

Hardware-in-the-Loop Pneumatic Braking System for Heavy Truck Testing of Advanced Electronic Safety Interventions

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ABSTRACT

The rapid innovation underway with vehicle brake safety systems leads to extensive evaluation and testing by system developers and regulatory agencies. The ability to evaluate complex heavy truck braking systems is potentially more rapid and economical through hardware-in-the-loop (HiL) simulation which employs the actual electronics and vehicle hardware. Though the initial HiL system development is time consuming and expensive, tests conducted on the completed system do not require track time, fuel, vehicle maintenance, or technician labor for driving or truck configuration changes. Truck and trailer configuration and loading as well as test scenarios can be rapidly adjusted within the vehicle dynamics simulation software to evaluate the performance of automated safety interventions (such as ESC) over a wide range of conditions. Hardware-in-the-loop simulation does not obviate the need for all track testing; vehicle models for simulation must be validated against track data for each truck platform. But HiL simulation can supplement and extend track data for tests at higher speeds, low friction surfaces, and alternate vehicle configurations. A HiL pneumatic braking system was developed for this purpose by the National Highway Traffic Safety Administration, with the goal of evaluating performance as it relates to safety. This paper describes the system in detail and includes some sample results of the testing.

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INTRODUCTION

The latest innovations in the automotive fields of active safety systems (e.g. electronic stability control (ESC)) and advanced driver assistance systems (e.g. Automatic Emergency Braking (AEB)) are driven by inexpensive electronics hardware and more capable software. Late model automobiles are computers on wheels. By some estimates, more than 80% of automotive innovations are software-based [1], and this trend is almost certain to continue as the capabilities of microprocessors, networks, and software grow.

Today's cars and trucks include dozens of electronic control units (ECU) that are connected via various network communications protocols like controller area network (CAN), local interconnect network, and FlexRay. Automotive-grade Ethernet chipsets and software have already been introduced which pave the way for 100MBPS networks in vehicles. This enables bandwidth support for sophisticated complex technologies such as driving, connected vehicles, and driver-assistance technologies. The complexity of this networked structure, combined with a great diversity of vehicle types, increases the challenge of developing and executing effective vehicle test procedures.

One such driver-assistance technology is ESC, which is now required in the US and the European Union for all passenger vehicles MY 2012 and later which are under 10,000 pounds (4536 kg) [2,3]. According to NHTSA (2007), a third of the fatal crashes could have been prevented by this technology [4,5], and this technology is mandated through Federal Motor Vehicle Safety Standard (FMVSS) No. 126. ESC automatically to maintain directional control in situations where the driver's own steering and braking cannot be accomplished quickly enough to prevent the crash. In 2015, NHTSA finalized the rule requiring ESC systems on heavy trucks and large buses (FMVSS No. 136). ESC systems are now available for heavy trucks and tractor-trailer combinations. Its presence in the heavy vehicle sector is expected to further reduce fatal crashes on the road.

Physical testing of heavy vehicles equipped with ESC is limited for many reasons. Safety considerations for the driver and vehicle stability often prevent heavy vehicle testing at higher speeds that can be attained on public roadways. There is a lack of large scale specialized testing facilities for heavy vehicles. The wide variety of tractor-trailer and straight-truck configurations makes full scale

experimental testing cost prohibitive. ESC testing on low-friction surfaces is complicated by the difficulty in achieving repeatable results. Operator variability can add uncertainty as well.

Hardware-in-the-loop (HiL) systems can extend field experiments and have the potential to reduce testing expenses and development time. HiL simulation for heavy trucks involves interdisciplinary engineering expertise that encompasses vehicle motion physics and computer modeling, software engineering, network communication expertise, electronics hardware and real-time applications, pneumatic brake systems, and proprietary ECUs. Figures 1, 2, 3 show the pneumatic HiL system architecture built at NHTSA's Vehicle Research and Test Center (VRTC) in 2012.

Figure 1 displays the tractor portion of the HiL hardware, housed in a room walled with sound-damping material. The pressure vessels are visible on the lower left side, with the dSPACE hardware and dashboard display directly above. On the right are 10 brake chambers, sufficient to simulate up to 5 axles. These chambers are appropriately sized for steer and drive axles, and connected to the modulators with a size and length of pressure hose to match real heavy truck applications. A Bendix EC-60 electronic control unit (ECU) is located on the upper level toward the center. Other features are highlighted throughout the paper.

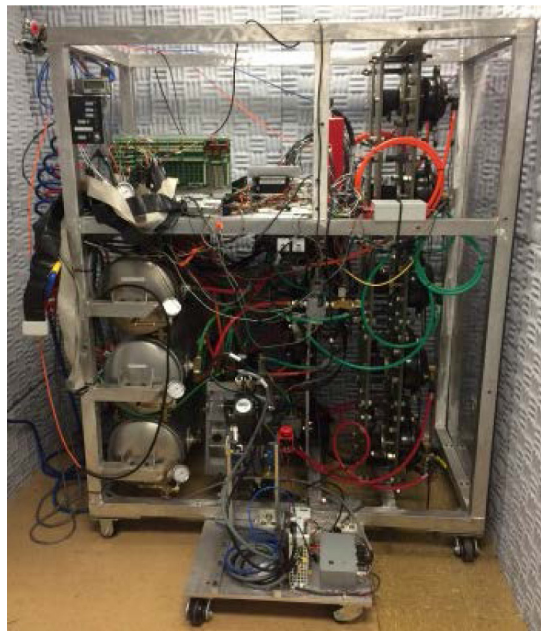


Figure 1. NHTSA Heavy Truck HiL System - Tractor

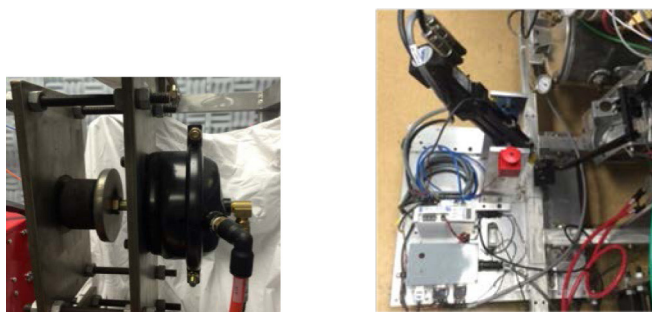


Figure 2. Brake chamber (left) and pedal actuator (right)



Figure 3. NHTSA Heavy Truck HiL System - Trailer

Figure 3 shows a separate module housing similar components for the heavy truck trailer. In addition, this system has a Bendix TABS-6 trailer ECU mounted in a servo-driven rotating housing to make the ECU react to the simulated trailer roll angle. A separate section is dedicated to the trailer ECU later in the paper.

HIL SYSTEM COMPONENTS

This paper discusses the development of NHTSA's pneumatic HiL for heavy trucks and buses. The system can simulate tractor and trailer combinations, as well as non-articulating single unit trucks, from Class 3 to 8, with push axle capabilities.

Figure 4 shows a schematic of the signal flow among the major components of this system. A host PC is used for all non-real-time operations, including model compilation, system monitoring, data storage and analysis, etc. During real-time simulation, the compiled software runs on the real-time dSPACE hardware.

ControlDesk® Next Generation is a dSPACE software that offers a graphical interface to the simulation running on the dSPACE real-time computer (Figure 5). It provides complete control over the simulator hardware and Simulink models through its virtual instrumentation interface during run time.

The heavy truck vehicle dynamics are modeled with TruckSIM® software (Figure 6). It is loaded in Simulink (Figure 7) as a DLL file through a special Simulink S-function. This feature is possible through a process that involves cross compilation of the model from TruckSIM to C and then finally to a dSPACE processor board target executable. The target executable is downloaded to and executed on the processor board by the ControlDesk software.

The data transfer between the dSPACE real-time system and the host PC's graphical displays is not as time-critical as the timing of the control loop. The time necessary to transfer data from the real-time system to the host PC is small compared to the PC's computing time required for tasks such as drawing graphics by TruckSIM real-time animator. However, data acquisition of model and ECU data is time-critical, and dSPACE software includes options through ControlDesk to check real-time integrity and accuracy. Currently, the tractor and trailer is running on a single processor with a real-time time

step of 1 ms; the system uses only 0.86 ms to complete one cycle, so no overruns are experienced. The system is capable of running on four processors, but only one processor is used for basic ESC simulations. A dual processor simulation system is under development for the new hydraulic HiL system at NHTSA, and for systems that include advanced driver braking assistance systems. TruckSIM® animation feature is used to display real time graphics of the simulated vehicle and environment (Figure 8). The animation runs on the host PC and does not affect HiL simulation real-time performance.

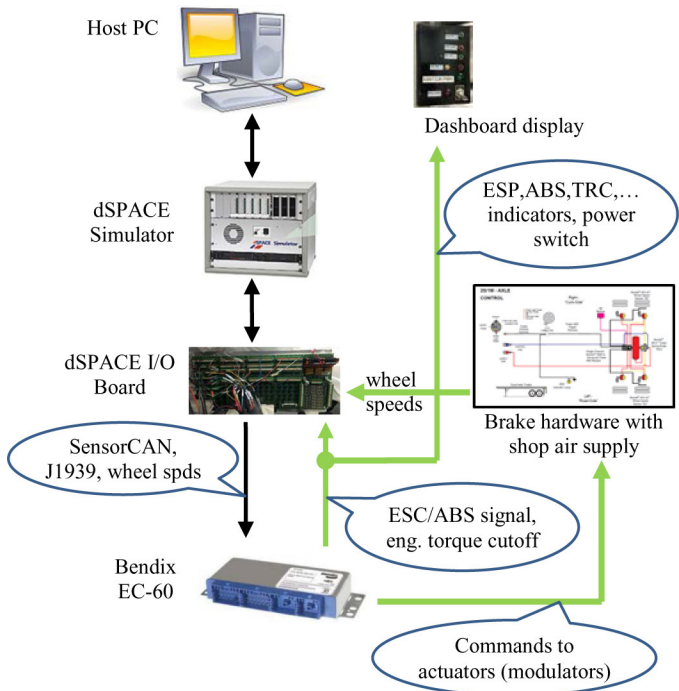


Figure 4. Pneumatic HiL System Flowchart [6]



Figure 5. dSPACE ControlDesk Next Generation

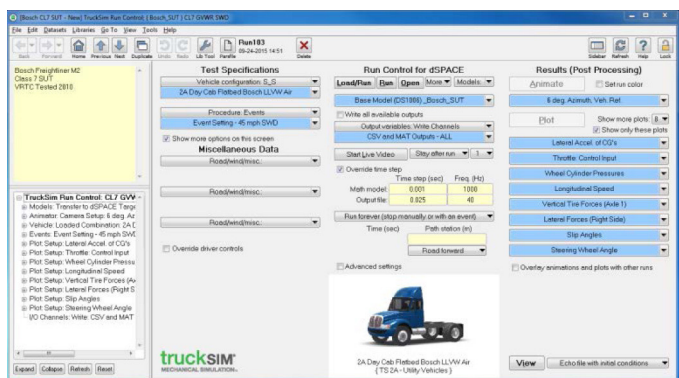


Figure 6. TruckSIM interface

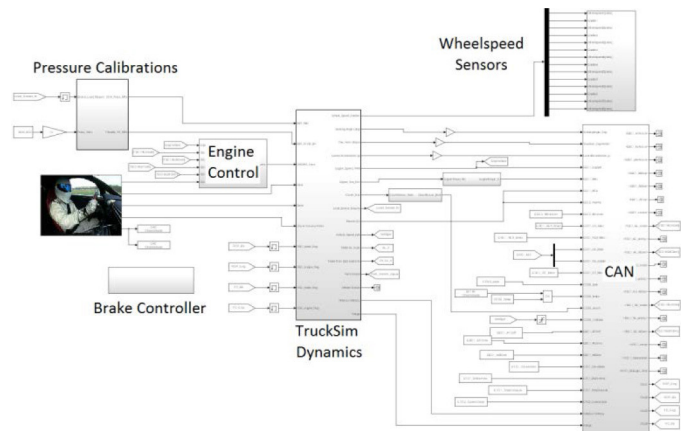


Figure 7. Simulink model

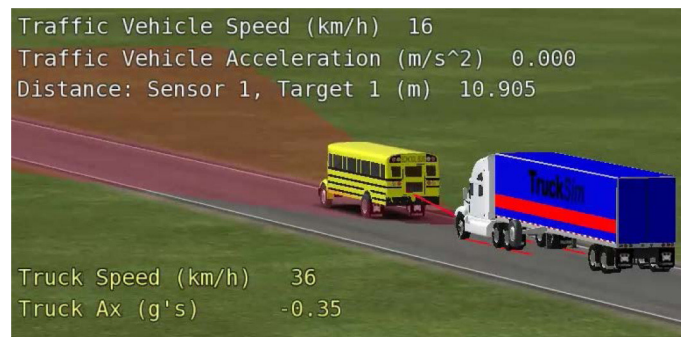


Figure 8. TruckSIM model real-time animation

dSPACE Simulator

NHTSA’s HiL Simulator is equipped with dSPACE real-time hardware composed of one real-time-processor (DS1006-QC quad core multiprocessor) and three I/O processor boards housed in a PX10 chassis. The DS1006-QC board provides the host PC access to the real-time program and is connected to I/O Boards via a PHS (peripheral high speed) bus communicating at 20Mbyte/s.

Three dSPACE I/O boards are used. The first is the DS2211 board, which is tailored to simulation and measurement of automotive HiL systems [7]. It contains signal conditioning for signals up to 42 Volt and it supports 2-voltage systems. It is the central I/O board for this simulator with 16 analog differential input channels, 20 analog differential output channels, 8 wheel speed channels based on a Texas Instrument DSP board, 16 digital input channels, and 2 bus CAN communication interfaces. The DS2211 board also has other capabilities that are currently not needed for the pneumatic HiL. A detailed description of this board is available at dSPACE web site.

A DS5376 breakout board is added to allow flexible signal routing from the DS2211 50-pole connectors (P1A, P1B, P2A, P2B, P3) to the ECUs and the remaining HiL electric/electronic circuits. The DS5376 offers terminals for loads with up to 8A per channel. Twelve and 24 volt battery supply voltages are connected to this board and used to power digital signals and power relays. All analog inputs and outputs are differential and share a common ground with the power supply.

The HiL system for heavy trucks requires the sampling and recording of many brake line pressures to be fed to the software simulating vehicle motion. The 16 analog input channels available at the DS2211 are not enough to record all the necessary data of the HiL hardware system, thus a second I/O board (DS2002) is added for the input of single-ended channels.

The HiL is also designed to handle interfaces to radar systems and other vehicle devices, so a DS4302 CAN Interface Board is added to the system which adds four extra CAN channels to the system (Figure 9). NHTSA's HiL system has a total of six CAN channels available to connect to ECUs and other hardware.

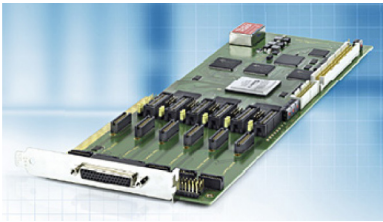


Figure 9. DS4302 CAN Interface Board [8].

ECU Systems

The current NHTSA HiL system is set up to simulate tractor-trailer combinations with up to 10 axles and pneumatic braking. Single-unit medium to heavy trucks with up to five axles can be simulated as well. Two ECUs are used to control the heavy truck ESC systems, Bendix EC-60 Advanced for the tractor (Figure 10) and Bendix TABS-6 Advanced for the trailer (Figure 16). Both ECUs are electronically connected as in real-life applications with OEM (Bendix) original embedded software. The system can handle ECUs from different manufacturers, but efforts thus far have focused on the Bendix ECU.

The tractor electronic and stability system applied in the HiL is Bendix EC-60 configured for ABS and ESC with the following manufacturer designation: "ABS6 ROM7 ESP System 6S/4M" (six speed sensors and four modulators). It is vehicle-specific and programmed for the Volvo Tractor with VIN K040157. Bendix provides a detailed discussion of this system in their publication SD-13-4869 [9]. The system provides ABS-based stability features and automatic traction control. For directional stability, it is equipped with yaw control (YC) that enables brake application of individual wheels, as well as applying equal left and right braking for all trailer wheels. It also mitigates rollover with its roll stability program (RSP). This latter option reduces engine speed and applies brakes on all axles as needed to mitigate rollover through speed reduction.

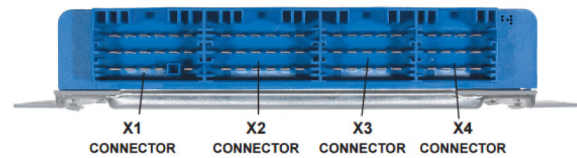
EC-60 Advanced Connections

The EC-60 electronic connections to dSPACE real-time computer, manual switches, LED indicators, and pneumatic actuators are shown in Figure 10. The ECU input impedances were made to match those in real vehicle applications. Figure 12 shows the modified wiring schematic for the 6S/4M EC-60 controller for HiL applications; the

original schematic is available in the Bendix SD-13-4869 manual [9]. The main differences are where the dynamic sensors are replaced with inputs generated from the real time vehicle simulation.

Simulated inputs replace those from the yaw rate sensor, lateral acceleration sensor, wheel speed sensors, and the load pressure sensor. The retarder and the stop light inputs are passed to the E-60 through J1939 bus. A 6 kΩ load is added to the computer generated signal of the load sensor, while the load itself is generated within the TruckSim dynamic model. Wire gages were kept similar to the requirements indicated by the original Bendix wiring schematics.

EC-60™ Controller Wire Harness Connector Part Numbers and Pin Assignments:
ADVANCED CAB



Advanced Cab Model EC-60™ Controller

Advanced cab models utilize four AMP connectors for wire harness connections.

X1 Connector Pin Assignments

Pin	Designation	Pin	Designation	Pin	Designation
1	Ground	7	J1939 Low	13	J1587 (B)
2	Trailer ABS Indicator	8	J1939 High	14	J1587 (A)
3	Ignition	9	SLS Input	15	ABS Indicator Interlock
4	TCV CMN (DA)	10	WSS DA Right (+)	16	Battery
5	TCV (DA)	11	WSS DA Right (-)	17	Retarder
6	ATC/ESP Indicator and ATC ORS	12	ABS Indicator Ground	18	ABS Dash Indicator

Figure 10. Bendix ECU pin assignments [9].

The HiL system functions with several variants of the Bendix EC-60 ECU, each of which is attached to the system with modular quarter-turn multipin connectors (Figure 11). Shown below are ECUs programmed for a bus, single unit truck, and tractor-trailers with different automated safety features.



Figure 11. Various ECU-60s with modular quick disconnect

The pneumatic hardware is listed below, and was connected through the recommended tube sizes.

Actuators

- Five Bendix M-32 pressure modulators (Figure 13). These control the pressure applied to the trailer brakes during system intervention.
- Bendix ATR-6 drive axle traction control valve.
- Bendix TR-3 steer axle traction control valve.