Powertrain and Chassis Hardware-in-the-Loop (HIL) Simulation of Autonomous Vehicle Platform

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ABSTRACT

The automotive industry is heading towards the path of autonomy with the development of autonomous vehicles. Ford Motor Company is currently working on research prototype autonomous vehicles. The Autonomous Vehicle Platform (AVP), which is an upgraded version of the vehicle platform, intended for SAE Level 4 autonomous vehicles is currently under development. The AVP consists of the vehicle itself and its corresponding subsystems which encompass all the hardware aspects of the physical vehicle which are responsible for vehicle motion such as the engine, brakes and steering subsystems along with their corresponding controls. For SAE Level 4 autonomous vehicles, where an automated driving system is responsible for all the dynamics driving tasks including the fallback driving performance in case of system faults, redundant mechanical systems and controls are required as part of the AVP since the driver is completely out of the loop with respect to driving. As in-vehicle testing for autonomous vehicles will be considered expensive, time-consuming, and unsafe due to the number of scenarios and driven kilometers required for validation, a simulation platform, which can provide a controlled and consistent testing environment, is required for rapid prototyping and testing of the hardware and software components of the AVP. This research focuses on a powertrain and chassis hardware-in-the-loop (HIL) simulation of the AVP and the correlation of the performance of the corresponding subsystems with those of the AVP portion of the actual research prototype autonomous vehicle. This setup includes powertrain controllers and actuators, redundant brakes and steering controllers, alongside full brake hydraulics hardware. 2017 Ford Fusion Hybrid was used as the vehicle platform for simulation. The simulation of other subsystem plants and controllers was achieved by using a real-time Simulink®-CarSim® co-simulation environment representative of the 2017 Ford Fusion Hybrid through a dSPACE® HIL simulator.

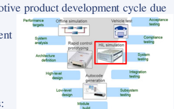
INTRODUCTION

An autonomous vehicle consists of two main high-level components:

- Virtual Driving System (VDS)
  - This consists of the algorithms for localization, path planning, computer vision, and high-definition 3D maps along with the sensor hardware for radars, cameras, lidars, and INS (Inertial Navigation System)
- Autonomous Vehicle Platform (AVP)
  - This consists of the upgraded version of the vehicle itself and its corresponding subsystems which encompass all the hardware aspects of the physical vehicle which are responsible for vehicle motion such as the engine, brakes and steering subsystems along with their corresponding controls.

Hardware-in-the-Loop (HIL) simulation is a testing method which has become an integral part of control validation in the automotive product development cycle due to the following benefits:

- Controllers tested in a simulated environment
- Scalability and repeatability of scenarios
- Improvement in test consistency
- Reduction in system variation

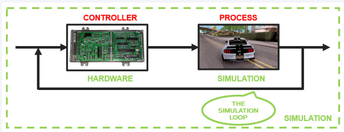


The objectives of this research were as follows:

- Develop a HIL simulation for the AVP for powertrain and chassis, including redundant systems for brakes and steering.
- Correlate the performance of the different subsystems of the HIL simulation with those on the vehicle to understand the fidelity and accuracy of the HIL simulation.

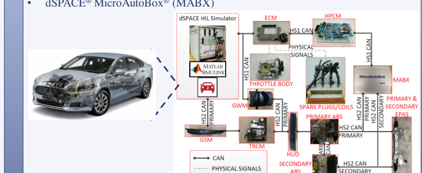
MATERIALS & METHODS

A Hardware-in-the-Loop (HIL) simulation provides a test platform where the system under test consists of actual hardware components with the remainder of the system simulated with mathematical or physics-based plant models of the processes via a real-time simulation platform.

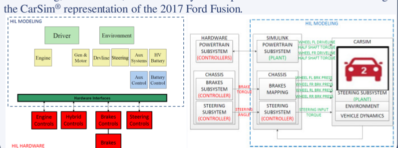


The HIL hardware setup of the vehicle level HIL simulation consisted of:

- Engine Control Module (ECM)
- Hybrid Powertrain Control Module (HPCM)
- Powertrain actuators such as throttle body and spark plugs/coils
- Gear Shift Module (GSM)
- Transmission Range Control Module (TRCM)
- Gateway Module (GWM)
- Heads-Up Display (HUD)
- Primary and Secondary Anti-Lock Brakes System (ABS)
- Full brakes hydraulics hardware
- Primary and Secondary Electronic Power Assisted Steering (EPAS)
- dSPACE® MicroAutoBox® (MABX)



The simulation of non-hardware subsystem plants and controllers was achieved by using a real-time Simulink®-CarSim® co-simulation environment representative of the 2017 Ford Fusion Hybrid. A high fidelity plant model of the power-split powertrain comprising an engine, motor-generator, high voltage battery, and planetary gear set driveline was defined in Simulink®, which formed the basis of the vehicle level plant model representation. The Simulink® plant model representation also included high voltage battery and auxiliary subsystem controller and plant models. The steering, environment, and vehicle dynamics plant models were simulated using the CarSim® representation of the 2017 Ford Fusion.



MATERIALS & METHODS

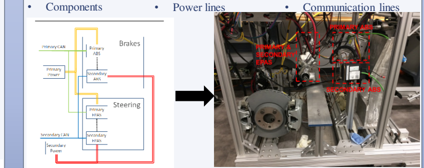
Most electronics systems such as ABS and EPAS (power steering) have inherent redundancies in place due to the presence of the driver. If ABS or EPAS fail, the driver is still able to actuate the brakes or steering physically with the loss of electronic assist features. For SAE Level 4 autonomous vehicles, redundancies will be required to mitigate the failure of important components and systems due to:

- Driver not being in the loop at all
- All vehicle control handled by autonomous system

Level	Name	Driving	Monitoring	Fallback
4	High Automation	System	System	System

SAE Level 4 autonomous vehicles must be designed such that the chassis controls are fail-operational or fail-functional, i.e. if a single controller or actuator fails, the drivability of the vehicle is maintained, however with degraded performance. In this design, the chassis control systems and their corresponding actuators must have independent and separate sets of:

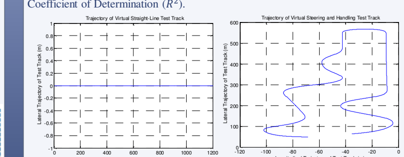
- Components
- Power lines
- Communication lines



SIMULATIONS & TEST RESULTS

The simulations were conducted on the Simulink®-CarSim® HIL simulation platform representation of 2017 Ford Fusion.

Simulations were conducted on a virtual straight-line track to correlate the powertrain and braking responses, and a virtual steering and handling course to correlate the steering response using the measures of Correlation Coefficient (r) and Coefficient of Determination (R^2).



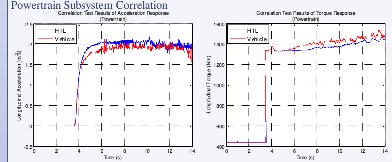
$$r = \frac{n\sum_{i=1}^{n} V_i N_i - \sum_{i=1}^{n} V_i \sum_{i=1}^{n} N_i}{\sqrt{n\sum_{i=1}^{n}(V_i)^2 - \left(\sum_{i=1}^{n} V_i\right)^2}\sqrt{n\sum_{i=1}^{n}(N_i)^2 - \left(\sum_{i=1}^{n} N_i\right)^2}}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(V_i - N_i)^2}{\sum_{i=1}^{n}\left(V_i - \frac{1}{n}\sum_{i=1}^{n} V_i\right)^2}$$

Where:
N_i = Nominal value
V_i = Varied value
n = Total number of data points

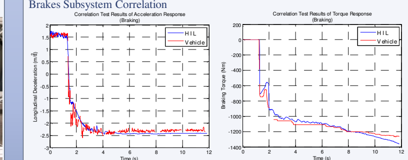
SIMULATIONS & TEST RESULTS

Powertrain Subsystem Correlation



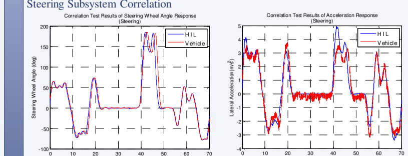
Response	Correlation Coefficient	Coefficient of Determination
Acceleration	0.9971	0.9823
Torque	0.9778	0.9487

Brakes Subsystem Correlation



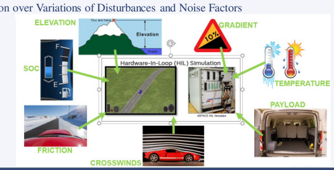
Response	Correlation Coefficient	Coefficient of Determination
Deceleration	0.9902	0.9788
Brake Torque	0.9890	0.9746

Steering Subsystem Correlation



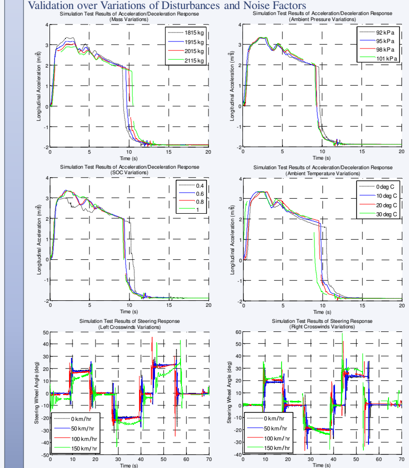
Response	Correlation Coefficient	Coefficient of Determination
Steering Wheel Angle	0.9669	0.9345
Lateral Acceleration	0.9645	0.9167

Validation over Variations of Disturbances and Noise Factors



SIMULATIONS & TEST RESULTS (CONT.)

Validation over Variations of Disturbances and Noise Factors



CONCLUSIONS

- Consistent and controlled test environment for repeated tests
- Different disturbance conditions/noise factors for robustness/analysis
- Unsafe driving scenarios tested in safe simulated environment
- Testing & validation costs over time: HIL <<<< Vehicle

Vehicle Testing		CarSim® HIL Simulation	
One-Time Costs		One-Time Costs	
Instrumentation	$50000	Lab construction	$120000
Recurring Costs		Recurring Costs	
Test vehicle and installation	$40000	Energy	$2000
Transportation	$20000	Installation	$5000
Fuel	$8000	Labor	$20000
Staff	$180000		

FUTURE WORK

- Addition of more high fidelity systems
  - High-Voltage Battery Subsystem HIL
  - Steering Subsystem HIL
- Addition of VDS hardware and software

CONTACT

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