

A Primer on Building a Hardware in the Loop Simulation and Validation for a 6X4 Tractor Trailer Model

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ABSTRACT

This research was to model a 6×4 tractor-trailer rig using TruckSim and simulate severe braking maneuvers with hardware in the loop and software in the loop simulations. For the hardware in the loop simulation (HIL), the tractor model was integrated with a 4s4m anti-lock braking system (ABS) and straight line braking tests were conducted. In developing the model, over 100 vehicle parameters were acquired from a real production tractor and entered into TruckSim. For the HIL simulation, the hardware consisted of a 4s4m ABS braking system with six brake chambers, four modulators, a treadle and an electronic control unit (ECU). A dSPACE simulator was used as the "interface" between the TruckSim computer model and the hardware.

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INTRODUCTION

As economies expand and populations grow so will the need for transportation of goods and the demand for large cargo vehicles. Commercial road vehicles such as tractor-trailers are perhaps the most common means for transporting goods in the U.S. With over 46,000 miles of interstate highway systems, 16,000 miles of non-interstate highways and nearly 3.9 million miles of other roads [1], today's tractor-trailers have plenty of infrastructure to deliver goods to all corners of the continental United States. With the number of tractor-trailers traveling on the U.S. roads each day it is important to continually work to improve the safety of these vehicles.

Whenever new control algorithms, brake hardware or essentially any new vehicle component is developed, it must be tested. Typically this is done with real world testing on a proving ground. Real world testing can be time consuming, costly and dangerous since a test driver is needed along with a test vehicle. When conducting severe maneuvers, the vehicle can potentially be damaged and the driver can be injured. Due to these short comings, HIL and SIL simulations techniques are becoming more and more popular. This paper explains the development of a hardware in the loop (HIL) simulation and the evaluation of the HIL process to accurately simulate the tractor

performance under braking maneuvers. This was accomplished by integrating the tractor model with MATLAB Simulink and utilizing actual braking hardware for the simulation. A dSPACE Midsize was used as the interface to facilitate interaction between the vehicle model, which operates in the computer realm, and the brake hardware, which operates in the physical realm. A braking system equipped with ABS was chosen. Upon completing the HIL simulation, the model was ran through several braking maneuvers in order to compare the simulated vehicle performance to the performance of the real tractor.

THE SAE J1939 PROTOCOL

Today's modern vehicles utilize many onboard computers which control different components throughout the vehicle. These controllers, also known as electronic control units (ECUs), are designed to control one or more sub-systems within the vehicle and do so in an efficient and optimal manner. For example, an electronic engine controller (EEC) may send and receive messages with an electronic transmission controller (ETC) in order to adjust engine speed and torque while a gear change is being performed. In this particular example, the EEC and ETC are connected in a CAN bus network, also known as a CAN network. The EEC and ETC

controllers are each considered to be “nodes” on the CAN network. There are several different types of CAN networks used in different applications. However, this research will focus on the Society of Automotive Engineers (SAE) J1939 CAN protocol [4,5,6,7]. The SAE J1939 protocol was developed with the goal of standardizing CAN network topology and communications for heavy-truck control applications. A list of some of the primary SAE J1939 document names and descriptions is given in Table 1. Of these J1939-14, -21, -71, -73 were the most relevant and useful for implementing CAN communications with the braking system ECU used in this research. See Ref. [2] for a more detailed discussion of the CAN communication.

Table 1. SAE J1939 Core Standards

Document Name	Description
J1939	Recommended Practice for a Serial Control and Communications Vehicle Network
J1939-01	Recommended Practice for Control And Communications Network for On-Highway Equipment
J1939-02	Agricultural and Forestry Off-Road Machinery Control and Communication Network
J1939-03	On Board Diagnostics Implementation Guide
J1939-05	Marine Stern Drive and Inboard Spark-Ignition Engine On-Board Diagnostics Implementation Guide
J1939-11	Physical Layer - 250k bits/s, Twisted Shielded Pair
J1939-14	Physical Layer - 500k bits/s, Twisted Shielded Pair
J1939-13	Off-Board Diagnostic Connector
J1939-15	Reduced Physical Layer, 250K bits/sec, Un-Shielded Twisted Pair (UTP)
J1939-21	Data Link Layer
J1939-31	Network Layer
J1939-71	Vehicle Application Layer
J1939-73	Application Layer - Diagnostics
J1939-74	Application - Configurable Messaging
J1939-75	Application Layer - Generator Sets and Industrial
J1939-81	Network Management
J1939-82	Compliance - Truck and Bus
J1939-84	OBD Communications Compliance Test Cases for Heavy Duty Components and Vehicles

Within the HIL simulation, a plant model runs on a platform using a real time processor. The plant model interacts with real world hardware via an input/output signal board. With HIL simulation, the hardware can be fully exercised just as if it were being tested on the real life plant. Fig. 1 is a simplified illustration which represents the overall working principle of the HIL simulation. Essentially, the plant consists of the heavy truck model which was designed in TruckSim and integrated into

MATLAB Simulink. This plant model runs on a dSPACE simulator in which the simulation is processed in real time. A host PC is used to run ControlDesk instrumentation software so the operator can observe the simulation and interact with it in real time as it runs. The simulation hardware consists of a real world ABS braking system. This hardware sends brake pressure signals to the plant model and receives wheel speed signals from the plant model via the dSPACE input/output board. In addition to this, CAN messages are transmitted back and forth between the hardware ECU and dSPACE.

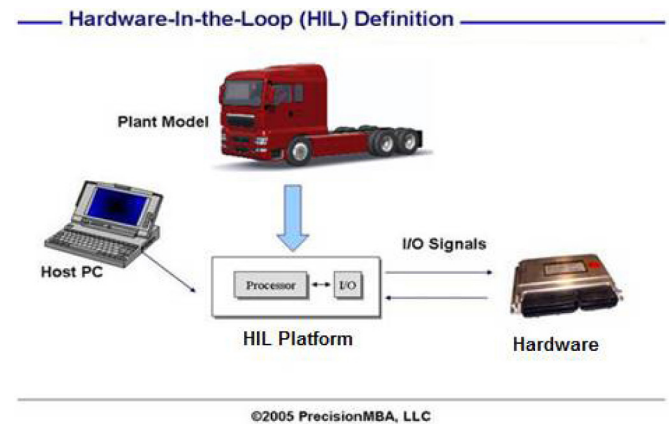


Figure 1. HIL Layout

The braking system utilized for the HIL simulator was a traditional pneumatic ABS system with pneumatic braking control. After the basic functionality of the braking hardware is understood, integrating the hardware with the TruckSim vehicle model was developed. The simulator was designed so the TruckSim model calculates the wheel speeds of the vehicle. These wheel speeds are then transmitted to the ABS ECU which controls the brake chamber pressures with the ABS modulators when severe wheel deceleration is sensed. The pressure modulation then causes a corresponding pressure fluctuation in each of the six brake chambers. These pressure fluctuations are sensed by six separate pressure transducers and the pressure data is transmitted back to the TruckSim model and converted to brake torque. The brake torque then influences the wheel speeds of the TruckSim vehicle mode. Finally, the wheel speed values are then transmitted from the TruckSim model back to the ABS ECU again. By configuring the brake hardware and TruckSim model in this fashion, a loop is created which consists of real life ABS braking hardware and software based vehicle dynamics computer model. This configuration is referred to as hardware in the loop.

Figure 2 is a signal flow diagram for the HIL simulator. Blocks have been added which represent the dSPACE real time processor (RTP) and the dSPACE input/output (I/O) board. The dSPACE RTP can be thought of as the main processor inside the dSPACE unit that actually runs the TruckSim vehicle model, also known as the TruckSim S-function, and corresponding Simulink model. The dSPACE RTP is configured to run in real time. This means if the TruckSim model numerical solvers are set to solve the model at a time interval of once

every millisecond in simulation time, the dSPACE processor will solve the model once every millisecond in real time. By solving the vehicle model in real time, one can integrate real life hardware, such as the braking system, which is designed to operate in the real time domain.

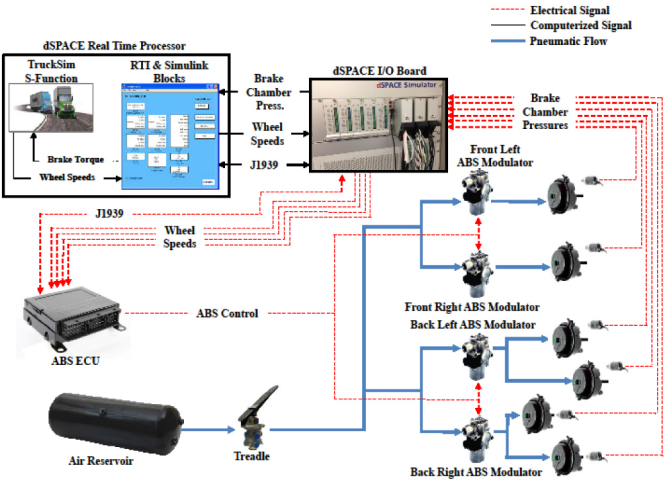


Figure 2. HIL Signal Diagram

In addition to receiving brake chamber pressure signals and transmitting wheel speed signals, dSPACE has the capability of transmitting and receiving J1939 messages. This is done through the use of special RTI blocks that come with the J1939 software toolbox known as the CAN J1939 Multimessage toolbox.

HIL Hardware Configuration

In order to create a rig that could accurately replicate the compliance of the truck brake assembly, bench test data from a vehicle manufacturer was analyzed. Figure 3 is the results from a static deflection test conducted by the manufacturer. As can be seen there are three significant points along the pressure versus stroke curve. Also, the force exerted on the piston at each point is given in Table 2. These forces are calculated using equation 1 which multiplies the brake chamber diaphragm area by the chamber pressure.

Table 2. HTM Brake Chamber Deflection Test

Point	Stroke [mm]	Chamber Pressure [bar]	Piston Force [N]
A	0.0	0.15	215
B	34.5	0.30	429
C	45.0	7.00	10010

$$F_p[N] = P[bar] \cdot \frac{100,000[N/m^2]}{1[bar]} \cdot A_{diaph}[m^2]$$
$$= P[bar] \cdot \frac{100,000[N/m^2]}{1[bar]} \cdot 1.43 \cdot 10^{-2}[m^2]$$

Equation 1

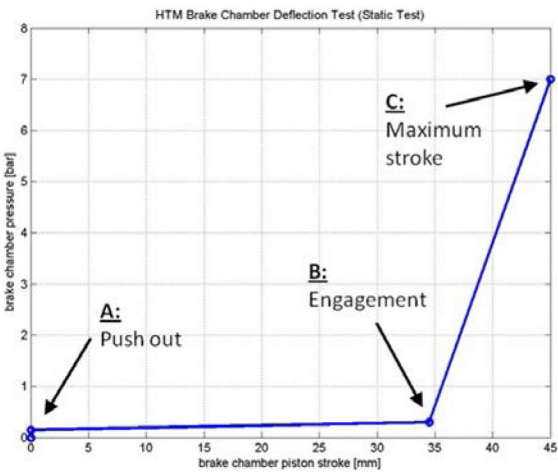


Figure 3. Drum Brake Deflection Test

When developing the brake chamber rig, the goal was to design it in such a way that the brake chamber would produce a similar pressure versus stroke curve as seen in Fig. 3. This was achieved by evaluating the stiffness characteristics of the plant drum brake assembly. Once the stiffness of the drum brake assembly was evaluated, a material with similar stiffness properties needed to be selected for the brake chamber rig and placed at a distance equal to the engagement point. By doing this the compliance of the entire plant drum brake assembly could be properly replicated.

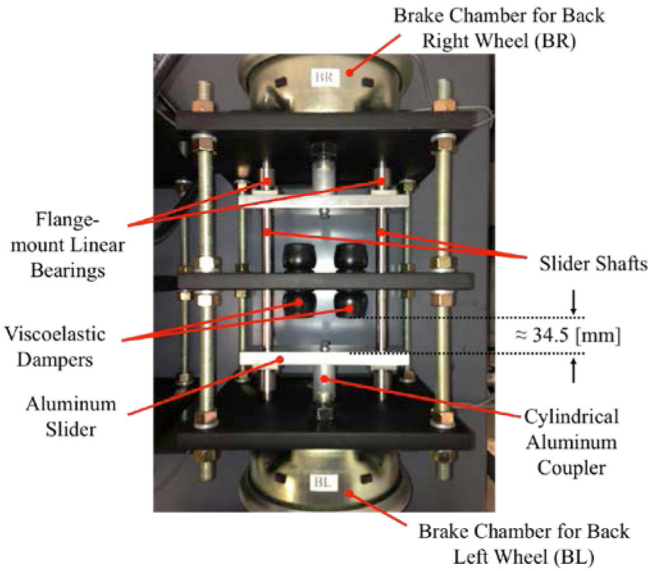


Figure 4. Brake Chamber Rig

Figure 4 is a top view of the final brake chamber rig design. Two brake chambers are integrated into each brake chamber rig. Each brake chamber piston is coupled to a cylindrical aluminum coupler which is then bolted to a rectangular aluminum slider. Each aluminum slider also contains two flange-mount linear bearings which allow the piston assembly to travel smoothly along two slider shafts. Finally, two rubber dampers are configured in parallel for each brake chamber. In total there are three brake chamber rigs and six brake chambers. To validate

the stiffness characteristics of these rigs, a static deflection test was conducted and the results were compared to the bench test. The result is shown in Fig. 5 and the deflection performance of the brake chamber rig (represented by HIL) is very similar to the performance recorded by the actual truck (represented by HTM). At seven bar, the test vehicle chambers have a stroke of 45 millimeters and the HIL rig has a stroke of 42 millimeters (a difference of 6.7%)

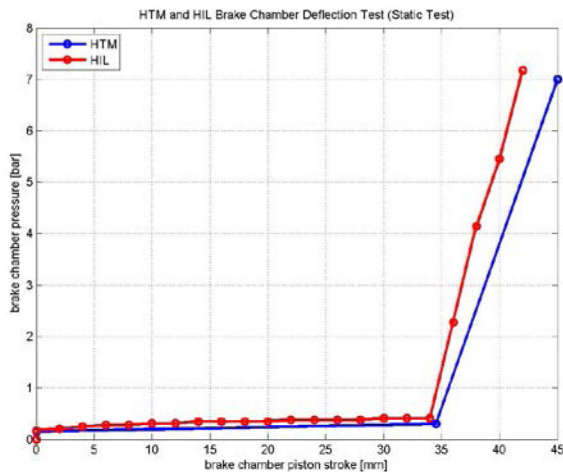


Figure 5. Emulating Drum Brake Stiffness

Validation of Hardware in the Loop Simulation

In order to assess the stopping performance of the ABS system, the manufacturer subjected a 6×4 tractor, identical to the one being modeled, to several straight line braking maneuvers and recorded the resulting performance data. Validation of the HIL simulator was accomplished by replicating the real world test maneuvers in TruckSim, running the simulation and then recording and comparing the resulting performance data. Variables including the ABS modulation time (the time span in which ABS brake pressure modulation occurs), average brake chamber pressure, stopping time and stopping distance were chosen as validation metrics since they directly measure how the ABS system controls the brake chambers, and vehicle speed during braking.

Braking Test Procedures

Four different road conditions were tested along with two different vehicle loading conditions. The first road condition was on a homogeneous low mu surface. The second was on a homogeneous high mu surface. The third was a low to high jump mu surface. Finally, the fourth road condition tested was on a split mu surface. These four surfaces were tested with the tractor subjected to two different loading conditions; unladen and laden. Next, the road friction characteristics had to be entered into TruckSim, see Ref. 3 for a more detailed discussion. Also, before the actual HIL braking tests could take place, the pressure rise performance of the brake hardware was evaluated and compared to similar data provided by the brake manufacturer. This test consisted of applying a step brake command, accomplished by actuating the brake treadle as fast as possible, with full pressure

in the air reservoirs. This test was conducted while the vehicle was stationary and without any ABS intervention. The purpose of this test is to assess how the transport delays and first-order time delays of the HIL brake hardware compare to bench test data from the braking system manufacturer. Table 3 compares the pressure rise time from the brake system manufacturer (BSM) and HIL test data. This illustrates that for the front chambers the difference is less than 8%. For the rear chambers the difference in rise time was greater. This is due to the fact that the rear relay valve found on the test vehicle was not utilized in the HIL simulator. For future works, it is recommended that such components be utilized in order to better replicate the test vehicle's dynamic brake response.

Table 3. Brake Chamber Pressure Rise Times

Brake Chamber	BSM	HIL	% Difference
Front Left	390 [ms]	420 [ms]	+7.7 [%]
Back Left	410 [ms]	740 [ms]	+80.5 [%]

Braking Tests

Test 1: Unladen Tractor on Low Mu Surface

For the initial braking test, the tractor was unladen (9320 kg) and the road conditions were set to homogeneous low mu (0.16 friction coefficient). The vehicle model started from a stop and was accelerated to a velocity of 50 k/h in accordance with the actual test. After maintaining the desired velocity for a few seconds, the brake treadle was manually pressed to 100 percent stroke and held there until the vehicle came to a complete stop. Upon pressing the treadle, the Simulink model was configured to automatically shift the transmission to neutral so torque and inertial effects from the engine were not experienced by the wheels. The resulting validation variables for the HIL and HTM tests are shown in Table 4. A graphical representation of the results can be found in the appendix.

Table 4. HIL Test 1 Validation Metrics

Validation Metrics	HTM		HIL		% Difference	
	Front Left Wheel	Back Left Wheel	Front Left Wheel	Back Left Wheel	Front Left Wheel	Back Left Wheel
ABS Modulation	11.04 [sec]	11.01 [sec]	11.98 [sec]	11.94 [sec]	+8.5 [%]	+8.4 [%]
Avg. Pressure	0.96 [bar]	0.48 [bar]	0.87 [bar]	0.57 [bar]	-9.4 [%]	+18.8 [%]
Stopping Time	11.73 [sec]		13.03 [sec]		+11.1 [%]	
Stopping Distance	88.96 [m]		95.02 [m]		+6.8 [%]	