Simulation of BSFC for WHTC using VECTO Engine and VECTO Vehicle Engineering Mode for various VMS and Field Test data

Thesis submitted for partial fulfilment of the requirements for awarding the degree of

MASTER OF ENGINEERING IN AUTOMOBILE ENGINEERING

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We hereby recommend that this thesis under our supervision by **Akash Mahanty**, Entitled, "**Simulation of BSFC for WHTC using VECTO Engine and VECTO Vehicle Engineering Mode for various VMS and field data**" to be accepted in partial fulfilment of the requirements for awarding the degree of Master of Engineering in Automobile Engineering under Department of Mechanical Engineering of Jadavpur University.

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The foregoing thesis entitled "**Simulation of BSFC for WHTC using VECTO Engine and VECTO Vehicle Engineering Mode for various VMS and field data"** is hereby approved as a creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is notified to be understood that by this approval, the undersigned do not necessarily endorse or approved any statement made, opinion expressed and conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

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ABSTRACT

VECTO (Vehicle Energy Consumption Calculation Tool) is a simulation software tool developed by the European Commission to calculate and assess the CO_2 emissions and fuel consumption of heavy-duty vehicles (HDVs). It is specifically designed for trucks and buses and is used to support the implementation of EU regulations on CO_2 emissions from HDVs.

The Version of the tool used in this study is VECTOv3.3.10.2401. It aims to provide a standardized and transparent methodology for measuring and reporting the energy efficiency of HDVs. VECTO takes into account specific Engine test data along with various factors that influence fuel consumption and CO_2 emissions, including vehicle characteristics, such as weight, aerodynamics, axle configurations, rolling resistance and drive train efficiency, as well as operational parameters like speed, road grade, and vehicle load.

The tool enables manufacturers to input data related to their vehicle models, including technical specifications and test results. It uses this information to calculate the vehicle's energy consumption and CO_2 emissions based on simulated driving cycles. The driving cycles represent typical real-world driving conditions and are based on different vehicle categories.

This study consists of VECTO Engine WHTC simulation and VECTO Vehicle Simulation in Engineering Mode and Engine Only Mode.

VECTO Engine simulation targets to simulate WHTC cycles with minimum BSFC deviations with test cell WHTC runs. In the present work, several WHTC simulation runs were conducted and BSFC deviations were compared with test cell results.

In VECTO Engineering mode simulation different VMS and Field route cycles were simulated for a 1923 tipper with 5.6L OBD2 Cummins Diesel Engine with 950DD gearbox. Several runs were conducted with changing various parameters in Engineering Mode.

Several Engine Only Mode simulations were conducted over load cycles generated from respective VMS and Field runs.

The simulation output of Engineering and Engine Only Mode speed-torque/ speed-gradient profile were compared with respective Field data and VMS data to verify the capability of the VECTO tool to run as per the input route/load cycle.

Simulation output BSFC and CO_2 emissions compared with respective VMS and Field values further verifies the simulation capability of the VECTO tool be used as a simulation tool for vehicle and engine simulation for experimentation, validation and research purposes.

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ABBREVIATIONS

- FC - Fuel consumption
- FE - Fuel efficiency
- CV - Commercial vehicle
- EU – European Union
- LDV-Light Duty Vehicle
- HDV-Heavy Duty Vehicle
- ICE-Internal Combustion Engine
- FLC - Full load curve
- PTP- Part Throttle Performance
- FTP-Full Throttle Performance
- HDT - Heavy-Duty Truck
- WHTC - World Harmonized Transient Cycle
- FCMC - Fuel consumption mapping cycle
- BSFC- Brake Specific Fuel Consumption
- VMS- Vehicle Mission Simulation
- POC- Proof Of Concept
- FIP- Fuel Injection pressure
- SOI- Start of Injection
- HRR- Heat Rejection Ratio
- VECTO- Vehicle Energy Consumption Calculation Tool

Chapter 1

INTRODUCTION

1.1 VECTO Overview

Vehicle Energy Consumption Calculation Tool (VECTO) is an open-source, publicly available software program that was developed by the European Commission and its Joint Research Centre to be the centerpiece of the European Union's CO_2 certification process for HDV. It is a simulation tool for energy demand, fuel consumption and CO_2 emissions. The main characteristics of the current VECTO version are,

- Driving model considers real life driving behavior (acceleration)
- Backward calculation approach (predominantly)
- "Look ahead" functionalities
- Approx. 0.5 s simulation time steps.

1.2 VECTO Engine Simulation

The Goal of the tool is to calculate the BSFC values by simulating WHTC from the given engine input data. Specific engine tests are required to be performed in test cell and these test data are required for the WHTC simulation in VECTO Engine as per the tool requirement. Upon a successful simulation VECTO Engine will provide the output BSFC values over a simulated WHTC run.

1.3 VECTO Vehicle

For a given driving cycle and payload, VECTO uses the results of component testing and vehicle characteristics to simulate the fuel consumption and CO_2 emissions of a given vehicle. The majority of the user inputs into VECTO consists of the data from standardized testing of five vehicle subsystems—engine, transmission, axle, aerodynamic drag, and tires. No testing is required for the inputs of the auxiliary systems, such as the cooling fan and steering system. Basic information about these technologies is the inputs.

Finally, vehicle curb weight (empty weight), gross vehicle weight (GVW), and axle configuration are required inputs. Using the weight and axle configuration data, the VECTO software automatically assigns the vehicle's segment and the corresponding cycles, payloads, and other default parameters, as pre-determined by regulators.

VECTO outputs the results of CO_2 emission (gm) and Fuel consumption (liters) in three forms: by distance (km), by payload (tonne-km) and by volume (m^3-km). Different Simulations modes in VECTO are as shown in the **Fig1.1** below.

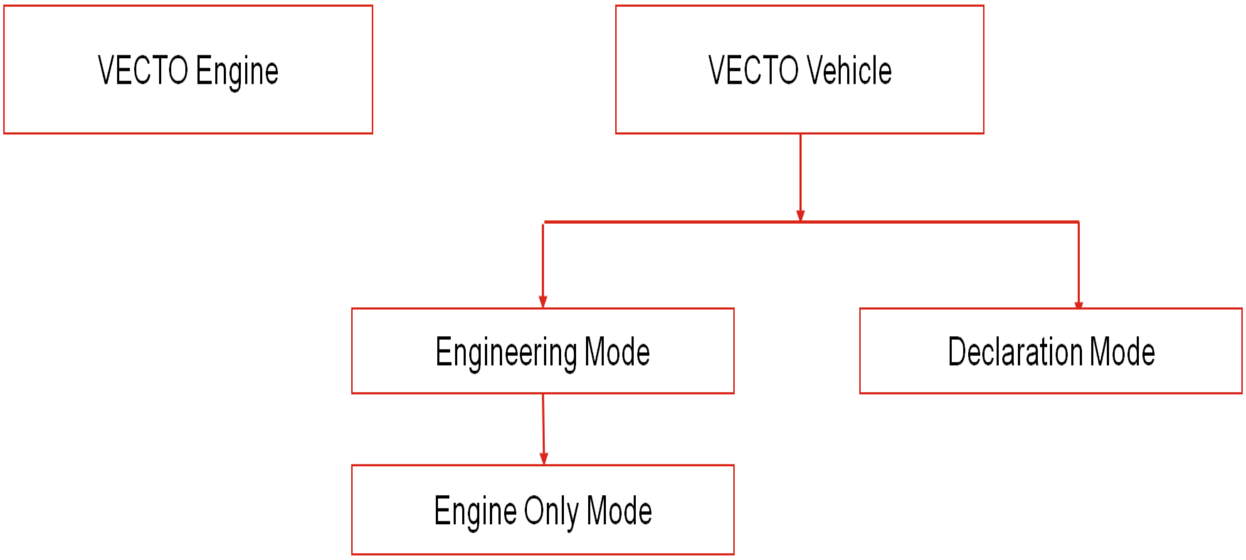

Fig1.1: Different Simulation Modes in VECTO

1.3.1 Engineering Mode

VECTO Engineering Mode allows manufacturers to perform in-depth analysis and optimization of vehicle designs. It provides access to a wide range of parameters and inputs, enabling engineers to examine the impact of various factors on energy consumption and emissions. This detailed analysis helps to identify areas for improvement and supports the development of more fuel-efficient and environmentally friendly vehicles.

- In Engineering Mode, the cycles can be freely selected.
- Every aspect in the component model of the vehicle can be defined hence with different driving parameters and strategies vehicle simulations can be performed as per the requirement of the project.
- The driving cycles can be defined as required and the Gear Shifting strategy as well can be modified as required for the run.
- This flexibility of Engineering Mode makes it a very useful tool for experimenting and research purposes.

1.3.2 Declaration Mode

Declaration mode use simplified assumptions for quick estimates, while engineering mode would allow for precise calculations based on a broader and more accurate set of parameters, specific properties of VECTO declaration mode simulations are as following,

- In Declaration Mode driving cycles are automatically chosen depending on vehicle category and cannot be changed by the user.
- Many input parameters are predefined for the official certification (shift polygon and routes are predefined as per the HDV).
- These predefined cycles are of type target-speed, distance-based.
- One or more checked job files in the Job List. The job files don't need to include driving cycles, these cycles are automatically assigned by the tool.
- In VECTO Declaration Mode, various standardized drive cycles are used to calculate the CO_2 emissions and fuel consumption of heavy-duty vehicles

Here are some of the commonly used drive cycles in VECTO Declaration Mode:

- Coach: 275Km
- Construction: 21km
- Heavy Urban: 30km
- Inter Urban: 123km
- Long Haul: 100km
- Municipal Utility: 10km
- Regional Delivery: 26km
- Sub Urban: 23km
- Urban: 40km,
- Urban Delivery: 28km

These drive cycles represent typical driving conditions and are designed to provide consistent and comparable results across different vehicles and manufacturers. Based on the type of HDV, VECTO chooses the composite cycle that combines segments of the urban, rural, and motorway cycles to provide an overall representation of mixed driving conditions. It aims to capture a balanced mix of driving scenarios encountered in real-world situations. [5]

1.4 VECTO Tool Simulation Process

VECTO simulation process involves several steps to calculate the CO_2 emissions and fuel consumption of heavy-duty vehicles. Here is an overview of the VECTO simulation process:

- The simulation begins with selecting the appropriate vehicle configuration, including the vehicle type, weight class, and any optional features or components. This information is used to define the vehicle characteristics and specifications for the simulation.

- A drive cycle represents the speed and acceleration profile that simulates real-world driving conditions. VECTO provides various standardized drive cycles based on the vehicle's usage, such as urban, rural, and motorway cycles. The appropriate drive cycle is selected based on the vehicle's intended operation.
- VECTO requires input parameters related to vehicle performance and characteristics. These parameters include vehicle dimensions, mass, aerodynamic drag coefficient, rolling resistance, engine specifications, transmission ratios, and other relevant data. The accuracy of these inputs significantly impacts the simulation results.
- With the vehicle configuration, drive cycle, and input parameters defined, VECTO performs the simulation run. It uses mathematical models and algorithms to calculate the energy consumption and emissions of the vehicle based on the defined inputs and the selected drive cycle [4,5].
- Once the simulation is completed, VECTO generates results that provide information on CO_2 emissions, fuel consumption, and other relevant parameters.

VECTO tool simulation process is illustrated in the following **Fig 1.2.**

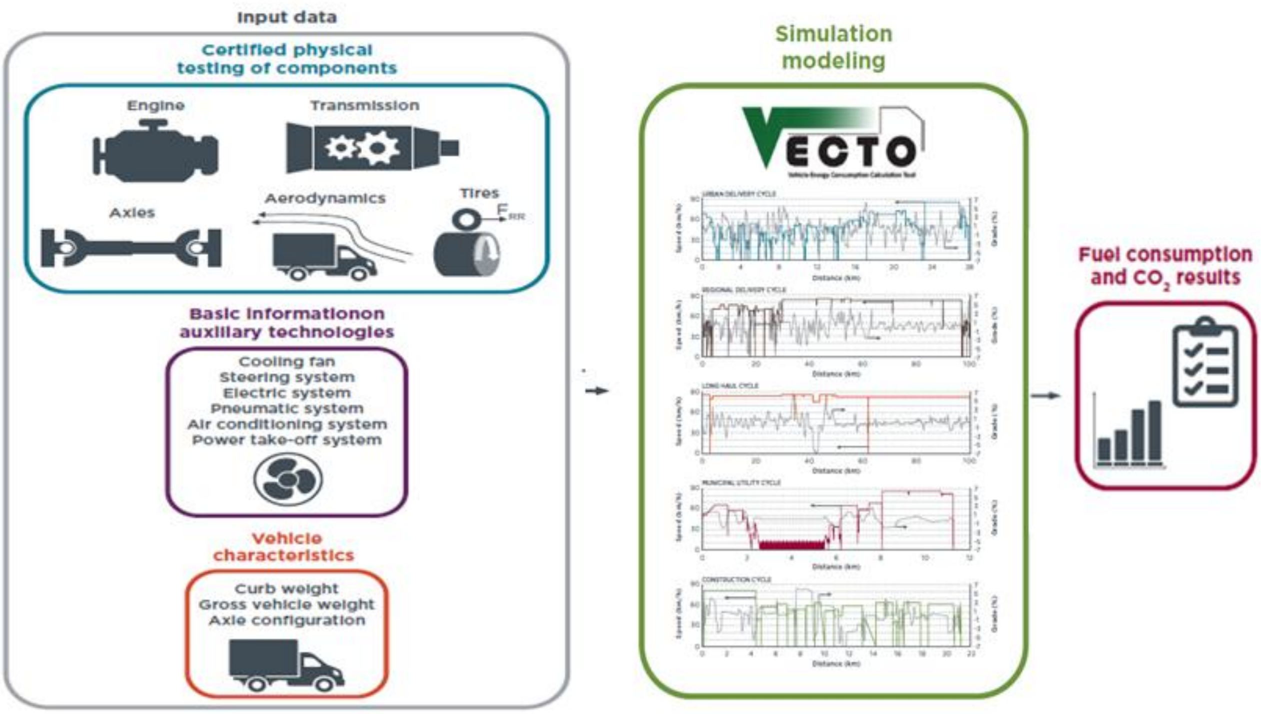

Fig1.2: Schematic diagram of the VECTO Simulation process

1.5 Worldwide Harmonized Transient Cycle (WHTC)

It is an international standard test cycle used to measure exhaust emissions from heavy-duty vehicles, including trucks, buses, and other heavy commercial vehicles.WHTC testing requirements were adopted for the first time by the Euro VI emission regulation for heavy-duty engines.WHTC test cycle is designed to simulate a range of driving conditions, including both urban and non-urban scenarios. The low-speed and medium-speed phases of the WHTC test can be considered representative of urban or city driving conditions, where frequent acceleration, deceleration, and stop-and-go traffic are common. On the other hand, the high-speed phase simulates highway or motorway driving conditions.[3]

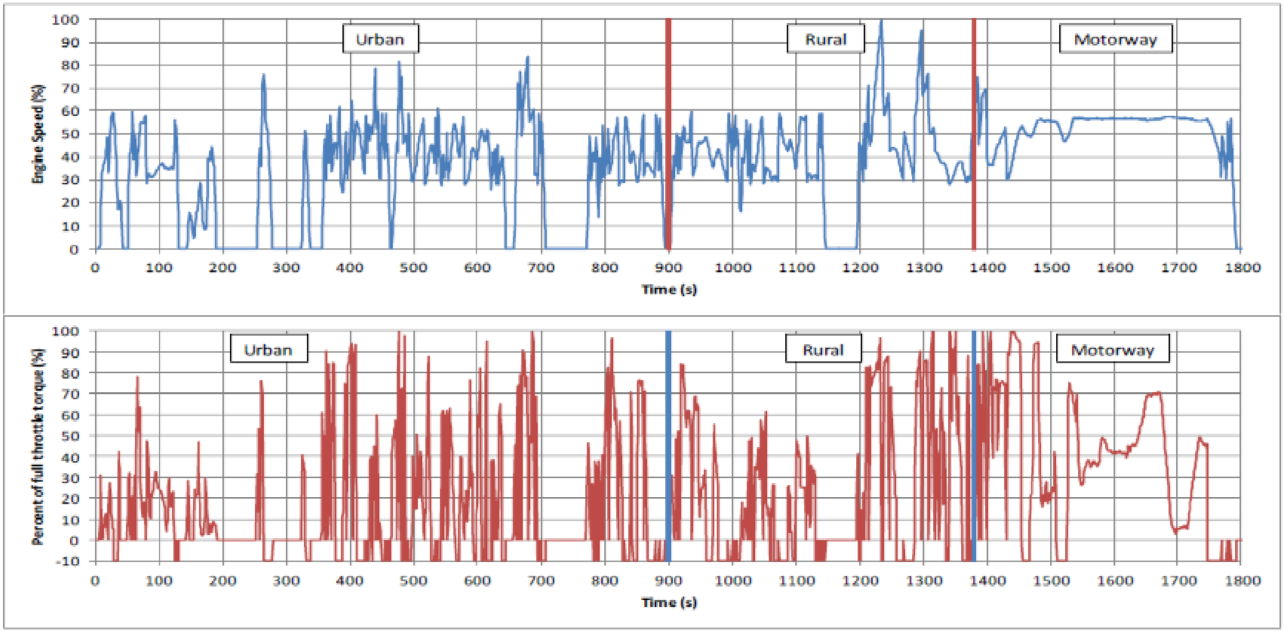

Fig 1.3: WHTC Cycle Standard Speed and Torque distribution

A sample Standard Speed and Torque distribution WHTC Cycle data are depicted in **Fig 1.3.** Key features of WHTC Cycle are discussed below.

- WHTC is designed to replicate operation of ‘average’ vehicle types. It Includes 3 sections to mimic operation on different types of duty cycle – urban, rural & motorway.
- WHTC is a transient test cycle with both cold and hot start requirements.
- WHTC consists of 1800s duration, with several motoring segments. Normalized engine speed and torque values over the WHTC are shown in the graph.
- Specific Fuel Consumption (BSFC) values of the cold and hot WHTC are needed in input of VECTO Engine and are to be measured from the WHTC test data.

For the FCMC data, due to absence of a test run data, it has been considered to interpolate the FC values at the FC Map grid points from a locked and unlocked PTP run data.

Chapter 2

LITERATURE REVIEW AND OBJECTIVE

2.1 Literature Survey

The purpose of thesis is to find out the present capability of the Vehicle Energy Consumption Calculation Tool to simulate real life drive cycle for Calculating the BSFC and CO_2 emission Values. Carbon and hydrogen construct the origin of diesel fuel. The exhaust gases of an ICE consist of harmful products as CO_2, CO, HC, NO_x, and PM. The combustion of fuel takes place at the end of compression stroke, by injection of highly atomized diesel fuel into compressed air. Complete combustion of diesel fuel would only generate CO_2 and H_2O in combustion chambers of engine.[1]

Air–fuel ratio, ignition timing, turbulence in the combustion chamber combustion form, air–fuel concentration, combustion temperature etc. play a major role in the exhaust emissions. Principal pollutants of concern have been shown to have variety of negative effects on public health and natural environment are regulated by the government and concerns are being raised for its emissions of CO, HC, NO_x and PM into the atmosphere. New techniques are being used to lower these emissions such as use of advanced after-treatment system consisting of DOC, DPF and SCR to reduce the emissions in the vehicle/system exhaust [2].

A literature review was done on different works done on the VECTO Tool on various applications, based on that a scope of the work has been identified and various simulations were performed in the latest Version of the VECTO simulation tool.[4,5]

A 40t Euro VI long haul truck and an 18t Euro V rigid truck, measurements were performed both on the chassis dynamometer and on the road. VECTO was used as the simulating software for simulating the tests. Simulation results closely matched those of the dynamometer tests with the final simulated fuel consumption deviating by about ±2-4% compared to the measured value. The simulated fuel consumption for on-road operation was calculated roughly within a ±3% range from the real-world measurement, while in several cases it proved to be even closer than that (in the order of ±1.5%).[6]

A study was made with a simple mathematical vehicle model, to find out the intrinsic differences between backward and forward vehicle simulation model. It was observed that the two methods neither predict the same expected energy use nor energy variation. The expected CO_2 emissions and the variance were identical either, in general. The variation was greater in the forward method.

Backward simulations ran about ten times faster than the forward simulations with an overall lesser complexity as it does not require a driver model. [7]

A Simplified CO_2 and Fuel Consumption Model for Buses Derived from VECTO Simulations. The model was derived from detailed VECTO simulations of numerous variants of a high floor, diesel low floor and CNG low floor bus. The proposed model can capture the general trend of the CO_2 emissions well, with an average model error of less than 0.04% and a standard deviation of less than 0.6% for each mission profile. The average model error is less than 0.01%, considering all vehicle variants and mission profiles, and the standard deviation is less than 0.4%.[8]

A duty cycle based simulation methodology for duty cycle based fuel consumption calculation for heavy duty commercial vehicles to calculate FC using VECTO for Indian Commercial Vehicles and operating conditions. Engine FLC, cold & hot WHTC, WHSC and motoring points were measured as per UNECE standard. To measure the FCMC data, the BSFC values were measured as per the methodology specific to VECTO. The overall FC variation in VECTO was found to be at 4.5% lower than the field measurements. Also, the CSFC values for 60km/hr& 40 km/hr from simulation were found to be on the lower side with respect to the track measured values.[9]

Another study investigated the use of VECTO on a city bus by modeling the on-road operating conditions of a vehicle in an urban route in Istanbul. The simulation results for constant auxiliary load showed a difference with the on-road measurements in the range of −1.6 to 3.2%, depending on the direction of the route. The investigation showed that further research is needed for properly implementing auxiliary use.[10]

The database of VECTO simulation results covering the 2016 HDT fleet, containing different vehicle types and different mission profiles were analyzed by the JRC in order to quantify how the energy is distributed depending on the different mission profiles and vehicle classes. The impact of air drag and rolling resistance losses was highlighted. The goal was to provide insight and information to build the energy consumption tree when certain proprietary inputs are missing in order to run VECTO or quick comparison of VECTO results of different vehicles under a common basis. The proposed method was found to be satisfying in terms of accuracy, showing relative errors within ±3% compared to VECTO results.[11]

This study was conducted to find out the effects of driving cycle on CO_2 emission of heavy-duty commercial vehicles based on VECTO simulation. In the study VECTO was used to evaluate the CO_2 emission for four types of vehicles including city bus, coach, heavy truck and trailer tractor. C-WTVC and CHTC were used as simulation cycles [12].The results show that CO_2 emissions of CHTC are higher than that of C-WTVC for these four types of vehicles with increase percentages ranging from 1.5% to 19%. For different cycles, average acceleration difference is the most predominant factor for the CO_2 emission, followed by driving strategy changes. For different types of vehicle under the same cycle, the mass or load has a direct relationship to CO_2 emission. [12]

A study was conducted on Experimental Evaluation and Modeling of Waste Heat Recovery in VECTO. A class5 lorry equipped with a prototype Organic Rankine Cycle system is tested on the chassis dynamometer during steady state and transient driving cycles, with the WHR enabled and disabled. The waste heat recovery system enabled a brake specific fuel consumption reduction of 3.1% over the World Harmonized Vehicle Cycle, 2.5% during the official EU Regional Delivery Cycle, and up to 6.5% at certain engine operating points during the fuel consumption mapping cycle. A model created in VECTO based on the experimental data, was able to predict the BSFC within 0.15% over the regional delivery cycle, without WHR. With the best simulation approach for WHR, the error on the simulated BSFC increased to 0.27% over the regional delivery cycle when WHR was enabled [13].

The scope of this project was to find out VECTO Capability for the Indian context by modifying the datasets relevant for VECTO's declaration mode. For the POC VECTO-India, three vehicle types were chosen based on popular truck size and axle configurations for HDVs greater than 12 tones in India—a 4x2 40-tonne tractor-trailer, an 8x2 31-tonne rigid truck, and a 6x4 25-tonne rigid truck. Each of the three vehicle types is evaluated over the WHVC-India drive cycle, as such, the cycle contains distinct urban, rural, and motorway mini cycles. By demonstrating the relatively minor resource requirements for creating a POC VECTO-India model here, illuminated the path ahead for India in developing a VECTO-India model. [14]

Study conducted on detailed analysis of the gaseous emissions, focusing on CO_2 and NO_x, of diesel vehicles under several operating conditions. An assessment was also made on the impact and effectiveness of the Real Driving Emissions (RDE) test, which is mandatory by the European Union (EU) type approval regulation for passenger cars since September 2017.The method followed comprises emissions measurement tests on three Euro 6 diesel vehicles, under laboratory and various on-road operation conditions. Comparison of driving conditions on the chassis dynamometer over different driving cycles and on the road reveals that the emission performance substantially varies between different tests, even for apparently similar operation conditions. [18]

2.2 Scope and Objectives of the Present Work

The work objective of the present study can be divided into two parts, Simulating WHTC cycles in VECTO Engine and Simulating at various Drive Cycles in VECTO Vehicle. Present scopes of this work is described as following

2.2.1 VECTO Engine Simulation Objective

- VECTO Engine will simulate a WHTC and calculate the BSFC values based on the input fuel map given, that can compare with the Test Cell WHTC Run for BSFC values.
- The Objective of VECTO Engine is to Simulate the BSFC values as precisely as possible so that VECTO Engine can be reliably used for simulating WHTC Runs for certification purposes.

2.2.2 VECTO Vehicle Simulation Objective

- In VECTO Vehicle the Objective is to simulate real world behaviour of a vehicle over a particular route cycle and estimate the BSFC and CO_2 values for that particular vehicle over the specified route.
- In the present study, it has been simulated VECTO vehicle for both VMS and Field data.
- To check the capability of VECTO Tool, it has been compared the VMS and VECTO results for the same route and input details to compare the output results accuracy.
- From real life field data drive cycle were modified as per the VECTO requirements and output results were compared with real life field data.
- By incorporating representative drive cycles, vehicle parameters, road grade, and auxiliary loads, VECTO's Engineering Mode aims to simulate real-world driving conditions accurately. This allows for a more realistic estimation of energy consumption and emissions, supporting regulatory compliance and facilitating the optimization of vehicle design and performance.
- Engineers can analyze how different driving styles and scenarios impact the vehicle's performance and efficiency.

2.2.3 Scopes of the Present Work

- Minimising the deviation in the output results VECTO Tool can be reliably used as a virtual testing platform, enabling engineers to perform extensive testing and validation before physical prototypes are built.
- Primarily to be used to estimate the energy consumption and emissions. It helps identifying any potential issues, and optimizes vehicle performance early in the development process, saving time and resources.

- VECTO offers a more streamlined and efficient workflow for energy consumption calculations. With its predefined calculation methodologies and standardized inputs, manufacturers can quickly estimate energy consumption and emissions for their vehicles. This can save significant time and resources compared to the extensive modelling and simulation work required in VMS for comprehensive vehicle dynamics simulations.
- VECTO-Engine Only mode can be used as a diagnostic tool for understanding the engine's contribution to overall vehicle energy consumption and emissions.
- By isolating the engine's energy consumption and emissions, VECTO Engine Only Mode provides a more detailed and specific analysis of the engine's performance allowing manufacturers and regulators to focus on evaluating the engine's efficiency and emissions characteristics independently from auxiliary systems or components.

Chapter 3

EXPERIMENTAL SETUP

3.1 TEST CELL

Engine testing in a test cell is a crucial step in the development, evaluation, and maintenance of engines. Test cells provide controlled environments where engines can be operated under various conditions to gather performance data, assess durability, analyze emissions, and conduct other evaluations. A test cell typically consists of an enclosed chamber with provisions for engine mounting, intake and exhaust systems, fuel supply, instrumentation, and data acquisition systems. The cell is designed to isolate the engine from external factors and provide controlled conditions.

Fig3.1: Test Cell Layout

A complete test cell set up with the Engine, ATS and emission measuring devices are illustrated in the test cell layout in the **Fig 3.1**. A few notable points about the test cell are described as following,

- **Instrumentation**: Various sensors and instruments are employed to measure and monitor engine parameters such as temperature, pressure, fuel consumption, torque, speed, emissions, and more. These measurements help assess engine performance, efficiency, and compliance with regulatory standards.Electronic Control Module (ECM) collects the engine data through the engine sensors.
- **Test Procedures**: Engine testing involves following specific test procedures tailored to the intended purpose. These procedures can include steady-state testing, transient testing, endurance testing, emission testing, or specific performance evaluations based on the engine's application.
- Different types of Test Cycles, Emission Cycles (On highway and Off Highway Emission Cycles) and Performance can be performed based on the project criteria.
- **Data Acquisition and Analysis**: Test cells are equipped with data acquisition systems to collect real-time data from engine sensors and instruments. This data is then analysed to assess engine performance, diagnose any issues, optimize operation, and guide further design or development iterations.
- The logging frequency of the data accusation can be set as 1hz, 5 Hz or 10Hz depending on the project requirements.ECM collects the engine data through the engine sensors The data collected by the sensors connected to boom box and emission devices will be available in the computers outside the test cell.
- **Emission Bench:** Several emission measuring devices are connected in the engine exhaust and after-treatment Exhaust, known as the emission bench, Such as Pre-CAT(Before the ATS) and Post-CAT (After the ATS) analyser, FTIR (Fourier-transform infrared spectroscopy) analyser, Opacimeter, Micro Soot Sensor, Smoke meter, SPC (Smart Particulate controller), PNC(particulate Number Counter) depending upon the requirement of the project.
- **Iterative Testing and Development:** Engine testing is often an iterative process, with multiple test runs and modifications to refine the engine's design, optimize performance, and address any identified issues. Testing may involve comparing different engine configurations, evaluating new components or fuels, or validating design changes.

3.1.1 Emissions from diesel engines

- Carbon and hydrogen construct the origin of the emissions from diesel fuel.
- The complete combustion of diesel fuel would only generate CO_2 and H_2O in combustion chambers of engine.

- Air–fuel ratio, ignition timing, turbulence in the combustion chamber combustion form, air–fuel concentration, combustion temperature etc plays a major role in the exhaust emissions.
- Pollutant emissions have a rate of less than 1 % in the diesel exhaust gas. The most significant harmful products are CO, HC, NO_x, and PM as depicted in **Fig. 3.2.**
- NOx has the highest proportion of diesel pollutant emissions with a rate of more than 50 %.
- PM has the second highest proportion in pollutant emissions.
- The concentration of CO and HC is minimal.(Because diesel engines are lean combustion engines)
- Pollutant emissions include a modicum of SO_2 depending the specifications and quality of fuel. (Sulphate content in the diesel fuel). [2]

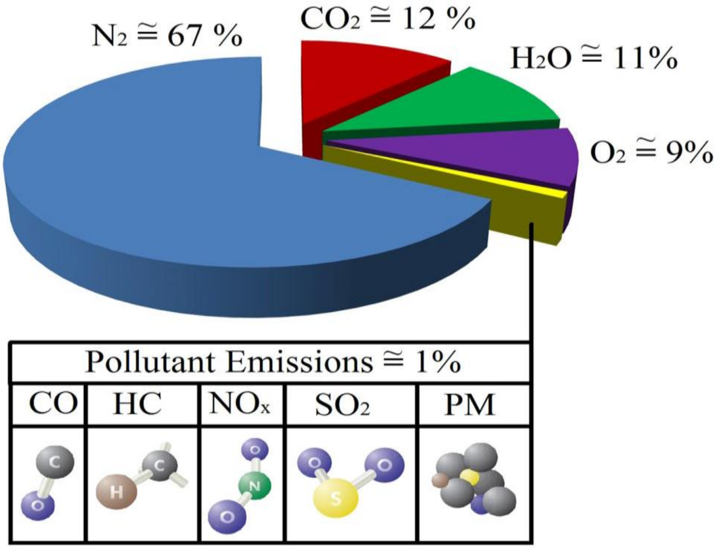

Fig 3.2: Approximate composition of Diesel Exhaust gas

3.1.2 Engine and Dynamometer setup

Engines are subjected to different load conditions to simulate real-world operating scenarios. Load can be applied through various means, such as dynamometers, hydraulic or electric systems, or mechanical setups, depending on the type of engine and testing requirements. The AC Dynamometer is mimics the load placed on the engine while it is powering a vehicle and also calculates the power output by measuring the magnitude of torque required to hold a spinning engine at a set speed (rpm) directly. This allows testing of the engine over its entire range of operation in a controlled environment of Test Cell with additional measuring systems needed for experimentation and research.

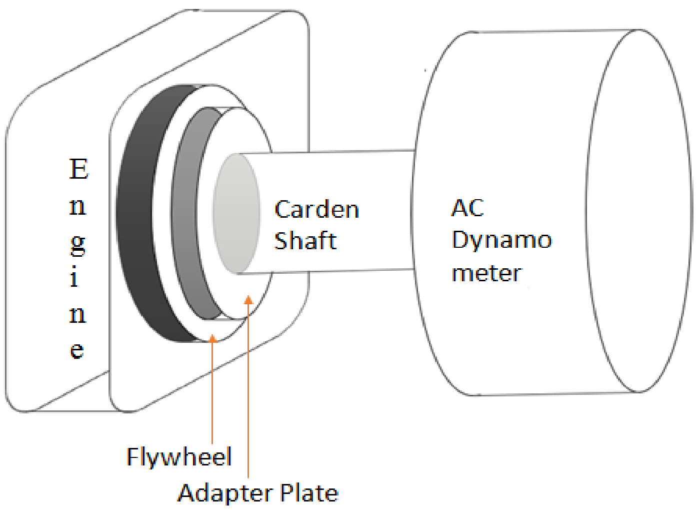

Fig 3.3: Block Diagram of Engine Dynamometer Connection

The Dynamometer is connected with the flywheel adaptor of the engine by the carden shaft as shown in **Fig 3.3**.The carden shaft is fitted with universal joints at each end, so that it can adapt itself to the inequalities of the drive hence this carden shaft can join the flywheel and the dynamometer at a certain offset distance. The selection of carden shaft mainly considers the speed of the shaft to be transmitted, the size of the load, the installation accuracy of the two parts to be connected, the stability of rotation.

3.2 Vehicle Mission Simulation Software (VMS)

The Vehicle Mission Simulation (VMS) software developed by Cummins is a tool used for simulating and analyzing the performance of their engines and power systems in various vehicle applications.It is used to simulate and analyze the performance of vehicles under specific driving conditions or missions by taking into account various parameters such as vehicle speed, road profiles, traffic conditions, and driver behaviour to predict the vehicle's behaviour, energy consumption, and emissions in real-world scenarios.

3.2.1 Comparison between VECTO and VMS

VECTO and VMS are both simulation software used for vehicle simulation in the industries. VMS is developed by Cummins where VECTO is newly developed software by European Commission specifically designed for HDVs. Following are the comparison between VECTO and VMS based on their specifications and utilizations.

- VECTO is specifically designed for calculating CO_2 emissions and fuel consumption of heavy-duty vehicles, such as trucks and buses. Its primary purpose is to assess the energy efficiency and environmental performance of these vehicles, particularly for regulatory compliance. VMS On the other hand is a more versatile tool used to simulate and analyze the performance of vehicles under specific driving conditions or missions.

- VECTO is primarily applicable to heavy-duty vehicles, such as trucks and buses, as it is developed specifically for the assessment of vehicle categories.VMS can be applied to various types of vehicles, including passenger cars, light-duty vehicles, heavy-duty vehicles, and even specialized vehicles. Its versatility allows for simulating and analyzing different vehicle types and configurations.
- VECTO Declaration Mode is designed to comply with specific regulations, particularly those set by the European Union for heavy-duty vehicle emissions and fuel consumption. VECTO Engineering Mode can be used for research and development purposes.VMS is not specifically developed for regulatory compliance but rather for research, development, and optimization purposes. It provides more flexibility in simulating real-world driving conditions and evaluating various parameters beyond the regulatory requirements.

In summary, VECTO is a specialized tool for calculating emissions and fuel consumption of heavy-duty vehicles, primarily for regulatory compliance, while VMS is a versatile simulation tool used for analyzing vehicle behaviour, energy consumption, and performance under different driving conditions, allowing for optimization and research purposes across various vehicle types.

3.3 Test run data needed for VECTO Simulation

For Cummins Diesel Engine, the run data is 5.6OBD2. These are the necessary test run data are needed for VECTO Simulation:

- Engine Full load Curve
- Engine Motoring Curve
- WHTC (Hot and Cold)
- FCMC (Fuel Consumption Mapping Cycle)

3.3.1 Full Load Curve (FLC)

The full load curve of an engine in a test cell represents the relationship between the engine's power output and engine speed (RPM) or torque at full load conditions .A full load condition to the engine at each selected load point is usually achieved using a dynamometer or load control mechanism capable of absorbing the engine's maximum power output. It provides a graphical representation of the engine's performance characteristics across the entire range of engine speeds as shown in **Fig. 3.4.**

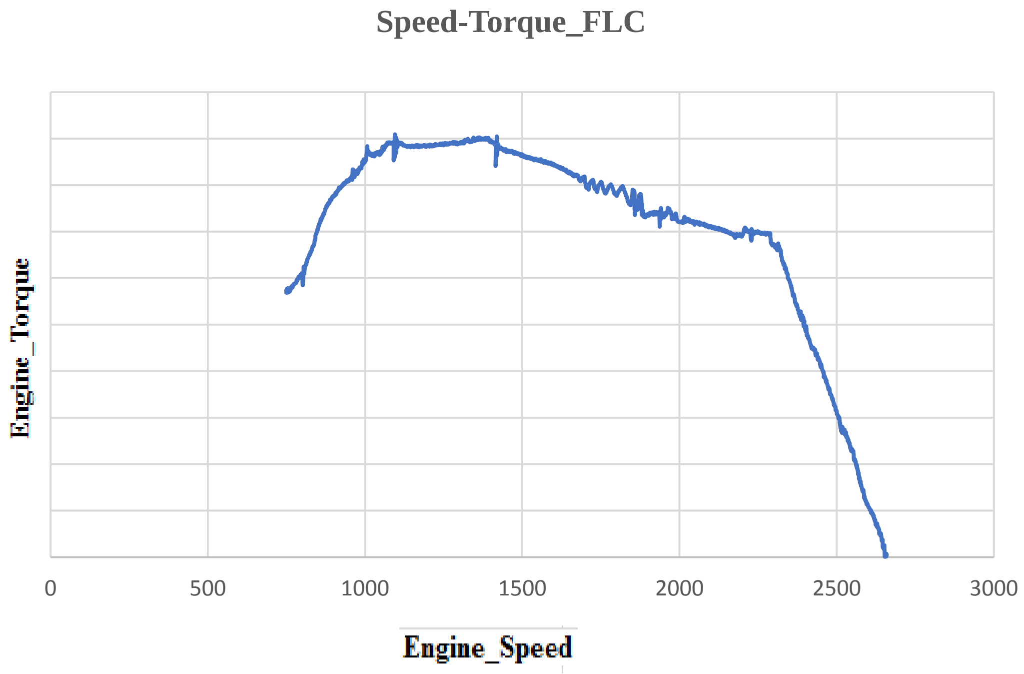

Fig 3.4: Full Load Curve

Full load Curve of the parent Engine is required for running a child Engine. As the same FC Map will be used for all the Engines in the same family, it is not required a separate FC Map for testing the child Engine. For Using the FLC data in VECTO it has to be modified accordingly for VECTO Engine and VECTO Vehicle.

3.3.2 Motoring Curve

The motoring curve of an engine represents the relationship between the engine's torque and engine speed (RPM) when it is operated as a motor, i.e., when external power is used to drive the engine as shown in **Fig.3.5**. The external power supply or the dynamometer is adjusted to impose different loads on the engine. The engine speed is carefully controlled throughout the test.

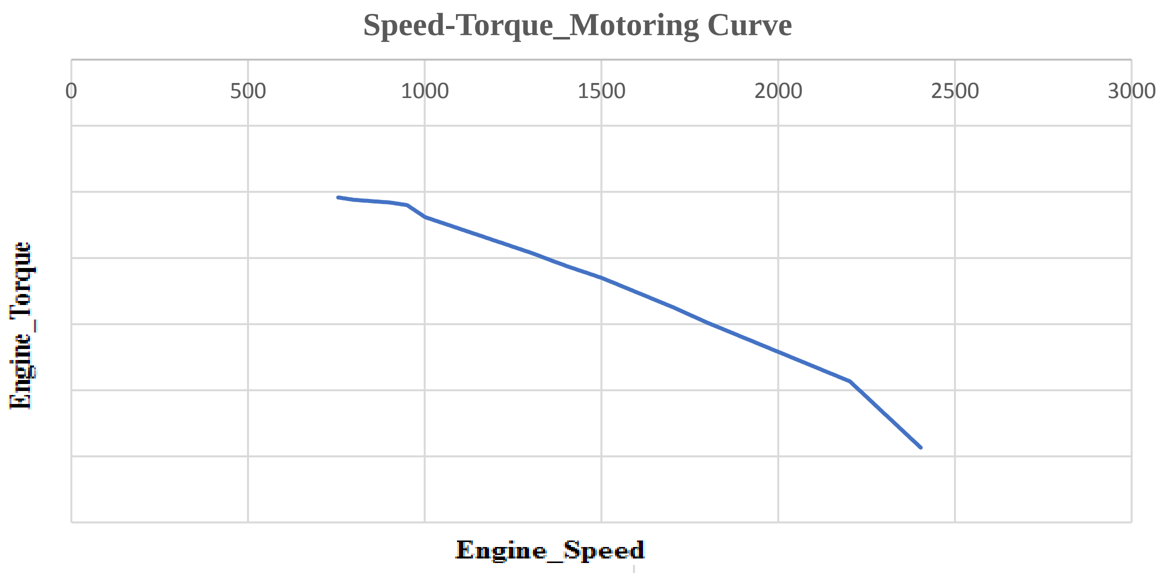

Fig 3.5: Motoring Curve

The resulting motoring curve provides information about the engine's mechanical losses, friction characteristics, and other internal factors that affect its performance when not combusting fuel. It helps in understanding the engine's efficiency, identifying areas of improvement, and optimizing the design for reduced losses and improved overall performance. These test data are then to be modified as per the VECTO requirements.Average engine speed step-width for the motoring curve input data should be less than 9rpm as per the VECTO input criteria. Hence for the VECTO motoring input data, 5rpm speed step were taken for the whole speed range and the corresponding motoring torque values were interpolated from test cell motoring speed torque data.

3.3.3 Part Throttle Performance Test (PTP)

(PTP) test is a type of engine testing conducted to evaluate an engine's performance under partial load or part throttle conditions. It involves measuring various parameters to assess the engine's efficiency, fuel consumption, emissions, and overall operating characteristics at less than full load conditions. The engine is operated at predetermined part throttle conditions, which simulate typical driving scenarios where the engine is not operating at maximum load. The load can be applied using a dynamometer or other load control mechanisms. The PTP speed-torque diagram shows the engine's torque output at various engine speeds during part throttle operation.

- At low engine speeds, the torque output is typically lower, representing the engine's response when the throttle is partially opened. As the engine speed increases, the torque output also increases, reflecting the engine's ability to generate more power as the throttle is opened further.
- The specific shape and characteristics of the speed-torque diagram will depend on the engine design, its control system, and other factors.
- It's important to note that the diagram is just a representative example and may not accurately reflect the characteristics of a specific engine without detailed specifications.
- It helps engineers and researchers analyze the engine's power delivery, torque response, and efficiency at different engine speeds during partial load operation.

3.3.4 WHTC Test Run data

A hot and cold WHTC test run are needed to be performed in the Test Cell for conducting the simulations in VECTO Engine.

Cold WHTC Test: For the cold WHTC run 2-3 practice WHTC cycles are run before putting the engine into a cold soak. The engine is cooled down naturally or forcefully until the temperatures of the engine's lubricant, coolant, and ATS are all between 20°C and 30°C. Then a WHTC cycle is ran, known as the cold WHTC test.

Hot WHTC Test: Once the cold WHTC run is completed the engine is left for 10 min hot soaking period there after another WHTC run is conducted known as the HOT WHTC test.

WHTC run data are not required for the simulations only the BSFC values of the cold and hot WHTC are required in VECTO engine input. These inputs are needed for VECTO Engine simulation.

- Urban, Rural and Motorway BSFC Values are needed in VECTO Engine input.
- These BSFC Values are calculated part wise from the HOT WHTC test data.
- This BSFC Value in inputs doesn’t impact the VECTO Engine simulation outputs.
- Rather VECTO Engine calculates the Fuel consumption correction factors that are to be used in the Engine file **(.*veng*)** file in VECTO Vehicle in declaration mode.

Chapter 04

VECTO Engine WHTC Simulation

4.1 Engine CO_2 Family Concept for Diesel engines

Engine CO_2-family is subset of engine emission family. Engine CO_2-family is defined by fuel consumption affecting parts (hardware and controls), if any of these parts are changed, a different family is created. The parent engine of the family shall be selected using the primary criteria of the highest fuel delivery per stroke at the declared maximum torque speed.

If two or more engines share these primary criteria, the parent engine shall be selected using the secondary criteria of highest fuel delivery per stroke at rated speed. For each CO_2-family only the parent engine (highest power rating) is to be measured.

All lower ratings of a family use the same measured fuel-flow map as of the parent engine.

4.2 Input Data Files

- Full Load Curve of CO_2 Parent Engine
- Motoring Curve of CO_2 Parent Engine
- FC Map of the CO_2 Parent Engine

(All the input data files should be in ***.csv*** file format)

- Specific fuel Consumptions Values were measured by the WHTC Cycles ran in the Test Cell, hence the Rural, urban and Motorway WHTC values were calculated from them accordingly.
- The correction Factor is taken as 1.00.
- For VECTO Engine Motoring and Full Load Speed and Torque values have to be round up to two decimal places.

In this study FCMC test cell data was not available, hence the FC Map grid was generated and the FC values were interpolated at the grid points as per the FC Values obtained from a PTP Test data of the parent engine. (Locked and Unlocked).

A locked PTP test is when the PTP test is conducted with the engine locked at a particular surface/mode where as in an unlocked PTP test the engine changes between surfaces/modes as per the speed-torque requirements over the run.

4.3 Pre calculate Characteristic Engine Speed and Grid for Fuel Map

Characteristic engine speeds are calculated by VECTO for the fuel map from the FLC of CO_2-Parent engine are as following.

For pre-calculating characteristic engine speed and grid for fuel map before FCMC test run only two inputs are needed: idle speed of CO_2-parent engine and full load curve of CO_2-parent engine.

n_idle, n_low, n_pref, n_95h: n_hi, n_57, n_A, n_B are pre calculated by VECTO.

Fuel Used is Diesel with NCV-45.50 MJ/kg,

All the other input values are plotted as well and the input data files are browsed to the respective data file window as shown in **Fig4.1.**

Due to confidentiality of the company the low idle speed and WHTC BSFC values are not disclosed.

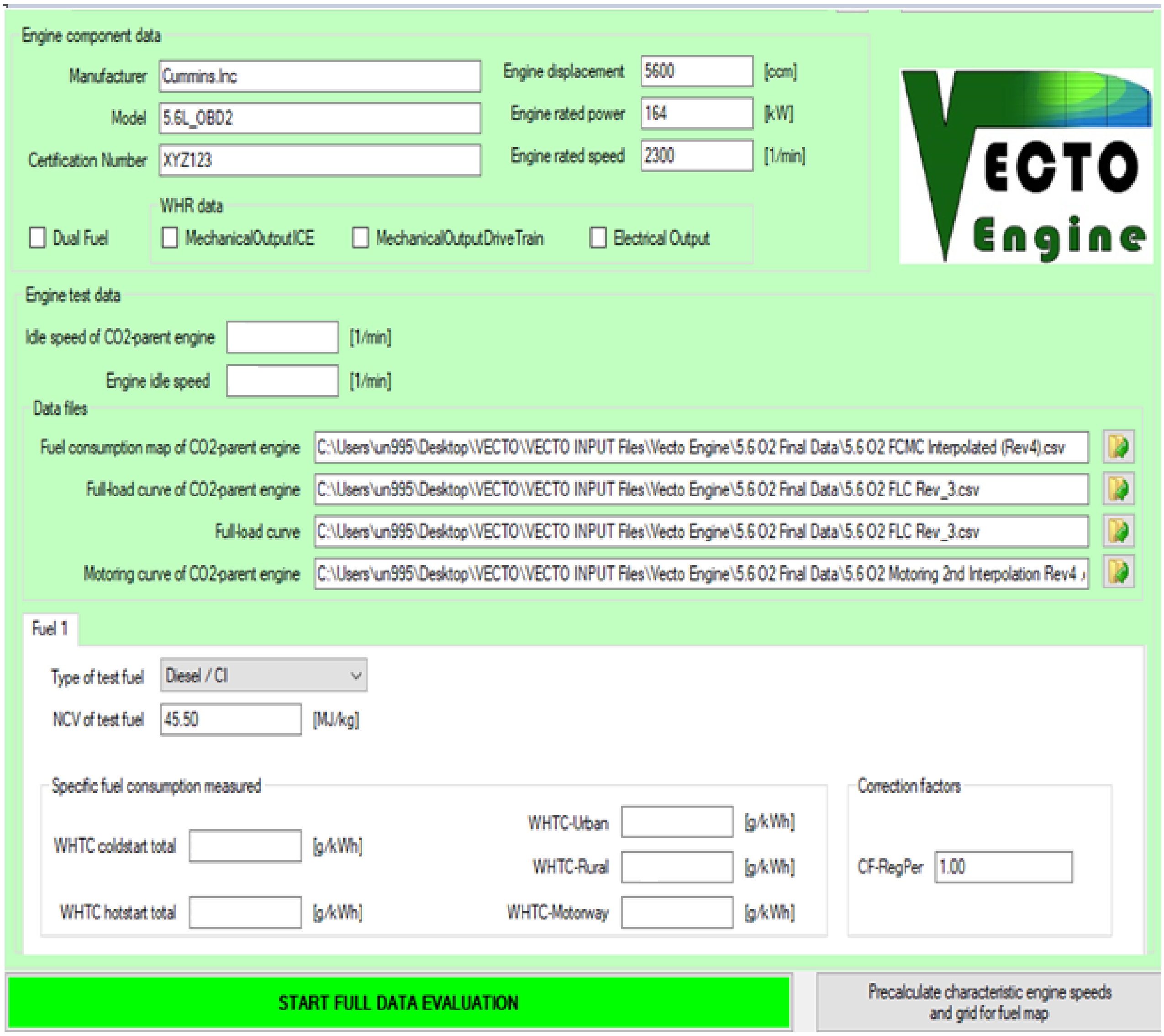

Fig4.1: VECTO Engine Input Interface

4.4 Steps to generate the FC Map

The FC Map grid points are generated by the characteristic speed and torque set points generated by VECTO as per the following.

VECTO calculates these target speed and torque points from the FLC input and low idle speed of the engine.

Target engine speed setpoints

Target engine speed points consists of 4 base speed and 6 additional speeds as illustrated in **Fig 4.2.**

4 BASE SPEEDS

- n_idle
- n_A
- n_B
- n_95h

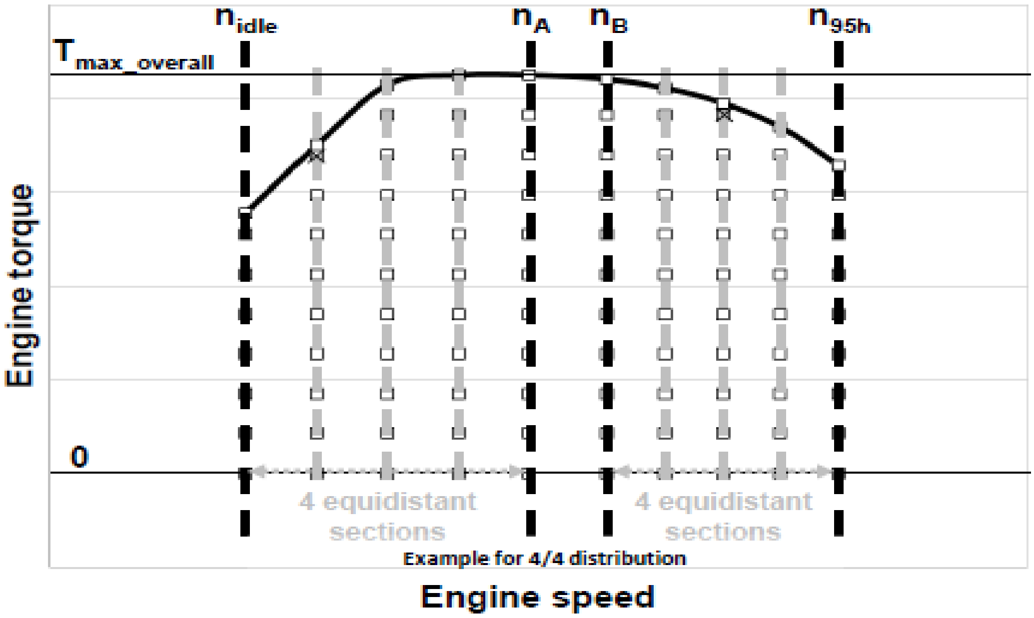

Fig 4.2: Target Speed set points

6 Additional Speeds

These 6 additional speeds are equidistant between base speeds as illustrated in **Fig 4.2.**

(Three additional speed points equidistantly placed in between **n_idle** and **n_A** and 3 speed points equidistantly in between **n_B** and **n_95h**)

In this case it's a 4/4 Standard distribution, it can be changed to 3/5 or 5/3 depending on the shape of the full load curve.

Target Torque set points

The total torque range is divided in 10 equidistant intervals of 10% of the maximum torque (T_{max}) between 0 Nm and highest torque value on FLC. (The maximum torque value over the FLC cannot be declared to maintain the confidentiality of the company).

A speed-torque grid was generated with the target speed and torque set points as shown in the figure **Fig 4.3**.Points located above FLC are replaced by full load torque values but the points at the FLC are only measured once as illustrated in **Fig 4.3**.

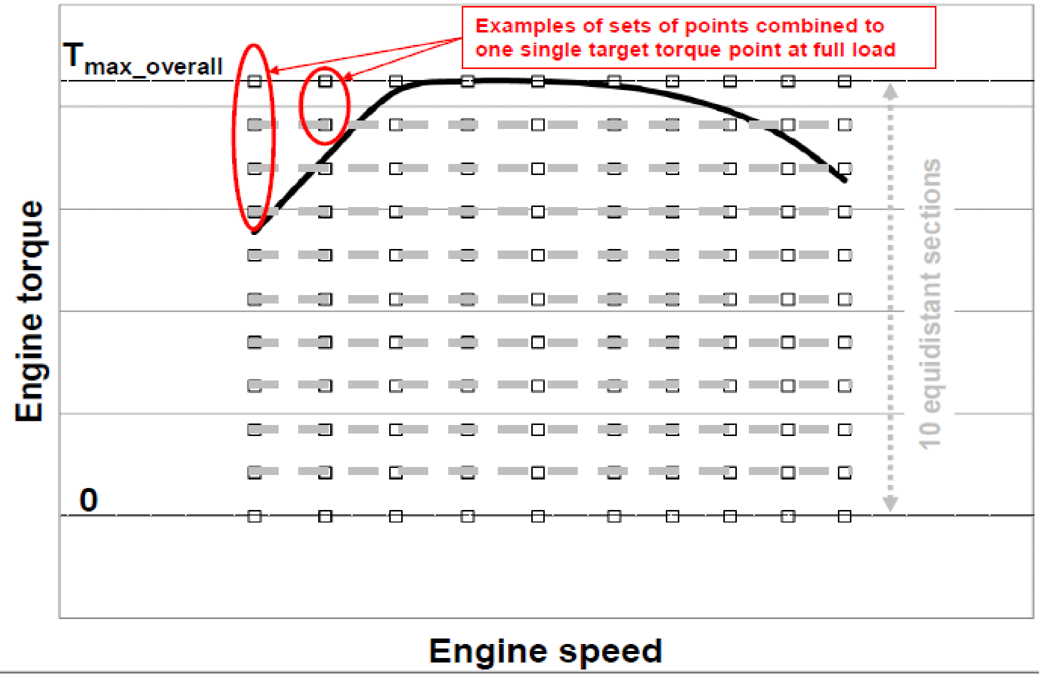

Fig 4.3: Fuel Consumption Map Grid Generation 01

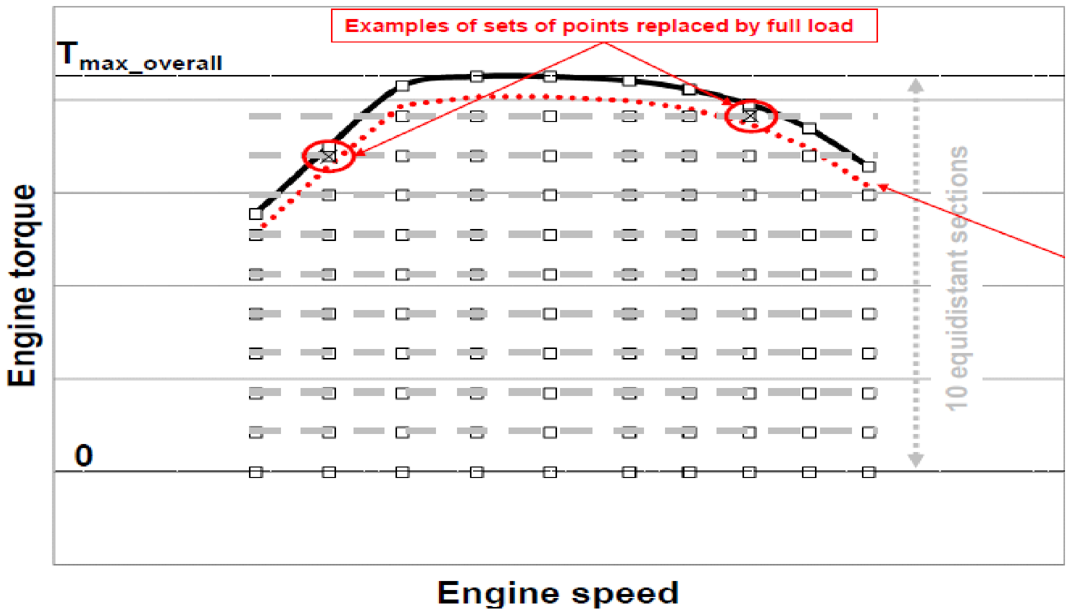

Fig 4.4: Fuel Consumption Map Grid Generation 02

For the points below the FLC a dotted line is drawn at 5% from the FLC. (The red dotted line shown in **Fig 4.4**).

Torque values at the red dotted line = FLC torque value at that speed -5% of T_{max} (Nm).

If any Set point lies between the FLC and the red Dotted line will be replace with the FLC torque value as illustrated in **Fig 4.4**.

The FC Map grid will be generated accordingly in between the full load curve and zero torque axis as shown in **Fig 4.5**. For the present work, the FC values were interpolated at the target grid points of the FC Map from the FC Values obtained from a PTP test run data of the parent engine.

An example of the FC Map is shown in the **Fig 4.5,** the FLC and Motoring curve are represented by the blue line where every red dot represent the target grid point of the FC Map. VECTO will interpolate the FC values at the speed torque points over the simulation from the FC values at these target grid points. Once all the input files are modified as per VECTO Engine requirements and the input WHTC BSFC values are calculated from the test cell data, the full data evaluation can be started.

For the WHTC simulations runs, VECTO Engine will simulate a WHTC run by simulating speed-torque points over the simulation run and calculating the FC values over the speed torque points for the runs from the FC Values provided by the FC Map.

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Fig 4.5: FLC, Motoring Curve and FC Map for VECTO Engine

4.5 VECTO Engine Simulation Results and Conclusion

Three WHTC simulation runs were conducted in VECTO engine for the 5.6OBD2 Cummins Diesel Engine, with two FLC (Hence two different Fuel Map grids will be generated) and two different FC maps (Hence the FC Values at the grid Points will be different for the different runs).

Locked and Unlocked FC Maps are respectively generated from a locked PTP (Engine is running at a fixed surface/mode) and an unlocked PTP (Engine is switching between different surfaces).

For our understanding a surfaces can be considered as a running mode of the engine depending upon the speed-torque requirements.

The motoring data and other input data were kept same for all the runs.

Several errors might come when the full data evaluation is started, the root cause behind the errors are needed to be find out and the errors are needed to be resolved for a successful run. Once the full data evaluation is completed without any errors a ***.xml*** output file will be generated, WHTC BSFC simulation output results will be written down in the message window.

4.5.1 Results

Rural, Urban and Motorway WHTC BSFC values along with overall WHTC BSFC are simulated by VECTO Engine. Due to confidentiality of the company BSFC values cannot be disclosed. The output BSFC values were compared with the WHTC BSFC results achieved in Test Cells, as shown in the **Table 1**.

Table 1: WHTC Simulation BSFC values Comparison with Test Cell results

WHTC Simulation Run	WHTC Urban BSFC (% deviation)	WHTC Rural BSFC (% deviation)	WHTC Motorway BSFC (% deviation)	WHTC Total BSFC (% deviation)
FLC1,FCMap1 (Locked)	-11.63	-14.9	-1.1	-5.8
FLC2,FCMap1 (Locked)	-13.93	-18.78	-1.34	-6.7
FLC1, FCMap2 (unlocked)	-5.31	-12.03	3.62	-0.95

4.5.2 Conclusion

Three WHTC simulation runs were conducted with two FLC data and two FC Map, keeping all the other parameters same for the 5.6L OBD2 Cummins Diesel Engine. The fuel maps were created as per the grid generated by VECTO Engine, the FC values taken at the grid points are interpolated from PTP Test Run FC values.

Following conclusions can be drawn from the simulation output results

- Runs taken with different FC Map but same FLC and keeping all other inputs same shows different BSFC outputs that signifies VECTO Engine is capable to simulate as per the input engine data.
- Negative deviation signifies that BSFC Simulation values are lower than the test cell results.
- WHTC simulation BSFC results with locked and unlocked FC Map conclude that VECTO Engine can simulate WHTC with good BSFC accuracy for different engine calibrations.
- The motorway section of the WHTC is being simulated with an higher BSFC accuracy,
  The reason behind that can be estimated to be lesser speed torque fluctuations over this section compared to WHTC Rural and Urban Sections.
- All the input BSFC values do not affect the results as those are only used by VECTO to calculate the BSFC Correction factors, given in the output ***.xml*** file.
- These Correction Factors are needed in the Engine File **(*.veng*)** as inputs in VECTO Declaration Mode, not required in Engineering Mode simulations.

Once the data for a FCMC run in test cell is available, then the simulation can be done with the test cell FCMC data and even better simulation results can be expected.

Chapter 05

VECTO Vehicle Simulation in Engineering Mode

In the present work the vehicle chosen for the simulation is TATA SIGNA 1923 Tipper with 5.6L BS6 220HP Cummins Diesel Engine. Several simulation runs were conducted in Engineering Mode with different parameters and different route data to simulate the BSFC and CO_2 emissions over these routes and simulation output results are compared with VMS and real life field data.

VMS drive cycle were attempted to simulate in Engineering Mode, for the simulations several runs were taken with the drive cycles generated from the respective VMS runs. It should be noted that all the values of the different parameters provided in the VECTO Engineering Mode input have to be same as that of the VMS parameters values for the respective runs.

All the required parameters to create a drive cycle to be simulated in Engineering Mode are not available in current field test data. Further work is being performed on this by various teams all over the globe to simulate field route cycle in Engineering Mode.

5.1 Input Files Details

Vehicle details , engine input files, gearbox details and gearshift statergies (shift poligons), auxiliary details, drivetrain configuration, aerodynamic resistance, maximum accelaration and decelaration file and a few other paramter values to incorporate driver models that replicate human driving behavior to provide realistic simulations. All the input files are needed to be saved in the respective file formats.This can be achived by creating an input file in the respective input interfaces or modifing the respective demo input files as per the required inputs as shown in **Fig. 5.1.**

5.1.1 Vehicle File (*.vveh*)

- The Vehicle files defines the non-Engine or Gearbox related vehicle parameters..
- Several runs were taken with different RAR (Rear Axle Ratio) of 6.43 and 4.48.
- The Gross Vehicle weight of the Vehicle is 19 Ton (Technically Permissible maximum Laden mass is 19 Ton).
- The loading mass is varied for different runs with 50% loading, 30% loading and Rated Load condition and there is no Extra Traler/ Body attached.
- The Aerodynamic Drag Coefficient is considered to be 0.44.

- The rear tyres are twin tyres with relative load of 0.27 on each side, accompanied by two single front tyres with rel load of 0.23.
- The actual tyre details is- 298/10R20 but it was not available in the wheel details window hence we have considered 295/80R22.5 tyre.
- While cross winds can indeed affect the aerodynamics and energy consumption of vehicles, VECTO's Engineering Mode does not have a specific input or feature to account for cross wind correction factors.

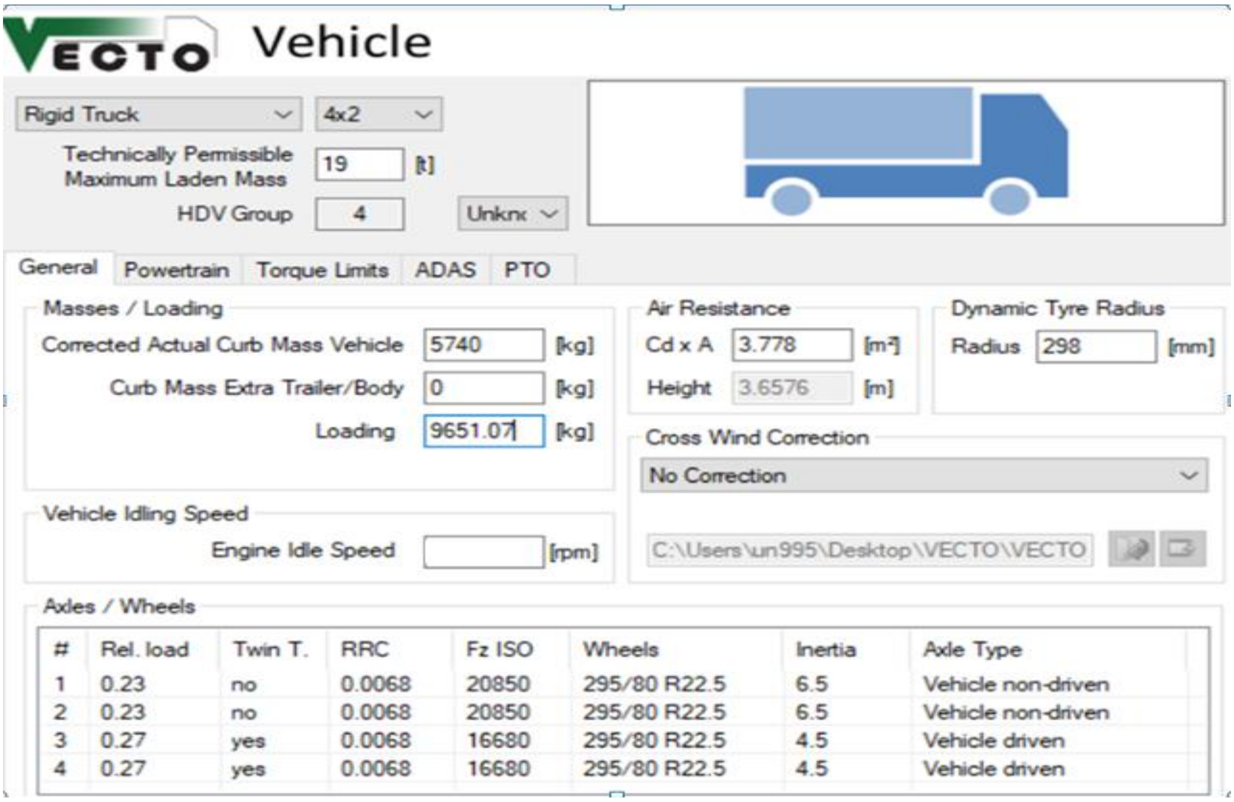


Fig 5.1: Vehicle Details Input interface for VECTO Engineering Mode

- The Rolling Resistance Coefficient for all the tyres is considered as 0.0068.
- All the input parameters are provided as required as illustrated in Fig 5.1 and saved as ***.vveh*** file in the input directory.
- This ***.vveh*** file can be browsed directly to the Vehicle file window for further requirements.

5.1.2 Engine File (*.veng*)

The required Engine data set for the Engine file in Vecto Engine Engineering Mode are

- The Full load Curve of the Engine
- Motoring curve data
- Fuel Consumption Map

These data sets are to be modified as per the requirement of VECTO vehicle Engine input file.

Merging FLC and Motoring Curve: Unlike VECTO Engine, the FLC and motoring curve is to be merged in a single file, rquired modifications in the FLC and Motoring data for that are as following.

- The FLC is to be modified as such there is a specific torque value for a specific speed,hence 1 rpm gap was taken between 2 speed points and the engine torque values of the FLC were interpolated for the whole speed range.
- For merging the motoring curve with the FLC same Speed pointsare needed in the FLC and the motoring curve.
- Hence the Speed points of the FLC were taken and the Motoring Torque values were interpolated from the motoring Speed Torque values in the motoring curve.
- FLC and Motoring file are to be merged in such a way that for every speed point there exists a motoring torque and FLC torque in the input file as shown in **Table2** for reference.

Table 2:FLC and Motoring data combined format for the engine input file

Engine Speed (1/min)	Full load Torque (Nm)	Motoring Torque (Nm)
762.01	673.01	-107.489
763.01	675.81	-107.529
765.01	680.71	-107.609
766.01	677.81	-107.649

The combined FLC and Motoring generated sheet is converted and saved into *.csv* format and browsed in the engine window of the Vecto-vehicle.

Modifing The FC Map: The FCMap used for Vecto Engine consists of grid points in between zero torque and full load curve.The FCMap grid is now extended in the motoring portion (Negetive torque region) in the similer way described earlier for generating the FCMap grid in between zero torque and FLCwith a torque stepsize of 10% of maximum torque.

The Fuel Consumption Correction Factors are not required as an inputfor the engineering mode.

- These factors values can be found from the .xml file of VECTO Engine output and are required to generate the Engine File (.veng) in declaration mode.
- WHR (Waste Heat Recovery) is not used**.**

Maximum engine torque value and low ilde engine speed for the 5.6OBD2 engine are not disclosed as per the confidentiality policies of cummins india limited**.**

All the other Engine details are given, combined FLC and Motoring data and FC Map data are browsed to the input window as illustrated in the **Fig 5.2** and saved as the .veng file in the input directory.

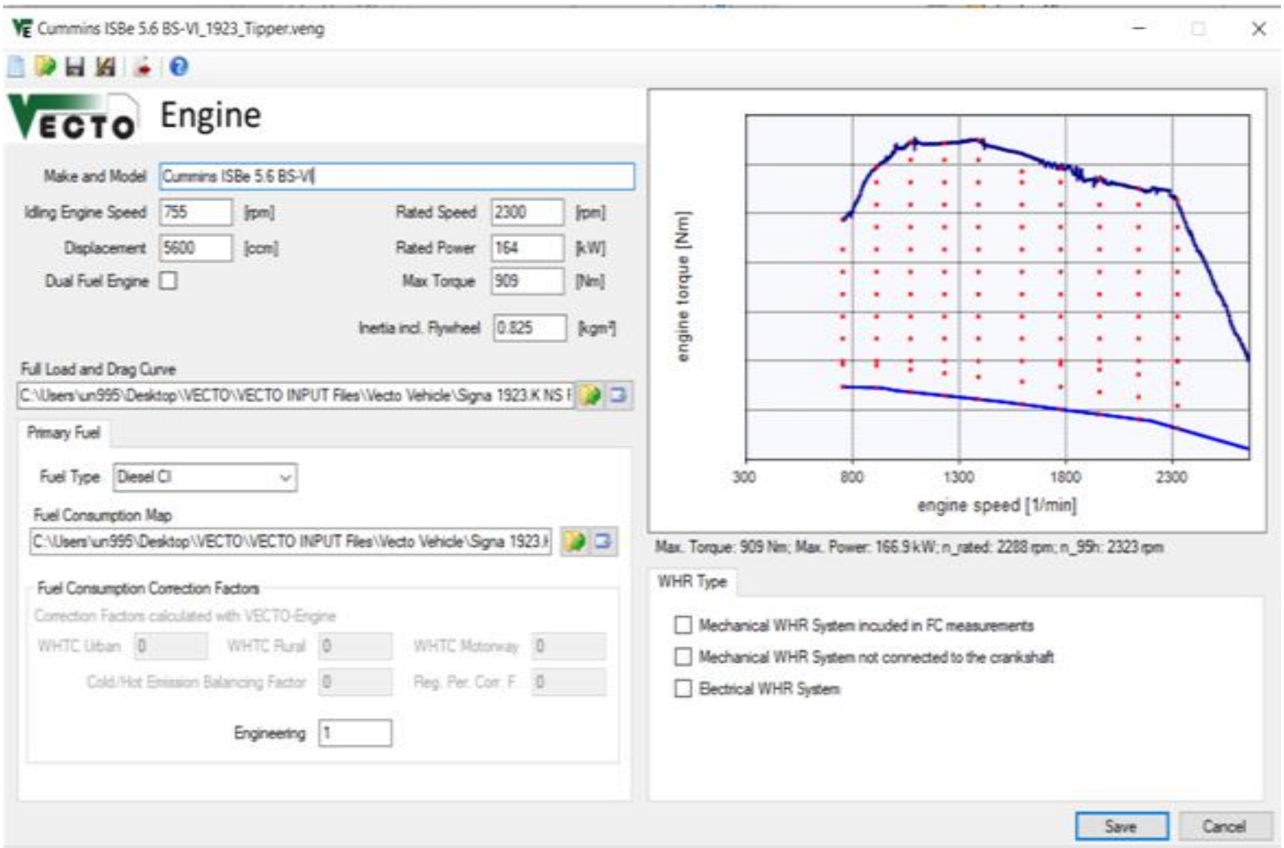


Fig 5.2: Vehicle Details Input interface for VECTO Engineering Mode

5.1.3 Gearbox File (*.vgbx*)

The gearbox file defines all gearbox related input parameters like gear ratios and transmission loss maps. The gearbox used in the 1923 tipper for the simulation is G950 Direct Drive Manual Transmission 6 speed Gearbox with different rear axle ratios (RAR) for different runs.

- All the gear ratios and the loss map for each gear is to be given.
- Several runs were conducted with RAR of 6.43 and 4.8.
- In Engineering Mode simulations either of the loss maps or constant efficiency values for the loss map can be used. (Not allowed in Declaration Mode)
- Gear Shift parameters and Shift Strategy parameter values are given as per the VMS input.
- A constant efficiency of 0.95 is considered for all the gear pairs.
- Unlike Vehicle and Engine File, the gearbox file cannot be created by putting the input files and parameters values and saving them.

- The gearbox file is to be modified as per the input gearbox file requirements and for that a standard MT gearbox file **(*.vgbx*)** from the demo files and was modified as per the project requirements as shown in the **Fig 5.3** and saved in the input directory.

Torque Reserve: Typically refers to a feature in certain high-performance vehicles equipped with advanced drive train systems. It signifies the amount of torque that is temporarily reserved or held back during a gearshift event to ensure a smooth and seamless transition between gears. During a gearshift, there is a momentary interruption in power delivery as the transmission disengages the current gear and engages the next gear. This interruption can result in a loss of acceleration or a sudden dip in torque delivery. To mitigate this interruption, the torque reserve system temporarily increases engine torque output and holds it at a predetermined level during the gearshift process.

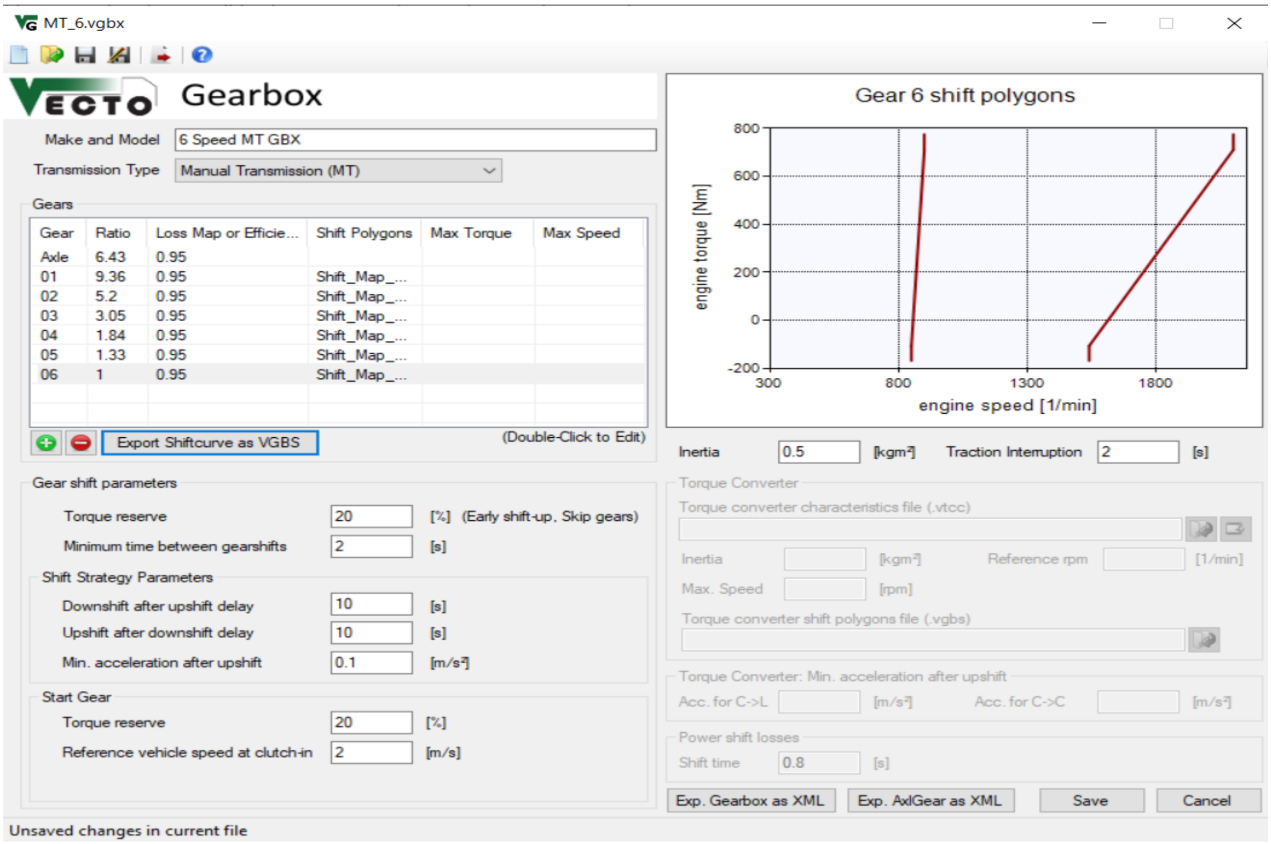


Fig 5.3: Gearbox Details Input interface for VECTO Engineering Mode

The minimum time between gearshifts: Also known as Shift time or Shift duration, represents the time it takes to disengage the current gear, engage the next gear, and synchronize the engine speed and vehicle speed for a smooth transition. Here 0s is taken as the minimum time between gearshifts as in VMS run no Shift Time was assigned between the Gearshift.

Shift Strategy Parameters: Gear shift strategy parameters refer to the various factors and settings that influence the decision-making process of a vehicle's transmission system during gear shifts.

These parameters are programmed and configured to optimize performance, fuel efficiency, drivability, and overall vehicle dynamics.

Upshift after Downshift delay refers to a delay or time interval between an upshift (shifting to a higher gear) and a subsequent downshift (shifting to a lower gear) in a vehicle's transmission system.

The purpose of this intentional delay is to allow the vehicle's drive train components, such as clutches or synchronizers, to settle and synchronize before initiating a downshift.

Downshift after Upshift delay similarly refers to a delay or time interval between a Down shift (shifting to a lower gear) and a subsequent Up shift (shifting to a higher gear) in a vehicle's transmission system.

The specific duration of these delays can vary among vehicles, depending on factors such as transmission design, drive train technology, and manufacturer preferences. The delay duration is typically optimized to balance the objectives of stability, control, drivability, and engine protection.

Minimum acceleration after up shift refers to the recommended or desired level of acceleration that is recommended or considered appropriate immediately after shifting to a higher gear in a vehicle with a manual or automatic transmission.

Traction interruption in gear shifts refers to a temporary loss or reduction of traction or grip on the driving wheels during the process of shifting gears in a vehicle with a manual or automated manual transmission.

The traction interruption during gear shifts occurs due to the disengagement of the current gear and engagement of the next gear in the transmission. As the transmission shifts, the power flow to the wheels is momentarily interrupted, resulting in a loss of traction. This interruption can cause a temporary reduction in traction, particularly in high-performance vehicles or vehicles with high torque outputs.

It must be noted that all of these gearbox parameters values should be same as per the respective VMS runs. Once all the input files and parameters are given the ***.vgbx*** gearbox file can be saved in the input directory and browsed later on accordingly for the simulation runs.

5.1.4 Shift Polygons ***(.vgbs)***

Shift Polygon refers to a graphical representation or plot that illustrates the ideal or recommended shift points for each gear during the acceleration or deceleration.

In VECTO, the gear shift polygon is a representation of the vehicle's gear shifting strategy or pattern. It simulates real-life gear shift behaviour to estimate the energy consumption and emissions of heavy-duty vehicles during different driving cycles. It consists of a series of lines or data points that represent the optimal engine speed for up shifting and downshifting at various vehicle speeds and engine loads. The shift polygon is based on extensive testing and engineering analysis to determine the engine speed ranges where shifting to a higher or lower gear is most efficient and conducive to optimal performance. It takes into account factors such as engine power characteristics, torque curves, fuel efficiency, and the intended driving experience. It simulates real-life gear shift behaviour by providing a visual and tactile guide to engage different gears in a manual transmission vehicle. It simplifies the gear selection process, making it more user-friendly and enhancing the driving experience.

The shift polygon consists of lines or data points that connect specific engine speed values corresponding to each gear. These lines or points illustrate the recommended or ideal engine speed range for up shifting and downshifting at various vehicle speeds.

- It consists of an Upshift line and a Downshift line.
- The Shape of the Upshift or Down Shift Line can be linier line or Curved line or consisting of several line segments depending on the vehicle's transmission design, engine characteristics, and intended performance objectives.

Up-shift Curve: Up-shift is initiated when the current engine speed is above the up-shift curve.

Down-shift Curve: As soon as the current engine speed falls below the down-shift curve a down-shift is initiated. An example of a generic shift polygon in between the FLC and Motoring curve, indicating the Up-shift and Down-shift Curve is shown in **Fig 5.5**.

Fig 5.4: A Shift Polygon generated in between the FLC and Motoring Curve

Shift Polygon Generation:

The shift polygon consists of lines or data points that connect specific engine speed values corresponding to each gear. These lines or points illustrate the recommended or ideal engine speed range for up shifting and downshifting at various vehicle speeds. The steps of generating a shift polygon are described as following,

- In this study for the runs taken in Engineering Mode shift polygons are created as per the shift strategies used in VMS inputs.
- For experimentation purposes with a goal to get better conclusion, several runs were conducted by changing the shift polygon, keeping all the other parameters same.
- From the VMS input file the rpm values of the ABCD points (The 4 corner points of the shift polygon) are obtained.
- There after the torque values of the corresponding points from the FLC and Motoring curve can be obtained. The downshift line end points and upshift line end points speed torque values are tabulated respectively in **Table3** and **Table4**. (Depending upon if the Shift Polygon is extended in the Motoring Section or Not, If not then the polygon will be constructed in between the FLC and Zero Torque Line).

Table 3: Downshift Line end points

	Engine Torque[Nm]	Downshift rpm[1/min]
Downshift A	775.31	900.01
Downshift C	-107.006	850.01

Table 4: Upshift Line end points

	Engine Torque[Nm]	Upshift rpm [1/min]
Upshift B	805.61	1750.01
Upshift D	-181.456	1650.01

The up shift and downshift lines will be generated from these 4 points, each line consists of three line segments.

Both the up shift and down shift lines consists of three line segments, to create a Shift Polygon file, the Engine Torque, Up shift and Downshift rpm values are needed to be arranged in a specific way as can be seen in the **Table 5**.There after this table have to be saved in ***.vgbs*** file to be browsed later on into VECTO inputs as the shift polygon file.

Table 5: ***Speed-Torque points of the Shift Polygon***

Engine torque[Nm]	**Downshift rpm [1/min]**	**Upshift rpm [1/min]**
-181.456	850.01	1650.01
-107.006	850.01	1650.01
775.31	900.01	1750.01
805.61	900.01	1750.01

Upshift and Downshift lines are separately generated from this speed and torque values and then combined as shown in the **Table 5** to generate the shift polygon as can be seen in the **Fig 5.5**.

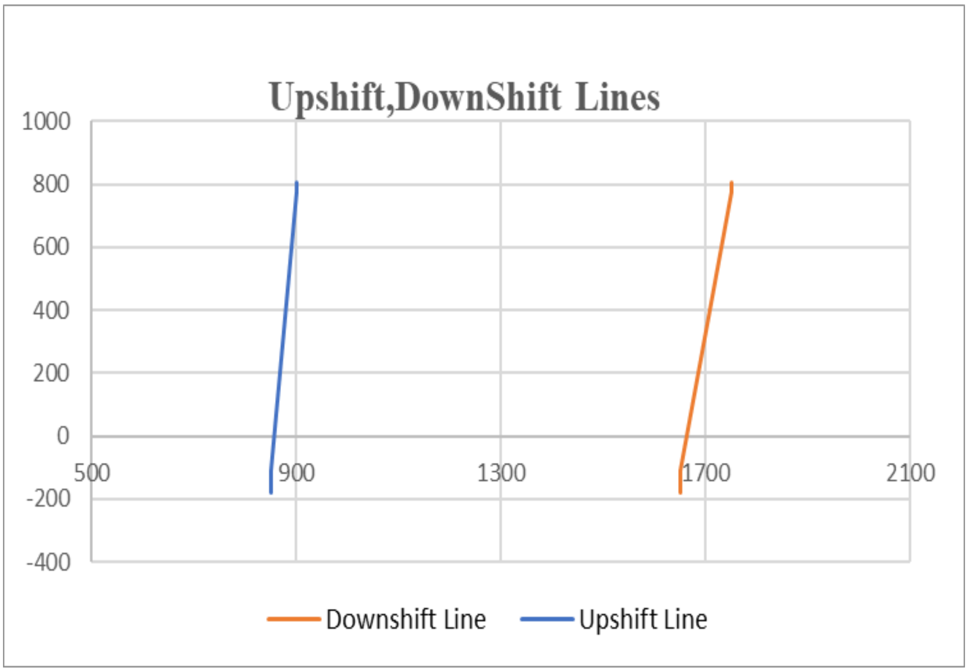


Fig 5.5: Upshift and Downshift Lines

In Engineering Mode we have the flexibility to create the shift polygon and shift strategy as per the need of the simulation. In Declaration Mode the generic shift polygons are computed from the engine's FLC. It computes the shift polygons and uses characteristic values from the engine such as n95h, n_pref etc. which are also derived from the FLC. A constant efficiency of 0.95 is considered for all the gear pairs and the same shift polygon was used for all of them. (Different efficiency values and loss maps can be used as well, if required).

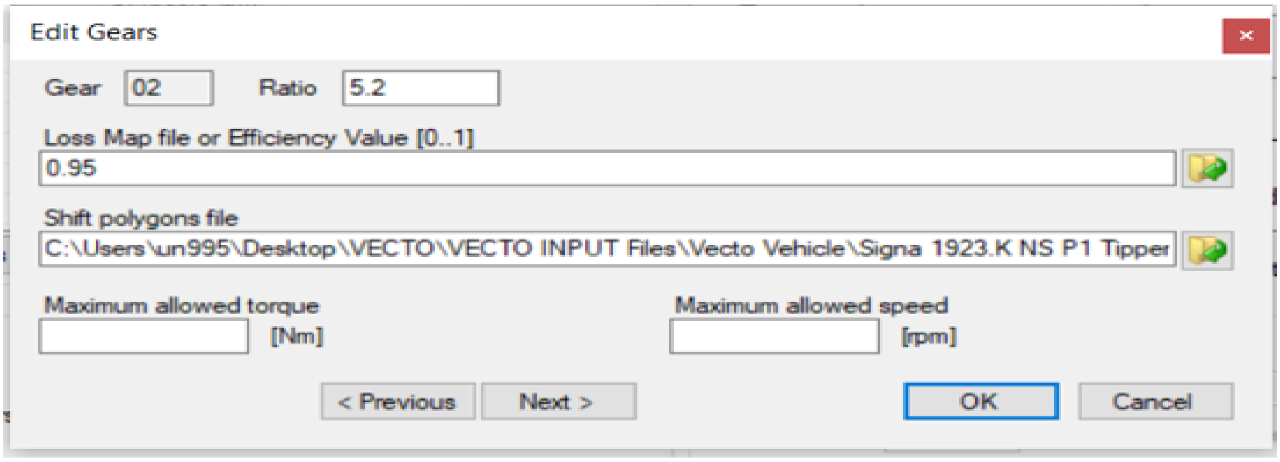


Fig 5.6: Gear details window in Gearbox File

The shift polygon files are to be created in the required format (***.vgbs***) and to be saved in the input directory as shown in **Fig. 5.6.**

In the gear details window in the gearbox input window gear ratios, loss map/efficiency values are given and the shift polygon files are browsed as illustrated in **Fig 5.6**.

5.1.5 Driver Acceleration Deceleration File *(.vacc)*

The Driver Acceleration Deceleration File contains data related to the vehicle's acceleration and deceleration characteristics. It provides information about the driving behaviour and patterns of the vehicle's operator.

By incorporating the Driver Acceleration Deceleration File, VECTO considers the actual driving behaviour and characteristics of the vehicle's operator during energy consumption and emissions estimations. This enables more accurate and realistic simulations that reflect real-world driving conditions.

v [km/h],	acc [m/s^2],	dec [m/s^2]
0,	1,	-1
25,	1,	-1
50,	0.642,	-1
60,	0.5,	-0.5
120,	0.5,	-0.5

Fig 5.7: Example of driver acceleration deceleration file

It should be noted that the maximum acceleration and deceleration values used in the ***.vacc*** file should be as per the input values used in respective VMS runs.

In this a standard 4x2Rigid truck ***.vacc*** file was used and it was modified as per the input requirements, example of the .*vacc* file is shown in the **Fig 5.7**.

5.1.6 Other Input Parameters

The total power consumption by the auxiliaries is assumed to be consumed from the power generated by the engine and no auxiliary power is consumed when the engine is off. The auxiliary power consumption inputs are shown in **Fig 5.8**.

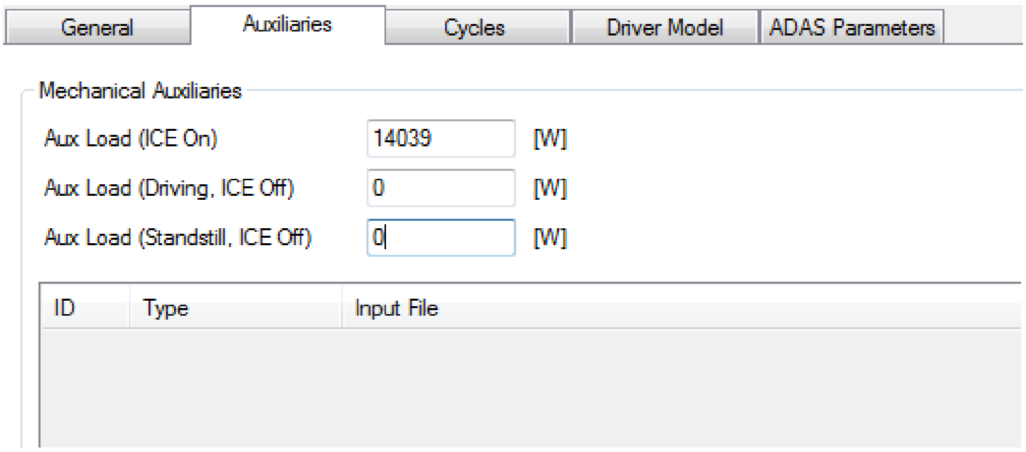


Fig 5.8: Auxiliary Power Consumption Input

Details of the auxiliaries are not needed in Engineering Mode but in declaration mode it is needed to be maintained.

For the runs taken in the present work, it has taken turned off for the over-speed.

Look ahead coasting parameters and ADAS parameters are not mandatory for the runs.

5.2 Route Cycle/Drive cycles For Engineering Mode Simulations

VECTO Engineering mode provides the flexibility to Simulate the Vehicle over any route cycle as required for the project.

In Declaration Mode driving cycles are automatically chosen depending on vehicle category and cannot be changed by the user.

In this study VMS data of different route and extracted the parameters required to create the route data as per engineering mode requirements and saving them in ***.vdri*** file forma**t** to be browsed onto the VECTO cycle window.Mode route cycles can be of two types as following.

- Target-Speed, Distance-Based Cycle
- Measured-Speed, Time-Based Cycle

Output filter of 1Hz is available for distance based mode only, not available for time based cycles. Hence distances based cycles were taken for the runs.

5.2.1 Target-Speed, Distance-Based Cycle

This driving cycle defines the target speed of the vehicle over distance. VECTO tries to achieve and maintain this target speed throughout the simulation run.

```
<s>,<v>,<grad>,<stop>
0,      0,      0,       21
0.02, 1.23, 0.047,       0
0.28, 3.24, 0.406,       0
1.37, 7.57, -0.692,      0
2.63, 8.06, -1.833,      0
```

Fig 5.9: Example of a distance based drive cycle

These specific parameters represent the following in the Target Speed drive cycle as shown in the example of a target speed drive cycle is shown in **Fig 5.9**.

<**s**> **-**Vehicle Position or Distance Travelled in M.

<**v**>- Target Velocity of the Vehicle in Km/Hr.

<**grad**>-The road gradient in percentage.

<**stop**>**-** Defines the time span the vehicle is standing still at a point.

5.2.2 Measured-Speed, Time-Based Cycle

This driving cycle defines the actual measured speed over time. VECTO tries to simulate the vehicle model using this speed as the actual vehicle speed. Example of a measured speed cycle is shown in the **Fig 5.10**.

Due to deviations in real life and simulated shift strategies a small difference in speed can occur, but VECTO immediately tries to catch up after the gears are engaged again.

```
<t>, <v>, <grad>
1,    0,     0
2,    0,     0
3,    0,     0
4,   3.51, 0.47
5,   5.53, -0.61
```

Fig 5.10: Example of a time based drive cycle

These specific parameters represent the following in the measured speed drive cycle.

<t>- Represents the absolute time in Seconds.

<v>- The actual velocity of the vehicle in Km/hr

<grad>-The road gradient in percentage (Ratio of elevation differenceand vehicle position between two consecutive road points.)

5.2.3 Common Errors while generating the distance based route cycle

There might me some points in the route data where the actual speed is not zero just before a stopping point, but the targeted speed is zero, hence as the vehicle is not actually stationary and gradient may change in those consecutive points, but as the target speed is zero VECTO will evaluate the vehicle is stationary resulting an error. The following **Table 6** contains a patch of the 1Hz VMS Plug in data, out of which the drive cycles will be generated. In the line 1927 it can be clearly seen that vehicle target speed is zero but actual speed is not hence the vehicle position is also changing. For the distance based drive cycle generated from this data, during the simulation run VECTO will consider that target speed is zero but vehicle position and gradient is changing hence this discrepancy will result the abortion of the simulation run.

Table 6: Patch of a VMS Plug-in data containing the error causing points

Points	Vehicle Position (Km)	Vehicle Speed (Km/hr)	Speed Target (Km/hr)	Grade (%)
1923	7.354887	13.73908	13.49532	-3.11101
1924	7.358721	13.91062	13.85347	-3.08643
1925	7.362684	14.64324	14.66491	-3.09234
1926	7.375416	10.98656	8.606369	-3.02835
1927	7.377308	2.389068	0	-3.0144
1928	7.377442	0	0	-3.01371
1929	7.377442	0	0	-3.01371
1930	7.377442	0	0	-3.01371

To eliminate the errors caused by these points, these points are needed be found throughout the route cycle and have to be eliminated from the route cycle.

5.3 Engineering Mode Simulation Run and Errors Elimination

Once all the input files are generated, they are browsed directly to the respective VECTO job file input interface and upon successfully saving them a single job file ***(.vecto)*** will be generated and saved in the input file directory. This ***.vecto*** input job file can be directly browsed from the input directory as illustrated in **Fig 5.11**.

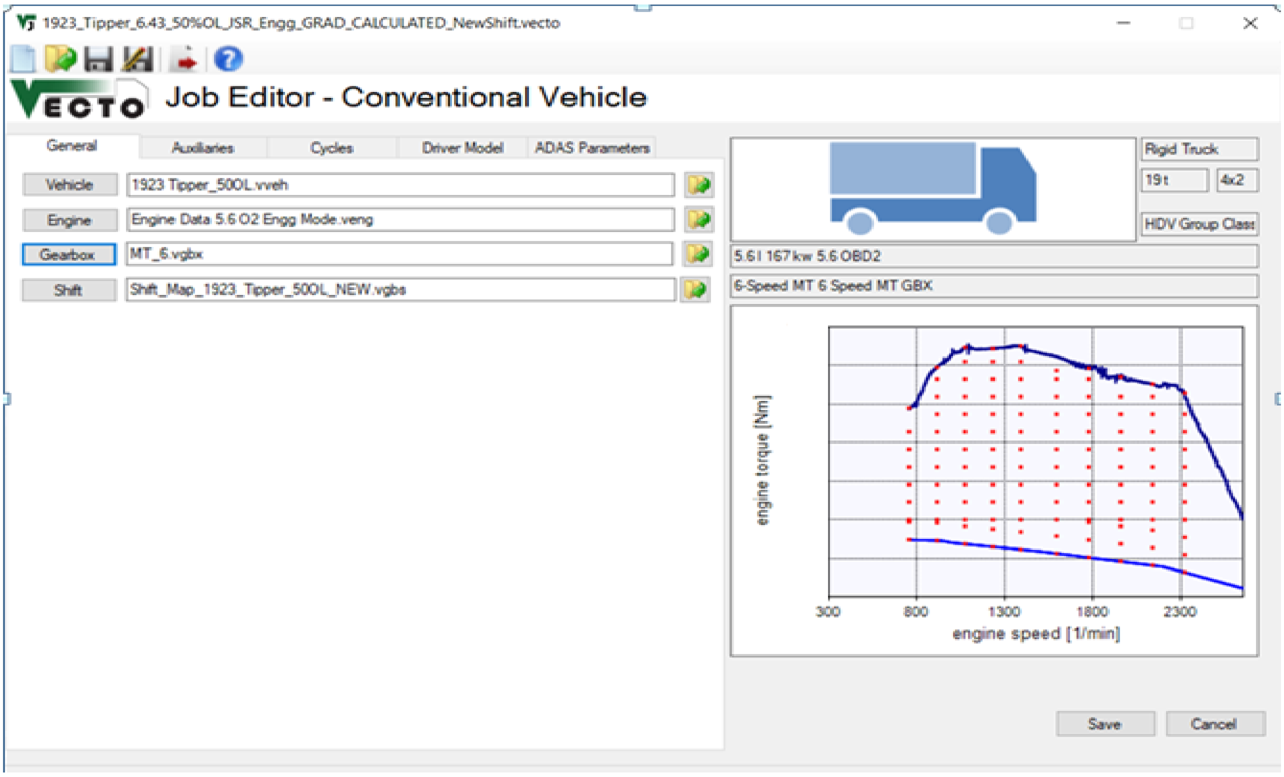


Fig 5.1: VECTO Input files interface of the job file

Modal results are only created if enabled in the options tab, after choosing the output directory, mode of the run, selecting the model output to be in 1 Hz in the option tab as shown in the **Fig 5.12**.

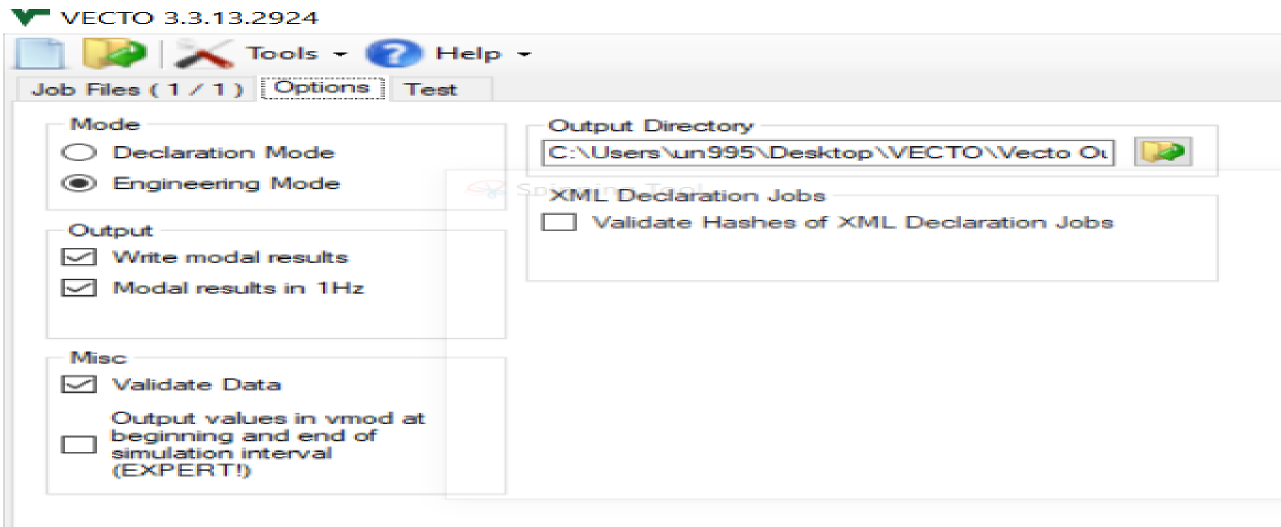


Fig 5.12: VECTO Input interface Option Tab

Once the run is started, VECTO will interpolate the fuel consumption from the FC Map and other parameters from the input files as per the engine speed- torque input over the route cycle. Any error encountered throughout the simulation will result in abortion of the run as can be seen in **Fig 5.13.**

Two types of common errors might occur during the run,

- First type of error is generated because VECTO is not being able to interpolate the FC and other parameters at some of the points over the drive cycle.
- In the internal calculations of VECTO, interpolating the parameters might lead to abnormal outcomes leading to the second type of error.

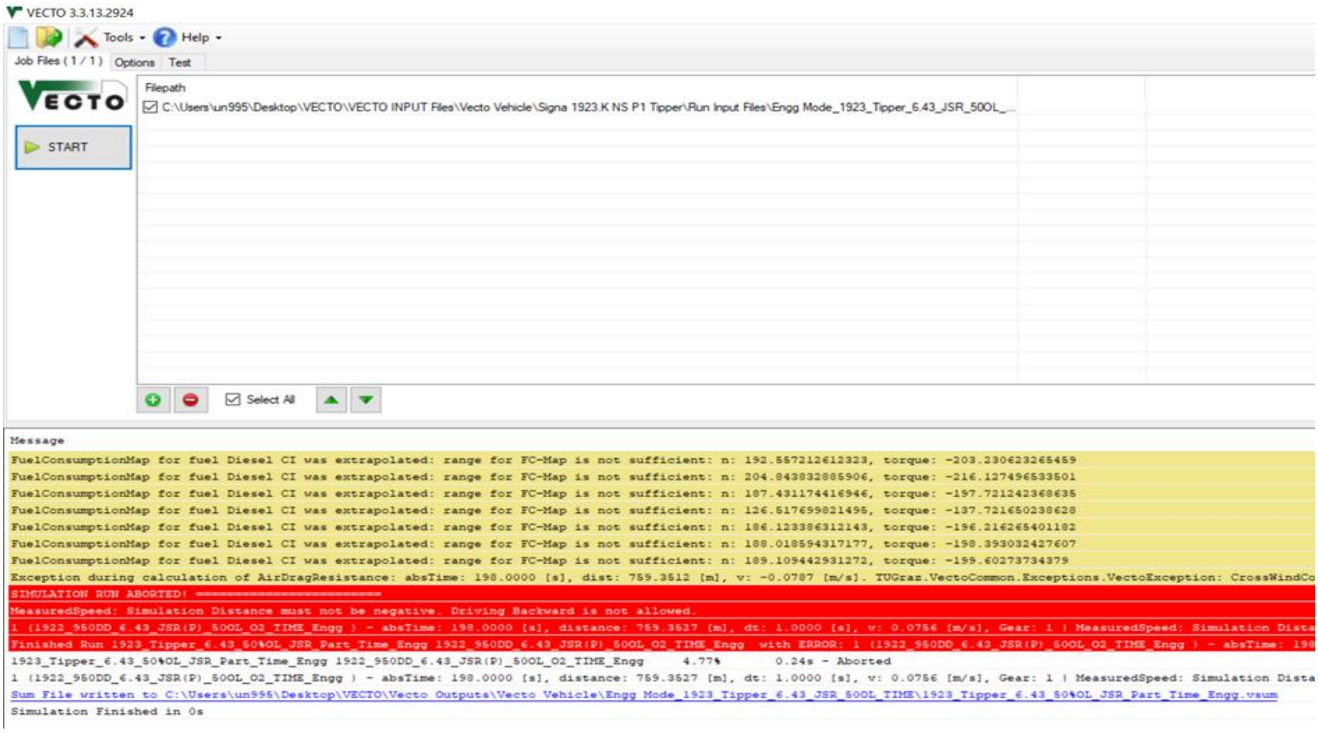


Fig 5.13: Simulation interface, run is aborted due to multiple errors

To have a successful run errors are needed to be resolved. This is to be done by identifying the points causing the errors, modifying or eliminating them.

A few common types are errors are illustrated as following with the respective snapshots of the errors from **Fig 5.14, Fig 5.15, Fig 5.16, and Fig 5.17.**

Vehicle Velocity is smaller than zero

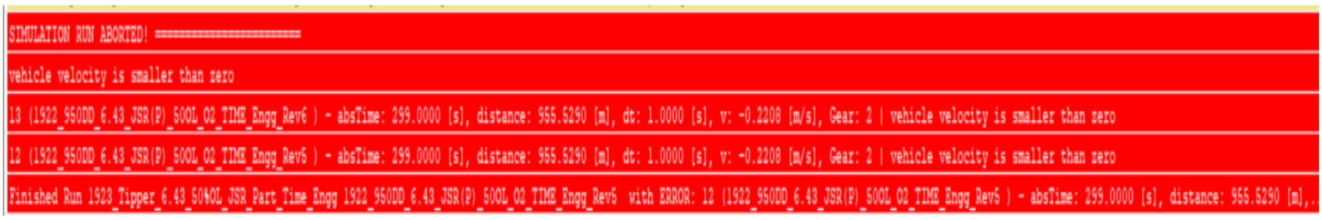


Fig 5.14: VECTO is calculating vehicle velocity at a point to be negative, causing an error

Torque has to be zero for idle requests

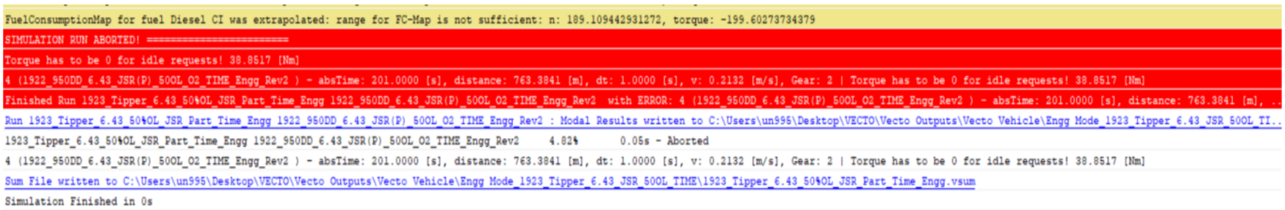


Fig 5.15: Error due to torque calculated by VECTO at some of the idle speed points is not zero

Distance must always be increasing/ driving backward is not allowed

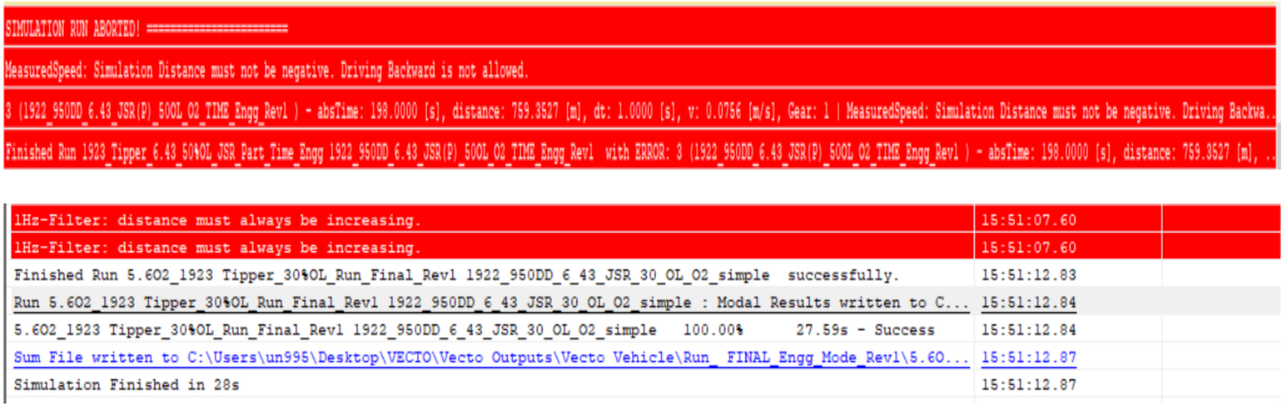


Fig 5.16: Error generated as distance calculated by VECTO at some of the points are negative

Infinity is not allowed for SI-Values in VECTO

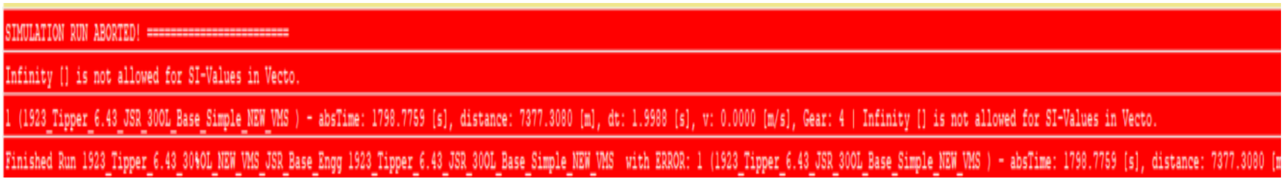


Fig 5.17: Error due to divided by zero error occurred in the internal calculations of VECTO

In the internal calculations of VECTO, interpolating the parameters error might occur due to abnormal outcomes calculated, resulting in these types of errors. These error causing points are needed to be modified or eliminated to resolve the error. The cause of the errors needs to be checked with different parameters. The errors caused due to the discrepancies in the internal calculations of VECTO might occur for a particular set of parameters and might not occur if one or more parameters are changed.

For example if the "Distance must always be increasing" error shows up changing the vehicle loading percentage keeping all the other parameters same resolve the error.

Once these errors are resolved and the run is completed successfully, a ***.vmod*** and a ***.vsum*** files are generated in the output directory. Simulation output result of 1 Hz is generated in the ***.vmod*** file.

Every line in the ***.vmod*** file represents the simulation interval from time - dt/2 to time + dt/2. All values represent the average power/torque/angular velocity during this simulation interval.

The ***.vsum*** file includes total / average results for each calculation run in one execution, and it's only generated once the run is successful without errors.

The output results of the several runs taken in Engineering Mode were compared with the respective VMS runs.

5.4 VECTO Engineering Mode Simulation results

The route data used for the Engineering mode runs are generated from the VMS plug-in by pulling the required parameters. Hence the Engineering Mode simulation result will show the variations between a vehicle simulation run in VMS and in VECTO. Several runs were taken from different VMS runs performed on 1923_950DD Tipper. Total 21 runs were performed in Engineering Mode with different routes, Vehicle loading %, Axle Configuration, Gearshift Polygons and FC Maps.

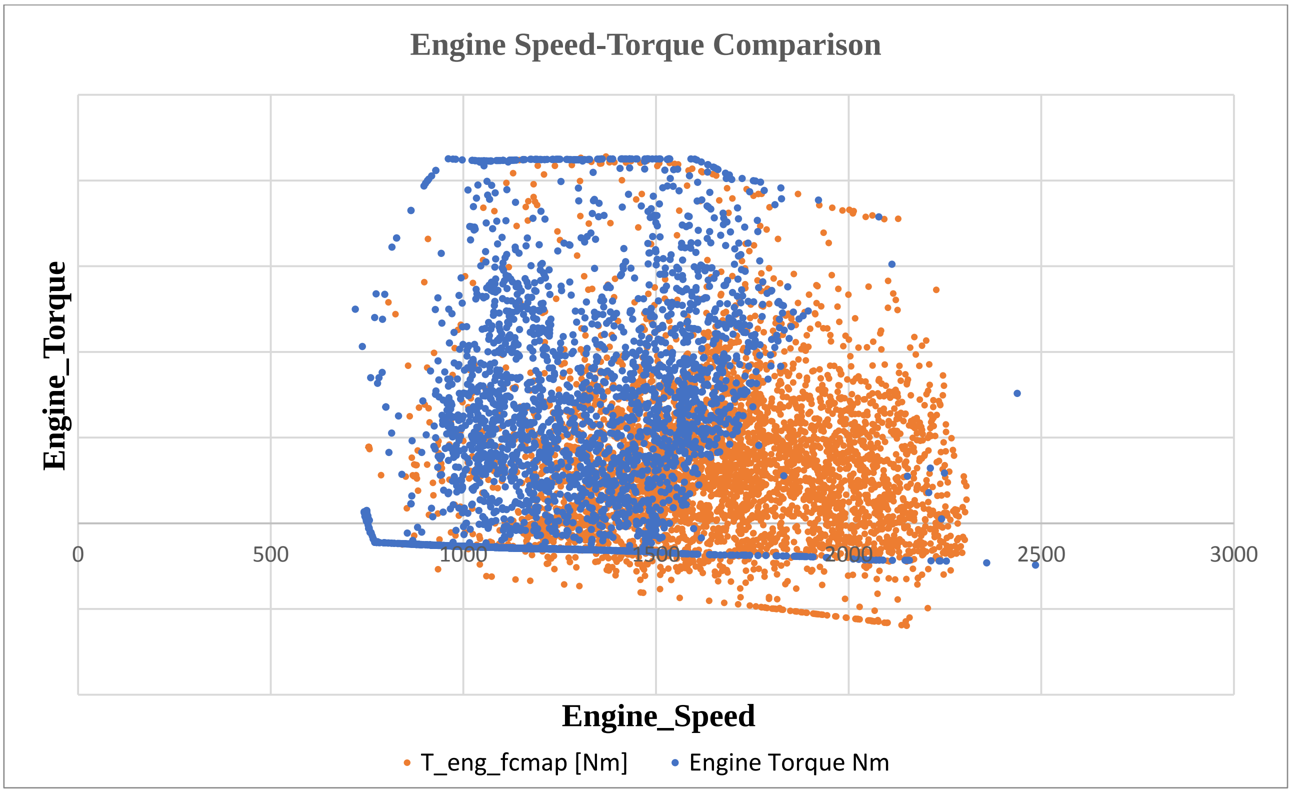


Fig 5.18: Speed Torque Comparison in VMS and VECTO Simulation run

For all of these runs performed, the output simulation results are showing a significant deviation in the Engine speed torque profile as can be seen in **Fig 5.18**.

Further looking into the cause of this deviation, the gear distributions over the route cycle simulation was compared for VMS and VECTO run as shown in **Fig 5.19** and **Fig 5.20.**

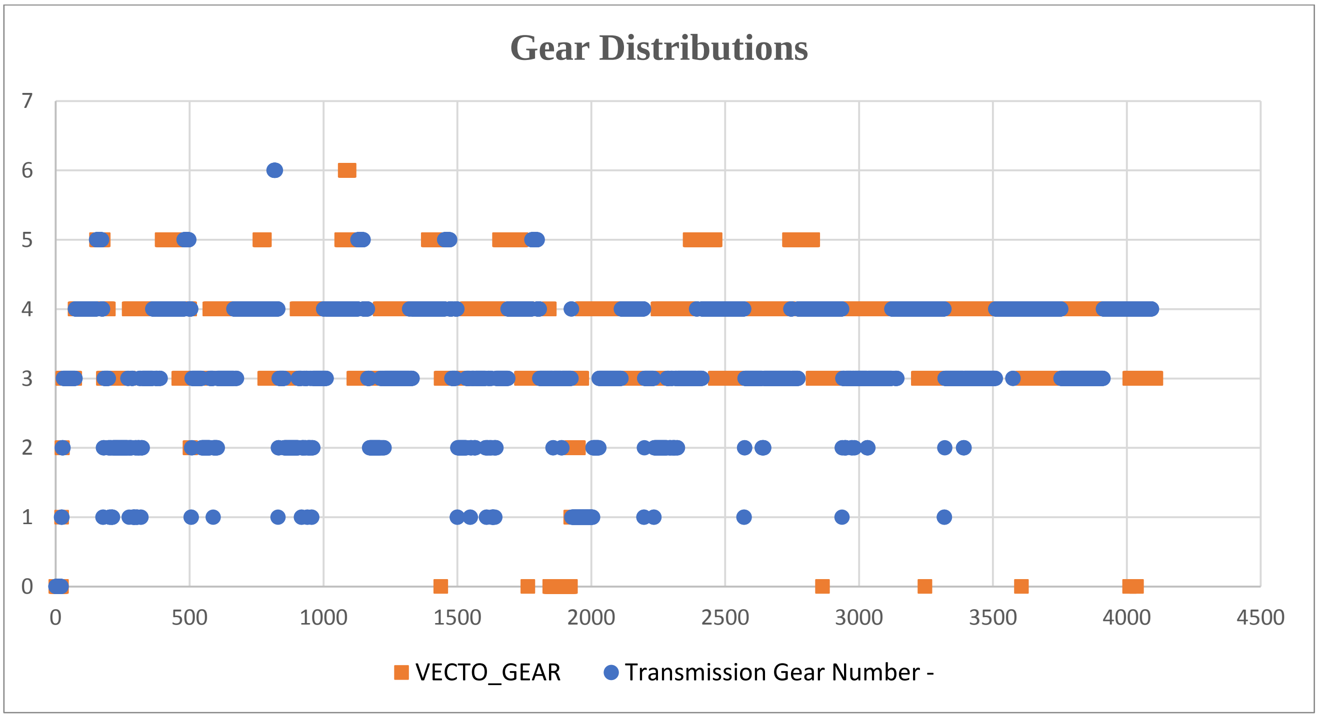


Fig 5.19: Gear Distribution over the Simulation Run for VECTO and VMS

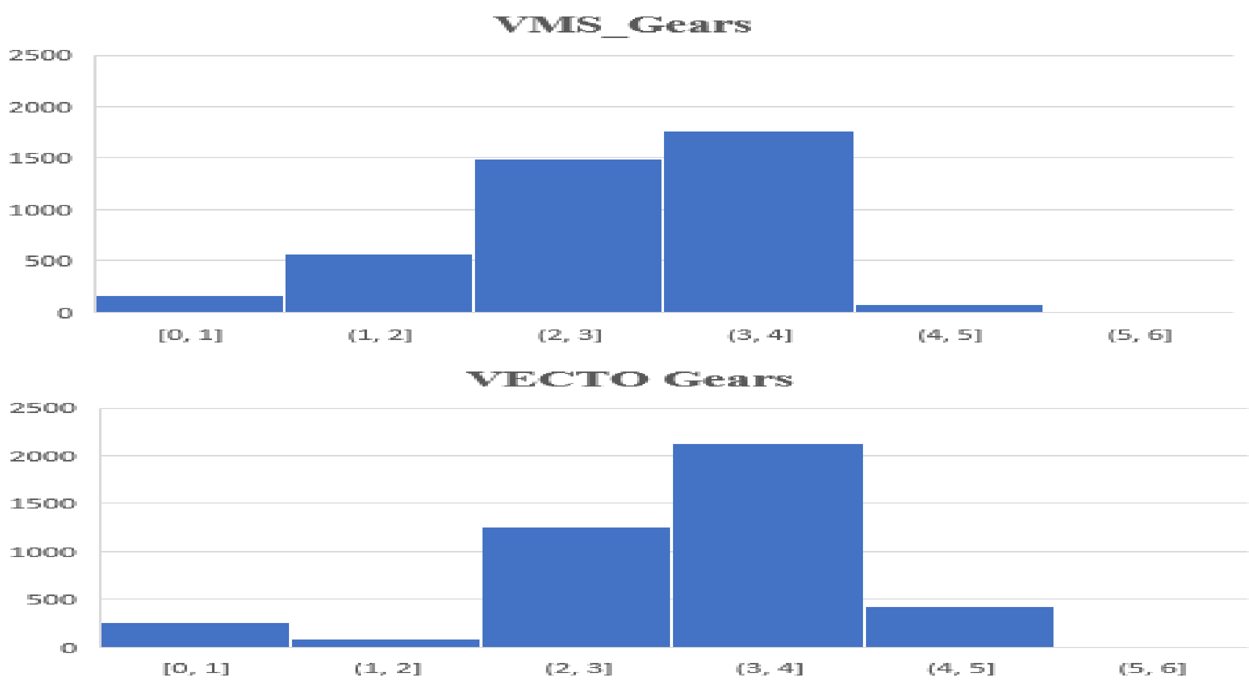


Fig 5.20: Gear Engagement distributions Comparisons

It can be clearly seen that over the simulation runs VECTO is running predominantly on higher gears and over the run with very few points in first and second gear as can be seen in **Fig 5.19.**

Significantly high no zero gear points are present in the VECTO simulation output along with the initial ideal points. It can be further concluded from **Fig 5.20** that VECTO gear distributions are completely different than VMS over the simulation run. VECTO output Engine Speed and Torque are significantly higher leading to a very high BSFC for all the runs (22%-37% deviation).

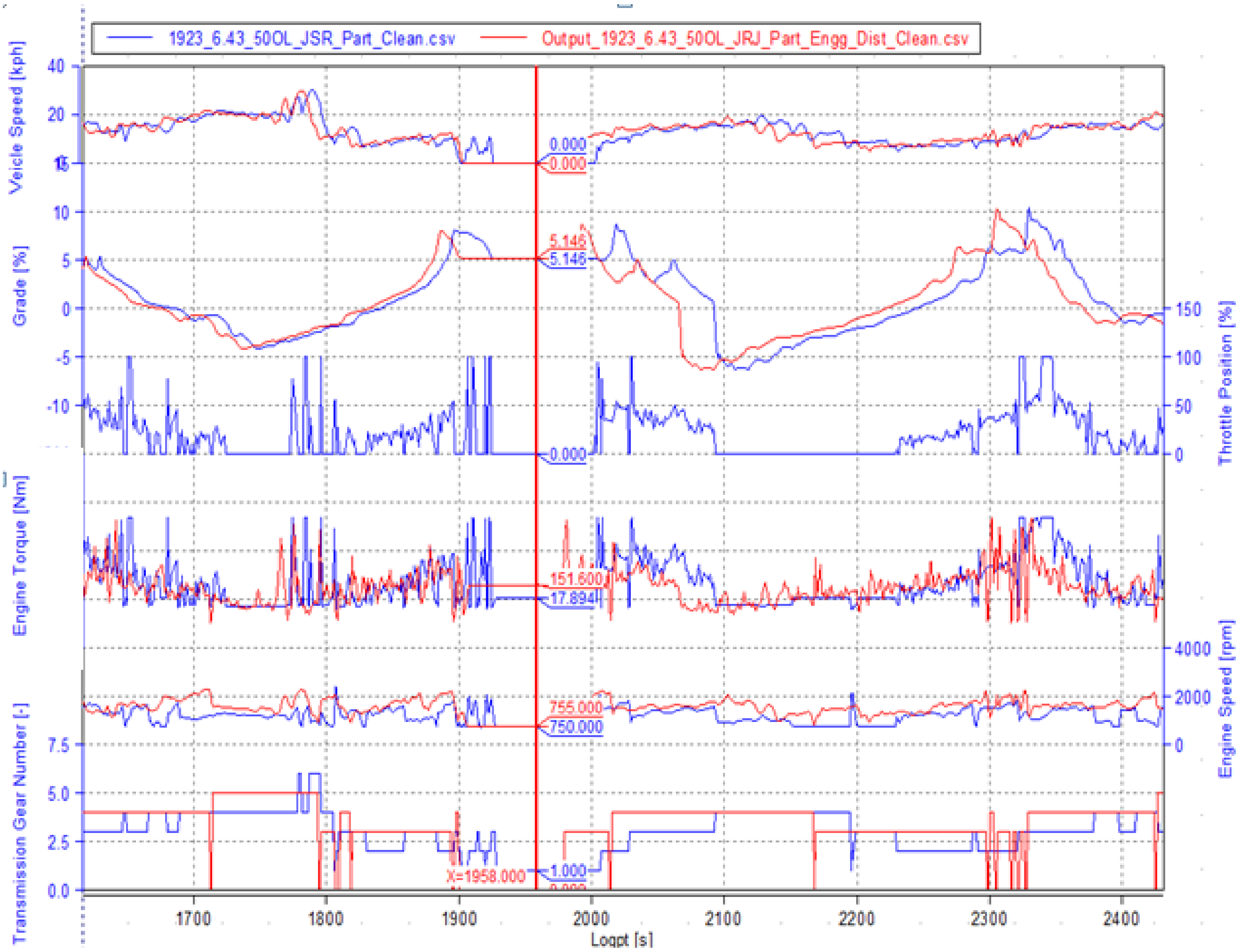


Fig 5.21: Comparison plots of different parameters Over the Simulation Run (4095 points)

Following Observations were done from the plots between various parameters against several runs as can be observed in **Fig 5.21**.

- The Vehicle Velocity and Gradient in input and output are in offset except for the initial portion of the run.
- Points where vehicle Speed, Gradient in input and output, even the gear engagements are same engine speed and Torque are drastically different.
- In these points Same Vehicle actual speed and gradient signifies that even at the points where vehicle is running as per the given inputs, yet engine is not running as is should.

- In the points where the Vehicle Speed, Gradient, Gears are same and Engine is idling, Throttling is Zero, there also the engine torque is having huge difference.

For all the runs taken with changing combinations of the stated input parameters, comparison of VECTO input and output simulation results have led to similar results. The average Engine Speed in the VECTO Output is **1655 to 1697 rpm** with the input Engine speed of **1180-1402 rpm** in the VMS route over all the simulation runs. The Average Engine Speed is high for all the runs with a deviation ranging from **17% to 31%.**

From the simulation results it can be observed that there are a significantly high number of motoring points in the simulation output, resulting in higher fueling in motoring conditions over the route cycle simulation in VECTO compared with the VMS run.

The input route cycle in VECTO is generated in the following way,

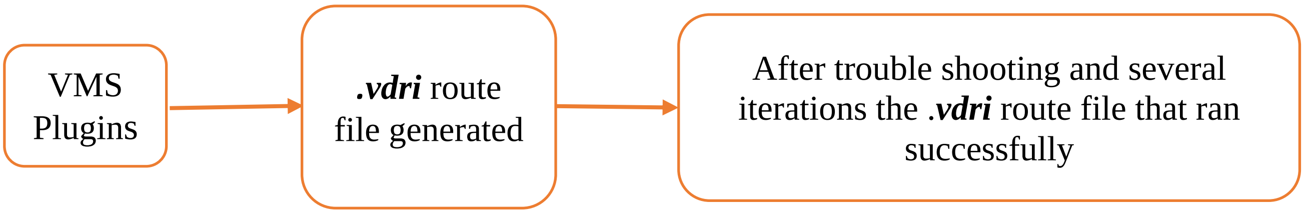


Fig 5.22: Steps of route cycle generation from VMS Plug-in

Some of the points in the input route are eliminated to remove the errors caused by them for different runs. (**Less than 1% of points were removed over the route cycle).**

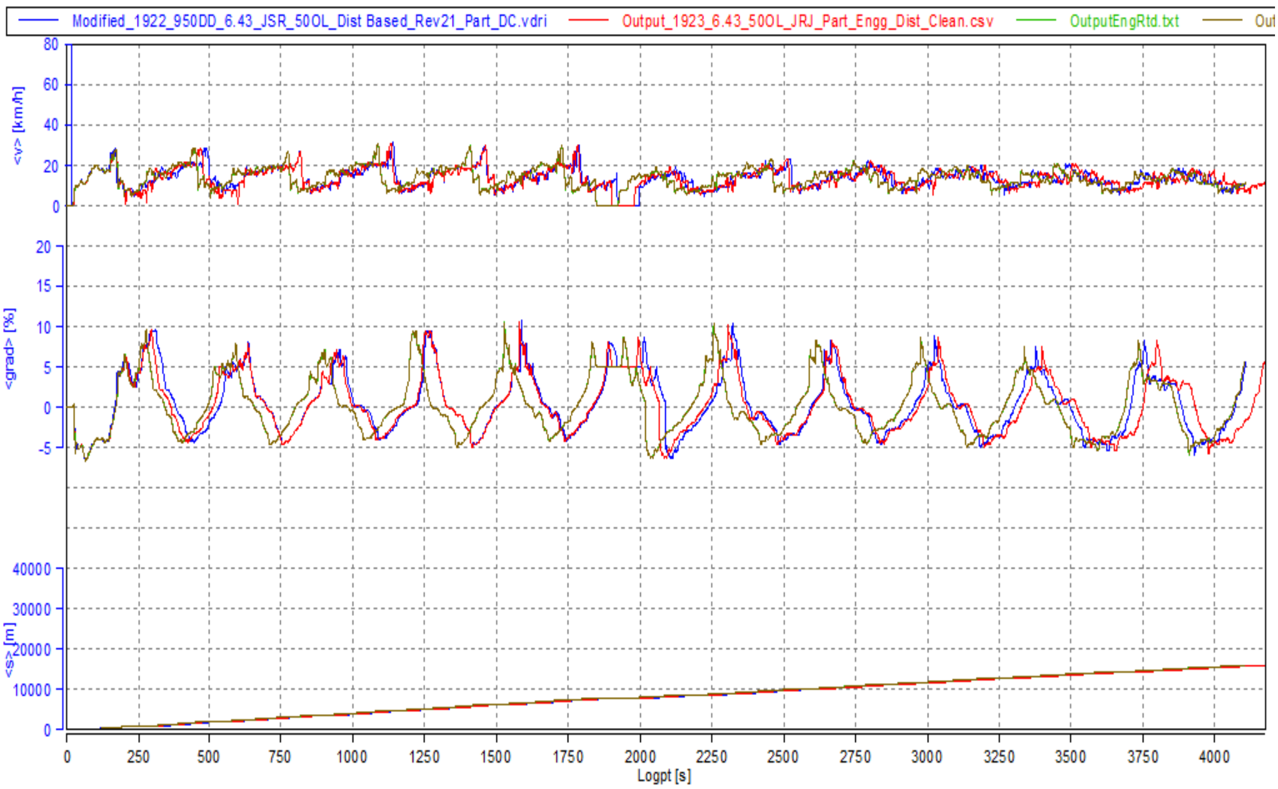


Fig 5.23: Comparison plots of Distance, Target Speed, and Gradient over the different Runs

The final route cycle data was compared with the VECTO output data for different runs taken by changing Gearshift Strategy, Fuel Maps, and Vehicle Loading percentage, keeping the route cycle same. It can be clearly seen that although VECTO can simulate the Vehicle Position as per the input route cycle, Vehicle Speed and Gradient are in offset for most of the run, Only for the initial points input and output Vehicle Speed and Gradient are overlapping as can be seen in **Fig 5.23.** The root cause of the discrepancy leading to the offset in Engineering Mode simulation is needed to be found out.

5.5 Conclusion

From the simulation output results obtained total 21 runs conducted in Engineering mode with different parameters and input data files following conclusions can be summarized,

- It can be stated that VECTO Engineering Mode is not being able to simulate the input route given (Vehicle Speed and Gradient) .At the initial points where vehicle Speed and gradient are being simulated as per the inputs route cycle there also output Gear Distribution, Engine Speed and Torque have no correlation with input values.
- In all the runs the discrepancy in Average Engine Speed and Torque is significantly high leading to a high BSFC deviation ranging from 22 to 37%.
- There are a significantly high number of motoring points in VECTO output as well as fueling in motoring conditions are also significantly higher in VECTO output than the VMS run.
- Further work is needed on how VECTO Engineering mode runs a route cycle and any other causes leading to the discrepancies are needed to be found out.
- VECTO is specifically designed for HDVs, this study was conducted only one type of HDV (1923 Tipper), similar experiments can be performed with different HDVs. Once the required input parameters are available in the field data, further experiments can be done with route cycles generated from field data.
- A huge no of parameters are included in the Engineering mode simulation, this makes the calculations more accurate and complicated at the same time.

  All of these parameters are needed to be fine tuned for further improvements in output results; further work is needed to be done regarding this.
- The gradient value from the VMS Plug-in does not match with gradient calculated from Vehicle Position and elevation data.(This question is yet to be answered by the VMS Team).
- Keeping all the other inputs same, a run was conducted with a route cycle generated from calculated gradient values but no significant changes were observed in the output deviation.

Chapter 06

VECTO Engine Only Mode Simulation

Engine Only mode is an extension of Engineering Mode in which the simulation is focused solely on the engine's operation and energy consumption by isolating the engine from the vehicle and its auxiliary components. As the parameters required for generating a load cycle in Engine Only mode are available in the field data, Engine Only Mode simulations were conducted for load cycles generated from both VMS and Field data.

6.1 Comparison between Engineering and Engine Only Mode

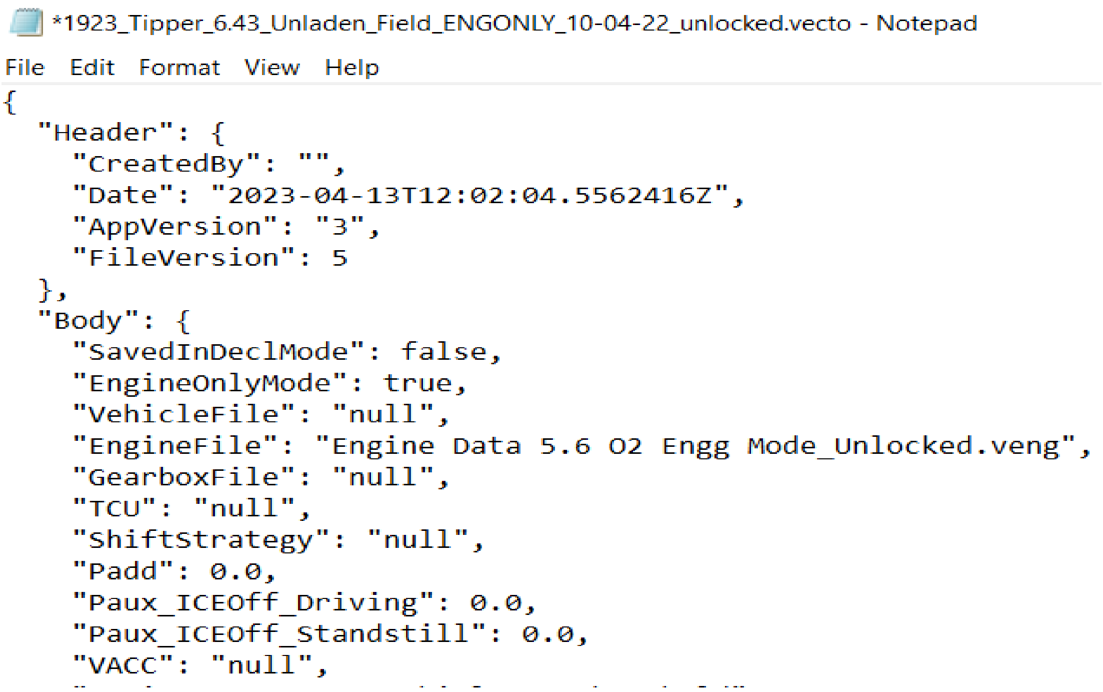
Engine Only Mode considers the same engine data as engineering mode such as FLC, Motoring curve, Fuel consumption maps, torque-speed curves, and other engine-specific data and simulating them over an input load cycle. The key differences between Engineering and Engine Only mode are as following.

- Engineering Mode considers the complete vehicle system, including the engine, gearbox, driveline configuration, tires, aerodynamics, and auxiliary components. Engine Only Mode Focuses solely on the engine's performance and does not consider other vehicle components simplifying the Simulation.
- Engineering Mode provides detailed modeling and simulation of various vehicle systems and their interactions provide more accurate simulation representation of the energy consumption and emissions of the entire vehicle system.Engine Only Mode isolates the engine and its associated systems hence the simulation is independent of the overall vehicle characteristics.
- Engineering Mode provides the flexibility to define every aspect in the component models of the vehicle and the driving cycle and can be used for experimenting and validation purposes. Engine only Mode is primarily utilized for research, development, and optimization purposes. It enables manufacturers and researchers to assess the engine's performance in isolation, explore different technologies, and optimize engine design parameters.
- Engineering Mode is more complex due to its comprehensive simulation of the complete vehicle system. It involves a broader range of calculations of the input parameters and modelling of various subsystems. Engine Only Mode is generally less complex compared to Engineering Mode since it focuses on the engine in the vehicle system.

Hence Engineering Mode provides more comprehensive assessment of the vehicle's energy consumption, where the Engine-only Mode offers a simplified approach focused, specifically on the engine.

6.2 Procedure to Simulate Engine Only Mode from Engineering Mode

The ***.vecto*** input job file made in engineering mode is to be modified to enable the Engine only mode for isolating the engine from all the other vehicle parameters.


*1923_Tipper_6.43_Unladen_Field_ENGONLY_10-04-22_unlocked.vecto - Notepad

File Edit Format View Help


```
{
  "Header": {
    "CreatedBy": "",
    "Date": "2023-04-13T12:02:04.5562416Z",
    "AppVersion": "3",
    "FileVersion": 5
  },
  "Body": {
    "SavedInDeclMode": false,
    "EngineOnlyMode": true,
    "VehicleFile": "null",
    "EngineFile": "Engine Data 5.6 02 Engg Mode_Unlocked.veng",
    "GearboxFile": "null",
    "TCU": "null",
    "ShiftStrategy": "null",
    "Padd": 0.0,
    "Paux_ICEOff_Driving": 0.0,
    "Paux_ICEOff_Standstill": 0.0,
    "VACC": "null",
```


Fig 6.1: Changes made in the Engineering Mode Job file for Engine Only Mode

The ***.vecto*** text file is modified to enable the Engine Only mode as shown in **Fig 6.1**.The Engine File is kept unaltered while the Gearbox, Vehicle, Shift polygon, Max acceleration deceleration files are changed to Null. All the other parameters related to vehicle details, gearbox, shift polygon are not needed to be altered in the ***.vecto*** job file as they are already isolated from the simulation consideration.

Auxiliary Power consumption (Padd) can be Zero or a finite value as. These auxiliary systems may include air conditioning, power steering, hydraulic pumps, or other electrical loads that draw power from the engine.

The Modified Load Cycle is edited into the ***.vecto*** file replacing the earlier route cycle. The job file is now saved and can be browsed to the simulation window to run the Engine Only Mode.

6.3 Engine Only Mode Load Cycle

When Engine Only mode is enabled in the Job File then VECTO only calculates the fuel consumption based on a load cycle (engine speed and torque).This driving cycle directly defines the engine's power or torque at the output shaft over time. VECTO adds the engine's inertia to the given power demand and simulates the engine.

```
<t>,  <n>,    <Me>,     <Padd>
1,    1476.9, -265.1,   11.94
2,    1489,   -266.63,  11.94
3,    1490.1, -266.21,  11.94
4,    1481.1, -264.87,  11.94
5,    1447,   -204.844, 11.94
```

Fig 6.2: Example of an Engine Only Mode Load Cycle

These specific parameters represent the following in the generated load cycle in **Fig 6.2.**

<**t**> is the absolute time

<**n**> is Engine Speed (Rpm)

Either of <**Me**> (Net Engine Torque-NM) or <**Pe**>(Brake Power-KW) must be defined.

<**Padd**> is auxiliary power Consumption is optional.

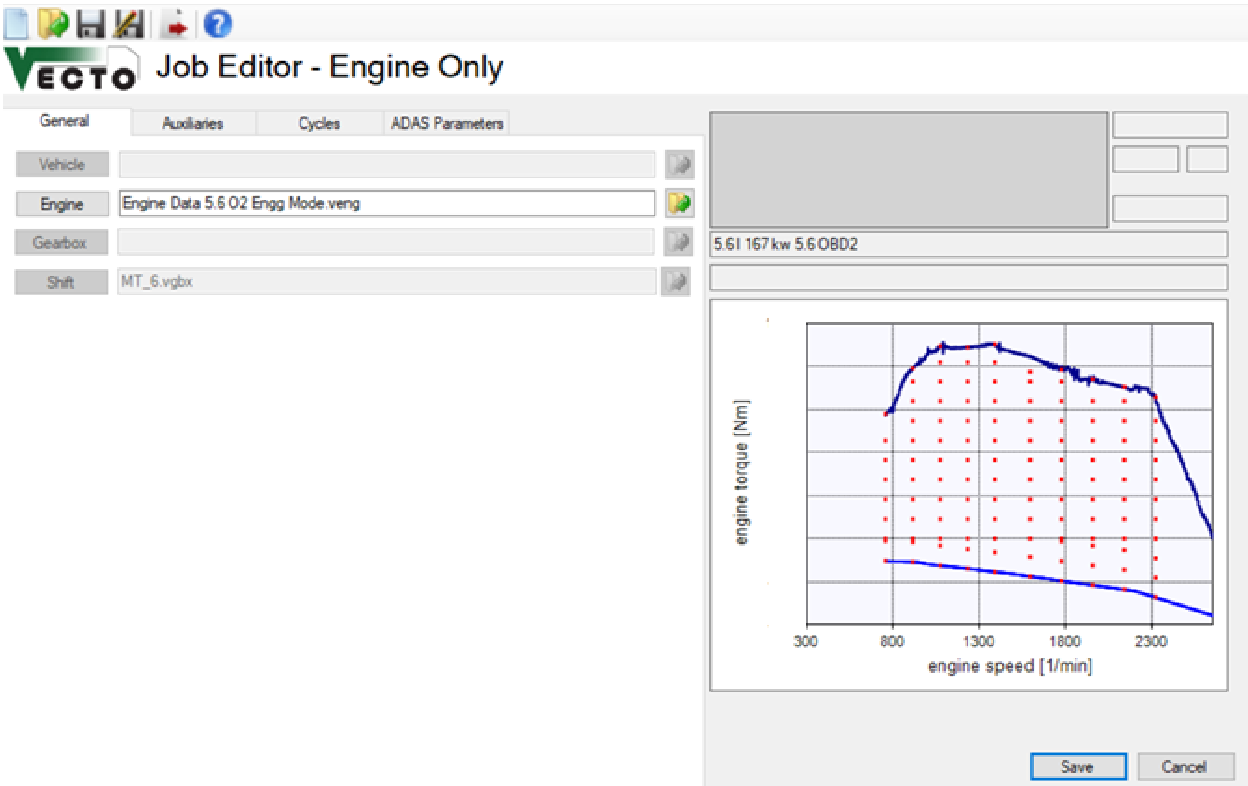


Fig 6.3: Engine is isolated from all the other Vehicle Inputs in the input Job Editor

It can be seen in **Fig 6.3** Vehicle, gearbox and Shift file inputs are blocked as in the job file the engine is isolated by blocking these inputs. Auxiliary power consumption inputs are optional, all the input parameters related to vehicle, gearbox and shift are redundant and no need to be modified in the ***.vecto*** job file as these inputs are already blocked in the input interface.

There were significantly low no of errors during the simulation run in Engine Only Mode compared to Engineering Mode for the same input VMS data used. The probable cause of this is simpler calculations to be performed by VECTO for lesser no of variables over the simulation run and unlike route cycle in the load cycle the gradient parameter is not there that eliminates the probable errors caused by the gradient calculation by VECTO.

6.4 VECTO Engine Only Mode Simulation Results

For Engine only mode simulation load cycles are generated from the input route data from both VMS and Field data. VECTO will isolate the engine from all the other vehicle inputs and will simulate the engine speed and torque over the given load cycle and output results will provide the FC values over the simulation. It should be noted that no changes are required to be done on the ***.veng*** engine file, locked and unlocked Engineering Mode ***.veng*** files are respectively used for the Engine Only mode simulation runs. The simulation results for both VMS and Filed data are as following,

6.4.1 Simulation results for VMS load cycle

Engine Only mode load cycle simulations were done based on load cycle generated from the VMS runs. Engineering mode ***.vecto*** job files were modified as per the Engine Only mode requirements respectively for different runs with locked and unlocked FC map. In the ***.vecto*** input job file the ***.vdri*** drive cycle file is replaced with the speed-torque load cycle generated from respective VMS runs. Engine Only Mode simulation results over these VMS load cycles with unlocked and locked FC Map are summarized below.

1923_950DD_6.43_JSR_50%OL_VMS vs VECTOEngine Only Mode_Locked FCMap

The 1923 tipper with 6.43 RAR with 50% overload over the load cycle generated from Jamshedpur-Ranchi VMS route data with the locked FC Map used to generate the Engine file in VECTO input. It can be clearly seen in **Fig 6.4** that very good simulation accuracy is obtained for the run. The Engine Speed torque profile implying VECTO Engine Only mode is successfully simulating the Speed Torque profile as per the input load cycle.

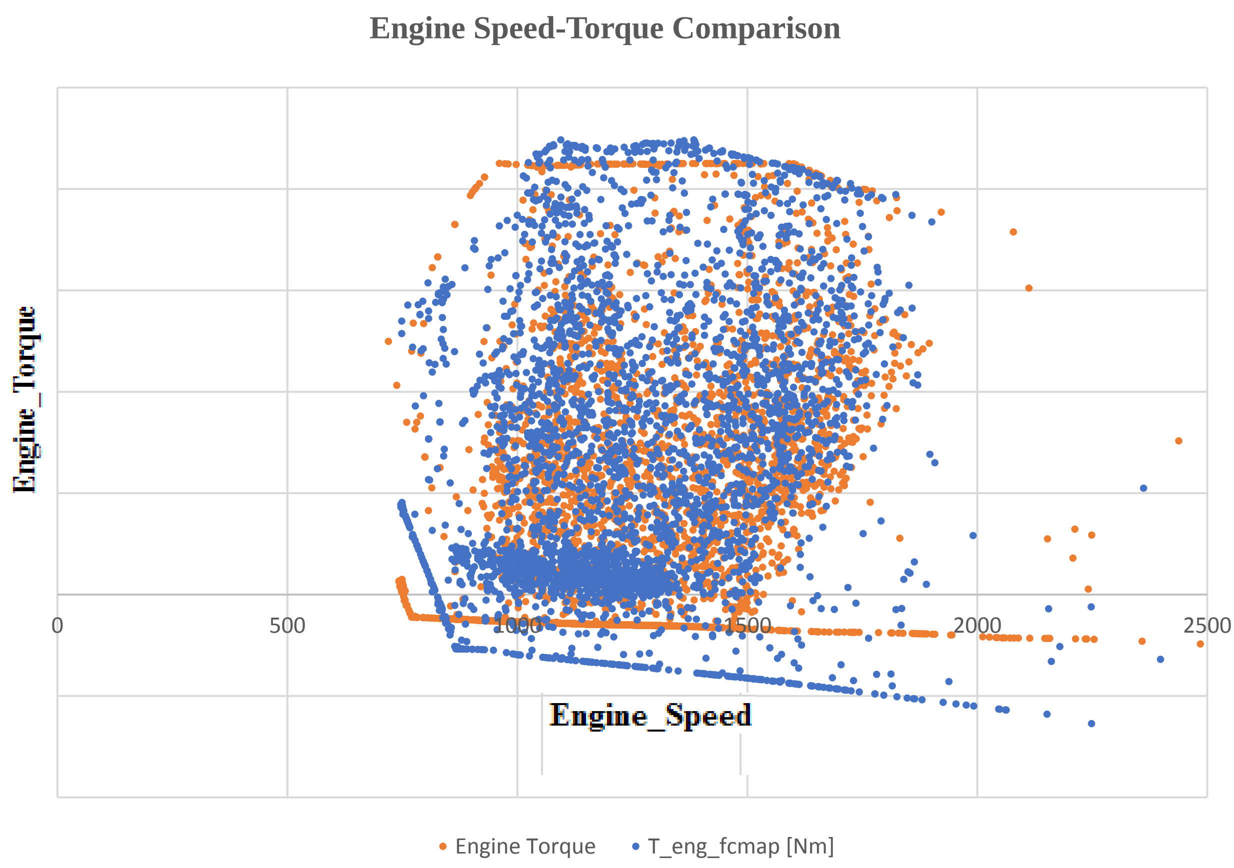


Fig 6.4: Speed-Torque Comparison of VMS & Engine Only Output, Locked FC Map Run 01

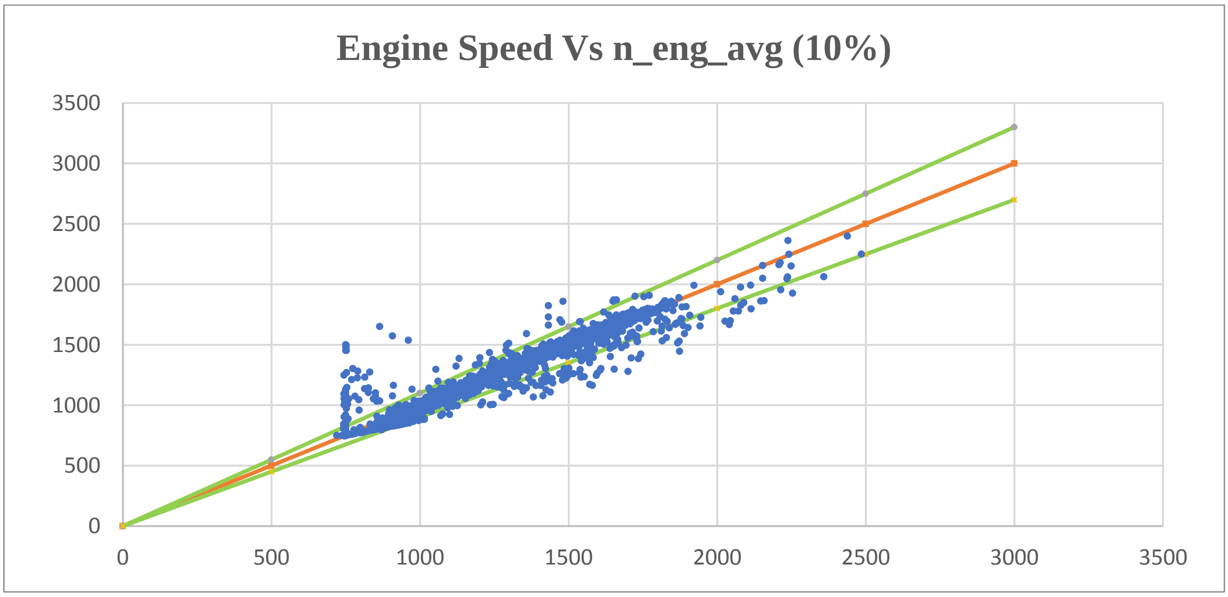


Fig 6.5: Engine Speed input plotted against VECTO Engine Speed output Run01

Engine Speed points in input and output were plotted against each other to compare the Engine Speed simulation accuracy. As can be seen in the **Fig 6.5** most of the points over the simulation run lie within 10% regression region.

1923_950DD_6.43_JSR_50%OL_VMS vs VectoEngine Only Mode_Unlocked FCMap

Keeping all other input parameters same changing only the FC Map in the engine input file another run was taken with an Unlocked FC Map over the same load cycle as of the last simulation.

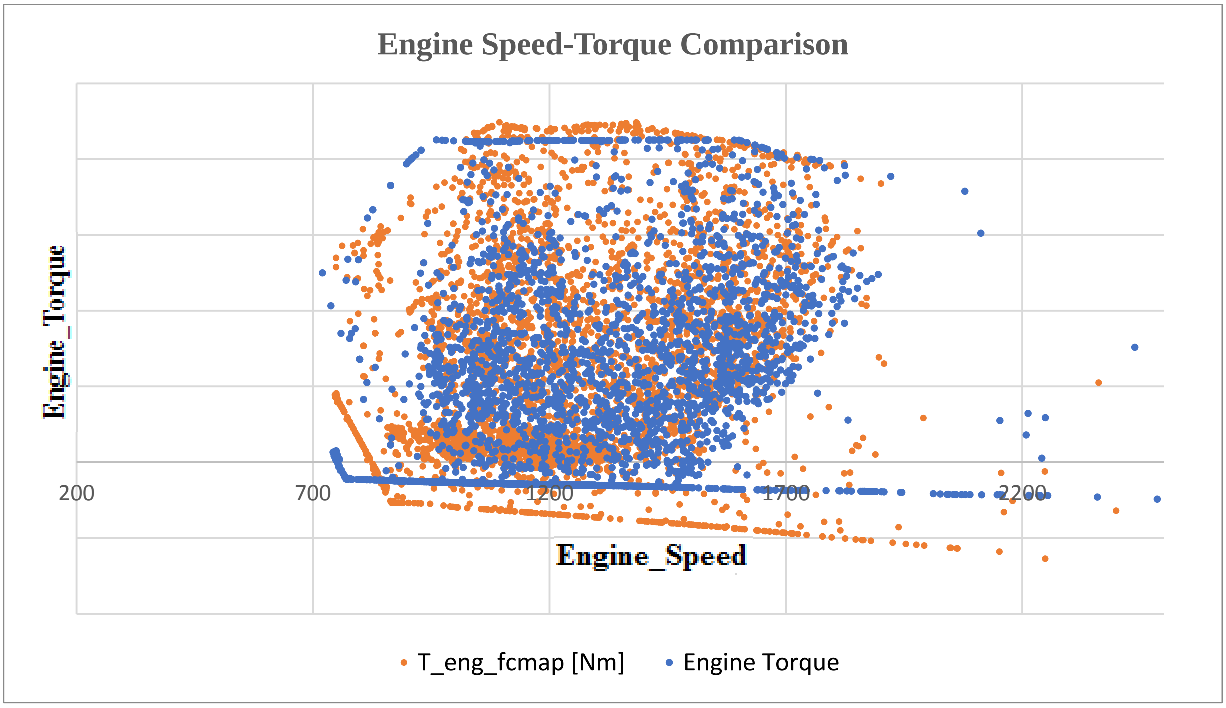


Fig 6.6: Speed-Torque Comparison of VMS and Engine Only Output, Unlocked FC Map Run02

For the same run taken with an unlocked FC Map the speed torque profile comparison shown in **Fig 6.6** implies that VECTO Engine Only Mode is well capable to simulate load cycle with good Speed-Torque accuracy irrespective of the calibration of the engine (FC Map).

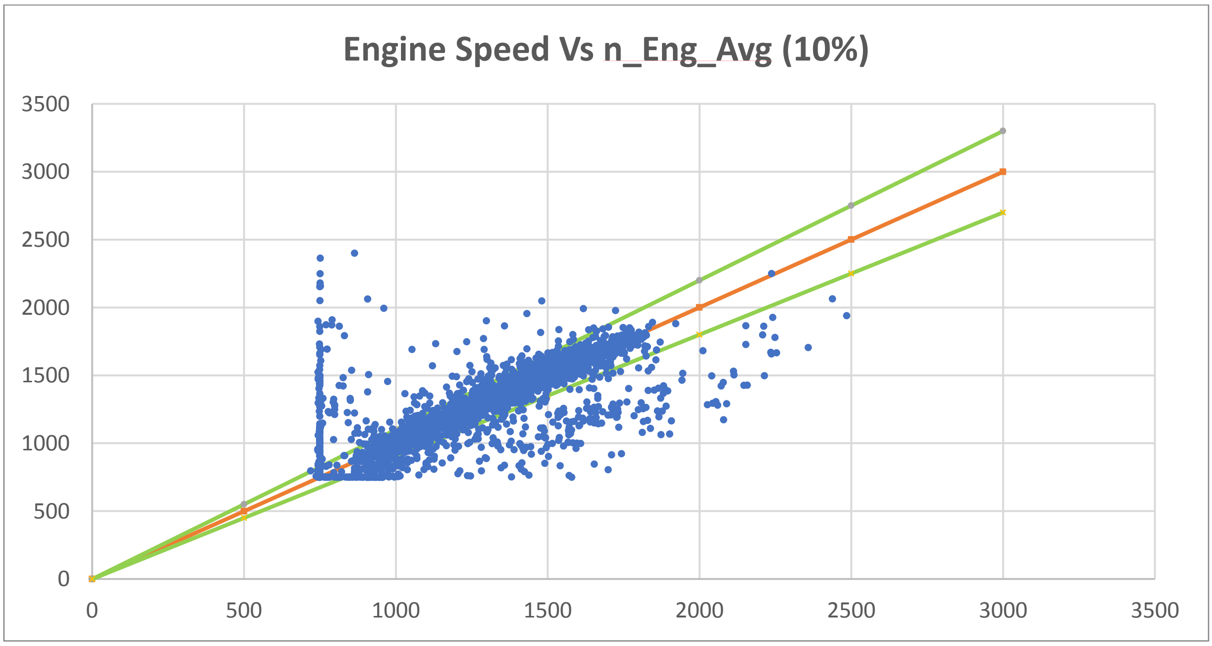


Fig 6.7: Engine Speed input plotted against VECTO Engine Speed output Run02

Fig 6.7 further confirms the input and output speed accuracy over the simulation run as the comparison of output and input engine speed at every point over the run comprises majority of the points within a 10% deviation range.

Several load cycles were generated from the same VMS data that ware earlier used to generate route cycles in Engineering Mode simulation. These load cycles are then simulated in Engine Only mode with the same Engine data and input parameter values used in Engineering Mode simulations with both locked and unlocked FC maps.

Once the simulation runs are successfully completed ***.vsum*** and ***.vmod*** files are generated in the output directory. Output results obtained simulating various VMS route data with both locked and unlocked FC Map in Engine Only mode simulation were analysed for speed torque simulation and similar trends were observed in the Speed-Torque points and Engine Speed Comparison.

Average Engine speed, percentage of fuelling in motoring conditions over the run and BSFC values were compared for the input and Output VECTO Simulation result.(BSFC Values can not be disclosed due to confidentiality policy of the company hence the percentage deviation of BSFC between input and VECTO output are mentioned.)

The simulation output results are tabulated below,

1923 Tipper with 950DD Gearbox and 6.43RAR with 50% OL over the Jamshedpur-Ranchi route VMS run was simulated in vecto Engine only Mode with locked and unlocked FC Maps and the BSFC deviations were compared.

For the VMS run input average engine speed was **1180.55** rpm with **0.73114%** of fuelling in motoring conditions over the run.

Table 7: Engine Only mode Simulation results_VMS Load Cycle 01

Engine Only Mode Simulation Run-01	Average Engine Speed (RPM)	Percentage of Motoring Fuelling over the cycle	BSFC Deviation (%)
locked FC Map	1180.648	0.25366	**4.57**
Unlocked FC Map	1180.648	0.3456	**11.76**

For both the runs in **Table 7** as the FLC is same hence the FC Map grid are same resulting in same engine speeds in the simulation, yet different FC values in the FC Maps is the reason behind different BSFC output and fuelling percentage in motoring conditions.

Another run was conducted for a 1923 Tipper with 950DD gearbox and 4.88 RAR over the Jamshedpur route for 30% of the vehicle loading VMS run was simulated in vecto Engine only Mode for locked and Unlocked FC Map and the BSFC deviations were compared.

For the VMS run input average engine speed was **1184.35** rpm with **0.458%** of fuelling in motoring conditions over the run.

Table 8: Engine Only mode Simulation results_VMS Load Cycle 02

Engine Only Mode Simulation Run-02	Average Engine Speed (RPM)	Percentage of Motoring Fuelling over the cycle	BSFC Deviation (%)
locked FC Map	1184.393	0.16528	**2.49**
Unlocked FC Map	1184.393	0.29264	**7.80**

In **Table 8** for the runs, same average Engine speed with different BSFC and fuelling percentage in motoring indicates same FC Map grids with different calibrations.

The results obtained indicates that VECTO Engine Only mode is simulating as per the input provided and it is very well capable to simulate VMS load cycles with high BSFC accuracies irrespective of the calibration of the engine. Unlike Engineering Mode in Engine Only mode CO_2 emissions are not obtained in the simulation output ***.vsum*** and ***.vmod*** files.

6.4.2 CO_2 Emission Calculation from BSFC Simulation results

The CO_2 emission over the cycle can be calculated from BSFC output values using the conversion formulas.

*CO_2 emission (g/kWh) = BSFC (g/kWh) * Carbon content of diesel fuel / Molecular weight of CO_2.*

The carbon content of diesel fuel is typically around 86.5% by weight

The molecular weight of CO2 is approximately 44.01 grams per mole.

Using these values CO_2 emission can be calculated in grams per kilowatt-hour (g/kWh) for a given BSFC value. The conversion factor may vary slightly depending on the actual carbon content of the specific diesel fuel used. [2]

However, the formula provided above can provide a good estimate of CO_2 emissions for diesel engines. One thing should be noted that these are approximate conversion factors, and actual emissions can vary depending on factors such as the composition of the fuel and the efficiency of the engine.

As the CO_2 emission is directly calculated from the BSFC values, CO_2 percentage deviations will be the same as BSFC % deviation, hence not stated separately in the result tables.

6.4.3 Engine Only Mode Simulation results with Field load cycle

Field data simulation was not possible in Engineering Mode due to the unavailability of the required parameters in field data to create a route cycle to simulate in Engineering Mode.

In Engine Only Mode only the Engine Speed and Torque is required to create the load cycle, hence it's possible to create a load cycle from the field data and simulate it in Engine Only Mode.

- Several field data (1Hz) were collected from field test run performed on 1923Tipper with 950DD Gearbox over different months and the respective load cycles were generated from these field test data.
- The same engine input files and input parameters were used for the simulation runs respectively with the locked and unlocked FC maps.
- The respective ***.vecto*** input job files generated in Engineering Mode are modified for the Engine Only Mode and the route cycles were replaced with load cycles generated from these field data.
- No changes are required to be done on the ***.veng*** engine file, locked and unlocked Engineering Mode ***.veng*** files are respectively used for the Engine Only mode simulation runs over the respective field load cycles.
- The modified ***.vecto*** file was saved, browsed to the input interface and simulation runs were initiated.
- Any error coming up during the simulation run is needed to be resolved by modification or elimination of the error causing points over the load cycle.
- 8 runs were conducted over 4 load cycles with both locked and unlocked FC Map, the field data were chosen consisting of speed torque profiles in low speed torque as well as high speed torque region to compare the simulation accuracies of VECTO Engine Only mode on different loading conditions. Graphical representations of few of the simulation outputs are described in the upcoming figures.

Field Test Data_01vs VECTO Engine Only Mode Run Locked FC Map

This run was taken with a field data consisting major no of points in low speed-torque region. The Speed Torque points were compared for VECTO and Field data.

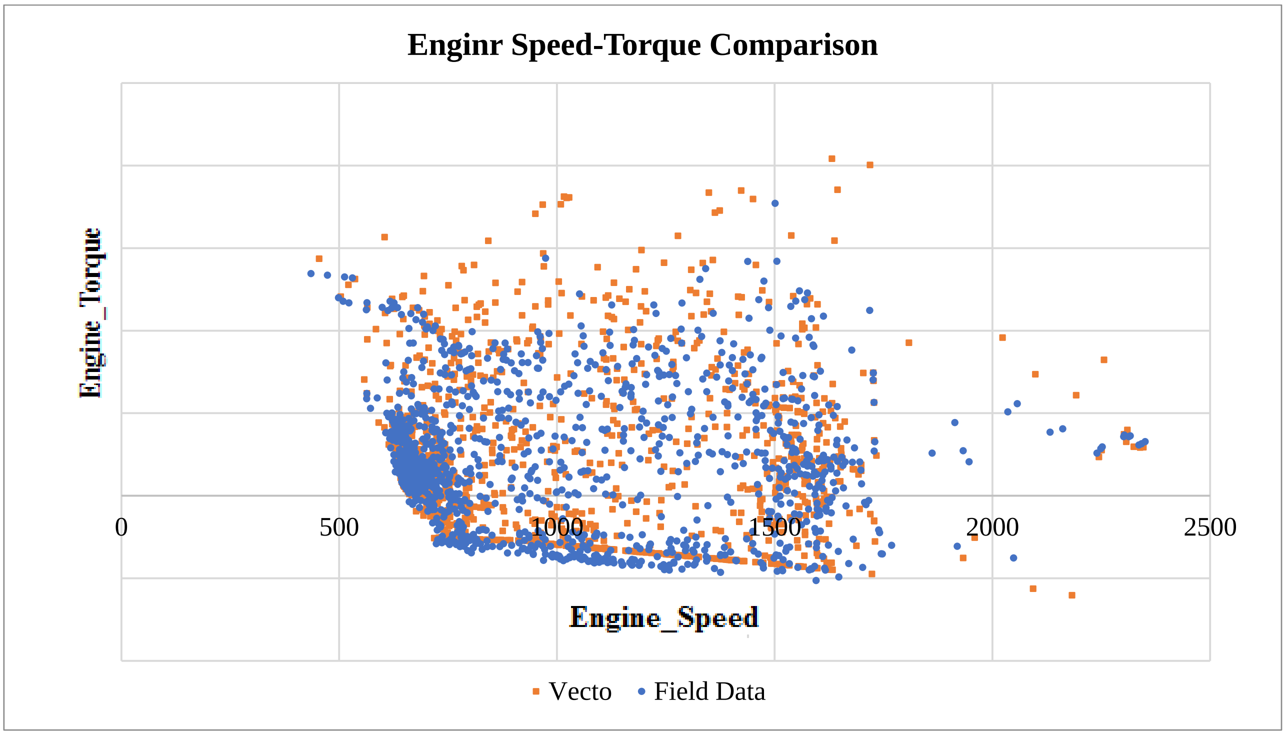


Fig 6.8: Speed Torque Comparison of Engine Only Mode Simulation for Field Data 01

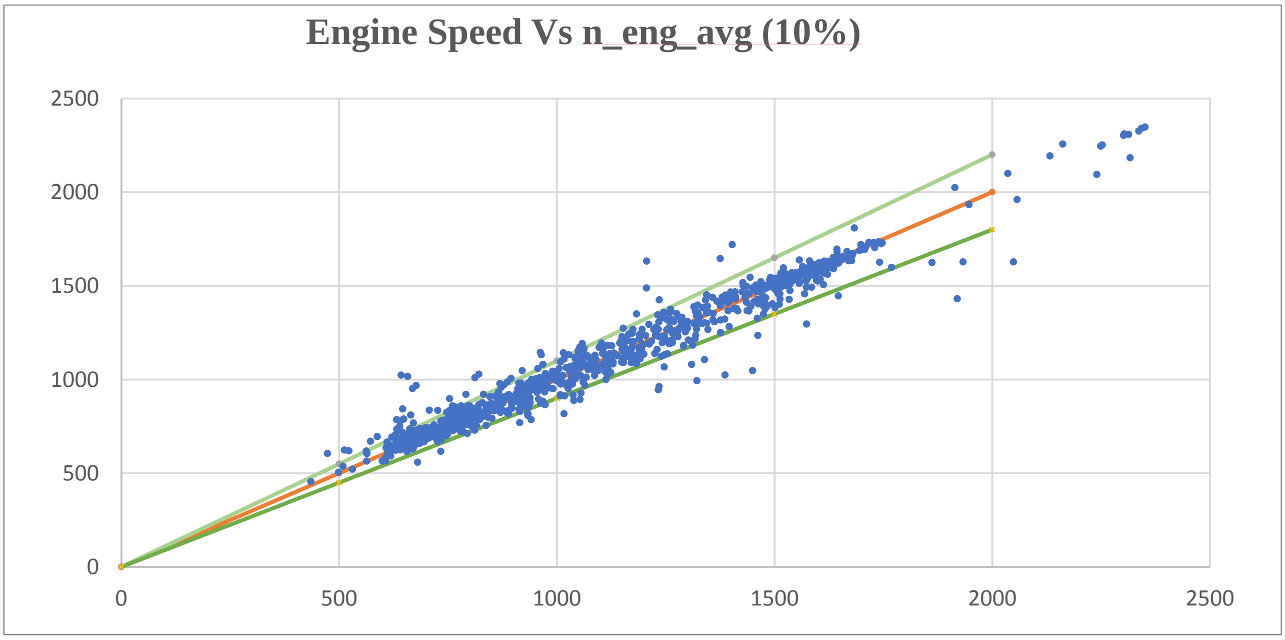


Fig 6.9: Engine Speed Comparison of Engine Only Mode Simulation for Field Data 01

The Speed torque points comparison for input and VECTO output for locked FC Map is observed in **Fig 6.8**. The results indicate good simulation accuracy. **Fig 6.9** concludes that VECTO can simulate engine speed within 10% range for almost all of the points throughout the simulation run.

Field Test Data_04 Vs VECTO Run Unlocked FC Map

This field data contains majority of points in high engine speed and torque. The input and output speed-torque points were plotted in **Fig 6.10.**

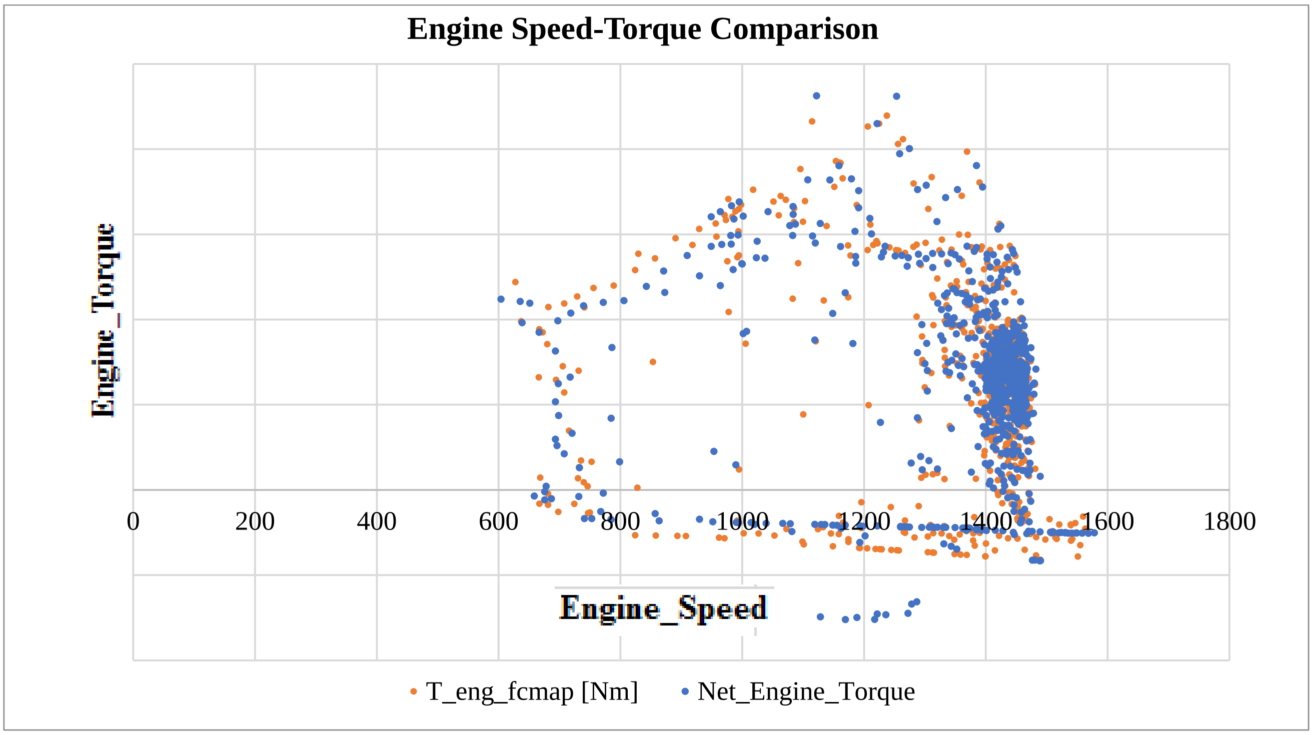


Fig 6.10: Speed Torque Comparison of Engine Only Mode Simulation for Field Data 04

Speed-Torque plot of **Fig 6.10** indicates good simulation accuracy for high speed-load cycles with an unlocked FC map. **Fig 6.11** implies VECTO can simulate engine speed within 10% range throughout the simulation run.

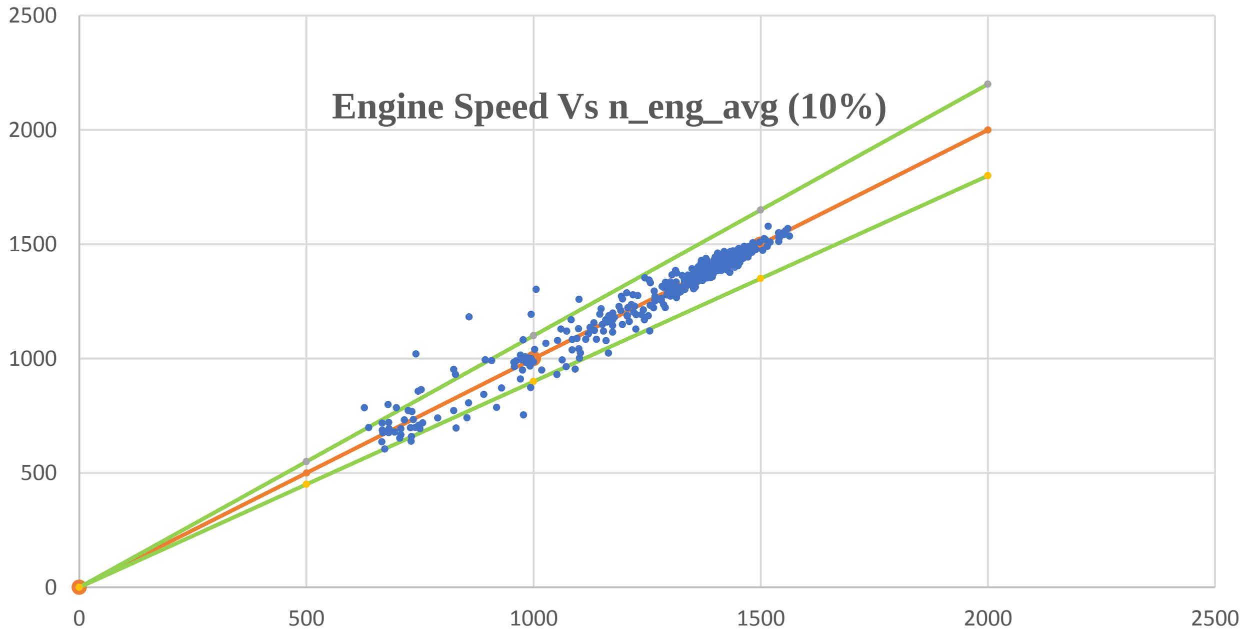


Fig 6.11: Engine Speed Comparison of Engine Only Mode Simulation for Field Data 04

This concludes VECTO Engine Only mode is capable to simulate a load cycle with great accuracy irrespective of the calibration of the engine and speed-load distribution of the load cycle. As in Engine Only mode all the vehicle parameters other than the Engine is cut-off the vehicle parameters will not make any impact in the results.

Total 8 runs were conducted with load cycles generated from field test data of 1923 tipper and 950DD gearbox the results are tabulated below as following. Field Test run 01 had average Engine speed of **932.659** rpm and motoring fuelling percentage **3.88%** over the run. Two simulations were conducted for this load cycle, one with locked and another with unlocked FC map, and results are compared with the field data as tabulated in the Table9. BSFC deviations calculated in percentage. (Exact BSFC results cannot be disclosed as it is confidential to Cummins)

Table 9: Engine Only mode Simulation results Field Test Load Cycle01

Simulation Run	Average Engine Speed (RPM)	Percentage of Motoring Fuelling	BSFC Deviation (%)
Field Test Data_01_Engine Only Mode Locked FC Map	932.56	1.21%	-3.50
Field Test Data_01_Engine Only Mode Unlocked FC Map	932.56	1.09%	7.77

Field Test run 02 had average Engine speed of **1138.915** rpm and motoring fuelling percentage **2.84**% over the run. Two simulations were conducted for this load cycle, one with locked and another with unlocked FC map and simulation output results were compared with the respective field data as tabulated in the **Table 10** below.

Table 10: Engine Only mode Simulation results _Field Test Load Cycle02

Simulation Run	Average Engine Speed (RPM)	Percentage of Motoring Fuelling	BSFC Deviation (%)
Field Test Data_02_Engine Only Mode Locked FC Map	1139.22	0.75%	-6.20
Field Test Data_02Engine Only Mode Unlocked FC Map	1139.22	0.81%	0.34

Negative deviation signifies that the BSFC output is lower than the actual field BSFC values. The closer the calibration of the Engine FC Map is to the field data the lower the BSFC deviations are.

Field Test run 03 had average Engine speed of **1108.349** rpm and motoring fuelling percentage **1.67**% over the run. Two simulations were conducted for this load cycle, one with locked and another with unlocked FC map. Following **Table 11** tabulates the comparison of field data and simulation output results.

Table 11: Engine Only mode Simulation results_Field Load Cycle 03

Simulation Run	Average Engine Speed (RPM)	Percentage of Motoring Fuelling	BSFC Deviation (%)
Field Test Data_03_Engine Only Locked FC Map	1107.47	0.70%	5.92
Field Test Data_03_Engine Only Unlocked FC Map	1107.47	1.06%	9.91

Field Test run 04 had average Engine speed of **1352.981 rpm** and motoring fuelling percentage of **0.38%** over the run. Two simulations were conducted for this load cycle, one with locked and another with unlocked FC map and BSFC results were compared as tabulated in the following **Table 12**.

Table 12: Engine Only mode Simulation results_Field Load Cycle04

Simulation Run	Average Engine Speed (RPM)	Percentage of Motoring Fuelling	BSFC Deviation (%)
Field Test Data_04_Engine Only Mode Locked FC Map	1352.95	0.30%	5.19
Field Test Data_04_Engine Only Mode Unlocked FC Map	1352.95	0.26%	8.10

The average engine speed for the runs with locked and unlocked FC Map is same as the FC Map grid is the same (As the FLC input is same) yet different BSFC and Motoring fuelling is because of different FC values in the FC Map grid points. This further concludes VECTO Engine Only Mode is running the simulation according to the respective inputs.CO_2 Emission deviation values will be the same as BSFC deviation results hence not given separately in the table.

6.5 Conclusion

The output Engine speed-torque profile and BSFC simulation results obtained from all the simulation runs conducted in Engine Only Mode over the speed-torque load cycles generated from VMS runs as well as field data have led to the following conclusions,

- Over all the runs the Speed-Torque profile comparison of the input and simulation output concludes that VECTO Engine Only Mode is simulating the speed torque points of the load cycle very accurately irrespective of a loading condition over the cycle with a BSFC deviation of less than 10%.

- Getting a good BSFC accuracy on simulating same load cycle over locked and unlocked FC Map implies that Engine Only mode simulation is capable to simulate with FC Map generated from PTPs with different calibrations of the engine and results are responding as per the inputs. Lesser BSFC deviation implies similar calibration of the Engine in input VMS or Field data and FC Map used for the simulation.
- Same load cycle simulated with locked and Unlocked FC Map gives the same average engine speed output because the FC Map grid points are the same (As the same FLC is used to generate the FC Grid) yet different BSFC and Motoring fuelling Values as the FC values at the FC Map grid points are different (Interpolated from a locked and Unlocked PTP respectively).This further confirms VECTO Engine Only Mode is running compatibly with the given inputs.
- Unlike route cycle in Engineering Mode, in Engine Only Mode load cycles the gradient parameter is not included that eliminates the probable errors caused by the discrepancy in gradient calculations by VECTO as discussed earlier, hence enhancing the simulation accuracy as well.
- Engine only mode provides the flexibility to create any load cycle from VMS plug-in as well as the field data and can Simulate the Engine for any load cycle as per our experimentation needs with a good FC accuracy. The simulation accuracy makes it eligible to be reliably used for various analysis, research and experimentation purposes.
- Engine Only mode primarily focuses on modelling and analysing the engine performance of heavy-duty vehicles by isolating the engine's performance, this mode could allow users to study and evaluate the efficiency, fuel consumption, and emissions specifically related to the engine operation.CO_2 emissions are not simulated in Engine Only Mode hence needed to be calculated from BSFC Values.
- Engines do not operate in isolation, and their performance is influenced by various factors such as vehicle speed, road gradients, and aerodynamics. Conducting simulations solely on the engine can be quicker and require fewer computational resources compared to full-vehicle simulations yet by excluding other vehicle components and external factors, the simulation may overlook important interactions and dependencies that can impact overall energy consumption and emissions. This might lead to incomplete or inaccurate assessments hence inapplicable for a vehicle level simulation.

Chapter 07

Conclusion and Future Scopes

7.1 VECTO Simulation Conclusion

Various VECTO Simulation runs conducted on over different input parameters, data and routes in VECTO Engine, Engineering Mode and Engine Only Mode have led to the following conclusions.

VECTO ENGINE CONCLUSION

- VECTO Engine can Simulate WHTC runs with overall BSFC deviation<10% for both locked and Unlocked FC Map with FC Values interpolated from a PTP Test Run data.
- Once a simulation run is taken with a test cell FCMC data, improvements in BSFC accuracy can be expected.

VECTO ENGINEERING MODE CONCLUSION

- Once the required input parameters for field data are available field data simulated in Engineering Mode, as of now in Engineering Mode simulation outputs of route cycle generated from VMS Plug-in are resulting very high BSFC deviations (22-37%)
- The input and simulation output speed-torque profiles are not matching as the gear distribution over the cycle are different.
- Further work is needed on how Engineering mode runs a route cycle, any other causes leading to the discrepancies are needed to be find out.
- A huge no of parameters is included in the Engineering mode simulation and those are needed to be fine-tuned for further improvements in output results.
- The gradient value from the VMS Plug-in does not match with gradient calculated from Vehicle Position and elevation data, a run was conducted with Calculated Gradient values but no significant changes occurred.

VECTO ENGINE ONLY MODE CONCLUSION

- It can simulate the Engine Speed regression with a very high accuracy, and the speed-torque profile comparison further implies VECTO Engine only Mode can simulate a duty cycle with high accuracy.
- VECTO Engine Only mode can simulate any load cycle generated from VMS as well as the field data as per the experimentation needs with a very good FC accuracy irrespective of the loading and engine calibration but the CO_2 emissions are not simulated hence needed to be calculated from BSFC Values.

7 .2 Future Scopes of VECTO in India

- While the tool is currently employed in the European Union to comply with the European CO_2 standards for trucks, its future scope in India can be envisioned in the following ways.
- **Emission Regulations for Heavy-Duty Vehicles**: India may consider implementing stringent emission regulations for heavy-duty vehicles, including trucks and buses, to address environmental concerns. If such regulations are introduced, a tool like VECTO could be adopted to estimate energy consumption and emissions of these vehicles, similar to the European CO_2 standards for trucks.
- **Transition to Electric Mobility**: As EVs become more prevalent in the heavy-duty segment, VECTO could be adapted to include models and calculations specific to electric and hybrid vehicles. This would help assess the energy consumption and emissions of electric heavy-duty vehicles and ensure compliance with environmental standards.
- **Sustainable Transport Solutions:** India is increasingly focusing on sustainable transport solutions, such as bio fuels and compressed natural gas (CNG). VECTO could be expanded to account for alternative fuels and their impact on energy consumption and emissions. This would assist in evaluating the environmental performance of heavy-duty vehicles running on different fuel types and facilitate the adoption of sustainable transport solutions.
- **Integration with Indian Vehicle Testing Infrastructure**: India is developing its vehicle testing infrastructure to ensure compliance with safety and emission standards. As this infrastructure evolves, VECTO could be used to validate and cross-verify the energy consumption and emissions data obtained through physical vehicle testing, providing more comprehensive and reliable results.
- **Collaboration with Indian Automotive Industry**: Collaboration between VECTO developers and Indian automotive manufacturers can help customize the tool to suit the specific needs and characteristics of the Indian heavy-duty vehicle market. This collaboration can facilitate the refinement and adaptation of VECTO's algorithms and models to accurately estimate energy consumption and emissions in Indian driving conditions.

It's important to note that the future scopes of VECTO may depend on regulatory decisions, industry advancements, and the overall global shift towards cleaner and more sustainable transportation.

VECTO tool will likely evolve to address emerging challenges and align with the changing landscape of heavy-duty vehicle technologies and environmental regulations.

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