the process is automated, different simulation parameters can be used. An example of how it looks can be seen (**Table 4**) below.

Table 4 Input data

Id.	Build [Y/N]	Model	Vehicle data file	Tyre data file	Engine	Transmission	Driver	Cycle
1	Y	MiL	V60_170305	T_225_60_r19	D_150hp	Aut_6_gears	Strict	WLTC
2	N	MiL	V70_120309	T_235_55_r19	P_230hp	Man_6_gears	Strict	WLTC
3	Y	MiL	XC90_160105	T_235_55_r20	P_330hp	Aut_8_gears	Regular	NEDC

Where: Build – indicates if the current build will be simulated. Y = yes, N = no.

Model – shows in which environment will the simulation be conducted, and points to the correct model.

Vehicle data file – contains parameters such as vehicle mass, road load etc.

Tyre data file – contains information related to the tire – width, height, rim dimensions

Engine – contains information required for the engine to be simulated – torque maps, pedal maps, inertia forces, motored torque, fuel type etc.

Transmission – contains data relevant for the transmission of the vehicle – gear ratios, final ratio etc.

Driver – contains parameters related to the driver model. These parameters decide how close the driver will be able to follow the target speed.

Cycle – contains data points for velocity value at different moments. These data points define the target speed that the driver needs to follow. In the paper, the main focus is on NEDC and WLTC, but depending on the test, other cycles can be used as well, Artemis, FTP etc.

The correct choice of the parameters is to be paid extra consideration. If the wrong files are chosen, the Unit Testing output might not show any problems. Also in this step, the user must make sure the required files have been added to the correct path before running the simulation.

3. Run the simulation

If all the files have been chosen, the next step is running the simulation. This is straightforward. The user has to open Matlab, go to the location of the main script and run it.

4. Analyse the output

The output result depends on the type of simulation that is being run and can be customised to have different outputs. A general output can be seen in the **Table 5** below:

Table 5 Unit testing output

Build	1	2	3
Fuel Consumption [l/100km]	5.16	5.7	5.45
CO ₂ [g/km]	136	151	144
Counter upper	0	0	4
Counter lower	0	0	1

Where: Counter upper and Counter lower – shows how many times the speed has exceeded the upper tolerance or has dropped below the lower tolerance. If they are different from zero, as it can be seen in build 3, that respective build has to be investigated closer.

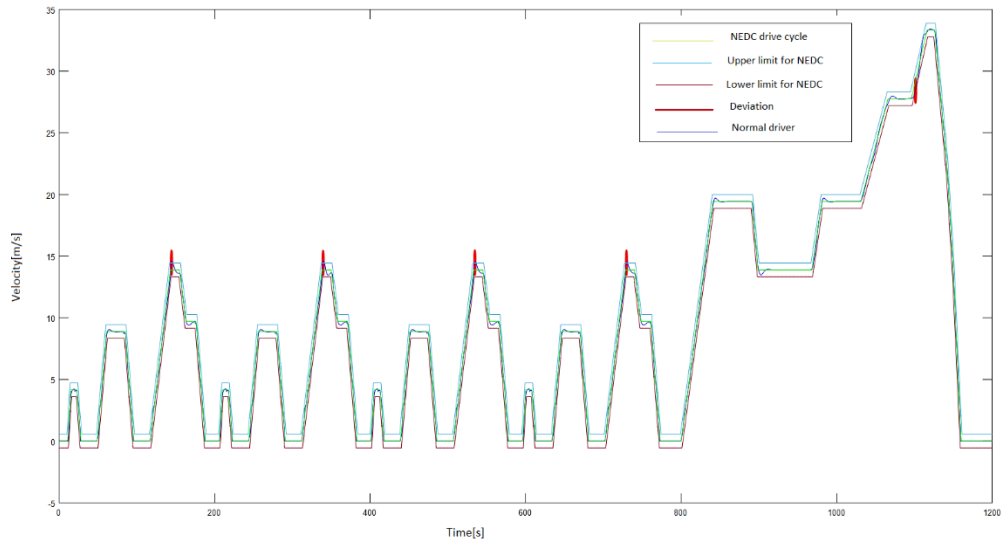
For the third build, the driver characteristics were altered in such a way, to make it impossible to stay between the limits, for the proof concept.

3.1 Sanity check

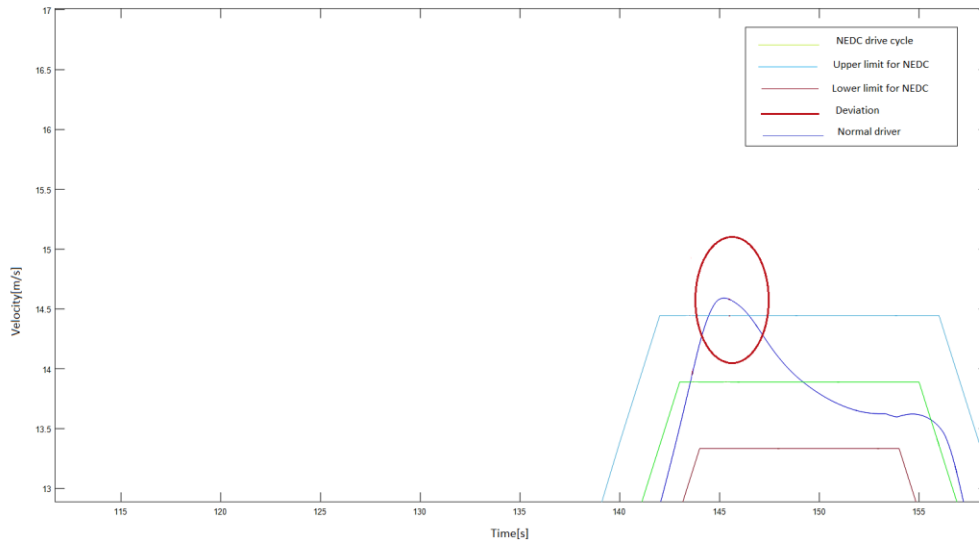
The sanity check is performed to make sure the model is running properly and it behaves as expected, without going out of the speed tolerances, without excessive speed oscillations etc. In the case of a standard NEDC or WLTP simulation, it can show e.g., if the driver goes outside the tolerances of the speed profile, or if there are unusual oscillations in the acceleration.

In the output example from **Table 5** in third build, the actual vehicle speed goes above the upper tolerance four times, and it drops below the lower limit once. In this scenario, the user has the possibility to run a more in-depth analysis, just for that specific scenario. In this case, more information is available for display.

After running the scripts, the user will be able to see the following results:



a. Speed profile in NEDC



b. Close up view on the deviation

Figure 16 Velocity deviations

Figure 16 a and b shows a typical NEDC plot with upper and lower tolerances, with corresponding driver behaviour, and indications where the actual speed of the vehicle exceeds the tolerance limits due to undesired driver behaviour. In **Figure 16** b, one can see a closer look on the indication where the actual speed exceeds the upper limit. Associated to the plot, the user also receives information in form of text, as it can be seen in **Figure 17** below.

```

=====

Velocity is out of bounds during cycle.

Upper limit
-----
Start time [s]    End time [s]
      144.5         146.5
      339.4         341.5
      534.6         536.4
      729.6         731.3

Lower limit
-----
Start time [s]    End time [s]
      1101.3       1101.8

=====

###Velocity deviation longer than 1 second###
No more than 10 velocity deviations

```

Figure 17 Information related to exceeding speed limits

In **Figure 17**, the user can see useful information for understanding when the actual vehicle speed is outside of boundaries. For the upper limit, start time indicates when the vehicle speed goes above the upper limit, while end time shows when the speed comes back below the upper limit. In a similar way, for the lower limit, start time shows when the speed drops below the lower limit, while end time indicates when the speed comes back above the lower limit.

Vehicle Equivalent Test Weight	ETW = 2040.00 kg
Effective Test Mass	Me = 2070.60 kg
Total Target Distance	DT = 10890.30 m
Total Driven Distance	DD = 10848.09 m
Total Distance Difference	DT-DD = +42.2171 m
Distance Rating	DR = -0.39 %
Target Absolute Speed Change Summation	ASCt = 293.333 m/s
Driven Absolute Speed Change Summation	ASCd = 307.874 m/s
Absolute Speed Change Rating	ASCR = +4.96 %
Root Mean Squared Speed Error	RMSSE = 0.170 m/s (= 0.612 km/h)

Figure 18 Information related to the test mass and travelled distance

In **Figure 18**, the user has access to information about the mass of the vehicle, total distance driven, and information about how well the driver manages to maintain the actual speed of the vehicle as close as possible to the target speed.

```

Fuel consumption for EC00:

                                part 1    part 2    total
Fuel consumption [l/100km]:      7.14      5.30      5.97
Fuel economy    [mpg]:           32.95     44.42     39.43
CO2 emissions  [g/km]:          188.24    139.64    157.31
Distance traveled [km]:          3.94      6.90     10.85
Mean eng speed [rpm]:            979       1336     1104
Mean torque [Nm]:                38.64

-----
engModelLowerHeatingValue, FC-data:                42.60 MJ/kg
engModelLowerHeatingValue, analysis:                42.82 MJ/kg
Fuel density, analysis:          0.8350 kg/l
CO2 factor, analysis:            26.36 100g/l

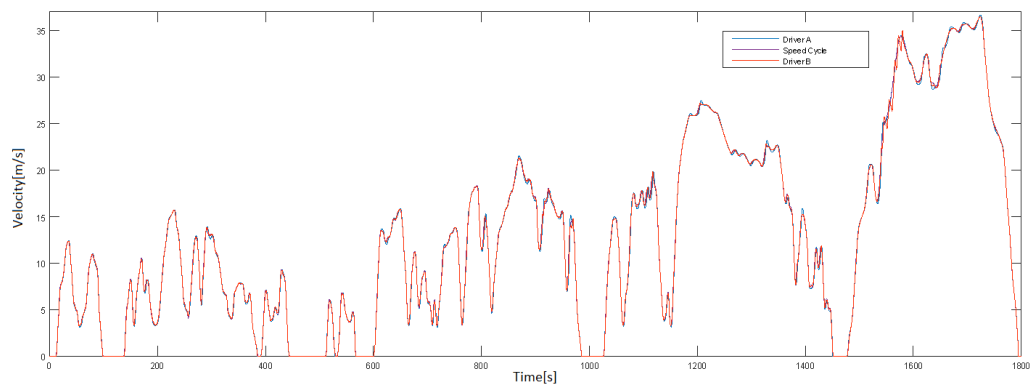
```

Figure 19 Information related to fuel, CO₂, engine speed and torque

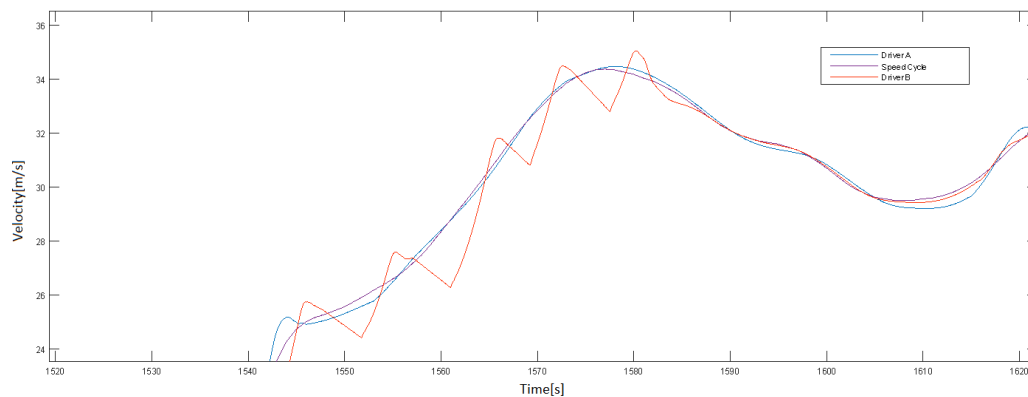
In **Figure 19**, the user receives information about engine speed and torque, fuel properties and fuel consumption results. By analysing this set of data, one can check if the right fuel was chosen, and if there are any abnormal values in engine speed and engine torque, and inspect fuel consumption and emission behaviour.

The above figures only show examples of the possible outputs. In reality, a lot more outputs can be shown, depending on the test case and on what it is useful to see in that test.

One peculiar case where the unit testing can be useful can be seen below in **Figure 20**.



a. Speed profile in WLTC



b. Close up view on undesired driver behaviour

Figure 20 WLTC driver behaviour

It can be seen that, driver B has problems following the target speed in a smooth way, even though it is still within the tolerance limits. Normally, this would not trigger a warning, because the speed does not go outside the limits. This proves that a lot more factors have to be taken into considerations when determining the sanity of the model, not just the condition of keeping the vehicle speed between the speed limits.

Analysing the vehicle acceleration, it was concluded that the accelerations are almost twice the acceleration required by the target speed. In this case, a warning will be issued, informing the user that there is a potential error in the driver model.

4. Results & Discussions

After understanding the methodology behind Chassis Dyno, HiL and MiL, the final set of questions still remain; How to analyse the results between various testing methodology? Are the results comparable? Any drawbacks?

This section settles all the aforementioned questions by taking first through the driver analysis stage and then moving onto the result stage comparing and discussing all the testing methodology.

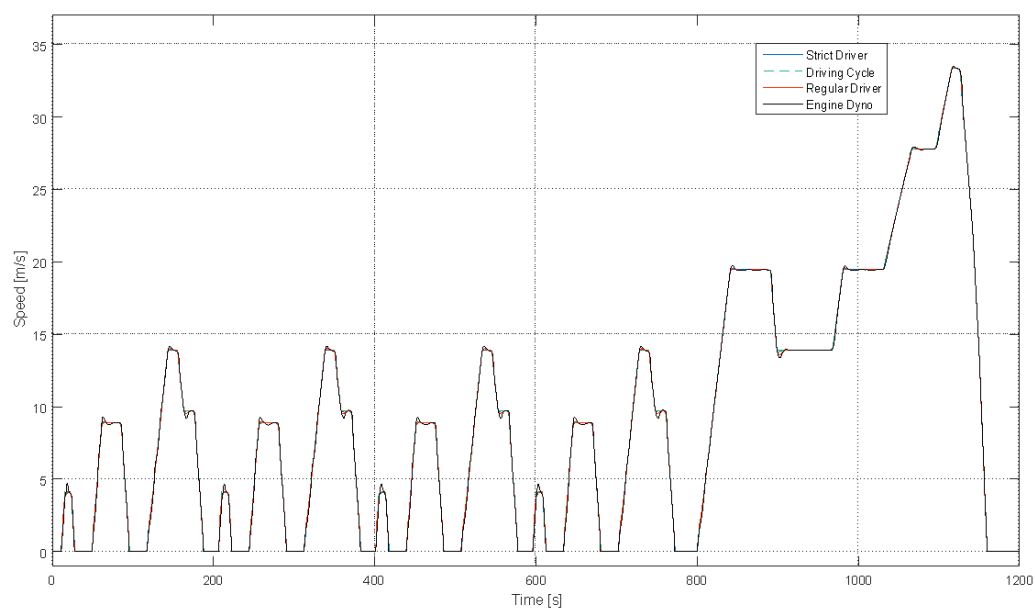
4.1 Driver comparison

The MiL testing must consider the required driving cycle for the Testing procedures of NEDC and WLTP. The NEDC testing procedure utilizes the single type of Driving cycle called NEDC for all types of vehicles and for WLTP, the WLTC driving cycle of Class 3b is considered based on the PMR ratio. This selection is done in the IO Port block of the MiL simulation platform which sends out the vehicle's target speed to the Driver model.

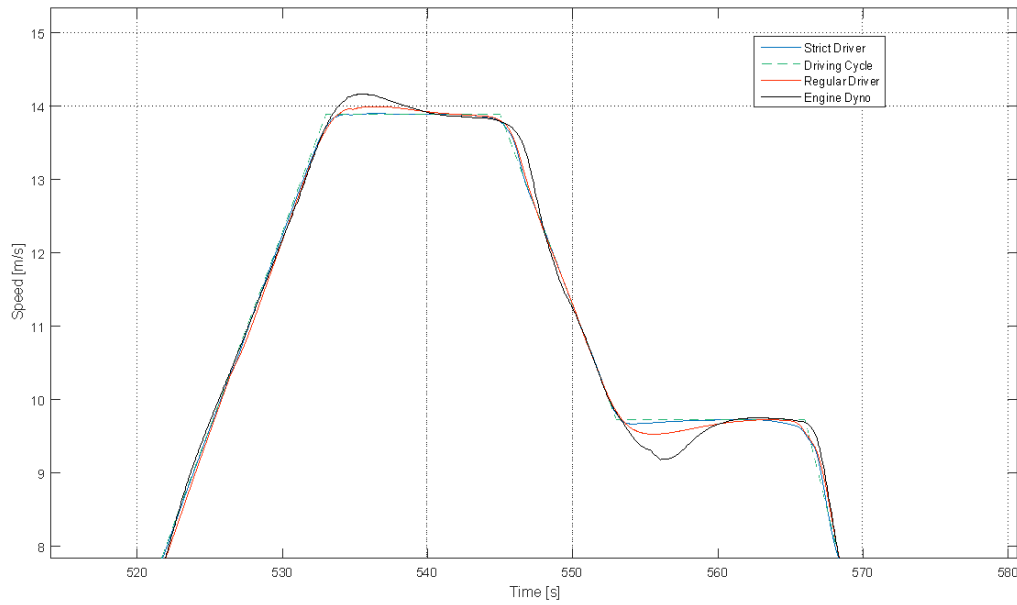
One important requirement of the driver model is to be able to emulate the behaviour of different drivers, with different skill levels. By adjusting the weights and the moments when the speed predictions are being made, the driver model is able to simulate different drivers. This driver model can be used for both fuel consumption simulations and also for performance tests.

4.1.1 Driver for NEDC cycle

The driver needs to be able to follow the speed target of the speed, while showing similar results to the tests from HiL. As it can be seen in the figures below, two driver models were used. One being a regular driver and the other one being a strict driver, capable of following the target speed with smaller deviations.



a. Speed profile in NEDC



b. Close up view on driver deviations

Figure 21 NEDC - Driver Selection

As it can be seen from

b. Close up view on driver deviations

Figure 21, the strict driver manages to follow the target speed with a higher precision, but it does not match with the test data from HiL. There is a discussion with relation to what driver settings should be used. Both the HiL and MiL should in the end have similar results to the ones from the dyno chassis. The problem with the tests from the dyno chassis is that the actual driver in the vehicle influences it.

4.1.2 Driver for WLTC cycle

The strict driver was chosen for WLTC cycle. This is because WLTC Cycle is close to realistic driving behaviour of the driver and it is intended that the driver follows the driving cycle closely in order to obtain the actual results.

4.2. Gear selection comparison

The gear selection is done based on engine speed and acceleration pedal position. There is a slight difference between the MiL and engine dyno due to the fact that the gear mapping was changed since the HiL test was performed, which meant it had to be recreated. The target gears were chosen in such a way that in normal driving mode, they would maintain the engine at speeds and loads characterized by low fuel consumption, but without sacrificing reliability.

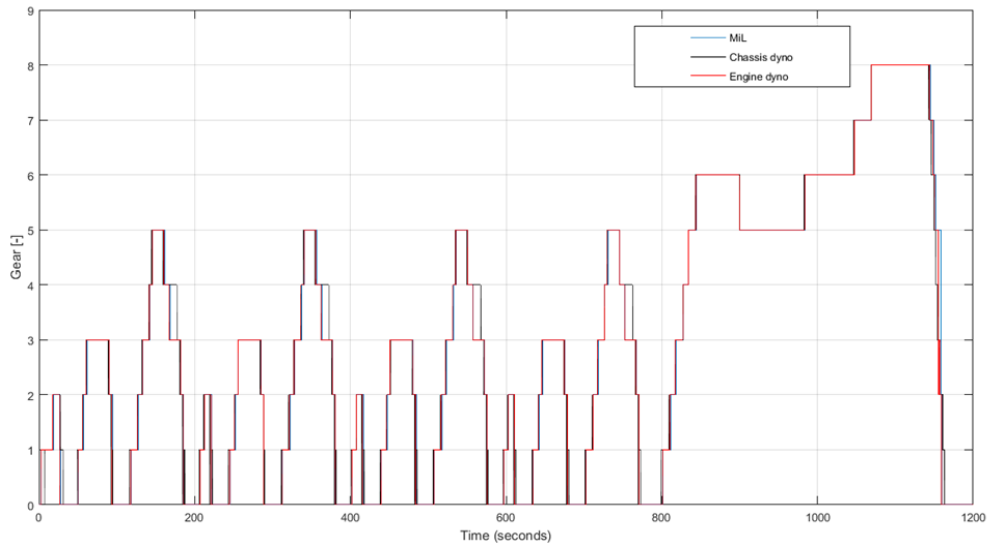
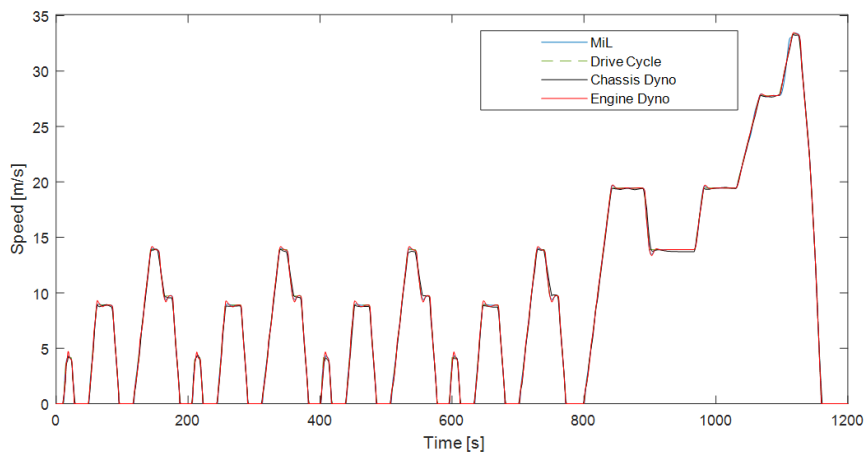


Figure 22 Selected gear comparison

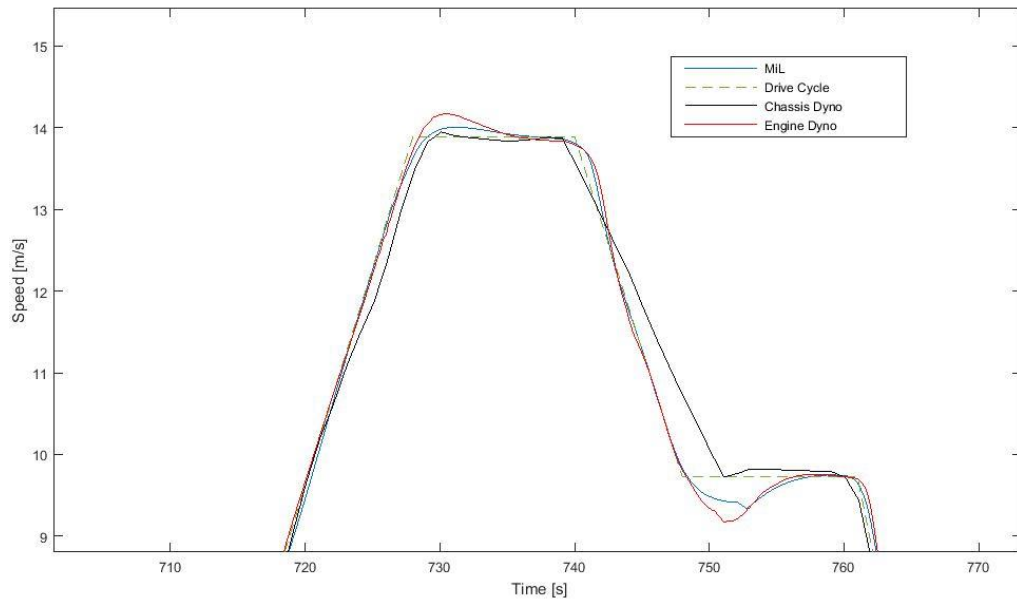
In addition, there is a difference in downshifting between HiL and the full vehicle as shown in **Figure 22**. This difference comes from the driver of the chassis dyno, and from the different maps that are being used, but it does not have any effect on the fuel consumption, because in those regions the vehicle is decelerating and there is no fuel feed while decelerating (engine brake).

4.3. Test cycle comparison

The MiL simulation must follow the driving cycle within the permissible deviation of ± 2 km/h and the results are compared against the Engine Dyno and Chassis Dyno. All the results follow the driving cycle quite closely as shown in **Figure 23**.



a. Speed profile in NEDC



b. Close up view for drivers behaviour analysis

Figure 23 Driver behaviour comparison of MiL, HiL and Chassis dyno

It can be seen there is a slight difference especially on the corners. This suggests that the driver model used in both HiL and MiL needs to be adjusted, to follow the target speed in such a fashion that it imitates the human driver in the chassis dyno better.

4.4. Engine Speed comparison

The engine speed is the function of vehicle speed and gear ratio. The comparison below in **Figure 24**, shows the proximity of the MiL result with the engine and chassis dyno tests. It can be seen that the MiL result follows similar profile of the HiL result. There are minor deviations in chassis dyno result that could be attributed to the difference between the human driver and the driver model.

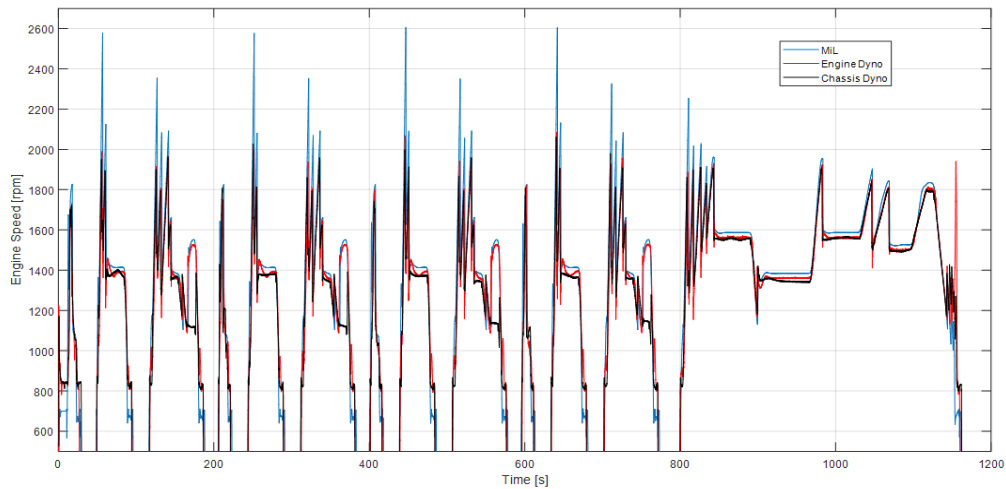


Figure 24 Engine speed comparison of MiL, HiL and Chassis dyno

4.5. Engine Torque comparison

The engine torque is based on the driver's pedal positions and in turn, the throttle opening, the MiL results shows significant deviations when compared to the engine and chassis dynos as shown in **Figure 25**.

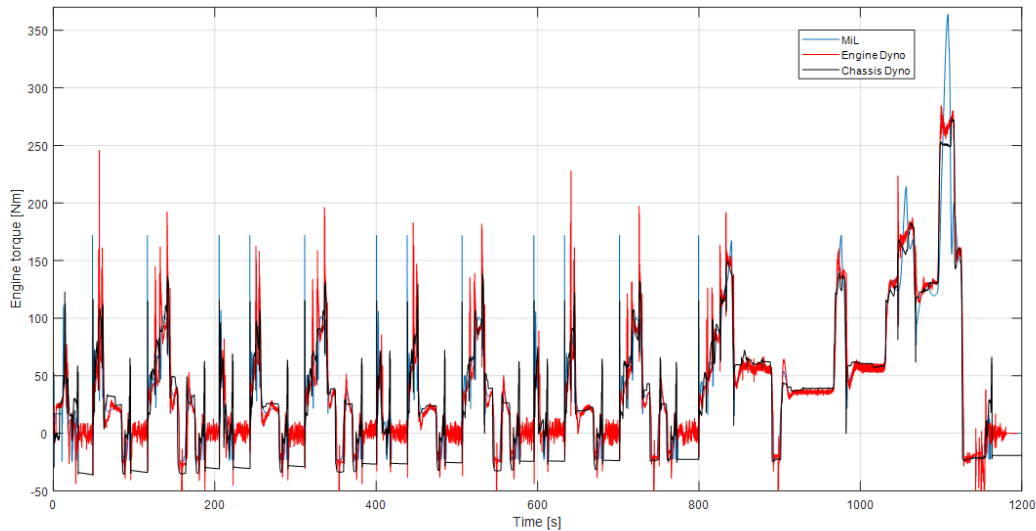


Figure 25 Engine torque comparison of MiL, HiL and Chassis dyno

In both the vehicle and the model, the torque demand is calculated through empirical approach from i.e. pedal map, which depends on the acceleration pedal status. In one scenario, the driver keeps the vehicle at a constant speed, and then suddenly presses the pedal to the maximum. When this happens, the driver asks for the maximum possible torque. The difference between the MiL and the vehicle appears in how fast the torque can increase.

In the real vehicle, the instantaneous maximum torque depends on the pedal input, but it is also calculated based on other factors, such as: air flow, turbocharger status, EGR status etc., while in the MiL, the model is simplified and it does not take into account so many factors, therefore the instantaneous maximum torque can be a lot higher.

4.6. Fuel Consumption comparison

The fuel consumption is based on the engine torque characteristics. It could be seen from **Figure 26**, that the results from the chassis dyno follows the behaviour closer to the MiL. However, the result from the engine dyno has abrupt high and negative fuel consumption throughout the cycle at particular instant of time. This can be attributed to the fact that the result considers the amount of fuel being sent to the engine rather than the actual fuel consumed by the engine.

In engine dyno testing, there exist a fuel tank outside the engine which takes in excess quantity of fuel before being sent to the engine, this validates the higher peak in fuel consumption. The engine takes in the required amount of fuel and kicks the remaining fuel back to the engine tank which confirms the negative peak. It can be inferred that, since the value of the positive and negative peaks are similar, it will nullify each other when considered the complete test cycle and the result will be closer to that of the chassis dyno and MiL.

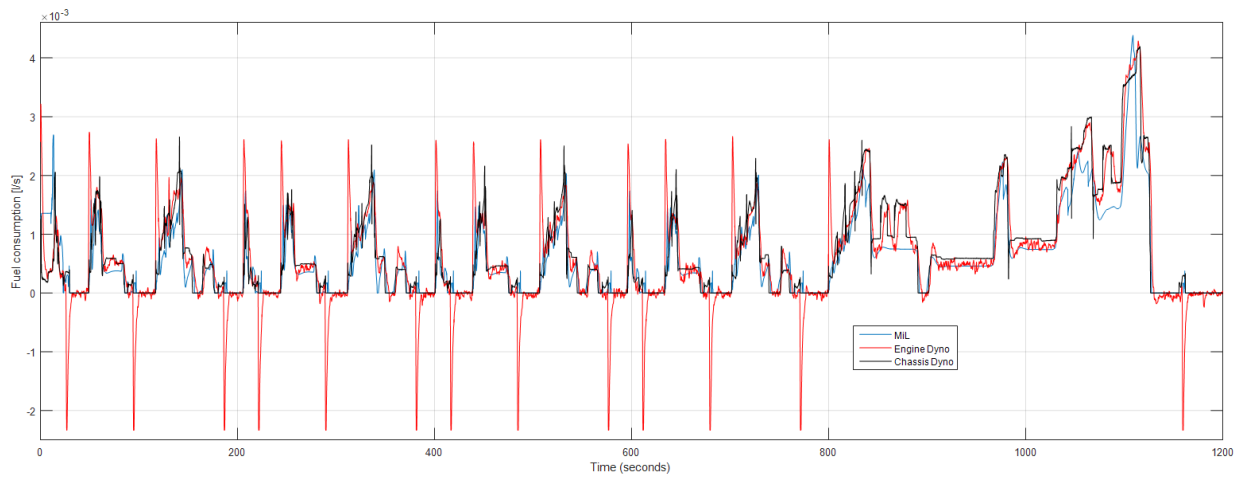


Figure 26 Fuel consumption comparison of MiL, HiL and Chassis dyno

5. Conclusions

The thesis work throws light on the advancement of simulation over the traditional testing approach. The advantages are clearly visible; reduced development and testing time, reduced expenses and close correlation with real-time testing.

This section describes the various steps taken to develop the vehicle model from its initial phase to the final correlation study.

5.1 Functional MiL

The initial study involved, understanding of complete vehicle architecture, the plant models, the control models, and the signal flows across the complete vehicle model. The rectification of signals was crucial at this stage, as the model was not functional. The missing signals were added, additional signals were created to retain the vehicle architecture and many unnecessary signals and models were removed to make the complete vehicle model functional.

5.2 Upgrading the model

The plant and control models of engine and transmission were initially outdated. After the MiL/vehicle model was made functional, it required upgrading to capture more realistic and functional behaviour. The upgrading of the model also involved the necessity of creation of more signals and functions which further increased the complexity of the vehicle model with the possible benefit of reliability and reduced dead-time periods in testcells.

5.3 Unit testing development

To make the MiL testing more automated and to create a testing tool to detect possible deviations and errors, Unit Testing was implemented. It involved creation of testcases in excel worksheet and an automated matlab testscript to call the required testcase, run the vehicle model and generate the results such as fuel consumption, velocity deviation etc. on an excel sheet. Using Unit Testing, the newly developed models can be simulated in an office environment before being implemented in the testcell. This approach will provide confidence, in the sense that the model will be functional in testcells, and perform as expected.

5.4 Correlation study

The MiL must be verified to understand the reliability with HiL and Chassis Dyno results. The results for a particular testcase from the HiL and Chassis Dyno were extracted from the inhouse tool and compared with the same testcase in MiL and Unit testing was performed. The results obtained from the MiL was compared with HiL and Chassis Dyno results. The correlation study was then performed to understand the closeness of the results and possible future work that has to be done in order to obtain more accuracy and conformity with actual tests.

Once the confidence level of the vehicle model is high enough, there will be a reduction of testing times, because different set-ups can be created and simulated, thus eliminating the ones that prove ineffective, before proceeding to testcells.

6. Future work

Are we there yet? Yes, you heard it right. The construction of MiL testing is still in progress and there exist certain loopholes that has to be covered, more space to develop, more to study and more to update.

6.1 Physical Approach

The engine model utilized in MiL testing is based on empirical approach i.e. map based which is simplified and fails to capture reliable torque behaviour. Instead, the GT suite modelled engine is based on physical approach, which could capture more realistic torque characteristics that could be implemented in MiL testing. However, it might require greater computation time and server connectivity.

6.2 Model Development

The MiL testing should be further strengthened with models to capture turbocharger, EGR and airflow effects. This facilitates more realistic torque behaviour for the engine model. The MiL must also be provided with updated tyre model to capture the lateral behaviour. The driver model has to be more realistic and the acceleration pedal map has to be upgraded to the latest version.

6.3 Relative correlation study

Emission is dependent on the drivetrain efficiency and the losses along the drivetrain play a key role in determining it. Steady state drivetrain losses occur when the vehicle is traveling at constant speed and the average angular acceleration is zero and dynamic drivetrain losses occurs while the vehicle is accelerating and the average angular acceleration is not zero. This means that the drivetrain has to correspond to inertial losses due to increased load that occur, along with the steady state losses corresponding to torque convertor, clutch, gearbox and final drive losses.

6.4 Model Updates

The Unit Testing provide an interface to extract useful information from the vehicle model. During subsequent course of time, the models within the vehicle model have to be updated to extract more information. The Unit testing then has to consider the upgraded vehicle model for evaluation. In order to enable this service, automatic upgradation has to be done on the server through Jenkins software.

References

- [1] „Statista – The portal for statistics,“ 2017. [Online].
Available: <https://www.statista.com/statistics/200002/international-car-sales-since-1990/>
[Accessed on 06 March, 2017].
- [2] M. N. Smith, „World Economic Forum,“ 2016. [Online].
Available: <https://www.weforum.org/agenda/2016/04/the-number-of-cars-worldwide-is-set-to-double-by-2040> [Accessed on 21 March, 2017].
- [3] The International Council on Clean Transportation, „REAL-DRIVING EMISSIONS TEST PROCEDURE FOR EXHAUST GAS POLLUTANT EMISSIONS OF CARS AND LIGHT COMMERCIAL VEHICLES IN EUROPE,“ 12 January 2017. [Online].
Available: http://www.theicct.org/sites/default/files/publications/EU-RDE_policy-update_18012017_vF.pdf [Accessed on 26 April, 2017].
- [4] B. University, „Brunel University London,“ 2017. [Online].
Available: <http://www.brunel.ac.uk/cedps/mechanical-aerospace-civil-engineering/mecheng/research/capf/detf> [Accessed on 25 June, 2017].
- [5] „EU: Heavy-Duty Truck and Bus Engines,“ [Online].
Available: <https://www.dieselnet.com/standards/eu/hd.php> [Accessed on 15 April, 2017].
- [6] R. Ahlawat, J. Bredenbeck and T. Ichige, „Estimation of Road Load Parameters via On-Road Vehicle Testing,“ Cologne, Germany, 2013. [Online].
Available: <http://www.aanddtech.com/Docs/TTX%202013.pdf> [Accessed on 02 June, 2017].
- [7] E. G. Giakoumis, Driving and Engine Cycles, Athens: Springer International Publishing AG, 2017.
- [8] A. Martyr and M. Plint, Engine Testing - Theory and Practice, Third Edition Hrsg., 2007.
- [9] J.-S. Chen, „Energy Efficiency Comparison between Hydraulic Hybrid and Hybrid Electric Vehicles,“ 26 May 2016. [Online].
Available: <http://www.mdpi.com/1996-1073/8/6/4697/html> [Accessed on 26 May, 2017].
- [10] „Vehicle t,“ 27 October 2014. [Online].
Available: http://www.clean-fleets.eu/fileadmin/files/documents/Publications/Test_cycles_-_Clean_Fleets_factsheet.pdf [Accessed on 14 June, 2017].
- [11] A. Stewart, A. Hope, P. Mock and U. Tietge, „Quantifying the impact of real world driving on total CO2 emissions from UK cars and vans,“ Cambridge , 2015. [Online].
Available: <https://www.theccc.org.uk/wp-content/uploads/2015/09/Impact-of-real-world-driving-emissions-for-UK-cars-and-vans.pdf> [Accessed on 18 June, 2017].
- [12] E. G. Giakoumis and A. T. Zachiotis, Investigation of a Diesel-Engined Vehicle’s Performance

and Emissions during the WLTC Driving Cycle - Comparison with the NEDC, Athens, 2017.
Available: <http://www.mdpi.com/1996-1073/10/2/240/pdf> [Accessed on 18 April, 2017].

- [13] J. Seiler, „Exhaust emissions - Worldwide Harmonized Light Vehicles Test Procedure,“ [Online].
Available: <https://www.vda.de/en/topics/environment-and-climate/exhaust-emissions/wltp-worldwide-harmonized-light-vehicles-test-procedure.html> [Accessed on 20 April, 2017].
- [14] A. Marotta, J. Pavlovic, B. Ciuffo, S. Serra and G. Fontaras, „Gaseous Emissions from Light-Duty Vehicles: Moving from NEDC to the New WLTP Test Procedure,“ Ispra, 2015.
Available: <http://pubs.acs.org/doi/pdf/10.1021/acs.est.5b01364> [Accessed on 17 April, 2017].