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Elaborato d'Esame di
CONTROL LAB

THROTTLE BODY MODEL IN A HARDWARE-IN-THE-LOOP SYSTEM

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Contents

Chapter 1

Overview: Propulsion HiL Environment

1.1 Introduction to Hardware-in-the-Loop

The complexity of modern automotive propulsion systems requires rigorous testing methodologies to ensure reliability, performance, and safety. Hardware-in-the-Loop (HiL) simulation has emerged as a standard industry practice, bridging the gap between purely numerical simulation and physical road testing. In this environment, the Electronic Control Unit (ECU) is connected to a real-time simulator that replicates the behavior of the vehicle's engine, sensors, and actuators.

This report documents the development of a simulated model for an electronic throttle body, designed to replace the physical component within a dSPACE-based HiL setup.

1.2 The dSPACE Environment

The simulation architecture utilized in this project is based on dSPACE technology, a market leader in real-time simulation for automotive applications. The workflow integrates several key software and hardware tools:

- **Configuration Desk:** Used for the hardware configuration of the real-time system, allowing the mapping of electrical signals to model ports.
- **Control Desk:** Provides the user interface for runtime visualization, instrument panels, and data acquisition.
- **INCA & CDA:** Tools utilized for ECU calibration and diagnostics.
- **Vector Tools:** Employed for CAN bus monitoring and communication analysis.

The hardware core is the **DS2680 I/O Unit**, a MultiCompact interface module specifically engineered for powertrain and vehicle dynamics applications. It serves as the central hub for signal exchange between the real-time simulator and the ECU, providing a high-density configuration of galvanically isolated channels capable of handling the complex dynamics of engine control. Its architecture features a versatile set of I/O interfaces:

- **Analog I/O:** Dedicated high-precision voltage input and output channels used for sensor simulation (ex: Pressure sensors, pedal position sensor) and actuator monitoring.
- **Digital I/O:** Standard digital lines configured for reading switch states or driving relays and also designed for Pulse Width Modulation (PWM) signals
- **Flexible Channels:** Highly configurable high-speed inputs and outputs measurement and generation, requested especially in case of current signals.
- **Resistance Simulation:** Specialized channels capable of simulating variable resistive loads, allowing the model to emulate temperature sensors (NTC/PTC) or specific circuit impedances.
- **Angular Signal Generation:** Dedicated hardware for generating complex, angle-synchronous crankshaft and camshaft signals required for ECU synchronization and engine speed simulation.

Moreover DS2680 integrates a **Failure Insertion Unit (FIU)**. This functionality allows to perform electrical faults such as short circuits to ground, short circuits to battery, or open circuits directly on the signal lines. This capability is paramount for validating the ECU's diagnostic logic (DTC detection) without the need for manual physical intervention on the wiring harness.

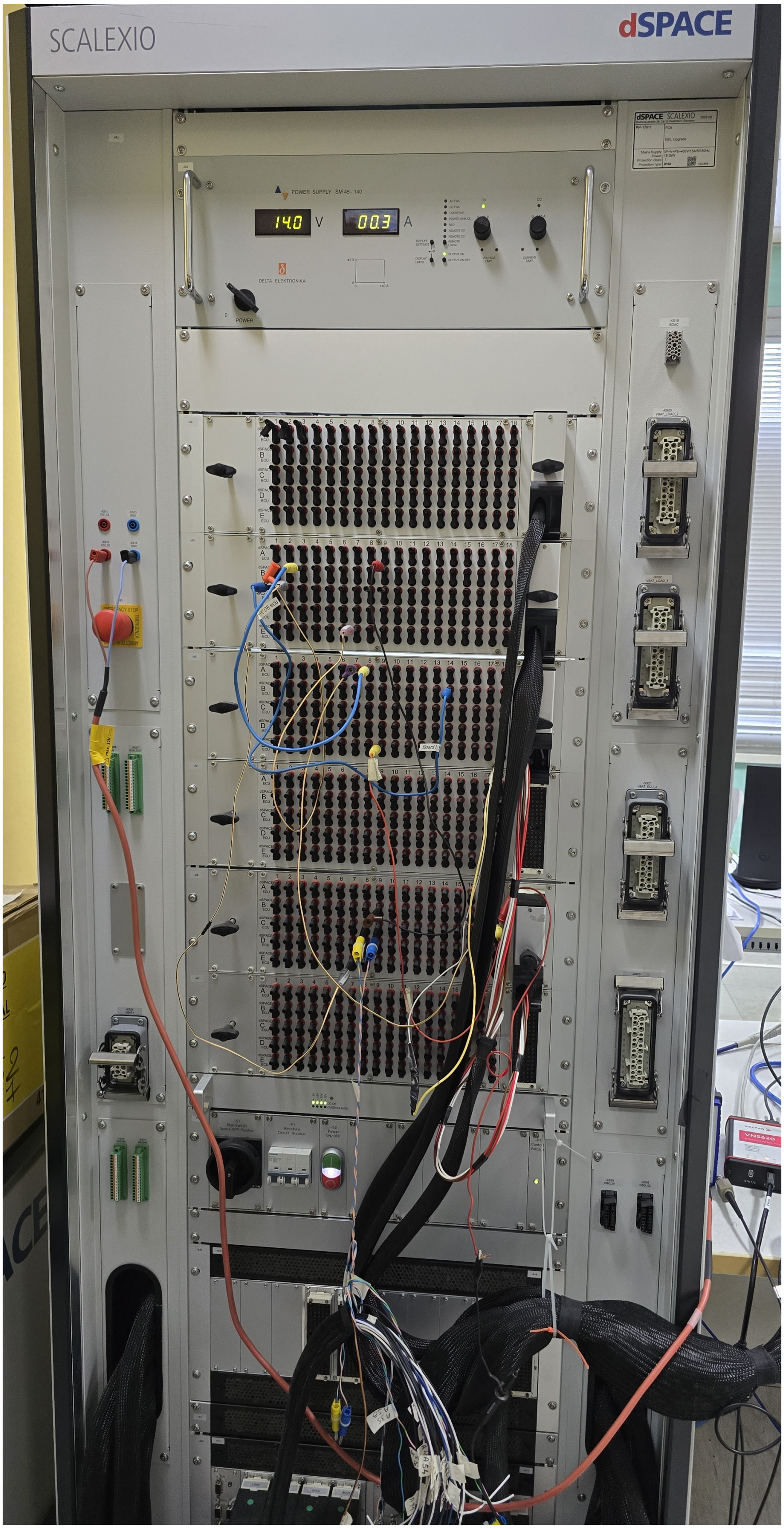


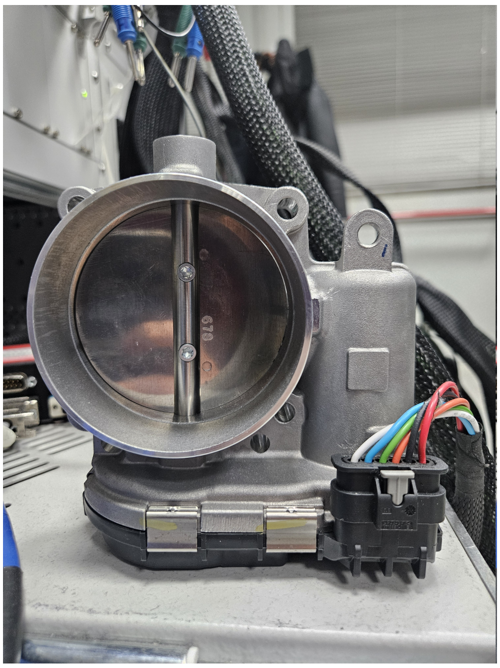
Figure 1.1: Scalexio Rack and DS2680 I/O Unit

Chapter 2

The Throttle Body: analysis

2.1 Component Description

The Electronic Throttle Control (ETC) mechanism is a critical component in spark-ignition engines, responsible for regulating the airflow into the intake manifold. It consists of a butterfly valve driven by a DC motor and equipped with dual position sensors for redundancy and safety. The software inside the Engine Control Module (ECM) has a controller (hidden by the product owner) that commands the throttle motor through two PWM signals (Motor+ and Motor-) and receives from the real component a position feedback through two voltage signals called Throttle Position Sensors (TPS1 & TPS2).
The accurate behavior of this component is crucial for engine torque management, idle speed control, and emissions reduction.



(a) Real Throttle Body Component

(b) Throttle Pinout from Datasheet

Figure 2.1: Throttle Body Component and Electrical Pinout

2.2 Simulation: motivation and challenges

The decision to develop a simulated model for the throttle body stems from practical operational challenges encountered during HiL testing.

1. **Component Durability:** During intensive validation cycles, the physical throttle is subjected to continuous, high-frequency actuation commands from the ECM. This often leads to mechanical failure (breakage of gears or return springs), causing downtime and increased hardware costs.

2. **Test Repeatability:** A mathematical model provides perfectly repeatable behavior, eliminating variations caused by temperature, aging, or mechanical wear.

3. **Test Flexibility:** A model allows for greater flexibility in testing than a real physical component, allowing any malfunction to be simulated. For example, an ice blockage failure can be achievable by simply limiting the end-of-course parameters in the model, something that cannot be replicated with real hardware.

Simulating the throttle is non-trivial due to its complex dynamics and the stringent diagnostic strategies employed by the Engine Control Module (ECM).

- **Non-linear Dynamics:** The system exhibits friction (stick-slip), non-linear return spring forces, and aerodynamic loads.

- **ECM Diagnostics:** The ECM continuously monitors the throttle's response. Any deviation between the commanded position and the actual position (e.g., during the delicate "Learning Phase") triggers Diagnostic Trouble Codes (DTCs), causing the ECU to enter a safety recovery mode (limp-home), effectively halting the test.

- **Parameters Definition:** A model is based on parameters as end-of-course, spring factor, gain and time constant that could change in case of different real throttle designed for other vehicles. So it is not "plug-and-play" as the hardware but needs a parameter calibration at every new implementation.

Chapter 3

System Configuration and Interface

3.1 Hardware Connections

The integration of the simulated model requires a precise electrical interface between the ECU and the dSPACE simulator. The physical throttle connects to the ECU via 6 wires: Motor+, Motor-, 5V Sensor Feed, Signal Reference, Position Sensor Signal 1 and Position Sensor Signal 2.

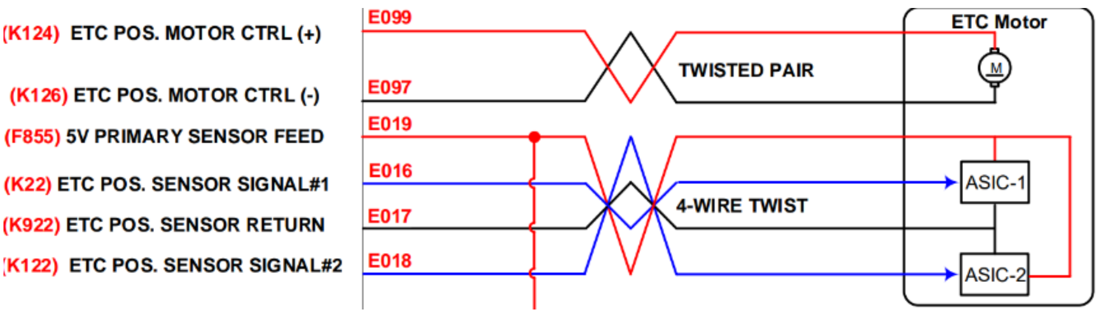


Figure 3.1: Throttle Body Electrical Schematic

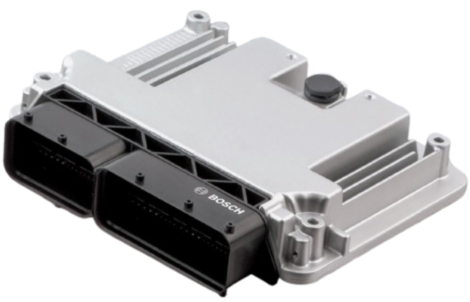


Figure 3.2: The Bosch Engine Control Module used in the HiL setup.

3.2 Configuration Desk Interface

Using *Configuration Desk*, the physical pins of the DS2680 Unit were mapped to the model ports. Communication between the simulator's electrical signals and Configuration Desk is possible by associating the Scalexio hardware with the project created in Configuration Desk, which in turn is connected to the simulink model through model ports provided by the dSPACE library.
This step is crucial to convert the electrical signals (Voltages/Currents) into floating-point variables accessible within the Simulink environment, and vice versa.

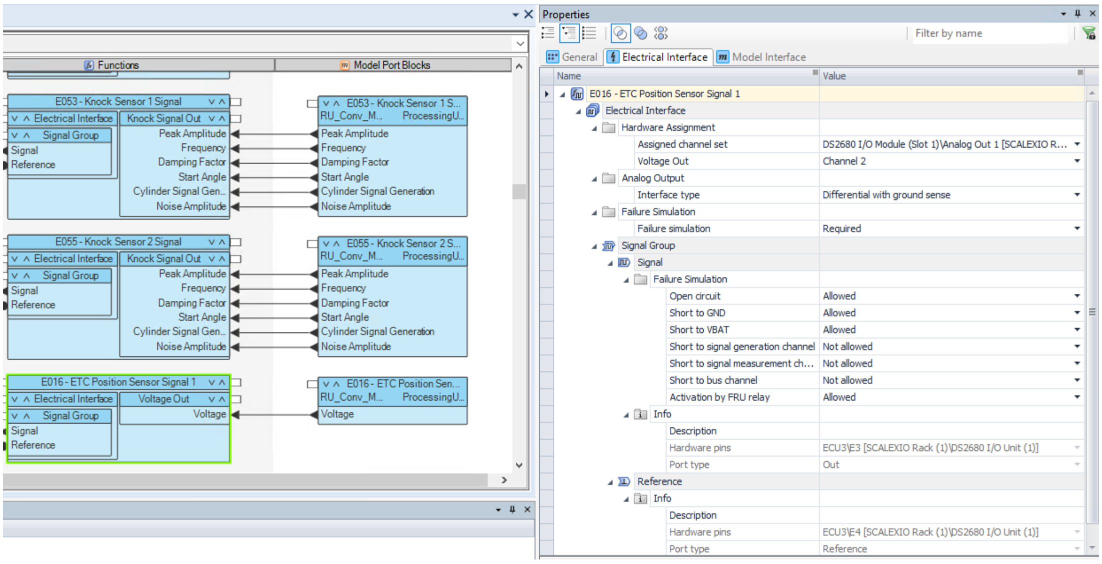


Figure 3.3: Configuration Desk interface showing the mapping of the TPS signals.

The hardware configuration was established as follows:

- **Throttle Position Sensors:** The signal lines were configured as **Analog Output** channels, as illustrated in the figure. Crucially, the failure simulation feature was enabled for these ports, allowing for the injection of Open Circuit, Short to GND, and Short to Battery faults.

- **Motor Commands:** The actuation signals (Motor+ and Motor-) were assigned to two **Digital Input** channels. This selection was necessary to utilize the PWM measurement functions for capturing the ECM duty cycle.

- **5V Feed:** The primary sensor supply was routed to an **Analog Input** channel to continuously monitor the voltage reference provided by the ECM.

- **Signals Reference:** The sensor ground was associated to the Analog Output Reference of the same channels chosen for TPS, ensuring the correct electrical behavior.

Chapter 4

Model Development

The goal of the simulation model is to replicate the electro-mechanical response of the throttle valve. The model accepts the raw control signals from the ECM and computes the resulting angular position of the butterfly valve in degrees.

4.1 Input Signal Processing

The ECM controls the throttle DC motor using an H-Bridge driver, providing two Pulse Width Modulation (PWM) signals: *Motor Control +* (DC_+) and *Motor Control -* (DC_-). As shown in Figure 4.1, the first stage of the model processes these inputs to determine the effective normalized command $u(t)$. The two duty cycles are subtracted and normalized to a range of $[-1, 1]$:

$$u(t) = \frac{DC_+(t) - DC_-(t)}{100} \tag{4.1}$$

This value represents the net voltage percentage applied to the motor armature, determining both the direction and magnitude of the actuation torque.

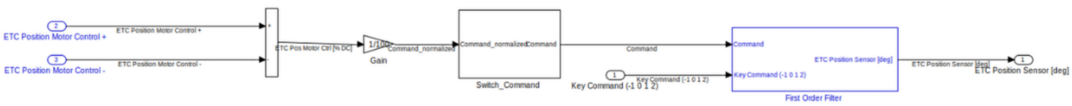


Figure 4.1: Overview of the Throttle Model

Furthermore, there is also a subsystem that allows the sign of the normalized command to be changed and therefore the polarity to be selected. This approach was chosen to provide an additional degree of freedom, making the model flexible and applicable to **both gasoline and diesel engines**; in fact, in the case of classic conventional engines, the throttle valve is normally closed, while in diesel engines it is normally open.

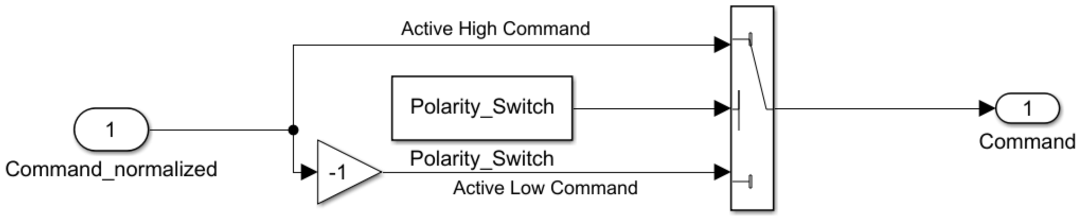


Figure 4.2: Switch Command Subsystem

4.2 Dynamic Modeling

While the physical throttle is a second-order mechanical system (Mass-Spring-Damper), the simulation utilizes a modified **First-Order Filter** approximation. This approach was chosen because the closed-loop controller within the ECU is robust enough to compensate for simplified plant dynamics, provided the dominant time constant is accurate.

So, this simplification is valid in an HiL context because the position control loop is closed by the ECM itself, acting a robust controller that compensates for minor plant model mismatches. Furthermore, a first-order model has fewer parameters to calibrate, making it easier to tune to match the rise time of the real component and a faster implementation in case of new project implementation.

However, unlike a standard unity-gain low-pass filter, the implemented model (Figure 4.3) explicitly includes a feedback term to represent the physical restoration forces (return springs) and friction.

The system dynamics are governed by the following differential equation:

$$\dot{y}(t) = \frac{1}{\tau} \cdot [K \cdot u(t) - K_{fb} \cdot y(t)] \tag{4.2}$$

Where:

- $y(t)$ is the throttle position output [deg].
- $\dot{y}(t)$ is the rate of change of position (velocity).
- τ is the integration time constant parameter (labeled as $1/tao$ in the diagram), determining the system's responsiveness.
- K is the forward gain, representing the motor torque constant and gear reduction ratio.
- K_{fb} is the **Feedback Gain**. This term is crucial as it simulates the "Friction and Elastic contributions," effectively modeling the spring force that constantly tries to return the throttle to its rest position.

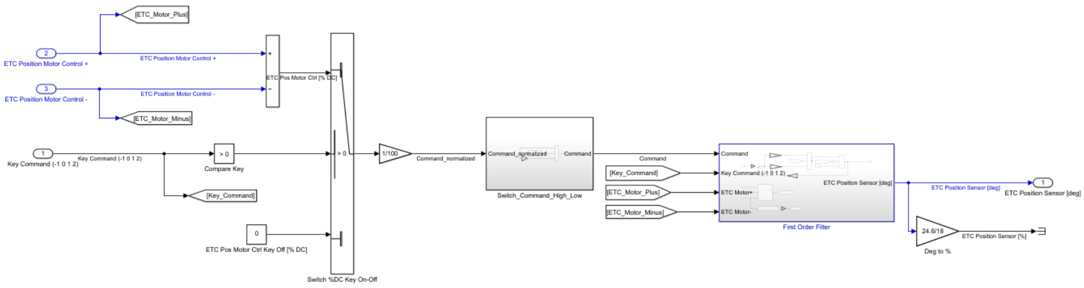


Figure 4.3: Model Overview

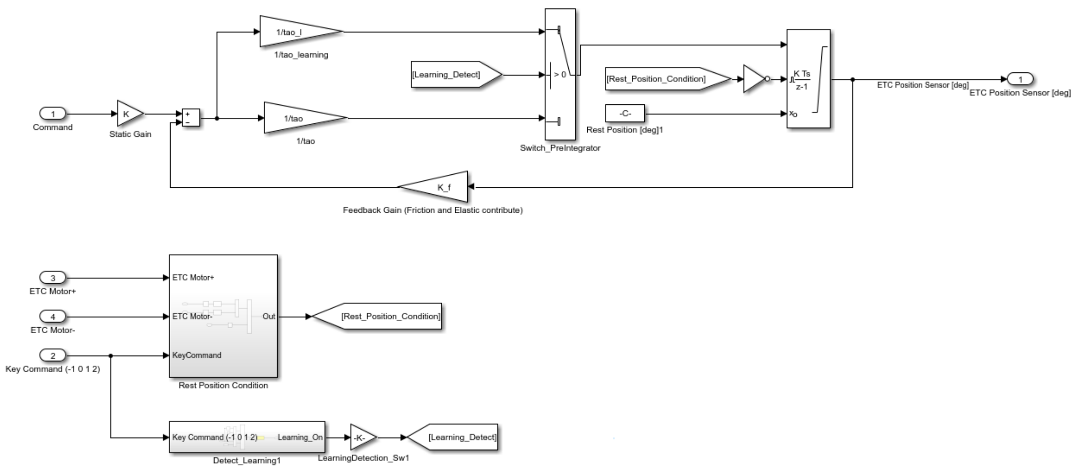


Figure 4.4: First Order Filter

4.2.1 Learning Phase handling

A critical aspect of the modeling involved the "Learning Phase".

At every key-cycle, the ECM performs a calibration routine to find the mechanical end-stops (fully open and fully closed) and the "limp-home" position (spring default).

The model features a dedicated logic switch to handle the "Learning Phase." When the ECM initiates the calibration procedure ('Detect_Learning'), the model switches the integration gain from the standard $1/\tau$ to a dedicated $1/\tau_{learning}$ value.

This allows the simulation to exhibit different dynamic behaviors during the end-stop search versus normal operation, ensuring the ECM's diagnostic checks are satisfied during startup.

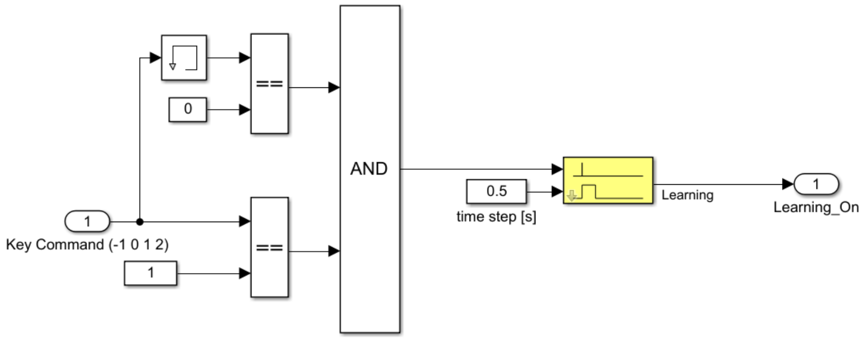


Figure 4.5: Detect Learning Subystem.

4.2.2 Rest Position handling

While testing the model in the entire HiL system, a new aspect was raised to consider. When the throttle body is de-energized, meaning it is no longer present in the engine, the ECM expects the throttle body to be at the rest position. This position is equivalent to the rest position of the spring in the real mechanical system, in the case of interest equal to approximately 8% opening and therefore 6.4 degrees.

To address this, a function was implemented to capture the ECM no-command condition, which requires the throttle body to be brought to the rest position. This logic was tied to the integrator default trigger, with the default set to 6.4 degrees.

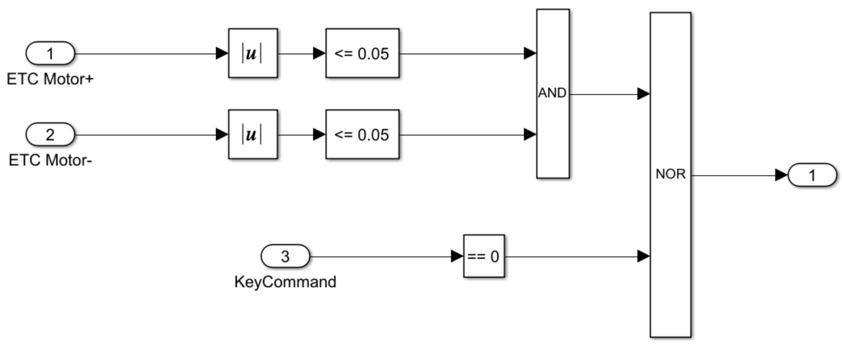


Figure 4.6: Rest Position Condition Subystem.

Chapter 5

Final Configuration and Electrical Load

5.1 Signal Conversion

Once the model calculates the position in degrees, this value must be converted back into the two analog voltages (TPS1 and TPS2) that the ECM expects.

As shown in the Simulink hardware interface block below, **maps** derived from the official datasheet are used to convert the simulated angle (deg) into Voltage (V). Note the inverse correlation between TPS1 and TPS2 is used for safety redundancy.

It is been added also a **switch** on the maps input that allows to change the use of the throttle body as simulated or real thanks a parameter editable by the user in real time; this is useful to show comparative tests in order to calibrate and validate the model.

The output signal from the conversion map routes to the model port linked to the ECM wires related to the two throttle position sensors.

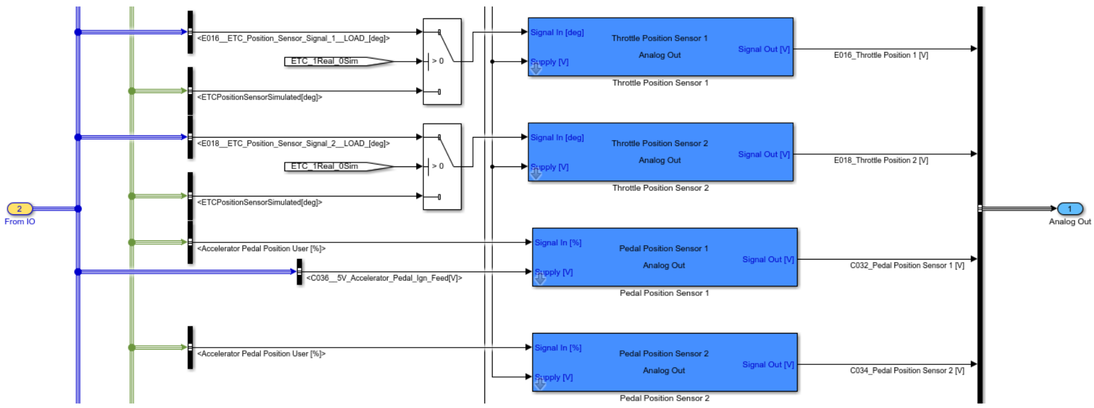


Figure 5.1: Switch between Real and Simulated signals and conversion to voltages (extract from the HiL vehicle Simulik model).

5.2 Electrical Load Emulation

Simply simulating the sensor feedback is insufficient. The ECM expects to see an electrical load (the motor windings). If the circuit is open, the ECM detects a "Open Load" fault which inhibits the motor commands.

The first attempt to replace the load of the real component with a simple resistor did not lead to a correct simulation. This happened because in the case of a real load, the resistance between the two throttle commands is variable; the throttle behaves like an active load that varies its resulting impedance depending on the applied command.

To emulate the electrical behavior of the throttle motor windings, the setup integrates the **dSPACE DS5380 Electronic Load Module**.This hardware is specifically designed for high-speed 12V DC motor emulation, acting as a programmable current sink that replaces the physical actuator coils[cite: 20].

Its primary characteristics and functionalities include the following:

- **Direct Current Control:** The module operates in a voltage-controlled current model. It accepts an analog control signal (0...10V) and regulates the load current proportionally with a ratio of 3A per Volt. This allows the real-time model to dynamically adjust the current draw based on the simulated motor resistance.
- **High Dynamic Performance:** The board is optimized for high-speed operation with a current settling time of approximately 5μs, ensuring it can accurately track the rapid PWM switching frequencies typical of ECM H-Bridge drivers.
- **Power Capability:** It features two independent channels, each capable of handling up to 300W of continuous power dissipation.
- **Protection Circuitry:** The unit includes integrated thermal overload protection and a disconnect switch to prevent damage during fault conditions.

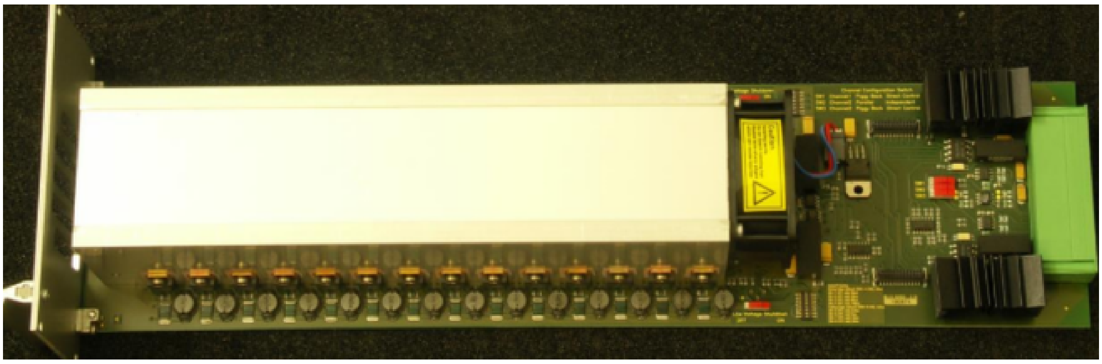


Figure 5.2: DS5380 Load Board.

A Load Emulation model was implemented to simulate the changing impedance of the motor brush contact and windings.

Figure 5.3: Load Emulation Model

An RC filter network was tuned based on the datasheet parameters to replicate the inductive kickback and current consumption of the real motor, ensuring the electrical diagnostics remained satisfied. This take in input the volatge average command from the ECM and outputs the resulting current.

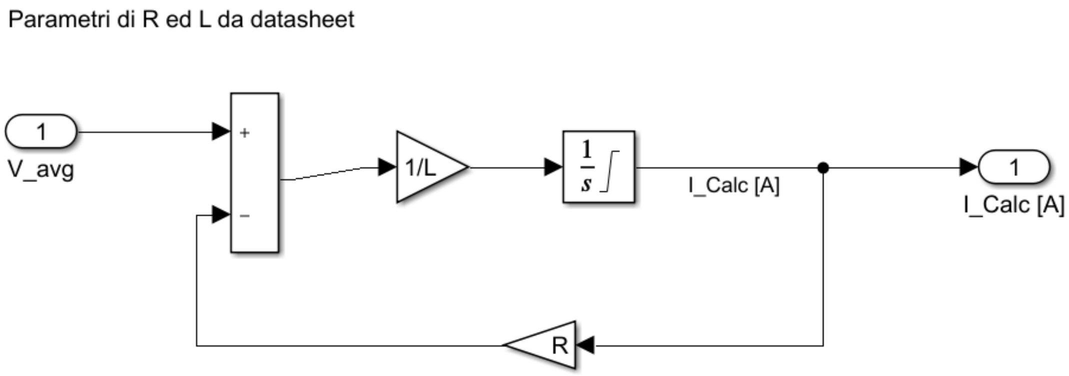


Figure 5.4: RL Subsystem

Finally, a conversion of the current into the resulting voltage is carried out on the pin of the DS5380 board according to the electrical characteristics of the board, which associates 1 Ampere to every 3 volts in output.

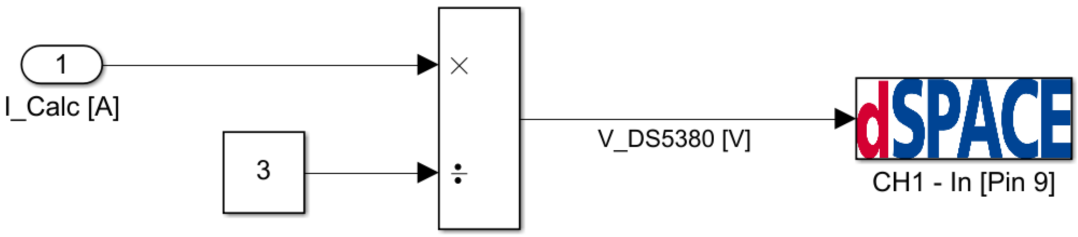


Figure 5.5: Load Conversion in DS5380 Subsystem

Chapter 6

Testing and Validation

6.1 Test Environment

The validation was conducted using an effective complete Hardware-in-the-Loop system, integrating the simulated throttle body model into a full **Jeep Wrangler vehicle simulation model**.

The dashboard below realized in *Control Desk* allows to use and insert many instruments linked to the simulink model variables that are in turn linked to the electrical signal to the ECM.

For example, when the Accelerator Pedal is pressed in the dashboard, the related variable in the model changes in real time and then it is sent to the simulink model port linked to the Accelerator Pedal output wire of the ECM.

The test environment also includes:

- **CAN Communication:** Designed and configured to allow message exchange between the ECM and the HiL system that simulates the vehicle, engine, and other ECUs on the network.
- **ETAS INCA:** Test environment used to read data sent and received from the ECM in real time within the proprietary software; this tool is crucial for the verification and validation processes.
  For our purpose, this is used to verify the accuracy of the data sent from the simulated environment and, at the same time, allows modifications to software parameters that test the validity of the simulated model.
- **CDA:** Diagnostic tool connected to the ECM that allows for the identification of any faults and active DTCs on an ECU.

Test Process The testing methodology involved a direct comparison: the real component was first used to generate benchmark data, and then replaced by the model to validate fidelity.

Figure 6.1: Control Desk Dashboard used for the Jeep Wrangler simulation and testing.

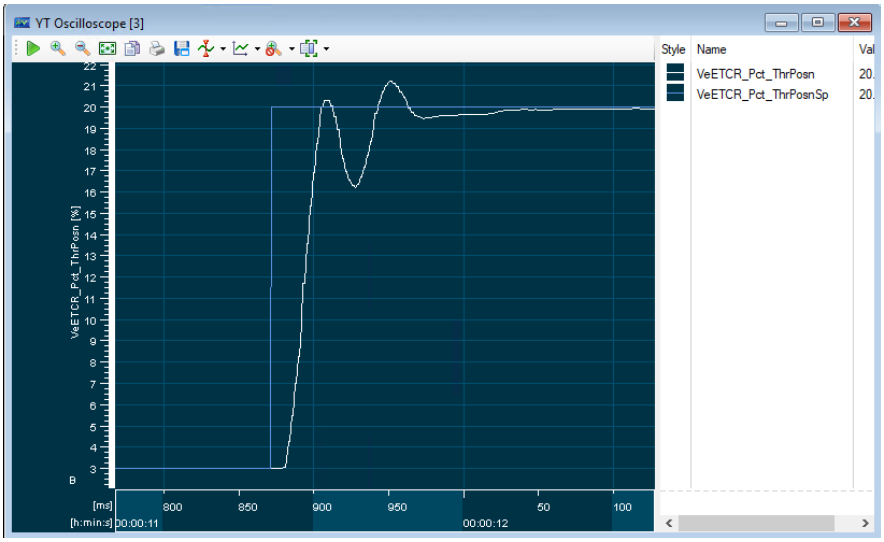
6.1.1 Tuned Parameters

Trial and Error approach was used to tune the parameters, final values here:

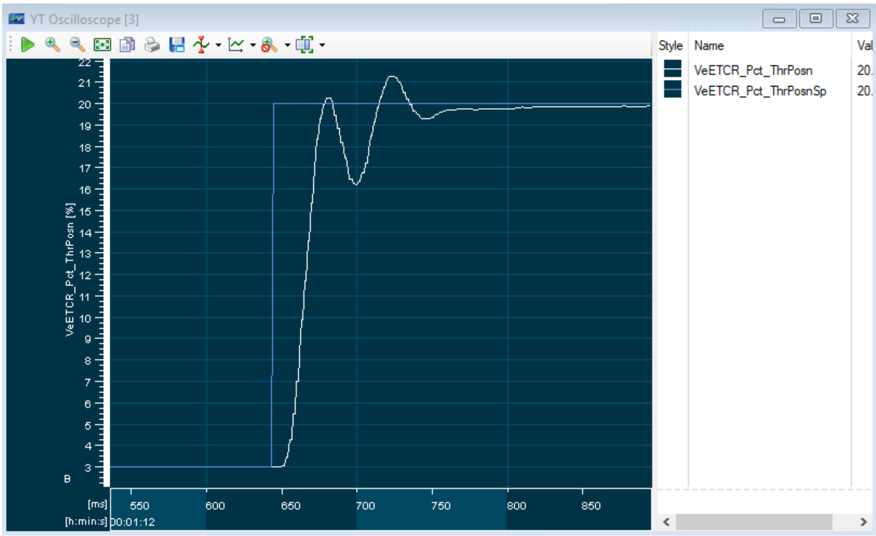
- Static Gain: $K = 12$
- Time Constant: $\tau = 0.06$
- Feedback Gain: $K_{fb} = 0.1$
- Time Constant in learning: $\tau_l = 0.04$
- Polarity Switch: set to 1, throttle body normally closed (gasoline engine).

6.2 Test 1: Step Response (Bypass)

The step response test evaluates the transient behavior of the model. A sudden change in position request was sent modifying in INCA the Throttle Position Setpoint sent by the ECM to force the throttle to open (20% in figure).
The white variable ("ThrPosn") represents the Throttle Position read from the model, while the blue one ("ThrPosnSp") is the setpoint sent by the ECM.



(a) Real Component Response



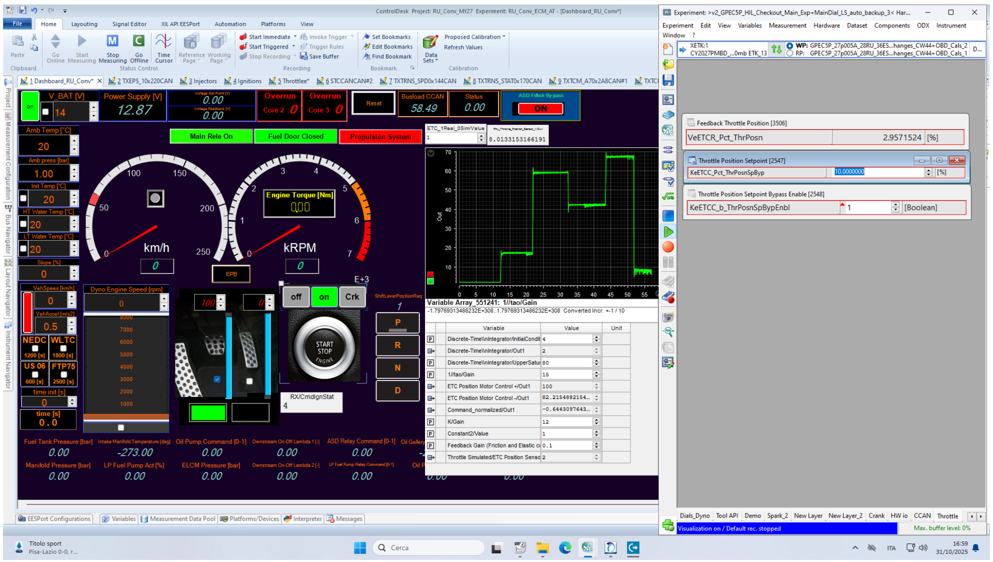
(b) Simulated Model Response

Figure 6.2: Step Response Test

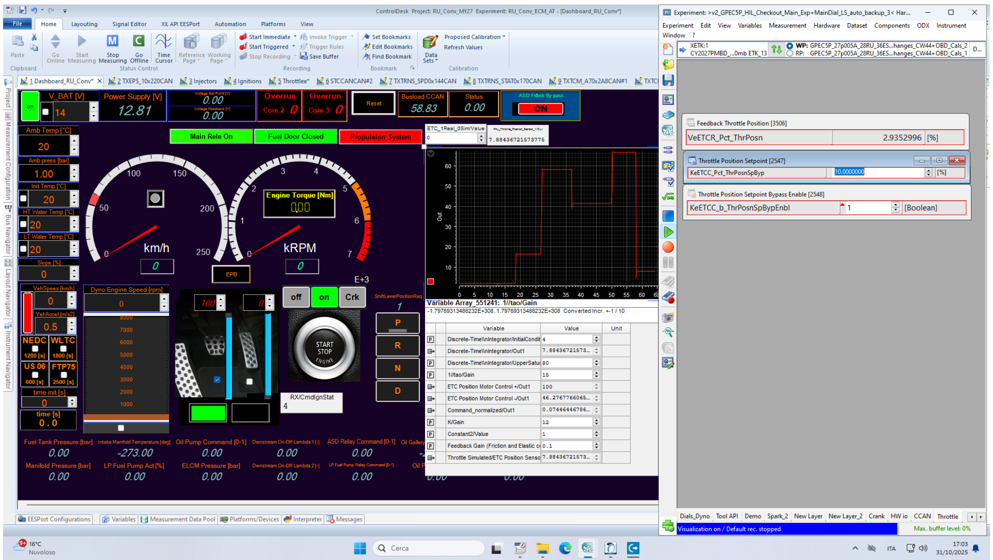
Analysis: The simulated response closely matches the real dynamics. The first-order filter, appropriately tuned, successfully replicates the settling time. The slight differences in the oscillation dampening were deemed acceptable as they did not trigger any instability in the ECU controller.

6.3 Test 2: Train Pulse (Dynamic Tracking)

A "Bypass Train" signal consisting of multiple steps of varying amplitude was applied to check the model's linearity and tracking ability over the full range.



(a) Real Component



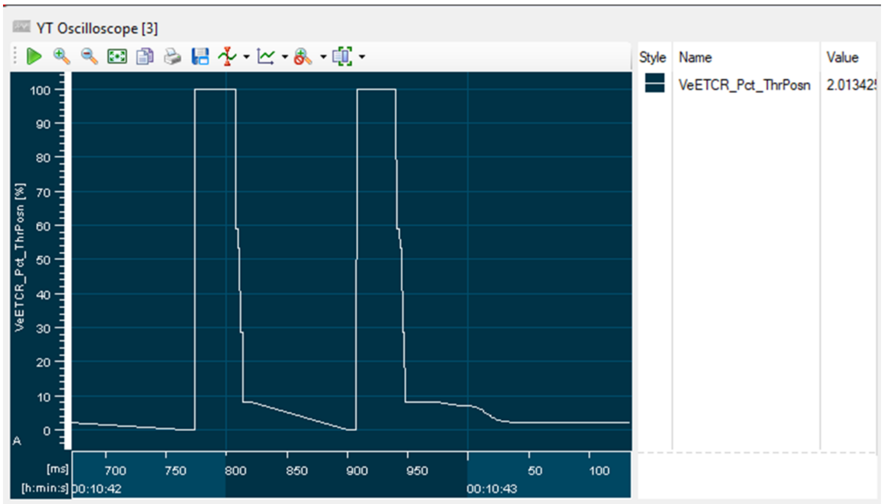
(b) Simulated Model

Figure 6.3: Train Pulse Test

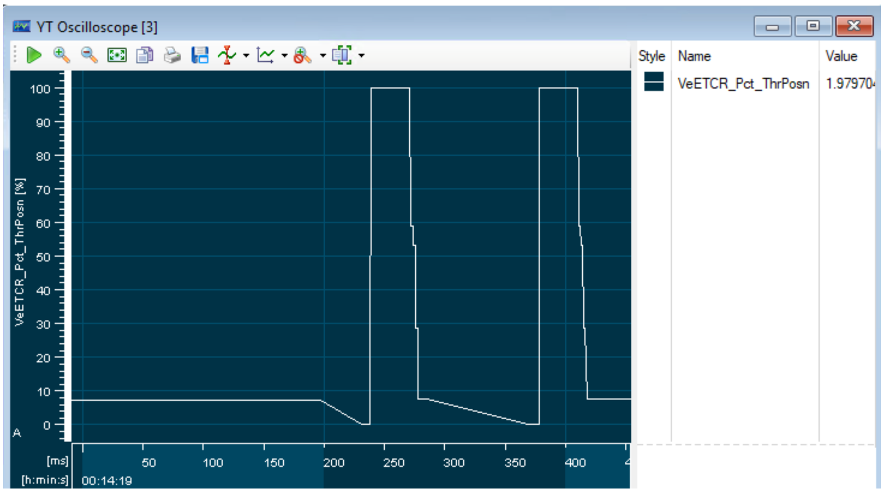
Analysis: Again, the simulated response closely matches the real dynamics. This confirms what was seen previously with the test response, also validating the normal operation when the setpoints vary continuously.

6.4 Test 3: Learning Phase Validation

This was the most critical test. The ECU must be able to "learn" the simulated end-of-course. The model needs to be able to have high-speed response in order to not set any "Limp-Home Position" or "Ice-Blockage" diagnostic failure (DTCs).



(a) Real Learning Phase



(b) Simulated Learning Phase

Figure 6.4: Comparison of the Learning Phase logic.

Analysis: the simulated signal reproduces the specific "search" pattern (opening fully, closing fully, and finding the spring rest position). The timing alignment confirms the correctness of the implemented logic.

As evidenced in figure 6.5 below, the ECM accepted the simulated component as valid also in the critical learning phase, allowing the rest of the HiL simulation (engine, transmission, etc.) to proceed without interruption.

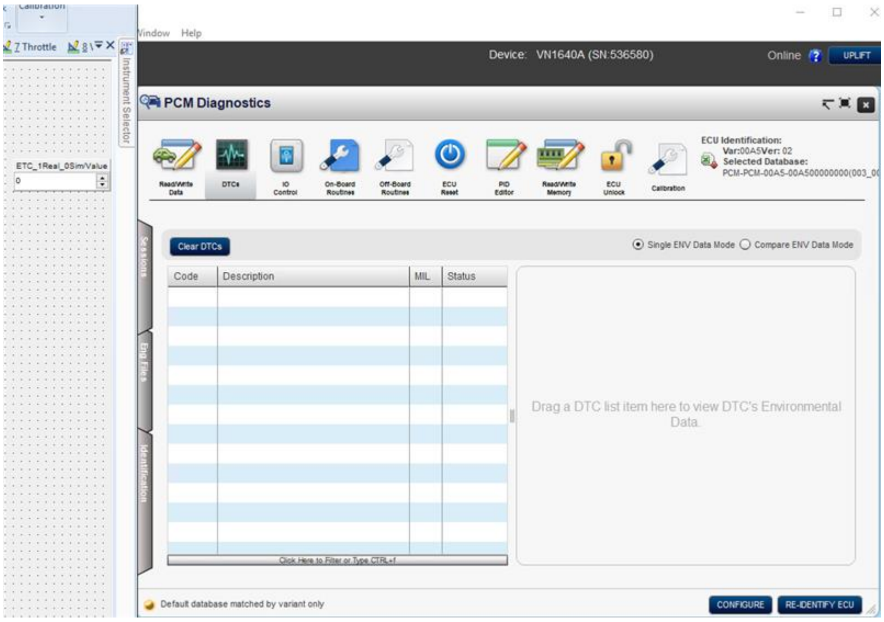


Figure 6.5: INCA Diagnostic window showing zero active DTCs after the simulation cycle.

Chapter 7

Conclusions

The experimental activity described in this report focused on the development, integration, and validation of a real-time mathematical model for an Electronic Throttle Body (ETB) within a Propulsion Hardware-in-the-Loop (HiL) environment. The primary objective was to replace the physical component, which is prone to frequent mechanical failures during intensive testing, with a robust software-based simulation capable of satisfying the stringent electrical and dynamic requirements of a production Engine Control Module (ECM).

7.1 Summary of Achievements

The project successfully demonstrated that a virtual model can seamlessly replace the physical hardware without compromising the validity of the ECU testing procedures. The integration process highlighted several critical aspects of HiL simulation:

- **Hardware-Model Interface:** The utilization of the **dSPACE DS2680 I/O Unit** proved essential for managing the high-speed signal processing required by the H-Bridge PWM commands. The correct mapping of Digital Inputs for duty cycle measurement and Analog Outputs for position feedback ensured low-latency communication between the simulator and the ECU.
- **Electrical Fidelity:** A significant achievement of this work was the successful emulation of the motor's electrical load. The integration of the **dSPACE DS5380 Electronic Load Module**, driven by a custom RL circuit model, allowed the system to mimic the variable impedance of the real DC motor. This prevented the ECU from triggering "Open Load" diagnostic faults, a common hurdle when moving from real to simulated actuators.
- **Control Logic Validation:** The tuned First-Order Filter approximation, augmented with a feedback loop to simulate return springs, demonstrated sufficient dynamic fidelity. The model correctly replicated the component's behavior during the critical "Learning Phase," allowing the ECU to successfully calibrate the end-stops (fully open and fully closed positions) at every key-on cycle without generating Diagnostic Trouble Codes (DTCs).

7.2 Benefits of the Simulated Approach

The transition from a physical to a simulated throttle component brings immediate and tangible benefits to the Control Lab workflow:

1. **Operational Continuity:** By removing the mechanical wear and tear associated with the physical gears and springs, the test bench availability is significantly increased, eliminating downtime caused by component breakage.

2. **Test Repeatability:** The mathematical model guarantees that the throttle response remains constant over time, unaffected by temperature variations or component aging, ensuring that any deviation in test results is attributable solely to the ECU software and not the plant.

3. **Advanced Fault Injection:** The simulated environment allows for the validation of failure scenarios that are dangerous or impossible to replicate with real hardware, such as the simulation of an ice-blockage (by dynamically limiting the model's range of motion) or electrical shorts (via the DS2680's FIU).

7.3 Future Developments

While the current First-Order model has proven effective for standard functional testing and ECU calibration, further improvements can be made to increase the physical realism of the simulation.

Future developments should focus on the implementation of a **Second-Order Mechanical Model** (Mass-Spring-Damper system). The differential equation governing such a system is:

$$J\ddot{\theta} + b\dot{\theta} + k(\theta - \theta_0) = T_{motor} - T_{friction} \tag{7.1}$$

Where J represents the moment of inertia, b the viscous damping coefficient, and k the spring stiffness.

Transitioning to a second-order model would allow for:

- **Inertia Simulation:** More accurate representation of the valve's overshoot and settling time during aggressive step commands.

- **Advanced Friction Modeling:** The inclusion of a complex friction model (e.g., Stribeck curve) to simulate static friction (stiction) and sliding friction separately. This is particularly useful for validating ECU control strategies designed to overcome sticky valves.

- **Aging Simulation:** By varying the parameters k (spring stiffness) and b (friction) in real-time, it would be possible to simulate the behavior of a degrading component, allowing the validation of the ECU's ability to adapt to an "aging" throttle over the vehicle's lifecycle.

In conclusion, the simulated throttle model is now a fully validated asset of the Propulsion HiL system, ready to support the development and testing of future engine control strategies.

List of Figures