HEAVY VEHICLE HARDWARE-IN-THE-LOOP CRASH AVOIDANCE SAFETY SYSTEM SIMULATION WITH EXPERIMENTAL VALIDATION

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ABSTRACT

Advanced crash avoidance technologies have the potential to address many of the high frequency crash scenarios involving heavy vehicles in the United States. For this paper, a heavy vehicle is defined as having a gross vehicle weight rating (GVWR) that exceeds 4536 kg (10,000 lb.). Test track research performed on heavy vehicles equipped with advanced crash avoidance technologies such as automatic emergency braking systems using real heavy trucks and buses is unavoidably limited by the dangers and expenses inherent in crash-imminent scenarios. High fidelity Hardware-in-the-Loop (HiL) simulation systems have the potential to enable safe, accurate, and repeatable laboratory testing that can provide performance data on heavy vehicle crash avoidance systems. This paper describes the setup and experimental validation of such a heavy vehicle HiL simulation system equipped with electronic stability control and automatic emergency braking systems.

INTRODUCTION

Automatic Emergency Braking system is an active technology system which includes, crash imminent braking (CIB) and dynamic brake support (DBS), that are specifically designed to help drivers avoid, or mitigate the severity of, rear-end crashes. CIB systems provide automatic braking when forward-looking sensors indicate that a crash is imminent and the driver has not applied the service brakes, whereas DBS systems provide supplemental braking when sensors determine that driver-applied braking is insufficient to avoid an imminent crash. NHTSA's recent market study, current through September 2016, shows that DBS systems are primarily deployed in the light vehicle market. The review of heavy vehicle manufacturer and supplier websites and news articles released by fleets and industrial trade groups indicates that new systems may be capable of DBS-like behavior and might become available in the upcoming new product offerings for heavy vehicles. Heavy trucks used to conduct test track research were not available with DBS at the time of their acquisition. Therefore, the simulation validation is confined for the CIB of the AEB systems.

Field testing of such systems using vehicles is necessarily limited by the dangers and expenses inherent in crash-imminent scenarios, especially when the system is not designed to eliminate all collisions but rather to reduce their severity. Moreover, testing of heavy vehicles is generally restricted to lower speeds because of space availability within proving ground facilities and safety requirements. HiL (Hardware-in-the-Loop) systems allow the expansion of testing to include aggressive scenarios not possible on the test track, like shorter following distances at higher speeds, aggressive lead vehicle decelerations, and other configurations reasoned impractical or dangerous with real vehicles. HiL systems for heavy trucks also allow simulations of different configurations of heavy vehicle classes, i.e., multiple loads and inertial configurations.

NHTSA constructed a HiL heavy truck pneumatic braking system operated through dSPACE hardware and integrated with Matlab/Simulink and TruckSIM co-simulation. This system was previously described in depth in [1] and validated for electronic stability control (ESC) testing in [2].

The system currently supports the Bendix EC-60 Electronic Control Unit (ECU) in various configurations. For this paper, a version of this ECU is used which includes the Bendix Wingman Advanced radar-based collision mitigation system. Specifically explored here is the AEB application. A single straight lane is used with one forward-moving vehicle (or target) to replicate NHTSA's test track crash scenarios designed to evaluate AEB systems' safety performance.

Two scenarios are used to compare simulated results with test track experiments. The first is the lead vehicle moving scenario (LVM), which evaluates the ability of the AEB system to detect and respond to a slower-moving vehicle in the immediate forward path of the truck. The second is the lead vehicle decelerating scenario (LVD). In this test, the lead vehicle is initially moving at a constant speed in the immediate forward path of the subject vehicle (SV), then after a short period the lead vehicle decelerates at a constant rate to a low constant speed in the range of 8 km/h (5 mph).

HiL Hardware and Software System

The HiL system uses identical radar hardware as is used in the Volvo Truck retrofitted with a Forward Collision Warning (FCW) and AEB system with a software option that accepts target position and speed injection through a CAN bus designed for testing and simulation. This capability allows for the testing of the logic and communication built into the radar, which is responsible for emergency brake activation signals. State-of-the-art radar technologies, like the FLR20, are smart sensors that detect targets and make appropriate calculations, sending brake commands to be executed by the vehicle's main ECU brake safety controller. The braking actions are finally executed by the vehicle dynamics ECU.

Figure.1 shows the Volvo tractor retrofitted with the Bendix FLR20 radar located on the center of the front bumper. This radar is integrated with the Driver Interface Unit (DIU) mounted on the vehicle dashboard. The placement of these units, as well as the ECU, in the HiL system can be seen in Figures 2 and 3. Both the simulated and experimentally tested tractor/trailer systems were loaded according to Federal Motor Vehicle Safety Standard (FMVSS) No. 121 GVWR requirements.

*Figure.1. Volvo truck with Bendix FLR20 radar and DIU*

Figure.2. Bendix ECU and FLR20 radar on HiL system
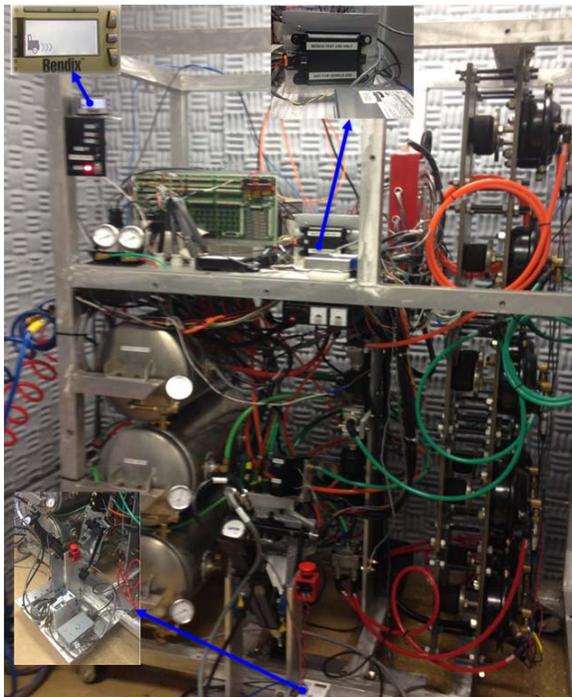
Figure 3. HiL pneumatic braking system with AEB – Arrows in the picture point to zoomed view-

The Controller Area Network (CAN) connections required for the HiL pneumatic braking system are shown in Figure.4. Note that the simulation hardware must simultaneously communicate on three different CAN networks. These are:

1) J1939 bus at 250 kbps (kbps = 1000 bit/sec), which is the society of Automotive Engineers standard used for communication and diagnostics among commercial vehicle components.
2) SenSor CAN at 250 kbps, which is a proprietary bus set by Bendix to transmit vehicle speed, yaw rate, lateral acceleration, and steering angle signal to the ECU. These variables are generated by the vehicle dynamics software, which is TruckSIM for this HiL system.
3) RadarCan at 500 kbps provides the radar unit (FR20) and ECU with speed and positions of the obstacles placed ahead of the vehicle. It is a proprietary bus developed by Bendix.
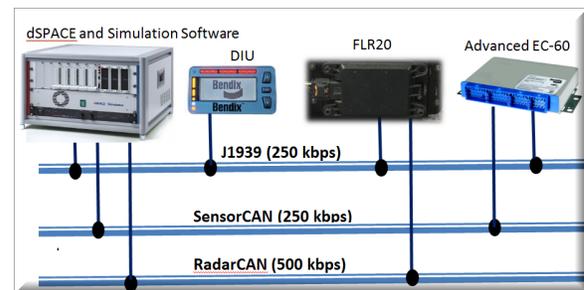
Figure.4. HiL CAN connections

NHTSA's HiL pneumatic system is designed to be applied with different classes of heavy vehicles. Only minor hardware changes are needed to switch the HiL for vehicles with different brake systems (brake chambers and brake lines with similar lengths and sizes to the actual vehicle). The system is built to accommodate these changes swiftly. Figure 5 shows different ECUs that can be connected in the HiL system. These are for a single unit truck, a bus, and tractor-trailer systems. The HiL system includes a trailer unit, in case trailer's ECU like those designed for roll stability control need to be connected and tested with the tractor. This unit is shown in Figure 6.

Figure 5. Different ECUs for HiL applications

Figure 6 HiL Trailer Unit

HiL System Validation

The HiL system was tested for most of the FMVSS No. 121 requirements that are usually applied to real production vehicles. These included longitudinal dynamics (stopping distance), pneumatic system response (delays), air-supply (chamber size versus brake chambers), ABS tests, and etc.

Vehicle dynamics model and simulation software was thoroughly validated with measured data [2], so as to produce simulated vehicle motion comparable to field testing. Lateral dynamics validations included evaluation of the understeer gradient, roll gradient, lateral acceleration and yaw rate. The evaluation was up to directional stability limit. Within the linear range, steady vehicle directional responses were evaluated in the frequency domain. Sweep sine steering at a constant speed was used to check vehicle bandwidth responses of yaw rate and lateral acceleration. As for the transient behavior, step steer input evaluation within the upper-linear range was used to check system responses timing and mechanical system damping properties (proper attenuation of lateral dynamics variables and their oscillatory properties need to be consistent with the modeled vehicle).

AEB Systems Validations

In this paper, the AEB system is validated with experimental data at low/mid-range test speeds. This allows to test system braking function and basic software operations. Since test data is not available for high speed testing or other potentially hazardous test situations (like close proximity between lead and subject vehicle), and with a properly validated vehicle dynamics model, the HiL system can then be applied to evaluate the AEB systems. This is primarily for conditions not possible to test on the track; like, high speed testing, low-mu or for a surface with degraded traction properties, split-mu cases, close proximity between lead and subject vehicles, cut-in driving, and scenarios with multiple target vehicles and obstacles, etc.

Dynamics Simulation and Radar Configuration

The simulated sensor range sensitivity is set at 100 m with a ±10° field of view. A school bus is chosen for the forward moving vehicle or target (Figure.7). The detection area is modeled as a box with length = 6.45m, height = 2.65m, and width = 2.44m. The simulated radar metrics are not affected by the particular choice or size of target vehicles, given the fact that the direction of travel is a straight path and the radar is on the vehicle centerline.

A typical graphical view of the real time animation is shown in Figure 8. The solid red line between the truck and the bus is the detection range, and the shaded area is the radar field of view. The radar graphics are enabled only when an object is detected within 100m. The speed and range of the forward moving vehicle are calculated by TruckSIM then injected into the FLR20 RadarCAN.

Figure.7. HiL target vehicle

Figure 8. TruckSIM simulation of AEB braking event

VALIDATION TESTS

Lead Vehicle Moving
This scenario evaluates the ability of the AEB system to detect and respond to a slower-moving lead vehicle traveling at a constant speed in the immediate forward path of travel. For this scenario, the truck (subject vehicle) is traveling at a constant speed of 40 km/h (24.9 mph) and the bus (target vehicle) is traveling at a constant speed of 16 km/h (9.9 mph). The initial range between the two vehicles is set at 35 m (114.8 feet.).

The truck approaches the bus at the relative speed of 24 km/h, and the driver does not intervene to avoid the crash either by braking or steering. When the time-to-collision (TTC) is approximately 2 seconds, the AEB system intervenes and applies the brakes automatically. Figure 9 shows the truck and bus speeds, and the range between them, all compared to experimental results. For this test, eight experimental trials were performed, and all are included in the comparison plots. The HiL AEB is initiated at a range (bumper-to-bumper distance) of 12.93 m, and the minimum range was 4.72 m. These values are very close to experimental metrics, where AEB is initiated between 12 and 14 m, and the minimum range varied from 2.5 to 5 m.

Figure 10 shows that the brake line pressures in the HiL system and the experimental truck are in agreement. There is a modest discrepancy in brake

line pressure #1 which corresponds to the left side of the steer axle. This difference between the HiL and test track experimental measurements is due to small discrepancies between the left and right sides of the front brakes as a result of unsymmetrical conditions. All rear left and right side brakes are symmetrical. The HiL system models symmetrical brake systems, and hence the front right and left brakes behave the same. Unless the experimental truck's asymmetrical behavior affects the nature of the test results, there is no need to tune the HiL hardware system to accommodate this small deviation. Alternatively, future research could be used to characterize the symmetry of real vehicles and then tune the simulator accordingly.

Figure 11 displays a comparison between HiL truck deceleration and measured experiments. The slight increase in deceleration at the end of the maneuver is attributed to a slight increase in brake line pressure. The TruckSIM brake model at the HiL uses a simple look-up table that relates brake chamber pressure to applied brake torque. This simple method is sufficient for this kind of simulations and produces results with reasonable fidelity.

Figure.12 shows that the HiL AEB initiation is at TTC = 1.93 seconds, while the experiments showed a variation from 1.75 to 2.15 seconds. The HiL minimum TTC is 1.78 seconds at 0.65 seconds after AEB initiation, which is within the range of experimental values which vary from 1.45 to 1.90 seconds.
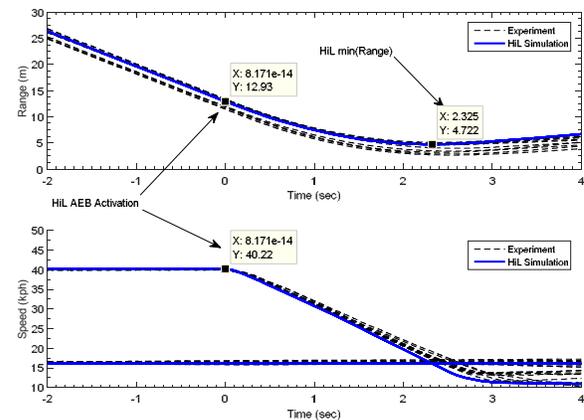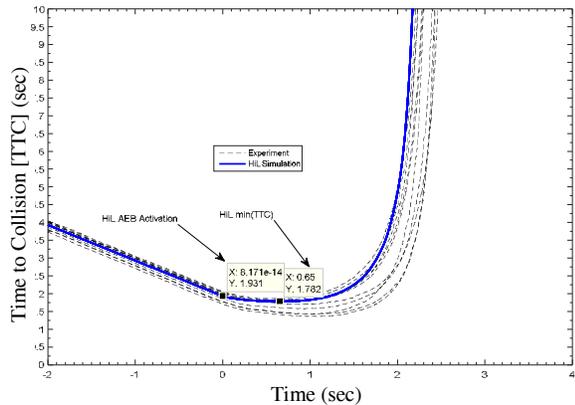

Figure 9 Truck and bus (lead vehicle: POV) speeds and ranges- 40/16 km/h SMLV scenario
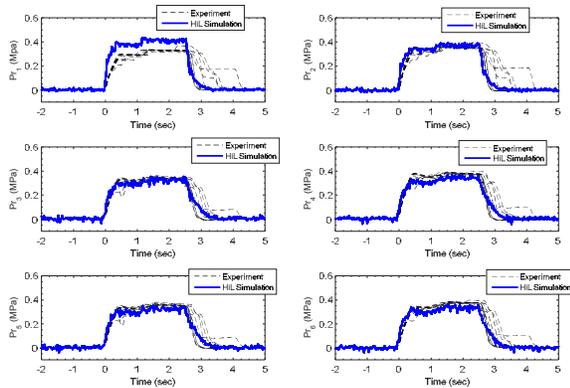
Figure 10. Brake line pressures - 40/16 km/h SMLV scenario
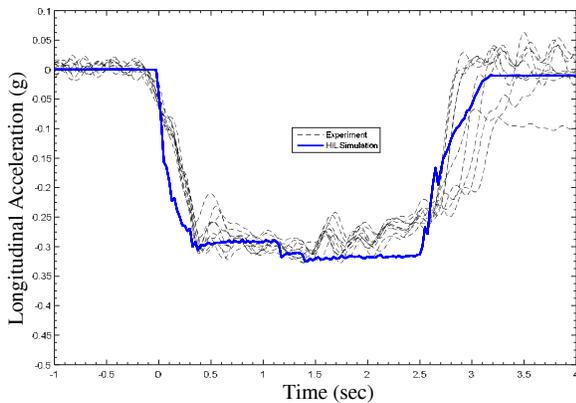
Figure 11. Truck and bus decelerations - 40/16 km/h SMLV scenario

Figure.12. TTC (Time to collision) - 40/16 km/h SMLV scenario

Lead Vehicle Decelerating

In the LVD scenario, the truck and the bus are driven at a nominal vehicle speed of 40 km/h (24.9 mph) with an initial separation of 80 m (262.5 feet). Then, as shown in Figure 16, the bus decelerates at a constant rate of 0.3g to a much slower constant speed of 5-10 mph. The TruckSIM lead vehicle is

programmed to follow an ideal deceleration path as shown in this figure.

For this scenario eight experimental trials were performed and these are compared to two HiL simulation results. Figure.13 shows the comparisons of speeds of vehicles involved. Overall the HiL system produces data comparable to experimental measures and with reasonable fidelity.

Figure 14 shows the comparison between HiL brake line pressure and experimental measurements. The AEB of all runs behaved differently toward the end, yet the main applications of brakes (first cycle) are very similar. As both the simulated and experimental trucks approached the lead vehicle, for a few numbers of runs, the AEB was applied more than once to avoid hitting the lead vehicle. This indicates sensitivity to small differences in relative speed and range, which is beneficial, since it could be used to further improve the AEB system's crash avoidance capabilities with a reasonable safety margin.
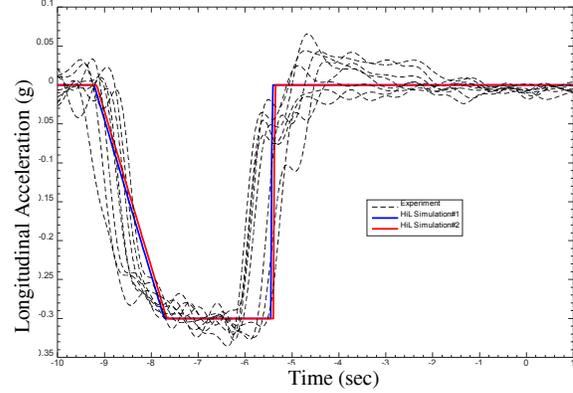
Figure.15 compares the simulated range to experimental measurements. The range at AEB activation was measured between 16.5 and 18.0 m, while the HiL values were 17.3 and 17.5 m. The simulated minimum range was 2.8 m for both cases and the experimental measurements varied from 0.5 to 3.0 m.

The TTC comparisons are shown on Figure 17. The TTC value at AEB activation is about 2.0 seconds for the HiL system, and the measured values vary from 1.88 to 2.10 seconds. The deceleration plot, Figure.18, shows that the AEB system intervened more than once on multiple runs for both simulation and field experiments. For the HiL system, the simulation runs were not identical runs, but the irregular behavior happened at very low relative speeds.
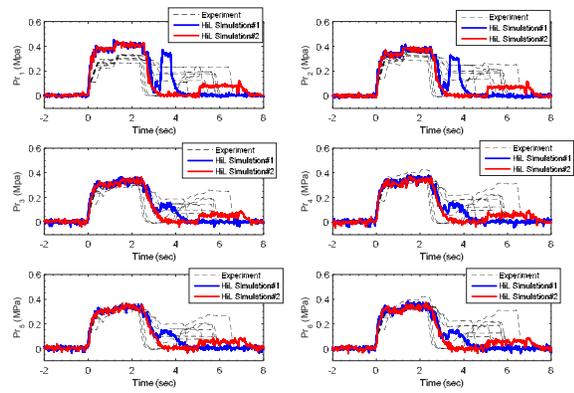
Although testing conditions were set judicially to guarantee testing repeatability and reproducibility, small kinetic differences of relative speed and range affect AEB activation cycles, and more multiple activations are possible. In spite of this, the metrics between all tests compare very well between experiments on the test track and HiL simulation, and the results from a crash mitigation/avoidance standpoint are the same.
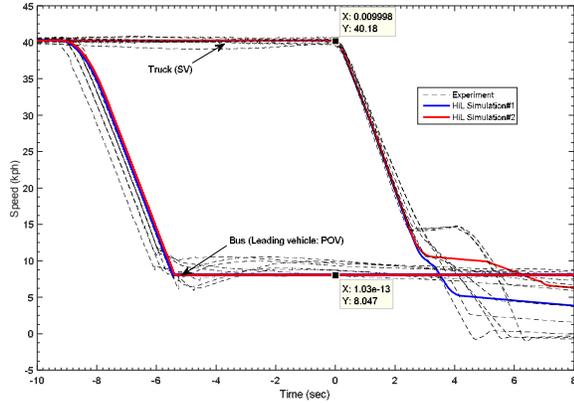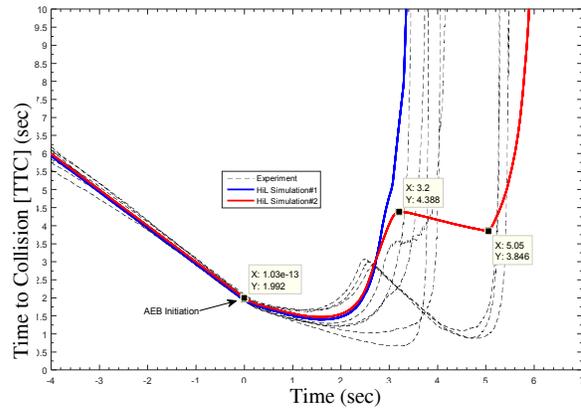
Figure.13 Truck and bus (lead vehicle) speeds - 40/40 km/h LVD scenario
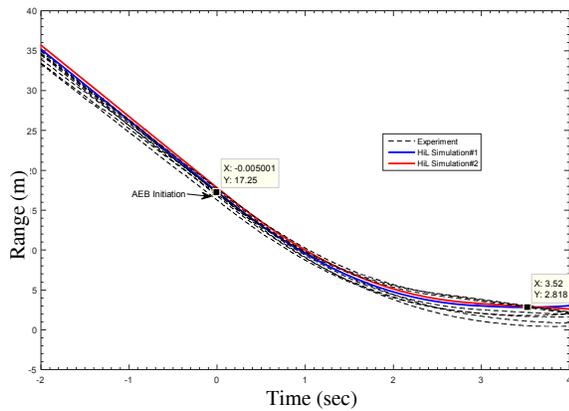

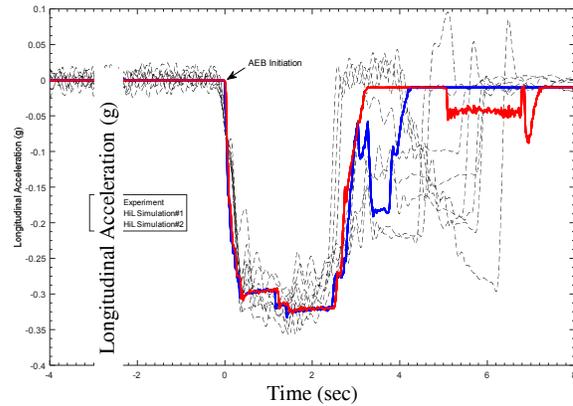*Figure 14. Brake line pressures - 40/40 km/h LVD scenario*

Figure.15. Range - 40/40 km/h LVD scenario

Figure 16. Bus deceleration - 40/40 km/h DLV scenario

Figure 17. TTC (Time to Collision) -40/40 km/h LVD scenario

Figure.18. Truck and Bus deceleration - 40/40 km/h LVD scenario

CONCLUSION

NHTSA's HiL pneumatic braking system employing an AEB-equipped Bendix ECU has been partially validated with data from experimental test track results with a limited number of crash scenarios. The validation used available experimental data at truck speeds of no more than 40 km/h. The results indicate

that the HiL technology predicts with fidelity the behavior of such complex systems. The testing metrics in terms of TTC values, range, relative speed, and end results (crash or no crash) are very similar. Other AEB scenarios such as lead vehicle stopped and lead vehicle decelerating need to be examined in future research for a more complete validation of the AEB systems.

With the HiL system, the AEB performance can be tested at higher speeds and in closer proximity to the lead vehicle. Moreover, the surface conditions can be altered to mimic low friction conditions, like wet surfaces, split-mu, etc. The HiL system in general, can expand the envelope of field testing and include conditions not possible to test systematically, or not safe to conduct on the test track. Nonetheless, simulation results require rigorous basic validations with experimental test track data.

REFERENCE

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1. Rao, S., Salaani, M., Heydinger, G., Guenther, D., Barickman, F., "Validation of Real Time Hardware in the Loop Simulation for ESC Testing with a 6×4 Tractor and Trailer Models," SAE Int. J. Com. Veh. 6(1):2013, doi: 10.4271/2013-01-0692.

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