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A Closed-Loop Drive-train Model for HIL Test Bench

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ABSTRACT

This paper presents a hardware-in-the-loop (HIL) test bench for the validation of production transmission controls software, with a focus on a closed-loop vehicle drive-train model incorporating a detailed automatic transmission plant dynamics model developed for certain applications. Specifically, this paper presents the closed-loop integration of a 6-speed automatic transmission model developed for our HIL transmission controller and algorithm test bench (Opal-RT TestDrive based). The model validation, integration and its application in an HIL test environment are described in details.

INTRODUCTION

In Zheng, *et al.* (2008), two main points were proposed for the extension of Delphi's transmission HIL capability. Those points were –

1. Increased model fidelity
    a. Add vehicle dynamics to the model by modeling a differential, longitudinal car dynamics and tires.
    b. Exercise the current to pressure generation portion so that it produces the clutch pressures for the transmission clutches.
    c. Add a hydraulic plant to model the transmission hydraulics.
    d. Dynamically tune the model parameters to refine model performance.
    e. Improved engine model.
2. Increased TCM HW and SW test coverage

Focus has been invested in 1(a) and 1(b) in order to model the other major components of the vehicle drive-train to improve the model performance and provide better dynamic response. The work will be augmented further with attention being given to 1(c) and 1(d) in the coming months.

BENCH CONFIGURATION:

The bench setup consists of the Host PC, HIL simulator (TestDrive), Current Measurement H/W (Current Probes and Signal Conditioning Module), Break-Out-Boxes (2 AutoBoBs) and the transmission controller module (TCM). Comparing with the previous work (Zheng, *et al.*, 2008), the key difference of this new setup is that the oscilloscope has been replaced with the Current Measurement H/W shown in Figure 1.

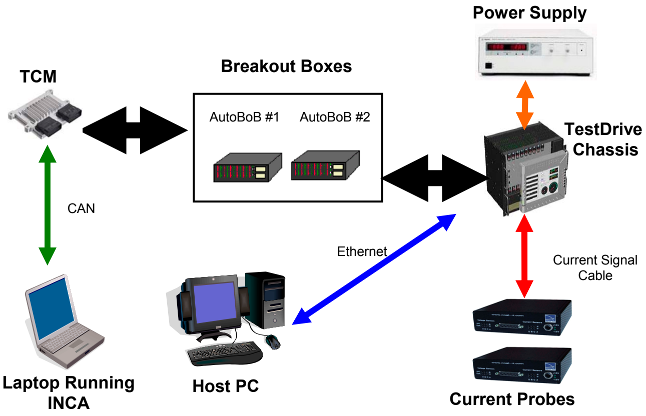

Figure 1 Bench Setup

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HOST PC:

It runs the simulator's console software (user interface) to communicate with the HIL simulator (i.e.) TestDrive.

TESTDRIVE SIMULATOR (PRIMARY CORE):

Provides the I/O interface and power to the controller, stimulates the controller inputs by simulating various sensors like (TRANSOILTEMP, PRNDL etc.). Communicates with the 2nd core of the Dual-Core processor, provides the Throttle and Brake inputs as commanded by the user, reads the gear-output from the TCM and feeds this to the plant model, measures the solenoid currents from the current probes (current measurement) commanded by the TCM and passes them as inputs to the plant model for solenoid currents to clutch pressures conversion. Retrieves the plant-model generated TISS, TOSS signals and stimulates the appropriate controller inputs. It also gets Vehicle Speed information from the plant-model to display to the console.

TESTDRIVE SIMULATOR (SECONDARY CORE):

It performs the drive-train plant-model calculations. It receives the Throttle, Brake inputs from the user and the commanded Gear and TRANSOILTEMP from the controller through the simulator's primary processor. It calculates the TISS and TOSS values from the drive-train model and outputs them to the I/O model where they are converted to real-world sensor outputs.

The current to pressure conversion subsystem accepts the commanded/measured solenoid currents from the I/O portion of the model and outputs the generated clutch pressures to the transmission clutches in the plant model to perform the necessary gear shifting.

CURRENT MEASUREMENT HARDWARE:

Current Probes:

The high-current and high-voltage input conditioning module allows the conversion of 4 current and 4 voltage signals to ±10V voltage level. This module is utilized for 4 current-measurement inputs which are factory configured for 5 Amps of continuous current. We utilize 2 such units since we need to measure the current on 6 transmission solenoids.

The front panel has activity and out-of-range LEDs for each channel. For current-measurement channels, the activity LED (green) turns on when a current above 200mA is detected, while the out-of-range LED (red) turns on when the current limit has been reached. These units are compatible with an analog input module available as a plug-in card for the simulator.

Analog Input Module:

This module allows up to 16 analog signals to be sampled simultaneously through a single module and features 16 differential channels with individual 16-bit Analog-to-Digital Converters (ADC). Each ADC can sample up to 500 kS/s, giving a total throughput of 8 Ms/s. It also features on-board signal conditioning and anti-aliasing filtering and flash memory for calibration parameters.

SOLENOID LOADS:

Transmission solenoids are available on the bench system to satisfy the output drivers of the TCM and also to provide current measurement feedback for the closed loop model.

BREAK-OUT-BOXES:

They are used to induce electronic faults through the simulator model for debugging purposes and testing of diagnostic algorithms, while allowing signals to be monitored externally.

TCM:

The transmission controller reads the TISS, TOSS sensor signals from the TestDrive simulator, performs the control algorithm calculations, determines the appropriate gear for the automatic transmission based on various input signals (Throttle, Brake, PRNDL, TRANSOILTEMP and other sensor inputs), calculates the solenoid currents and outputs the appropriate current waveforms onto the solenoid loads.

LAPTOP:

The laptop as such doesn't form part of the closed-loop simulation setup. However, it is used for flashing the software and calibrations into the controller, recording/displaying the internal controller variables and calibrating the controller through a calibration tool like ETAS INCA.

USER INPUTS:

1. Throttle
2. Brake
3. Shift Lever (PRNDL)

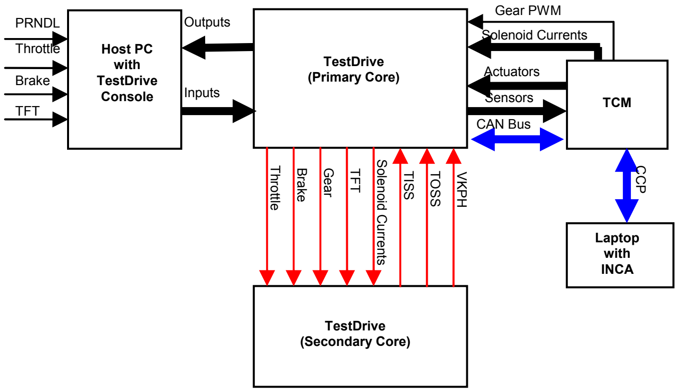


Figure 2 HIL Bench Architecture

6-SPEED TRANSMISSION MODEL

MODEL DEVELOPMENT

The model development is a continuation of the work reported in Zheng, *et al.* (2008). As explained in the earlier work, the motivation for the development of the plant model was to be able to check the transmission response to TCM command to enable algorithm and test engineers to verify controller performance.

Comparing to the previous work, the model is improved in the following areas:

- Longitudinal vehicle dynamics model with tire-road interactions
- Clutch pressure generation with solenoid current command as input

This section provides the details of these model improvements.

LONGITUDINAL VEHICLE DYNAMICS

The chassis and driveline portions of the plant model have been improved to add the proper loading effects to the transmission. This was achieved by representing the vehicle dynamics model by modeling longitudinal car dynamics and tires. Specifically, 'Longitudinal Vehicle Dynamics' and 'Tire' blocks from the SimDriveline library are used. The parameters for these blocks are obtained from the physical measurements of the test vehicle and the subsequent calculations.

The longitudinal vehicle dynamics model consists of the representation of the longitudinal dynamics of a two-axle, four wheeled vehicle. This block however, allows for connection schemes wherein single/dual tire models can also be utilized. As shown in Figure 3, the physical driveline connection is terminated into a single tire and the tire block's longitudinal force output is connected to the longitudinal force input of the Longitudinal Vehicle Dynamics block. The Vehicle Dynamics block feeds the normal force input of the Tire block. The frontal (longitudinal and normal) forces are ignored in this connection scheme.

This block represents the vehicle's total load as a sum of Rolling Load, Air Resistance and Gradient Resistance. The model parameters include vehicle mass, center of gravity (C.G.) location, frontal area and drag coefficient.

Tire:

The tire block models a single tire mounted on the wheel assembly. It utilizes parameters such as the tire (rolling) radius, relaxation length and rated vertical load. Certain parameters for this block were readily available while others were best estimates.

Currently, a uni-tire model is being used in the drive-train model but a 2-tire model performance is being looked at and looking ahead the plan is to evaluate the construction of a 4-tire model.

Analog braking-force estimation:

For the maximum brake force calculation we used the formula below that was presented in reference [3]

Front Brake Force =

$$Q*r_p/(\pi*D_M^2/4)*\pi*D_{Wf}^2/4*BEF_f*r_f\,/\,(Rr*2) \quad \textbf{(1)}$$

Rear Brake Force =

$$Q*r_p/(\pi*D_M^2/4)*\pi*D_{Wr}^2/4*BEFr*rr\,/\,(Rr*2) \quad \textbf{(2)}$$

where,

Q: Pedal working force (kg),

r_p: Pedal Ratio,

D_M: Master Cylinder Diameter (mm)

D_{Wf}: Front Cylinder Diameter (mm)

D_{Wr}: Rear Cylinder Diameter (mm)

BEF_f: Front Brake Factor

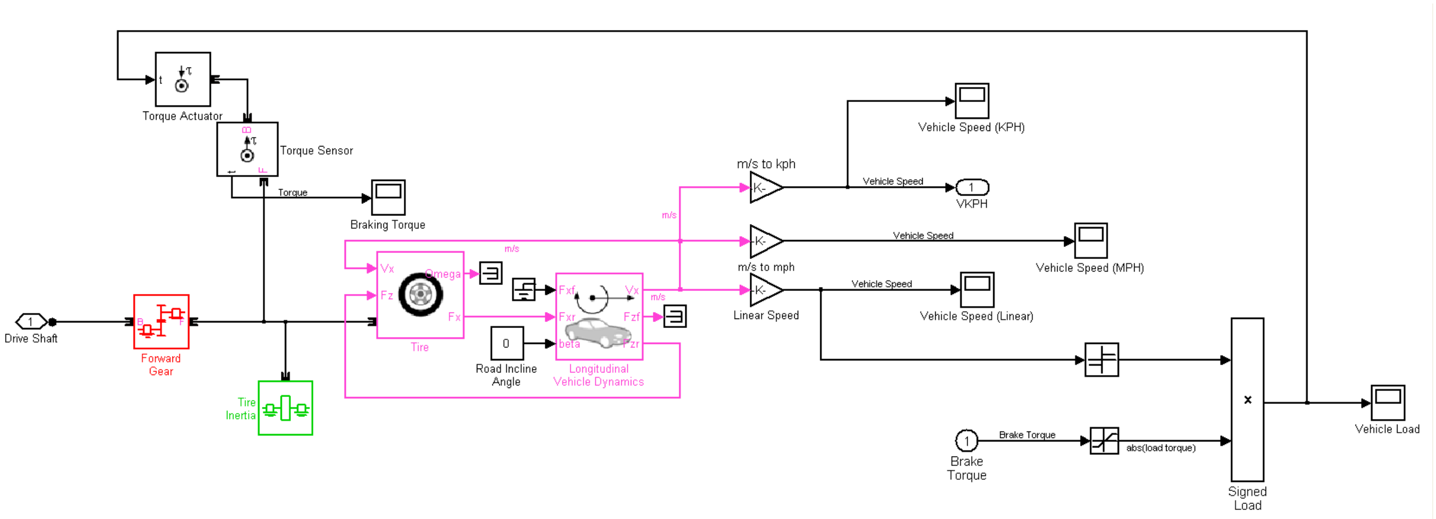


Figure 3 Vehicle Load (Longitudinal Dynamics and Tire)

BEF$_r$: Rear Brake Factor

r_f: Front Brake Effective Radius (mm)

r_r: Rear Brake Effective Radius (mm)

R_r: Tire Radius (mm)

So, based on the below indicated driver effort input value we get 2000 N-m (as shown in the last row of Table 1) and we used this value for the maximum brake force during simulation.

Table 1 Brake Force Calculation

Driver effort to the brake pedal (Kgf)	33
Master cyliner diameter (Dm, mm)	25.4
Pedal ratio(rp)	7
Front brake cylinder diameter (Dwf, mm)	60
Front brake diameter (mm), distance from wheel center	150
Front brake effect factor (disc type)	0.9
Rolling radius (mm), tire	340
Rear brake cylinder diameter (Dwr, mm)	34
Rear brake real diameter (mm), distance from center	150
Rear brake effect factor	0.9
Rolling radius (mm), tire	340
Braking force (N-m)	**1989.90**

CLUTCH PRESSURES GENERATION

This section addresses improvement of validation and integration of the solenoid currents to transmission clutch pressures generation subsystem.

The solenoid currents (average) are measured from the solenoid loads and serve as inputs to this model. First, based on the hardware configuration, this step calculates the control pressure for each solenoid based on the solenoid current from table look-ups using the solenoid up/down (P-I) characteristics and temperature effects.

Second, the clutch pressure is calculated based on the control pressure. However control pressure travels through the mechanical system and is boosted to clutch control pressure. There is a calculation formula for converting the control pressure to clutch pressure. This step uses the formula given below to calculate clutch pressure for each transmission clutch.

Calculation Formula:

The clutch pressure calculation formula is shown in Equation (3), where

P_{Clutch} is the clutch pressure

$P_{Control}$ is the solenoid pressure

Gain is the ratio between clutch pressure and solenoid pressure

P_{Offset} is the clutch preload

$$P_{Clutch} = P_{Control} * \frac{1}{Gain} - P_{Offset} \qquad \textbf{(3)}$$

Figure 4 shows the concept flow of the clutch pressure generation.

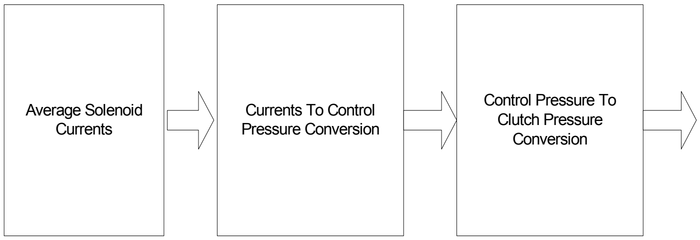


Figure 4 Clutch Pressures Control Block Diagram

Solenoid Currents to Clutch Pressures Conversion Model:

The current to pressure generation subsystem model shown in Figure 5, implements the clutch pressure control block diagram shown in Figure 4. Also, modeled is the pseudo hydraulics portion since the hydraulic flows haven't been implemented in the model yet. The hydraulic portion is represented by transfer functions at the moment.

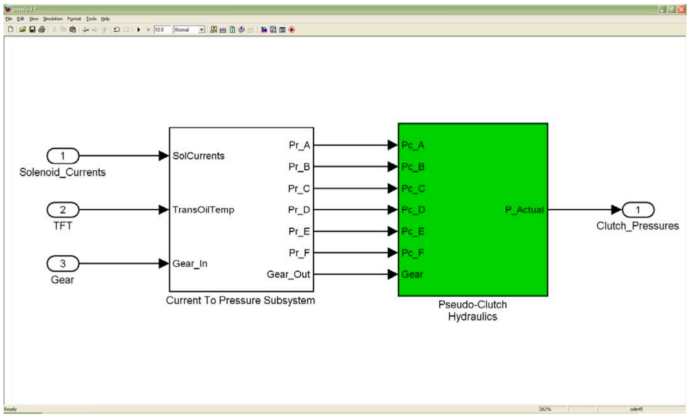


Figure 5 Current to Pressure Generation Subsystem

Pressure comparisons for 35R clutch (offline):

Figure 6 shows the comparison between the clutch pressures generated by the model (shown in Figure 5) against the measured clutch pressures from the test vehicle. Similar results were obtained for the other transmission clutches and hence this model's offline (simulation only) performance was validated.

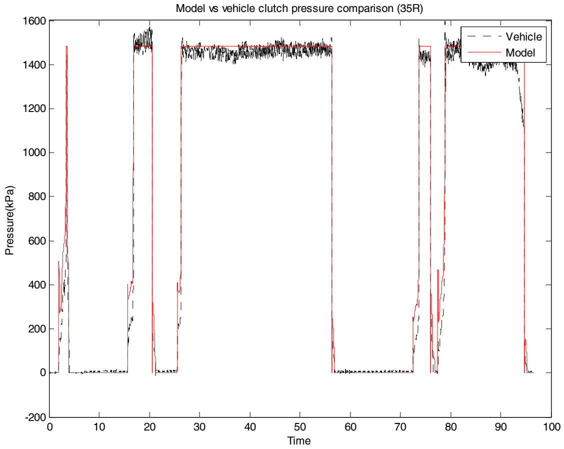


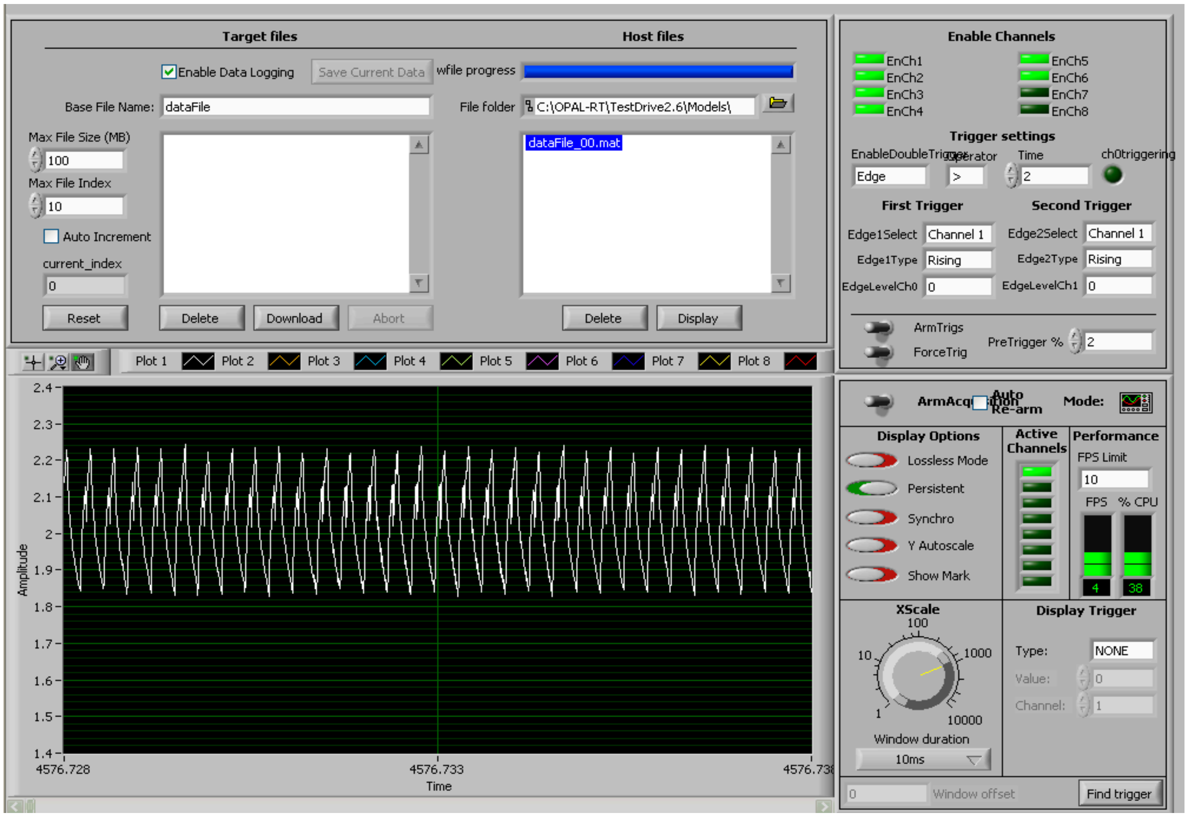
Figure 6 Pressure Comparison

Current Measurement on TestDrive Interface:

This section describes the integration of Current Sensing to provide solenoid currents feedback.

After receiving the current measurement hardware from our simulator supplier (Opal-RT) this year, substantial amount of work was done along-with their support team to integrate the hardware and the software for this solution into our bench setup. The performance of this solution was validated by comparing its measurements against that of the bench scope. The simulator model was edited to add real-time measurement capability in order to calculate average and RMS values from the current waveforms. These current values would be used by the Current to Pressure generation subsystem in the plant model to convert them to the respective clutch pressures. These pressures would then be applied to the transmission clutches in the plant model to perform the gear shifts.

Figure 7 is a screenshot of a measurement made by this device and displayed on the simulator console. This system also provides other features like triggering, acquisition and data-logging which are comparable to those offered by a conventional scope. The unique feature about it as a measurement device is that it is tightly integrated with our simulation environment and lends itself very well to forming our closed-loop bench. Further, it enables us to free the oscilloscope from the bench for using it elsewhere.



Target files

Host files

☑ Enable Data Logging

Base File Name: dataFile

File folder: C:\OPAL-RT\TestDrive2.6\Models\

Max File Size (MB): 100

Max File Index: 10

☐ Auto Increment

current_index: 0

dataFile_00.mat

Enable Channels: EnCh1, EnCh2, EnCh3, EnCh4, EnCh5, EnCh6, EnCh7, EnCh8

Trigger settings

EnableDoubleTrigger: Edge

Operator: >

Time: 2

First Trigger

Edge1Select: Channel 1

Edge1Type: Rising

EdgeLevelCh0: 0

Second Trigger

Edge2Select: Channel 1

Edge2Type: Rising

EdgeLevelCh1: 0

PreTrigger %: 2

Performance

FPS Limit: 10

FPS: 4

% CPU: 38

Window duration: 10ms

Display Trigger

Type: NONE

Value: 0

Channel: 1

Window offset: 0

Figure 7 Solenoid Currents Waveform

SIMULATION RESULTS

The simulation results are organized by recording signals from a typical test vehicle driven under selected driving conditions (this constitutes the test-data), running the plant model with its inputs being driven from the test-data and comparing the model outputs against the test-data outputs.

As can be seen from the following plots, the model and vehicle data show a close correspondence with the transmission up-shifts and down-shifts being modeled accurately. Further, with the recent updates, the transients are better represented and the overall model generated speed traces (TISS, TOSS) are much closer to the vehicle data.

MODEL (USER) INPUTS

Figure 8 shows the inputs to the model. Throttle, Brake switch and Gear request information constitute the inputs to the model. As is evident from the figure, there is 100% correspondence between the model and the vehicle data. The same inputs (as recorded in the vehicle) need to stimulate the plant model. This is required for validating the plant model's performance against vehicle data.

MODEL (TRANSMISSION) OUTPUTS

Figure 9 shows the comparison of model outputs and vehicle data. The model output of input speed (TISS) trace matches vehicle data fairly accurately, especially in the areas of shifting. The comparison of transmission output speed (TOSS) and vehicle speed are also shown which show close correspondence with vehicle response.

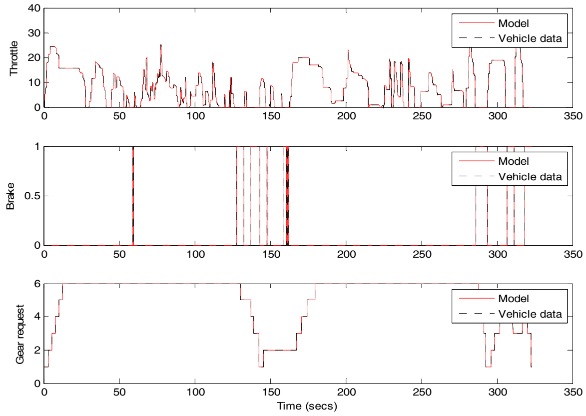


Figure 8 User Inputs Comparison

Figure 10 shows the simulation results comparison with last year's reported work. In Zheng, et al. (2008), the simulation results did not match well for the power-off downshift area. In the improved model reported in this paper, there is significant improvement of TISS response matching. This is mainly due to the better representation of the vehicle dynamics model.

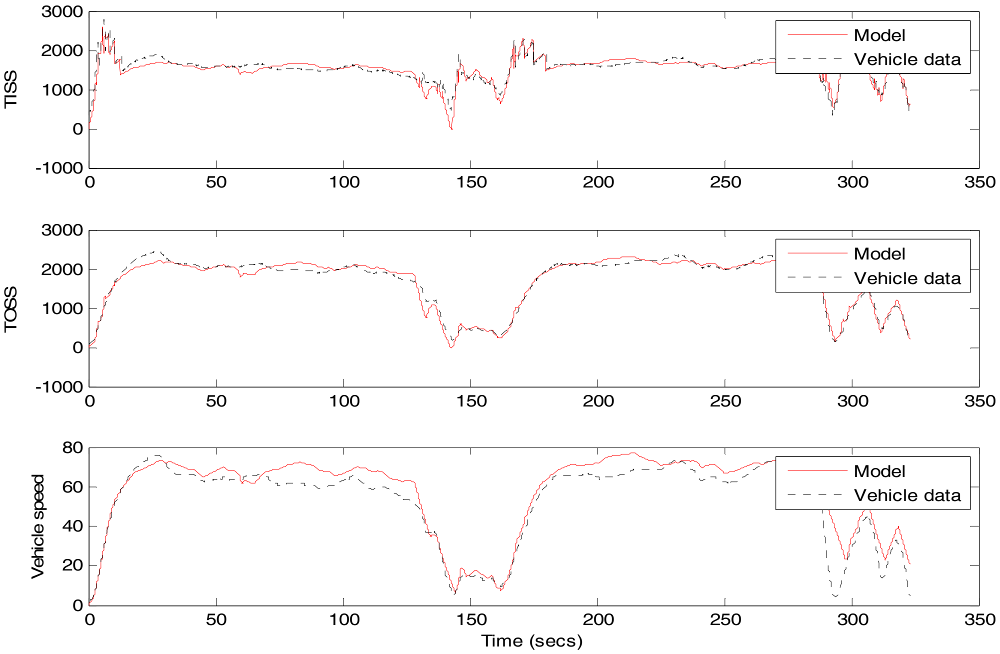


Figure 9 Transmission Outputs Comparison

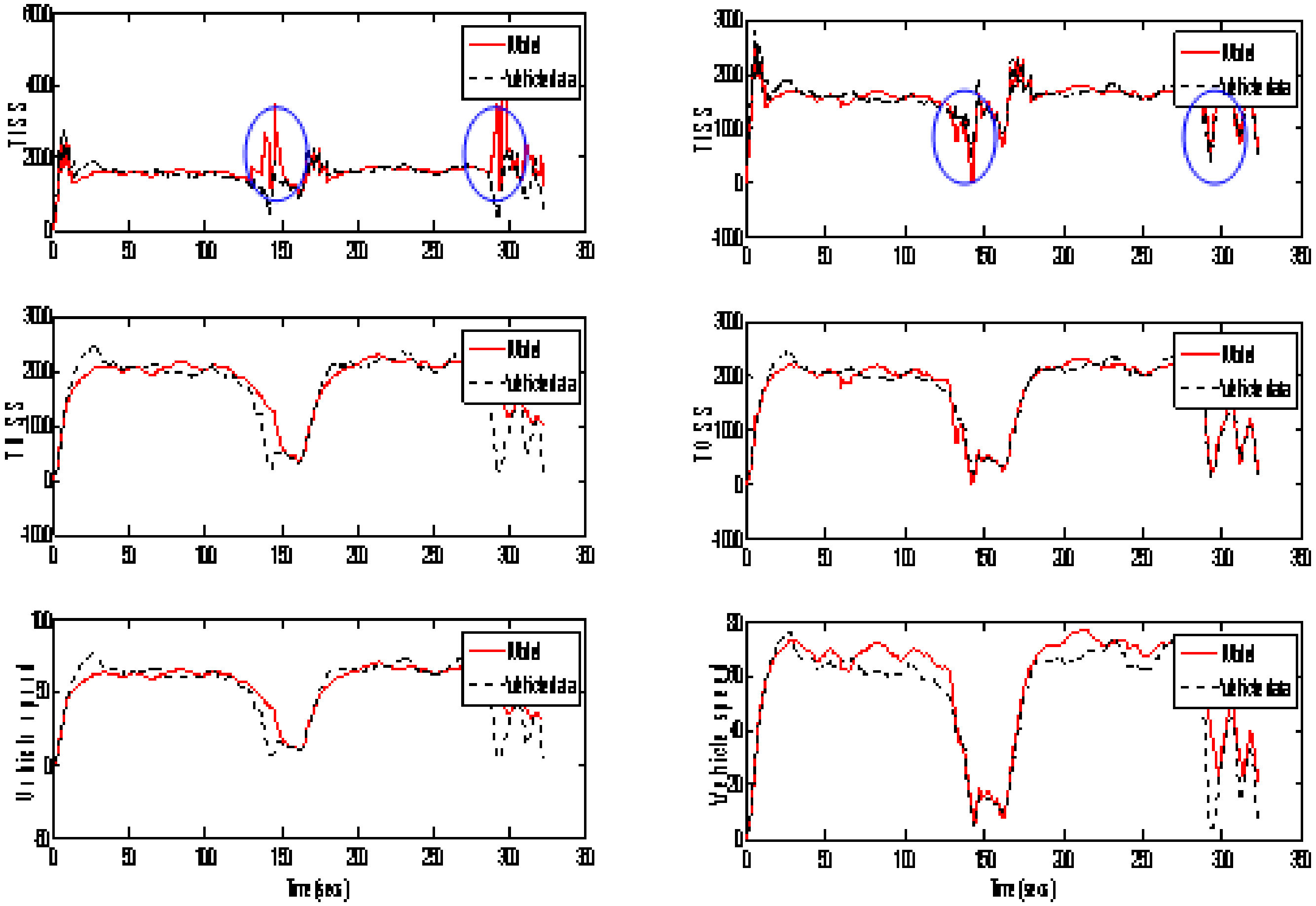


Figure 10 Highlighted Performance Improvement Areas

MODEL APPLICATION

Closed-Loop testing (Model feasibility verification)

As we explained in previous sections, we were able to develop the plant model and validated the offline model by comparing it against the vehicle data. For the online validation of the model (running on the HIL bench), we need to feed the signals listed in Table 2 into the plant model. Since these signals were captured in the vehicle we are imposing the same input signals to the plant model.

By using a conversion M-file, we convert this captured vehicle data (DAT file) into the model input file (MAT format). After playing back the generated file, we compare the output signals that were captured in the controller from the vehicle and the bench-model under the same input signals.

As can be seen from Figure 11, the engine RPM trace (intentionally time-shifted) is almost a 100% match with vehicle data. So, we were able to eliminate any input error(s) from the model verification process.

Figure 12 shows the test result for output shaft speed comparison. As can be seen the output shaft trace from the bench, driven by the same input signals as the vehicle, is fairly similar to the vehicle captured data. Thus, we have confidence in the feasibility of the model.

Table 2 Playback Input Signals

Row	Signal
1	Time
2	Throttle
3	Gear
4	Brake Switch
5	Engine Torque
6	Engine Speed
7	Calculated Brake

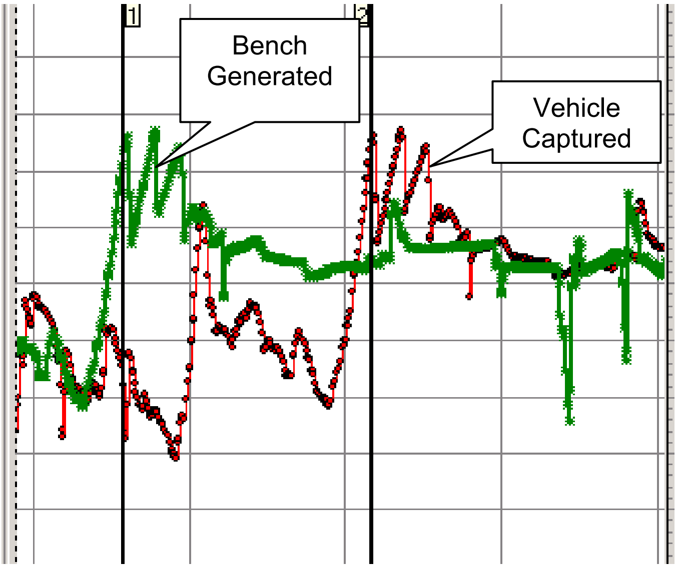


Figure 11 Engine Speed (RPM) Comparison

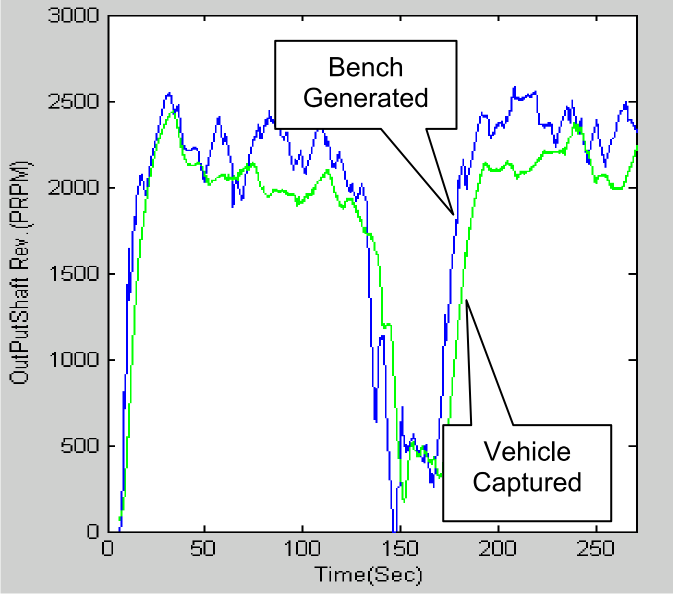
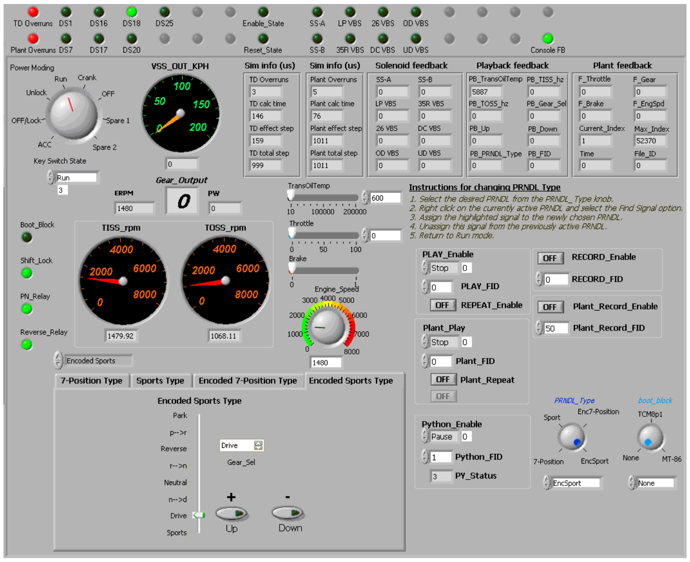


Figure 12 Output Shaft Speed (RPM) Comparison

CONTROL ALGORITHM TESTING

Based on the validation results of the model and the bench, we did feasibility tests of the model for algorithm test usage.

For this case, we performed some user-maneuvers from the user console panel (shown in Figure 13) so that tester can input the Engine Speed and Brake ON/OFF signals (when ON: it imposes 2000 N-m brake force).



Sim info (us)		**Sim info (us)**	
TD Overruns	3	Plant Overruns	5
TD calc time	146	Plant calc time	76
TD effect step	159	Plant effect step	1011
TD total step	999	Plant total step	1011

Solenoid feedback		**Playback feedback**		**Plant feedback**	
SS-A 0	SS-B 0	PB_TransOilTemp 5887	PB_TISS_hz 0	F_Throttle 0	F_Gear 0
LP VBS 0	35R VBS 0	PB_TOSS_hz 0	PB_Gear_Sel 0	F_Brake 0	F_EngSpd 0
26 VBS 0	DC VBS 0	PB_Up 0	PB_Down 0	Current_Index 1	Max_Index 52370
OD VBS 0	UD VBS 0	PB_PRNDL_Type 0	PB_FID 0	Time 0	File_ID 0

Key Switch State Run 3

VSS_OUT_KPH 0

Gear_Output 0

ERPM 1480

PW 0

TransOilTemp 600

Throttle 0

Brake

TISS_rpm 1479.92

TOSS_rpm 1068.11

Engine_Speed 1480

Encoded Sports

Gear_Sel Drive

Instructions for changing PRNDL Type

1. *Select the desired PRNDL from the PRNDL_Type knob.*
2. *Right click on the currently active PRNDL and select the Find Signal option.*
3. *Assign the highlighted signal to the newly chosen PRNDL.*
4. *Unassign this signal from the previously active PRNDL.*
5. *Return to Run mode.*

PLAY_Enable Stop 0

0 PLAY_FID

OFF REPEAT_Enable

OFF RECORD_Enable

0 RECORD_FID

OFF Plant_Record_Enable

50 Plant_Record_FID

Plant_Play Stop 0

0 Plant_FID

OFF Plant_Repeat

OFF

Python_Enable Pause 0

1 Python_FID

3 PY_Status

PRNDL_Type EncSport

boot_block None

Figure 13 Closed-Loop Model Console

In Figure 13, the front-end of the simulator console is shown. This allows the user to interact with the simulation and drive the plant model's inputs in the form engine speed, brake and also feed such inputs of the TCM as shift-lever position and transmission oil temperature. The plant model's outputs are shown in terms of TISS, TOSS speed traces and vehicle speed. Hence, this interface allows the user to create arbitrary driving test cases and allows for testing of control algorithms on the bench without having to use a vehicle.

The controller's reaction to the shaft speeds stimuli from the plant model is available over the vehicle CAN bus, with the target gear-shift indicator information being used for the plant model's gear input to trigger the shifting.

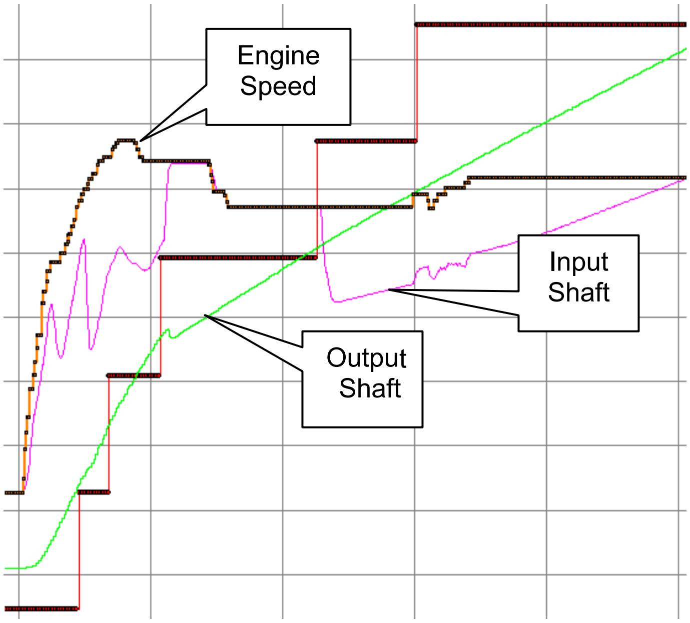


Figure 14 Up-shifts from 1st to 6th Gear

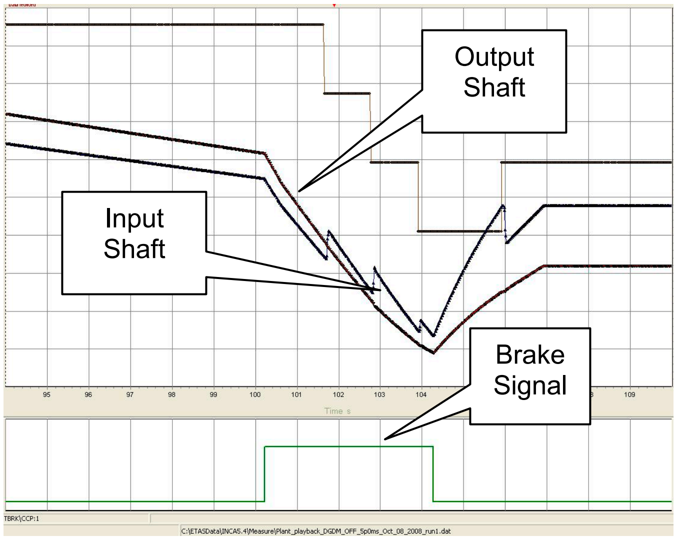
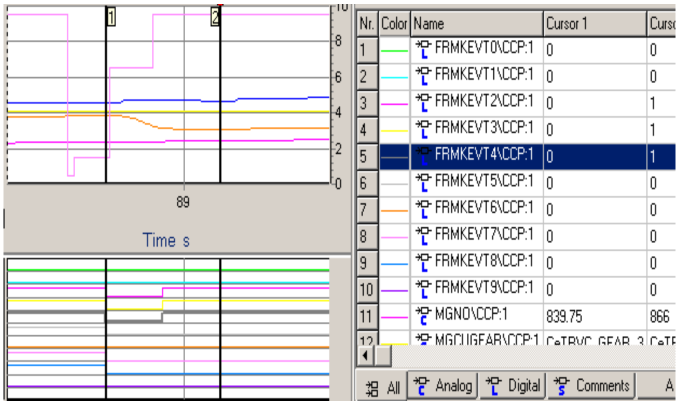


Figure 15 Down-shifts from 6th to 3rd Gear

Figure 14 shows the up-shifts case where we shift the transmission through 1 to 6 gears.

As can be seen in Figure 15, when the brake is applied, the output shaft RPM drops due to the braking force (2000 N-m constant). And, thus we were able to initiate down-shifts by the application of brake force.



Nr.	Color	Name	Cursor 1	Curs
1	—	FRMKEVT0\CCP:1	0	0
2	—	FRMKEVT1\CCP:1	0	0
3	—	FRMKEVT2\CCP:1	0	1
4	—	FRMKEVT3\CCP:1	0	1
5	—	FRMKEVT4\CCP:1	0	1
6	—	FRMKEVT5\CCP:1	0	0
7	—	FRMKEVT6\CCP:1	0	0
8	—	FRMKEVT7\CCP:1	0	0
9	—	FRMKEVT8\CCP:1	0	0
10	—	FRMKEVT9\CCP:1	0	0
11	—	MGNO\CCP:1	839.75	866
12	—	MGCUGEAR\CCP:1	CeTRVC_GEAR_3	CeTR

Figure 16 Power-Off 3 to 4 Up-shift Event

Figure 16 shows an example of the detailed shift events (power-off 3 to 4 up-shift case).

During shift control, we set the phase control conditions which are defined by output shaft and input shaft RPM relation and the variables in this figure show whether the conditions have been met for a specific shift event. In the presented case, the conditions were met as expected.

Thus, we were able to test and verify control algorithms by using the plant model available on the HIL bench since it can generate the needed RPM relations as shifting progresses similar to a real car.

Parameter Estimation

The MathWorks Simulink Parameter Estimation tool was used to dynamically tune certain model parameters to improve the model performance. This is a Simulink-based tool that is used to estimate and calibrate model parameters from test data. The tool uses optimization techniques to reduce the cost function (usually a least square error between test and model data). Table 3 tabulates the preliminary list of parameters selected for tuning and their values before and after estimation. Based on this table, it can be seen that the initial selection of parameter values was very close to the estimated values. This task doesn't yet encompass all the parameters to be tuned in the model.

Table 3 Parameter Estimation

Parameter (units)	**Pre-Estimation**	**Post-Estimation**
Tire Inertia (Kg-m^2)	180	175
Impeller Inertia (Kg-m^2)	10	1.07
Turbine Inertia (Kg-m^2)	1	0.34
Braking Force (N-m)	2000	1940
Vertical Load (N)	4000	4414
Peak Longitudinal Force (N)	4600	4694
Vehicle Mass (Kg)	2500	2786

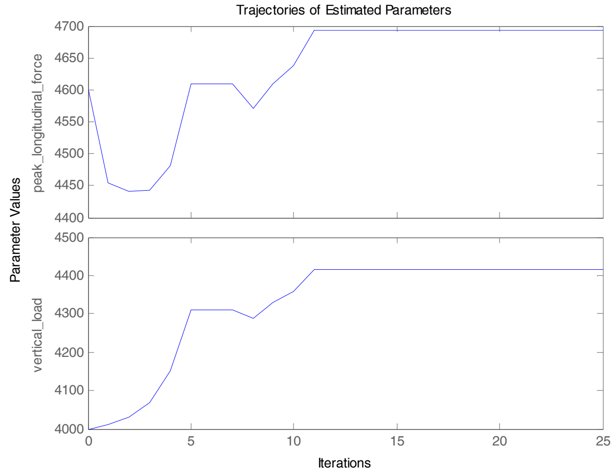


Figure 17 Parameter Trajectories

Figure 17 shows the trajectories of 2 parameters (Peak Longitudinal Force, Vertical Load from the Tire block) over the estimation iterations.

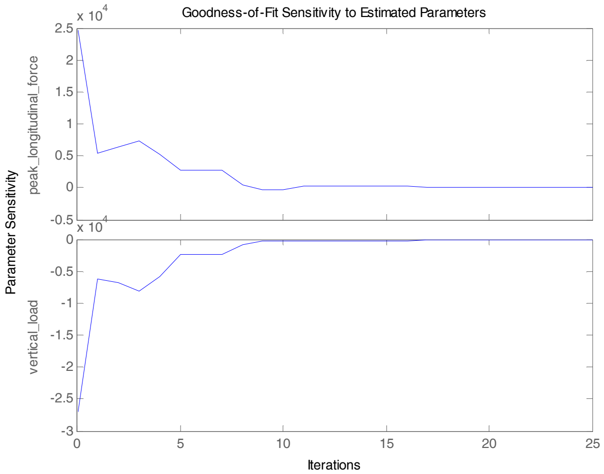


Figure 18 Parameter Sensitivities

Figure 18 plots the parameter sensitivities as the iterations progress. Sensitivity demonstrates the relative importance of certain model parameters compared to others.

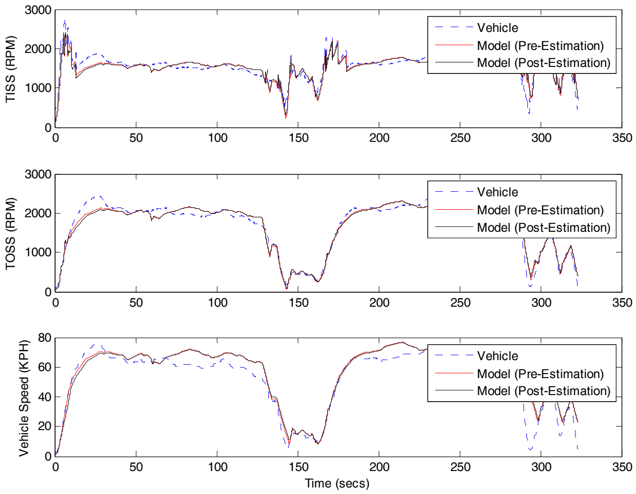


Figure 19 Transmission Outputs Comparison (before and after estimation)

In Figure 19, the comparison of model outputs (pre-estimation vs. post-estimation) with vehicle data is shown. It can be observed from this comparison that very little improvement in the model performance was achieved and this relates to the fact that the initial values of these parameters are reasonably correct.

FUTURE WORK

There are a few avenues to explore in the future to enhance this drive-train model. Some of these are listed below.

1. Use MathWorks Simulink Parameter Estimation tool to dynamically tune the model parameters to further refine performance.
2. Add a hydraulic plant to model the transmission hydraulics; we could utilize MathWorks SimHydraulics physical modeling block-set for this purpose.
3. Add a high-fidelity engine model to drive the detailed drive-train plant dynamics model.

CONCLUSION

In this paper, we presented the enhancement of Delphi's HIL bench in particular, the 6-speed automatic transmission plant dynamics model improvement and current measurement integration (model and H/W) has been discussed. Bench architecture, plant model development and validation, bench capabilities and test cases are presented. Finally, proposed future development is given.

REFERENCES

1. Q. Zheng, A. Habeebullah, W. Chung, "A 6-Speed Automatic Transmission Plant Dynamics Model for HIL Test Bench", SAE Technical Paper, No. 2008-01-0630.
2. Q. Zheng, W. Chung, K. Defore and A. Herman, “A Hardware-in-the-loop Test Bench for Production Transmission Controls Software Quality Validation”, SAE Technical Paper, No. 2007-01-0502.
3. Japanese Society of Automotive Engineers, Automotive Engineering hand book, Book #2, Design, page 559-560.

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DEFINITIONS, ACRONYMS, ABREVIATIONS

ECM: Engine Control Module

TCM: Transmission Control Module

PCM: Powertrain Control Module

AutoBoB: Automated Break-Out-Box

HAL: Hardware Abstraction Layer

HWIO: Hardware Input Output Layer

HIL: Hardware-In-the-Loop

CAN: Controller Area Network

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