

## Engine Testing In Dyno Close Loop Simulation Environment

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**Abstract**— Considering the advancement in technology and automation, there is wide scope for software simulation tools for testing. Hardware in Loop (HIL) is the most important and popular tool from Small control applications to complicated energy systems and machines. This paper focused on the HIL simulation platform to test Engine features. The main objective of using HIL is to simulate test scenarios to validate and verify customer-used cases. Engine development mainly includes designing, prototyping, testing, and manufacturing. Testing is an important element in the development process. Engine testing allows you to verify the product is designed correctly and validate that the right product has been designed for the right application. Testing on the assembled engine for performance validation and verification is always the ideal case, but it also incurs significant test overheads and challenges. Hardware in Loop (HIL) testing is a technique where a simulator replaces the real product and provides interface signals to the controller under test. This HIL assesses in terms of thousands of possible scenarios to validate your controller without the cost and time associated with actual physical tests. This paper presents the application of hardware in loop simulation testing for verification and validation field used cases in dyno close-loop environment.

**Keywords**— Hardware in the loop (HIL), engine, engine control module (ECM), validation, and verification, bench

### I. INTRODUCTION

The engine is a mechanical part that is used as a prime mover in many applications. The engine is ranging from Low Horsepower (LHP) (5Hp to 30Hp), Medium Horsepower (MHP)(45Hp to 170HP) to High Horsepower (HHP) (200Hp to 670Hp). According to Engine rating, it is used in suitable applications. Most common applications are in automobile industries in the passenger car, On-highway application like Trucks, Off-highway applications like a dump truck, Shipping boats, Road roller, Excavators, Backhoe loader, Railways, and Genset, etc. In earlier days engine was fully mechanical but with changing requirements of emission, achieving emission limits of NOx, HC, and PM with a mechanical engine is a bit difficult. At the same time, a green environment is an utmost priority for every manufacturer too. The government has revised the norms for carbon emission from time to time to achieve less pollution.

The major challenge that is faced by most engine manufacturers nowadays is to meet the stringent emission norms with the least modification in the engine design. So electronic engines were developed and available in the market in most applications which gives electronic control to meet the norms of it. In achieving the emission norms simplicity of the design must be maintained as far as possible by optimizing the available emission control techniques.

The development of the engine involved rigorous testing of engines to ensures the carbon emission within a limit as per government guidelines, engine performance, durability, etc.

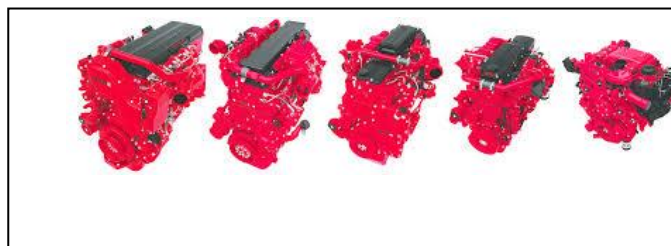


Fig 1: LHP to HHP Engines

The paper focuses on the validation and verification of the engine performance, features, using the Dyno close-loop simulation methodology. Section II explains the how dyno close-loop simulator methodology replaces the

actual test cell. Section III covers the test description and test cases. Conclusion and future work are mentioned in Section IV and Section V respectively.

II. METHODOLOGY

To test the electronic engine two methods are available based on the test scenario to be simulated.

A. Open loop Hardware in Loop

In open-loop HIL, the output does not affect the control logic. The output is neither measured nor feedback for comparison with input.

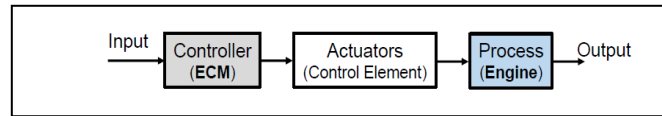


Fig 2: Open Loop HIL Block Diagram

Limitations:

- Sensors measures are user inputs and not from an engine dynamic response
- There is no feedback for controlling or reacting to actions.

B. Close loop Hardware in loop

In Close loop HIL, the output feedback is sent to input and the corrective action is taken to achieve desirable output. To run the system in a close loop various models, need to be integrated into the simulation environment. Knowing the limitation of open-loop HIL, Close loop HIL has a dynamic plant model that is used for validation of the dynamic performance of the system under various conditions. This HIL allows us to write and run system-specific test cases. This feature enables the user to create real-time scenarios and validate the dynamic response of the system.

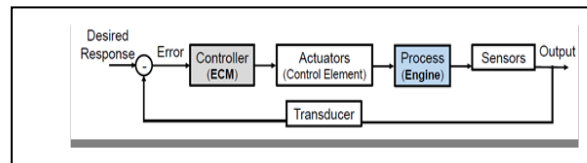


Fig 3: Close Loop HIL block diagram

To validate any system with a close loop simulation environment, below are steps involved as shown in fig 4

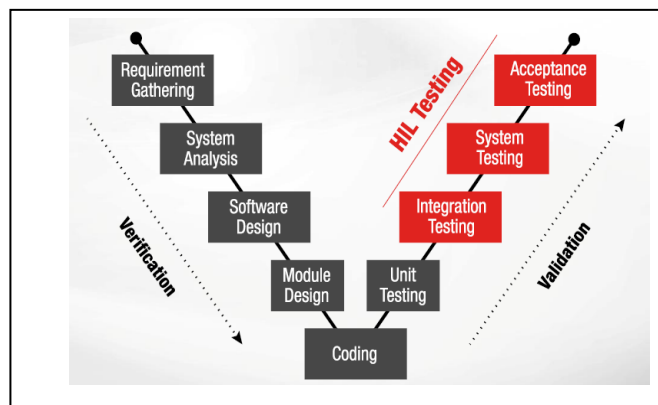


Fig 4: V Close Loop concept

Hardware-in-the-Loop (HIL) solution is a real-time system simulation connected to ECM with production controls software on Test Bench Platform connected to PC with simulation software.

Dyno close-loop simulation model replicates the actual test cell (details are mentioned in section III), we can say that the actual test cell system for testing an engine can be replaced with the dyno close-loop simulation model. There are prerequisites before starting actual model development as shown in fig 4. We will discuss a few of them.

**Requirement Gathering:**

This is the most vital step for any kind of model development. The objective of this step is to create thorough and consistent requirements efficiently. Any time anything interfaces with something else, there should be agreed-upon requirements defining this interface. The requirement specifies the exact need for the development of the Model. This requirement gathering will help software developers to design and code the overall system. All system models should satisfy all the applicable requirements that are considered Basic Functionality Requirements. A model that does not satisfy one of these requirements is not just a bad model, but rather, a broken model. While drafting a new requirement following guidelines to be considered

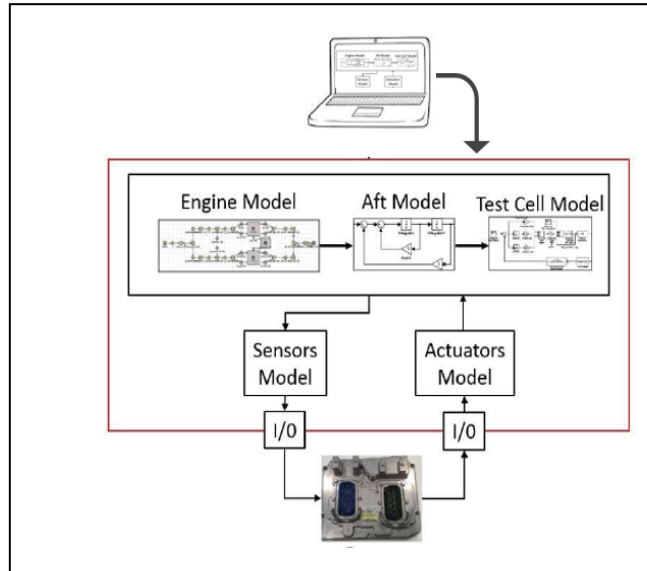


Fig 5: Controller-in-the-loop models interfacing with the ECM

- All requirement descriptions must be measurable and testable
- Requirements must be static in that they are not parameterized such that an ECM calibration change will change the requirement. For example, the following would be an invalid requirement:
  - The charge pressure as sensed by the ECM parameter charge pressure must match the simulated value of Engine charge pressure within 10 kPa for all values between the calibration values for OORL (Out of range low) and OORH (Out of range high)
  - This indicates that the requirement can change from one calibration to another indicating that one should re-validate the model for every calibration, which is impractical. The following is a proper requirement:
  - The charge pressure as sensed by the ECM parameter charge Pressure must match the Simulation value of Engine charge press within 10 kPa for all values between the calibration values for 50 kPa and 500 kPa

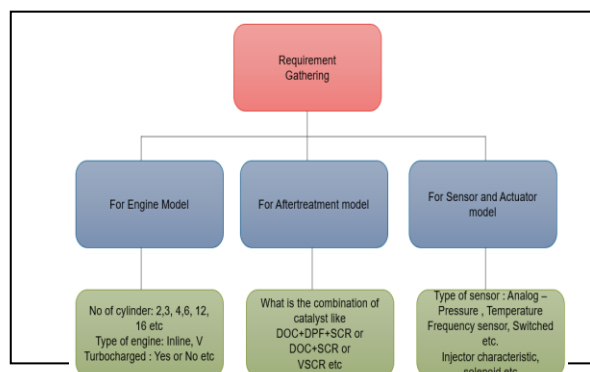


Fig 6: Requirement Gathering Diagram

**Model Design:**

Controller-in-loop system-level simulations consist of six different models integrated and configured by software to be executed in parallel on the real-time test benches. The models are listed here:

- a. Engine + Engine System
- b. Aftertreatment
- c. Test Cell/Vehicle
- d. Sensors
- e. Actuators

Each model is discussed here in brief.

## 1. Engine Model:

GT power engine model is used as engine model. It is a one-dimensional model; it converts all engine flow paths into series pipes thereby simplifying the flow problems. It models the turbocharger as a compressor as a turbine map from the turbocharger supplier. It models the in-cylinder combustion as a 1dimension DI pulse (direct injection) model for diesel engines. GT models have different levels of fidelity and run-time trade-off. DGM (Detailed GT model) offers higher accuracy and with slowest run time. RGM (Reduced GT model) offers the lowest accuracy and fastest run time. RGM is used in HIL benches due to the critical requirement of fast run time. Engine models predict engine performance quantities such as power, torque, fuel consumption, turbocharger performance and matching, airflow, efficiency, etc.

## 2. Aftertreatment Model:

An Aftertreatment system is a device that reduces harmful exhaust contains from the Engine. The after-treatment system can be used with various combinations of the following elements

- a. Diesel Oxidation Catalyst (DOC)
- b. Diesel particulate filter (DPF)
- c. Selective Catalytic Reduction (SCR)

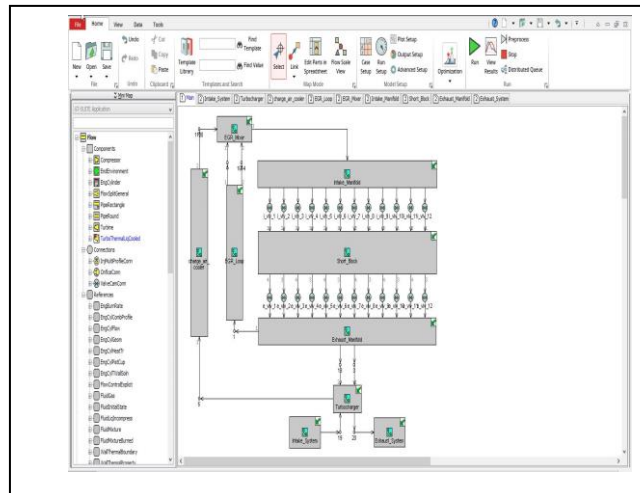


Fig 7: Indicative Engine mode

Engine model output is fed to the aftertreatment model. This model received information about the exhaust element contains like Nox, PM, HC, CO, CO<sub>2</sub> which is calculated with help of an estimator. According to emission norms, these elements from exhaust should be within the limit to control environmental pollution.

Accordingly based on input received from the engine model regeneration process start to maintain the emission limit.

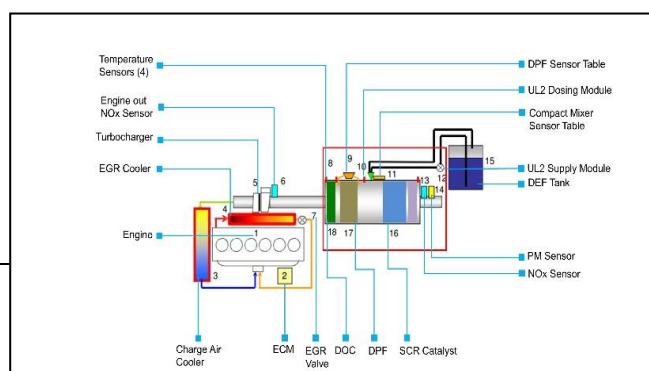


Fig 8: Representative Aftertreatment system arrangement

ATS models are of two types. AVL Boost offers higher accuracy and with slowest run time. Map-based ATS models offer the lowest accuracy and fastest run time. HIL benches used Map-based ATS models due to the requirement of fast run time. These models can predict temperatures and pressures of ATS, however not accurate in predicting chemical reactions.

3. Test cell model:

The test cell is the facility where the device or component or system under test can be validated for its performance, endurance, and quality. Test cell comprised of dyno which is connected to the engine by coupling shaft. Operation of dyno is controlled by an operator using dyno loaded software on the computer

For Engine testing usually eddy current dyno is used.  
The common operating modes used are;

1. **N Mode:** In this mode of operation dyno controls the Speed and the Throttle controls the load
2. **T Mode:** In this mode of operation dyno controls the load and Controller / ECM controls the speed

Test cell simulation model replicates above both operating modes in simulation.

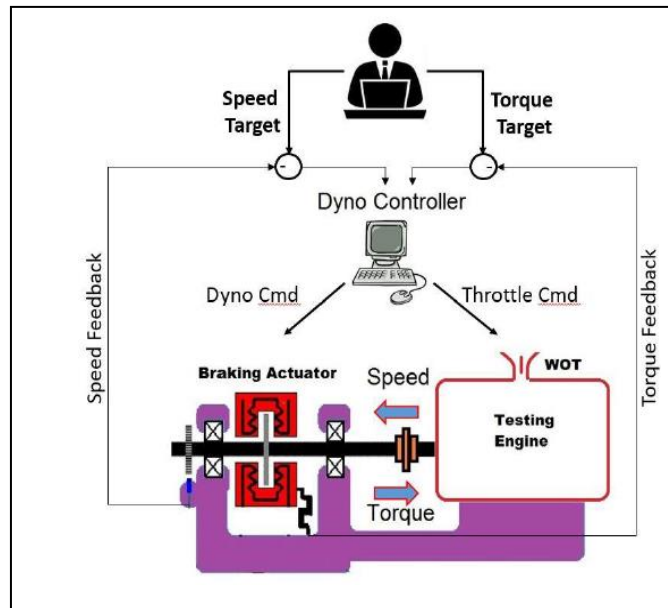


Fig 9: Test Cell loop model block diagram

4. Sensor model:

The sensors model acts as an interface between the various plant models and the ECM. The Sensor model serves as the model interface to the ECM. The sensor model where the engineering units such as Pa and Kelvins are converted to Ohms, Volts, Hz, duty cycle, or engineering units for DDS (Datalink Device simulator). These electronic signals are then passed to the bench hardware which is then sent to the ECM.

Various sensors are interfaced/ connected to the actual engine like

- a. Analog Sensor (Pressure, Temperature)

- b. Frequency Sensor (Speed and Position sensor)
- c. Switches etc.

Below is the representative diagram of analog pressure and temperature sensor

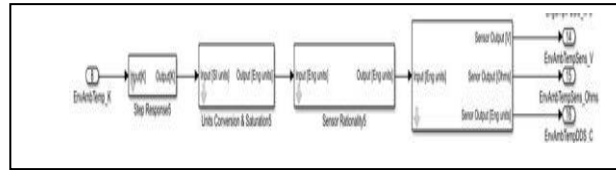


Fig 10: Components of Analog Sensor model

Depending on the sensor type, the voltage value is calculated for the resistance-based sensor as below:

**Resistance based sensor:**

When the sensor type is specified as ‘Resistance based sensor’, the voltage value is calculated using the formula shown below

Where,

$V_s$  is the supply voltage

$R_s$  is the shunt resistor used in the actual sensor.

$R_{th}$  is the resistance value and is the function of temperature.

The resistance value is then mapped to the Thermistor Simulator channel to simulate the resistance-based analog sensor.

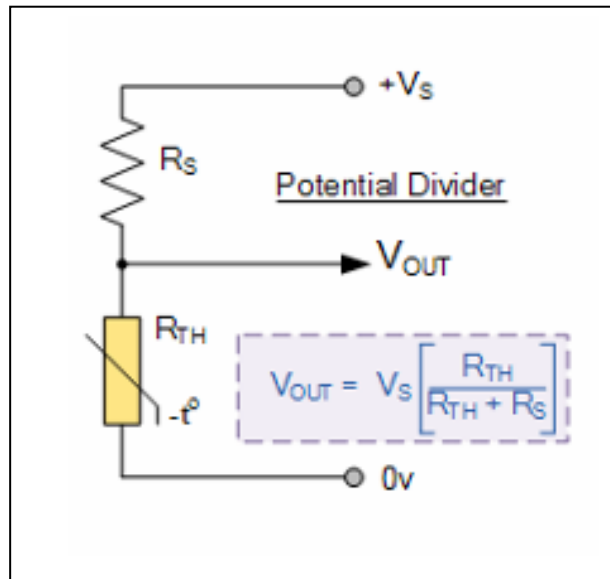


Fig 11: Resistive Sensor voltage calculation formula

**5. Actuator model:**

The actuator model acts as an interface where the fueling and other actuator commands received from the ECM are converted to the required units and passed on to the other component models like the engine model, aftertreatment model, etc.

Typically, the model of the actuator consists of four major components:

- a. Discrete Lamps (simulated using the digital actuator block from controller library)
- b. ECM Commands block
- c. Common Rail block
- d. Injector Waveforms Block

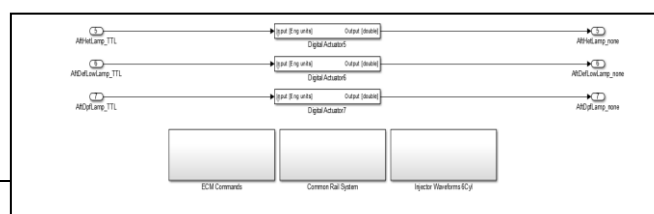


Fig 12: Components of Actuators model

The Actuator model serves as the model interface to the ECM. Outputs of the Engine/ ECM are linked with Actuator models. In this model characteristics of actuators like Injector as shown below, the solenoid is mapped and coded. It also contains information about the firing angle of the cylinders it depends upon the number of the cylinder-like, 4 cyl, 6 cyl, 12 cyl, or 16 cyl.

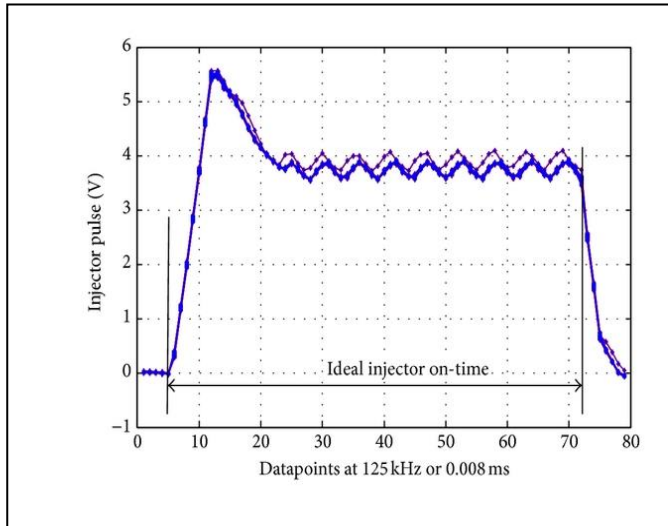


Fig 13: Diesel Injector typical waveform

Now in the next section, we will see test cases for testing the engine on a closed-loop controller HIL.

III. TEST CASES AND THE RESULT OF ENGINE TESTING WITH CLOSED LOOP CONTROLLER HIL

Engine development completed with testing and validation. To validate the design, certain tests are mandatory to conduct without fail, should get approved by the approval agency. Here in this section, we will discuss some of the test scenarios run on a simulation model.

The main objective of these tests conducted on the simulation model is to reduce the time and cost of engine testing time on actual test cells.

We will see some of the test cases run of close loop simulation

**5 mode emission cycle tests:** ISO 8178 defines the 5-mode emission cycle as describes in the below table.

Mode No.	Engine speed	% Load	Weighting Factor
1	Rated speed	100	0.05
2	Rated speed	75	0.25
3	Rated speed	50	0.30
4	Rated speed	25	0.30
5	Rated speed	10	0.10

Table 1: ISO 8178, 5 mode test condition requirements

5 mode emission cycle is the application for constant speed. Engine speed-rated means constant speed i.e 1500 rpm or 1800 rpm for Genset application. % load indicates % values of torque in N-m. The weighting factor indicates the value of time for that node. For example, consider the following values

Engine Speed: 1500 RPM

100 % load torque: 1400 NM

Cycle time: 30 mins

So above table will indicate the values as follows

Mode	Engine Speed	% load in Nm	Weighting Factor (Time/ node in min)
1	1500	1400*1=1400	2
2	1500	1400*0.75=1050	8
3	1500	700	9
4	1500	350	9
5	1500	140	3

Table 2: 5 mode test indicative conditions

Some of the input values are fed to the model such as torque target, ambient pressure, and temperature, dyno mode N mode or T mode, etc. According to the input received, the model runs and captures the data.

Below are plots for 5 mode speed torque, speed of the engine is controlled by ECM, and torque is controlled by dyno close-loop model. Here plot indicates the value of torque is increasing as per torque target and maintaining for the given time and according to torque demand, fueling is also increasing and maintaining the Engine speed constant.

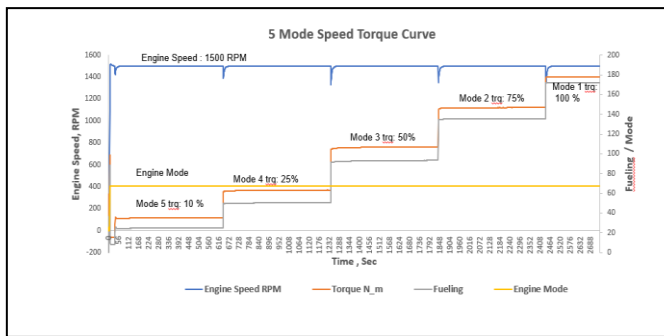


Fig 14: 5 mode Speed torque Curve

Along with the speed curve, there are performance parameters that also need to look and should be within the limits. We will look at one of the model data of charge pressure and temp which are compared with actual test cell data.

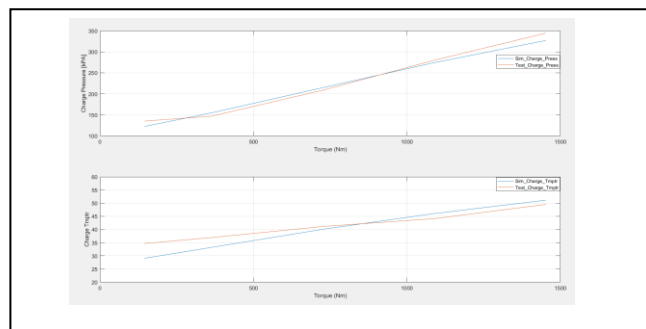


Fig 15: Charge pressure and temperature data comparison with the test cell

The above graph indicates the simulation model data is less than 10% error concerning test cell data. Refer to below data for % error with each mode

	Percentage Error				
Channels/Torque(Nm)	1401	1051	749	351	145
Charge Pressure	4.08	1.85	-1.98	-2.88	3.59
Charge Temperature	-2.23	-2.93	3.12	6.54	9.29

Table 3: % error table with test cell data



Error % is calculated using the formula

Percentage Error:

$$\left( \frac{TEST\ DATA - SIM\ DATA}{TEST\ DATA} \right) \times 100$$

#### IV. CONCLUSION

This paper walks us through how HIL simulation is integrated for Engine dyno close loop to create a virtual test cell. We also learned about the importance of each mode and its functionality. We discussed mainly controller hardware in the loop, which helps in verifying the Engine calibration tuning, features, sensor characteristics, steady-state performance at the early stages of the program without the physical engine. The number of iterations is possible with different test cases with negligible engine dyno component cost. HIL enhances product quality and reduces development time.

Time & cost cuts in:

- Test-Cell testing
- Robust Controls' feature testing
- Easy to link with other simulation tools
- Perform Off-Nominal Testing (Altitude)

#### V. FUTURE WORK/SCOPE

Now we have seen the engine and dyno close loop system, which is one part of the Genset system. The next work focuses on the integration of the alternator dynamic model so that we can simulate a complete Genset system. The validation of the Genset system performance in steady-state and mainly transient performance is also part of future scope. The proper hardware interface is needed to develop for the integration of the Genset system in close loop controller in the loop. and to finalize the communication topology for multiple (engine and Genset) controllers in the system, this work is going on for implementation of this system in Cummins India Limited. The future scope for this paper would be, to talk about the Genset close loop of the system and to create custom test cases to replicate real-time scenarios, which will reduce the number of iterations needed to tune PID in transient condition on physical Genset.

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