STUDY OF HEAVY TRUCK AIR DISC BRAKE EFFECTIVENESS ON THE NATIONAL ADVANCED DRIVING SIMULATOR

Paul A. Grygier
W. Riley Garrott
National Highway Traffic Safety Administration
US Department of Transportation, USA
M. Kamel Salaani
Transportation Research Center, Inc., USA
Gary J. Heydinger
The Ohio State University, USA
Chris Schwarz
Tim Brown
Michelle Reyes
The National Advanced Driving Simulator
The University of Iowa, USA
Paper Number 07-0290

ABSTRACT

In crashes between heavy trucks and light vehicles, most of the fatalities are the occupants of the light vehicle. A reduction in heavy truck stopping distance should lead to a reduction in the number of crashes, the severity of crashes, and consequently the numbers of fatalities and injuries.

This study makes use of the National Advanced Driving Simulator (NADS). NADS is a full immersion driving simulator used to study driver behavior as well as driver-vehicle reactions and responses. The vehicle dynamics model of the existing heavy truck on NADS has been modified with the creation of two additional brake models. The first is a modified S-cam (larger drums and shoes) and the second is an air-actuated disc brake system. A sample of 108 CDL-licensed drivers was split evenly among the simulations using each of the three braking systems. The drivers were presented with four different emergency stopping situations. The effectiveness of each braking system was evaluated by first noting if a collision was avoided and if not the speed of the truck at the time of collision was recorded.

The results of this study show that the drivers who used the air disc brakes will have fewer collisions in the emergency scenarios than those drivers using standard S-cam brakes or those using the enhanced S-cam brakes. The fundamental hypothesis that this research validates can be phrased in this question: "Does reducing heavy truck stopping distance decrease the number and severity of crashes in situations requiring emergency braking?"

INTRODUCTION

According to the Federal Motor Carrier Safety Administration [1], there were approximately 436,000 police reported crashes that involved heavy trucks; 4,289 of them resulted in fatalities. Of these crashes, 298,312 were recorded "Collision with a Vehicle in Transport" as the first harmful event and these resulted in a majority of the fatalities (3,312). The implication of these data is that most of the fatalities involving heavy truck crashes are the occupants of the light vehicles involved.

The National Highway Traffic Safety Administration (NHTSA) believes that reducing the FMVSS 121 (49 CFR Part 571) minimum stopping distance by thirty percent will result in saving a significant number of lives. In generating benefit analyses for estimating the safety effects of improved truck brakes, assumptions have to be made. It has been assumed that if a tractor-trailer can stop in a shorter distance, than fewer crashes will result. Based on kinematics, it is reasonable to assume if you can stop in a shorter distance it is more probable that a truck will avoid colliding with an object or it will at least collide with a reduced velocity. This theory holds true given that the operators' reaction times, control behavior, and their perceptions of available stopping distance remain constant.

Commercial truck drivers understand the braking ability of tractor-trailers and under most conditions drive accordingly. However, in the real world, truck drivers are faced with many adverse conditions in numerous scenarios brought about by other vehicles (light vehicles cutting in-lane, vehicles pulling out unexpectedly, etc.). When a crash-imminent situation occurs, the truck driver must decide to brake, brake and steer, steer, accelerate, or accelerate and steer. Depending on the control behavior adopted by the driver, it can be argued that shorter stopping distance may have little or no effect on avoiding a collision or reducing the delta speed of a crash.

The primary objective of this study is to provide test data that demonstrates the effectiveness of air disc brakes on heavy trucks. This test addresses whether shorter stopping distances reduce the number and severity of certain types of heavy truck crashes. The result will help NHTSA confirm or refine their benefit estimates based on improved truck braking performance.

APPROACH

The effectiveness of air disc brakes on heavy trucks is examined using three different brake system conditions and four simulator scenarios. The three different brake configurations are:

- Standard truck where S-cam brakes are used on all wheels
- Enhanced truck where only the steer axle is equipped with a higher capacity version of an S-cam brake
- Disc truck where all the wheels of the tractor are equipped with disc brakes.

The simulator scenarios are primarily based on those used in previous NHTSA Electronic Stability Control (ESC) research [2]. All simulated roads are built with a shoulder whose traction, vibration, and audio characteristics are different than the on-road pavement. This is to realistically simulate the environment that occurs when some of a vehicle's tires depart the roadway. The lanes are 12 feet (3.7 m) wide, there is 1.9 feet (0.58 m) of road between the white line (designating the outboard edge of the lane) and the shoulder, and the shoulder is 11.5 feet (3.51 m) wide. Beyond the shoulder, there is an additional 75 feet (23 m) of drivable terrain (see Figure 1). The scenarios take place on dry pavement. The virtual environment reflects conditions consistent with pavement. In particular, the scene is clear and the pavement appears dry.

The study used the NADS heavy truck cab and dynamics model [3, 4]. A typical 18-wheel tractor-trailer combination was selected with a gross weight of 73,100 pounds (33,200 kg). Three brake systems were modeled: standard S-cam, enhanced S-cam, and disc brake. Stopping distance is reduced by 17% and 30% when the standard S-cam brake system is replaced by the enhanced and disc systems respectively.

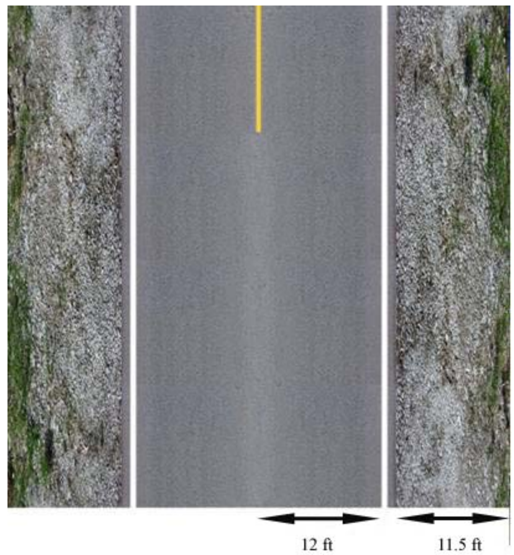

Figure 1. Road geometry.

Truck drivers were recruited from local Iowa trucking companies as well as through radio and newspapers ads targeted at all truck drivers in the area. Participants consisted of drivers who held a valid Commercial Driver's License (CDL) and were between the ages of 22 and 55 (current statistics show that approximately 75% of all drivers involved in heavy truck crashes are between the ages of 22 and 55 and drove on average 2000 miles during the last 3 months). This ensured that participants were actively driving heavy trucks. Since the population of commercial vehicle drivers is comprised of mostly males, no attempt was made to balance by gender. Participant pay in this experiment was comparable with a professional truck driver's hourly wage of $30 per hour plus incentive pay.

A repeated measures experiment design in which participants experienced multiple scenarios was used. Independent variables included brake system (3 levels: standard S-cam, enhanced S-cam, and air disc brakes) and event order (4 events were used, but only 3 events were fully randomized, giving 6 levels; 4th event was always last). A single age group was used (22-55). This design resulted in 18 experimental cells. To allow 6 repetitions of each event order per brake condition, 108 participants who would successfully complete all 4 events were needed. This recruiting goal was met. The principal measure for this study was whether the driver crashed or not. Secondary measures consisted of collision speed (or delta velocity), stopping distance, reaction time to event start, and average deceleration. Other behaviors were tabulated such as if the driver braked, steered, and/or accelerated.

SCENARIO DESIGN

To understand the effectiveness of heavy truck air disc brakes, scenarios were designed to emulate real world situations where heavy truck crashes are occurring. Dry asphalt pavement conditions were simulated. A total of four scenarios containing situations conducive to emergency braking were used. Events are presented to each participant as individual drives. Each participant drove all of the scenarios. Each scenario was approximately five minutes in length and ended immediately after presentation of a conflict event. The scenarios were designed to have consistent entry speed (maintained through monetary incentives) for all participants and no downshifting during the event itself. They were also designed such that the driver can stop without hitting the target vehicle, if the brakes are applied immediately. The scenarios conflict events were:

Right Incursion: The goal of this event is to force the driver to apply brakes to avoid colliding with oncoming traffic. A vehicle pulling out of a hidden driveway attached to a roadside farmhouse combined with carefully timed oncoming traffic creates the conditions for such a maneuver (Figure 2). The driver is approaching a driveway that can hide a vehicle. The driver is motivated via monetary incentives to maintain the speed limit of 55 mph (89 kph). Parked vehicles on the left shoulder prevent the driver from avoiding the oncoming traffic by going left. When the driver is 4 seconds from arriving at the driveway location, the hidden parked vehicle pulls out from the right and stops, blocking the right lane. Drivers who cannot stop within the available distance can collide with white incursion vehicle, green oncoming car, gray oncoming car, or parked truck on left shoulder.

Left Incursion: The goal of this event is to force the driver to react to an incursion from the left and to brake suddenly while traveling at highway speed. The driver is on a two-lane rural highway crossing a heavily wooded area with frequent oncoming traffic (Figure 3). The posted speed limit is 55 mph (89 kph) and the driver is motivated via monetary incentives to maintain speed. There are several parked vehicles on both shoulders. As the driver approaches the location of the event, one of the oncoming vehicles is tasked to arrive at the event location at a fixed relative position to the driver. Oncoming traffic is approaching a parked vehicle on the shoulder opposite to the driver's side. That parked vehicle begins moving and cuts off the oncoming traffic which is forced to veer into the driver's lane. The oncoming traffic will enter driver's lane at a fixed time-distance, 8 seconds away from the driver. Concrete barriers are placed on the right side so that the driver will not steer to the shoulder. If the driver cannot stop within the available distance, the driver can collide with the oncoming red SUV, the black compact, or the concrete barriers.

Stopping Vehicle: The goal of this event is to force the driver to react to an abruptly stopping lead vehicle while traveling at 55 mph (89 kph). There is a continuous flow of oncoming traffic throughout the event and there are barricades and construction vehicles parked along the sides of the road. These barricades and parked vehicles constrain the driver from steering off-road during the braking event (Figure 4). The driver is on a two-lane rural highway crossing a heavily wooded area with frequent oncoming traffic. The posted speed limit is 55 mph. There are several parked vehicles on both shoulders. As the driver is moving along, one of the parked vehicles enters the roadway behind the truck. As the driver cruises along, the following vehicle makes a lane change and overtakes the truck. It enters the driver's lane and maintains a distance of 132 ft (40 m) for approximately 2100 ft (640 m) before it decelerates at the rate of 0.75 g to a complete stop. The driver is precluded from steering via construction barriers on the edge of driver's lane and oncoming traffic in the adjacent lane. Collision can happen with the stopping green lead vehicle, oncoming traffic, or the concrete barriers.

Stopped Vehicle: The goal of this event is to force the driver to react to an obscured stopped vehicle on the highway. The driver is on a 4-lane rural highway traveling at the posted speed limit of 70 mph (110 kph) (Figure 5). There is a steady stream of traffic in the adjacent lane as well in the oncoming lanes. Once the driver achieves the posted speed limit, a delivery truck speeds past him, makes a right lane change into the driver's lane, and becomes the lead vehicle as well as the obscuring vehicle. The lead vehicle maintains a distance of 400 ft (122 m) in front of the driver. When the participant is 610 ft (186 m) from a stopped vehicle, the lead vehicle makes a lane change into a stream of traffic in the adjacent lane revealing the stopped vehicle. The driver can collide with the stopped vehicle or the adjacent oncoming traffic.

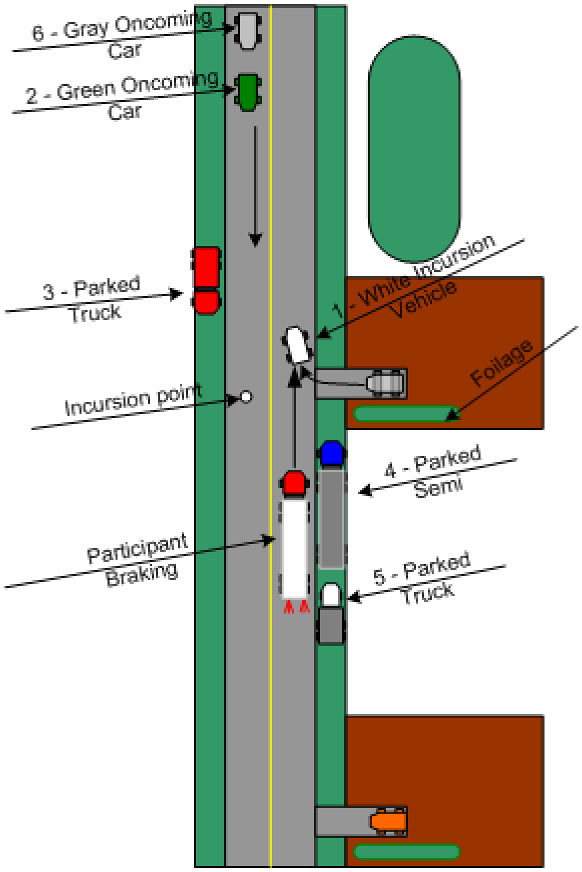

Figure 2. Right incursion.

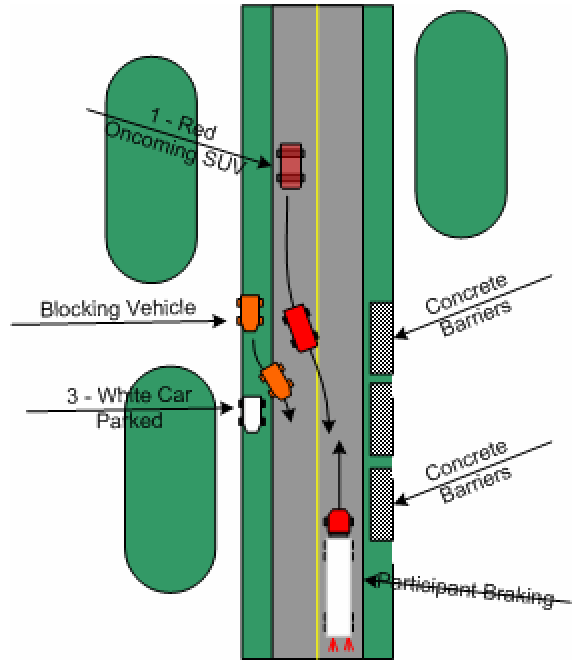

Figure 3. Left incursion.

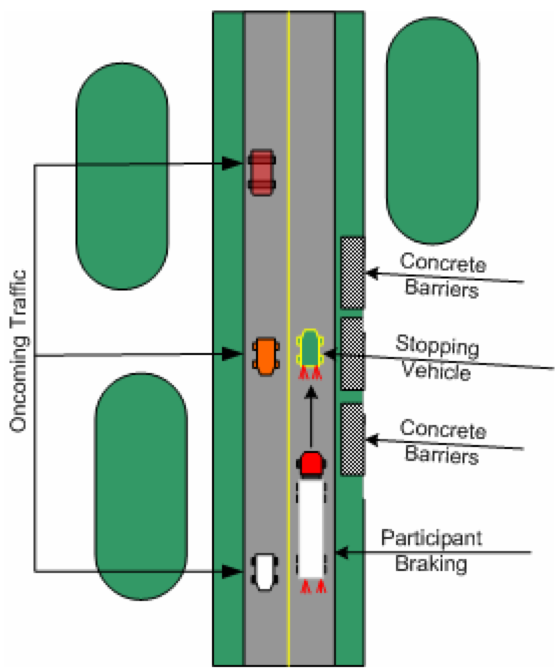

Figure 4. Stopping vehicle.

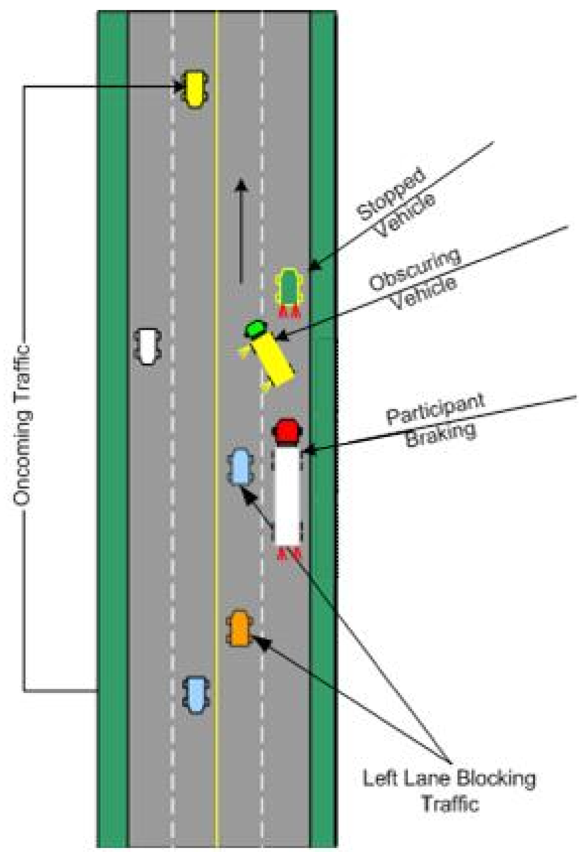

Figure 5. Stopped vehicle.

APPARATUS

The experiment was performed at the NADS facility, located at the University of Iowa's Oakdale Research Park in Coralville. The simulator hardware is described below. Modifications were required to be made to the vehicle dynamics software; in particular to the braking subsystem.

<u>Simulator</u>

NADS consists of a large dome in which an entire vehicle cab (e.g., cars, trucks, and buses) can be mounted. The dome is mounted on a 6-degree-of-freedom hexapod, which is mounted on a motion system, providing 65 feet (20 meters) of both lateral and longitudinal travel. There is a yaw degree of freedom between the hexapod and the dome, which allows 330 degrees of yaw rotation. The NADS motion system has a total of nine degrees of freedom as shown in Figure 6. To simulate high frequency road disturbances and high frequency loads through the tires and suspension, NADS contains four vibration actuators, mounted at points of suspension-chassis interaction. These vibration actuators are mounted between the floor of the dome and vehicle, and they act only in the bounce direction of the chassis. The vehicle cabs are equipped electronically and mechanically using instrumentation specific to their makes and models (Figure 7). The driver is immersed in sight, sound and movement so real that impending crash scenarios can be convincingly presented with no danger to the driver (Figure 8). The NADS capabilities were evaluated by independent simulation experts [5], and the truck system was evaluated by professional drivers [6]. This independent professional assessment of the system provides confidence on the level of realism that can be concluded from the simulator research results.

The Visual System provides the driver with a realistic 360º field-of-view, including the rearview mirror images. The driving scene is three-dimensional, photo-realistic, and correlated with other sensory stimuli. The image generator is capable of rendering 10,740,736 pixels at a frequency of 60 Hz. The Visual System database includes representations of highway traffic control devices (signs, signals, and delineation), three-dimensional objects that vehicles encounter (potholes, concrete joints, pillars, etc.), common intersection types (including railroad crossings, overpasses, bridge structures, tunnels, etc.), and various weather conditions. In addition, high density, multiple lane traffic can be made to interact with the driver's vehicle.

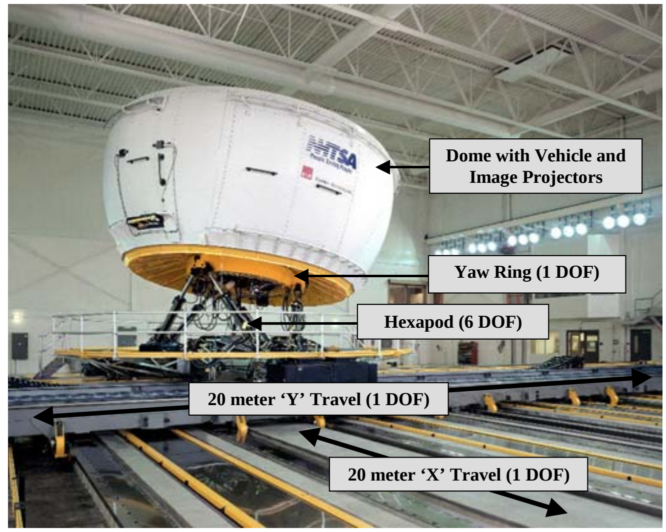

Figure 6. National Advanced Driving Simulator.

Figure 7. Freightliner cab interior.

Figure 8. Truck cab in the NADS dome.

The visual display timing is real time where the driver input and the visual display has less then 50 milliseconds of time delay. This eliminates driver overshoot reactions and possible instability as a result of time delay within a closed-loop-environment. An advanced compensator was developed and installed into NADS to keep the visuals and drivers input in phase [7]. The compensator is similar in capabilities to what is used by NASA at their simulator research facilities [8]. The heavy truck visuals are different from those of passenger vehicles due to the inclusion of the trailer visual display. The truck driver is able to see the trailer from the driver's side mirror, which accurately reflects the rear view of the truck. This is made possible by adjusting the rear image channel to compensate for the curvature of the dome and the offset placement of the mirror. This capability is unique to the NADS due to its 360º horizontal field of view capacity.

The Control Feel System (CFS) for steering, brakes, clutch, transmissions, and throttle realistically controls reactions in response to driver inputs, vehicle motions, and road/tire interactions over the vehicle maneuvering and operating ranges. The CFS is capable of representing automatic and manual control characteristics such as power steering, existing and experimental drivetrains, antilock brake systems (ABS), and cruise control. The control feel cuing feedback has high bandwidth and no discernible delay or distortion associated with driver control actions or vehicle dynamics.

The Motion System provides a combination of translational and angular motion that duplicates scaled vehicle motion kinematics and dynamics with nine degrees of freedom. The Motion System is coordinated with the CFS to provide the driver with realistic motion and haptic cuing during normal driving and pre-crash scenarios. The motion system is configured and sized to correctly represent the specific forces and angular rates associated with vehicle motions for the full range of driving maneuvers. The washout algorithm that is used to generate dynamic specific forces (acceleration at the drivers head with gravity effect) and cab orientation rates is tuned using high sensitivity cuing with a washout scaling of forty-five percent.

In addition, four actuators located at each wheel of the vehicle, provide vertical vibrations that simulate the feel of a real road (Figure 9). NHTSA's Vehicle Research and Test Center (VRTC) measured cab vibrations of a GM-Volvo tractor owned by NHTSA. The vibrations were measured at different engine speeds. Four accelerometers with a maximum capacity of ±4 g were mounted vertically on the truck floor, dashboard, driver seat (actually beneath the seat), and steering handwheel. These measurements provided information regarding the location of the fundamental frequencies and the level of magnitude associated with the vibration feel inside the cab. Harmonic functions that closely replicate the frequencies and magnitude levels (vibration energy) were derived and used to drive the vertical actuators. This method allowed the vertical vibrations to be reproduced with great fidelity inside the cab. The frequency content of these vibrations extended higher than the bandwidth of the hexapod and dome longitudinal and lateral motions. The intensity of these modes at different speeds were measured at VRTC, and in NADS the vibration cues that best represented the speed of the scenarios have been implemented. Figure 10 shows the power spectrum of the truck cab vibration felt at the NADS dome. The 2-Hz frequency is related to truck bounce mode, the 5-8 Hz frequencies are related to axles mode, 10-12 Hz frequencies are related to cab modes, and the 17-25 Hz frequencies are related to engine and power train modes.

Figure 9. Truck cab showing vertical actuator for vibration cues.

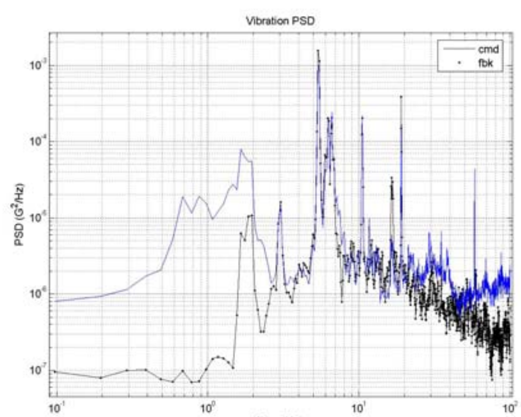

Figure 10. Vibration power spectrum measured on the NADS cab (commanded and measured).

A manual transmission with low and high gear range selection is being used for this study (Figure 11). Before drivers were engaged in the scenarios, they were given ample time (about 20 minutes) to drive and get familiar with the transmission system. Drivers expressed different skill levels; however, none of the scenarios involved in this study required transmission shifting during the braking event.

Figure 11. Truck cab shifting.

The cab steering system was calibrated and the controls were tuned to provide a close steering feel for both on-center and turning maneuvers. VRTC measurements provided the torque-steer curve and the amount of freeplay currently existing in the GM-Volvo truck.

The NADS truck cab system is equipped with a pneumatic brake hardware system. VRTC measured actual brake feel from the GM-Volvo truck and calibrated the NADS cab to reflect accurate brake pedal feel.

The Auditory System provides motion-correlated, three dimensional, realistic sound sources, that are coordinated with the full ranges of the other sensory systems' databases. The Auditory System also generates vibrations to simulate vehicle-roadway interaction. The auditory database includes sounds emanating from current and newly designed highway surfaces, from contact with three-dimensional objects that vehicles encounter (potholes, concrete-tar joints, pillars, etc.), from other traffic, and from the vehicle during operation, as well as sounds that reflect roadway changes due to changing weather conditions. VRTC measured the engine sound of the GM-Volvo truck at different engine RPM and provided the data to NADS to be displayed in real time and coordinated with the engine speed.

Vehicle Dynamics and Brake System Models

The Vehicle Dynamics (NADSdyna) Computer Simulation determines vehicle motions and control feel conditions in response to driver control actions, road surface conditions, and aerodynamic disturbances. Vehicle responses are computed for commanding the Visual, Motion, Control Feel, and Auditory Systems.

The vehicle dynamics model used in this project was developed by VRTC for the 1992-GMC truck manufactured by Volvo GM Heavy Truck, model WIA64T and a 1992 Fruehauf trailer model FB-19.5NF2-53 [2, 3].

The torque characteristics of commercial vehicle brakes have been studied by numerous investigators. Formulation of the brake model based on fundamental understanding of the development of the instantaneous brake torque as influenced by pressure, temperature, sliding velocity, work history, temperature gradients, and other factors has not been achieved. Recent research has been directed by treating the brake effectiveness as empirical functions. The brake models used in NADS are primarily empirical, based on fitting experimental data obtained from brake dynamometer and field test data (Figure 12).

The objective of this research is to study the functional effects of three different brake configurations:

- Standard truck where S-cam brakes are installed on all wheels
- Enhanced truck where only the steer axle is equipped with a higher capacity version of an S-cam brake
- Disc truck where all the wheels of the tractor are equipped with disc brakes.

The brake parameters were set such that severe braking from 60 mph (97 kph) provides a stopping distance of 307 ft (93.6 m) for standard brake, 256 ft (78.0 m) for enhanced brakes, and 215 ft (65.5 m) for disc brake (as shown in Figure 13). This is a reduction of stopping distance of 17% and 30% if the standard S-cam brake system is replaced with the enhanced and disc systems respectively. In this study all these systems are mounted on the same tractor-trailer model [9].

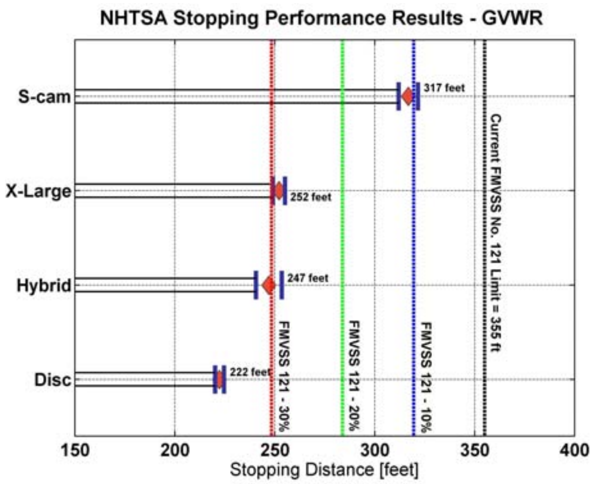

Figure 12 Brake performance measured by VRTC for a typical tractor-trailer with different brakes (x-large and hybrid in the graph refer to the enhanced brakes in this paper).

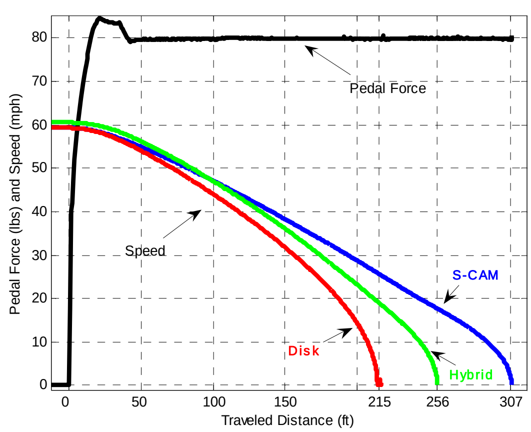

Figure 13. Brake performances on NADS.

PROCEDURE

The total number of participants in this study was 108. Upon arrival at the NADS facility, participants were given a verbal overview of the Informed Consent Document and were then asked to read and sign the document. Next, the participants completed the NADS Driving Survey and were given instructions on the monetary incentive scheme. Participants were assigned a single brake system condition for their participation. The order of scenario presentation was varied systematically across participants.

Prior to beginning treatment drives, participants received a familiarization practice drive. This drive provided them experience with the vehicle's brake system's capabilities, and also familiarity with shifting the transmission.

After each scenario drive, participants were told the amount of incentive they earned and the amount was recorded on a data sheet. After all driving was completed, participants completed the simulator sickness questionnaire. After the simulator was docked, the participant was escorted to the participant prep area, offered a snack or beverage, and given an opportunity to ask questions. Participants completed a realism survey and a post-drive questionnaire.

Finally, the participant was paid an amount consisting of the sum of the base pay plus incentive pay. The participant signed the payment voucher, describing how compensation was related to driving performance. The participant was then escorted to the exit.

INCENTIVES

Drivers were given incentives to maintain a constant velocity within ± 3 mph (5 kph) of the target speed. A driver could earn a total $3.00 per drive based on the percentage of time that his or her speed remained within the specified range. Generally, a short period immediately after the scenario start and the event itself were excluded from this calculation.

DATA REDUCTION

Each event was divided into five segments using six different time points and the final reduced data file spreadsheet included one line per event. These time points were T1 (event onset) through T6 (event completion) and are defined below.

- **T1:** Event onset (scenario specific)
- **T2:** Initiation of accelerator pedal release, determined by comparing whether the current accelerator pedal position to a running mean pedal position over one second of running time falls below a predefined threshold.

- **T3:** Completion of accelerator pedal release (when accelerator pedal position drops below 5% of full range).
- **T4:** Initiation of brake pedal depression (when brake pedal force exceeds 2.0 lbs).
- **T5:** Application of maximum brake pedal force.
- **T6:** Completion of the braking event.

The following variables were collected: longitudinal distance between each event, velocity and acceleration at each event, gear shift position, accelerator pedal position, brake pedal force, steering angle at T1, reaction time between events, braking distance from T4 to T6, total stopping distance from T1 to T6, maximum brake pedal force (brake pedal force at T5), mean and median brake pedal force from T4 to T6, mean deceleration rate, maximum deceleration rate, time from T1 to maximum deceleration, maximum absolute value of steering wheel angle from T1 to T6, time to collision at T1 (assuming driver's speed doesn't change, time before a collision would occur), distance to collision object at T1, Final distance to collision object at T6, collision (1 = yes, 0 = no), collision object name, collision velocity; relative velocity at time of collision, heading angle of tractor at each T, articulation angle at each T, maximum articulation angle, time of maximum articulation angle from T1, tractor accelerations in x, y, and z directions at each T, trailer accelerations in x, y, and z directions at each T (18 variables in all), tractor yaw rate at each T, and trailer yaw rate at each T.

Collisions with other vehicles were enumerated for each scenario. Collisions could occur with a single oncoming vehicle or with vehicles parked alongside the road. To provide better discrimination as to the meaning of collisions, the reduced data contained individual indicators of collision with each vehicle in each scenario.

RESULTS

Each event was analyzed separately using a similar statistical approach based on comparing drivers' reaction times, stopping distances and number of collisions. Reaction time was defined as the time interval between the time the event starts and the driver activating the brake. The main performance measures were based on whether there was a vehicle crash or not, the delta speed in case of a crash and the stopping distance if not. The hypothesis to be confirmed is that the average reaction time for drivers is statistically similar across the brake conditions. That is, drivers for the S-cam, enhanced brakes, and disc brakes perceive the obstacles with no significant variations. Reaction time was deemed as being the same if the mean values were within 0.3 seconds of each other. The second hypothesis is that there are more collisions (and with higher delta speed) with the S-cam brakes then with the other two systems. Delta speed is an indication of the collision severity; higher speeds indicate higher kinetic energy and consequently, higher severity collision. Drivers' braking efforts were compared for the three systems in order to confirm that reductions in collisions were the result of better stopping performance rather than a reduction of driver braking effort (pedal force) when driving a truck with an S-cam system.

Right Incursion

The collision information data listed in Table 1 show that the number of collisions decreased slightly when the S-cam brake system is replaced with the disc brake system.

The average stopping distance for the S-cam brake system was higher than for the other two systems (Table 2 and Figure 14) despite the drivers exerting more effort in braking as can be seen on the mean braking force in Figure 15. The difference between the three braking systems was statistically significant as the p-values included in the figures suggest. The distance traveled by the drivers to perceive the obstacle on the road (Figure 16), time of action between obstacle perception and the starting of hard braking (Figure 17), lane deviation (Figure 18) and the speed at the onset of hard braking (Figure 19), show that the experimental procedures were well controlled and these human reaction/perceptual natural differences were not a factor in the differences seen in the number of crashes and stopping distances (summary in Table 3).

Table 1.
Right Incursion Collisions

Brake Type	Collision With Incursion
S-cam	**1**
Enhanced	**1**
Disc	**0**

Table 2.
Right Incursion Stopping Distance

Brake Type	Mean ft (m)	P
S-cam	**292 (89)**	**0.023**
Enhanced	**270 (82.3)**	
Disc	**262 (79.8)**	

Table 3.
Right Incursion Drivers' Performances Before Heavy Braking

Type	S-cam	Enhanced	Disc	P
Entry Speed mph (kph)	**53.3 (85.7)**	**53.7 (86.4)**	**52.8 (84.9)**	**0.234**
Distance before T1 ft (m)	**47 (14.3)**	**49 (14.9)**	**48 (14.6)**	**0.322**
Time of Action (T1-T4) sec	**0.93**	**0.90**	**0.95**	**0.708**
Speed Before Heavy Braking mph (kph)	**52.1 (83.8)**	**52.6 (84.6)**	**52.6 (84.6)**	**0.192**
Lane Deviation ft (m)	**3.2 (1.0)**	**2.6 (0.8)**	**2.6 (0.8)**	**0.545**

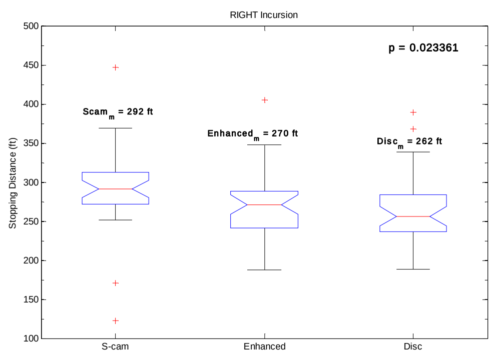

Figure 14. Right incursion stopping distance.

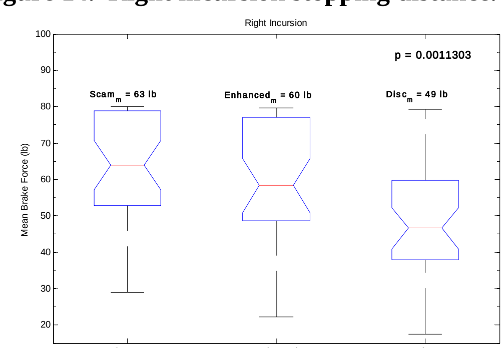

Figure 15. Right incursion drivers' braking efforts.

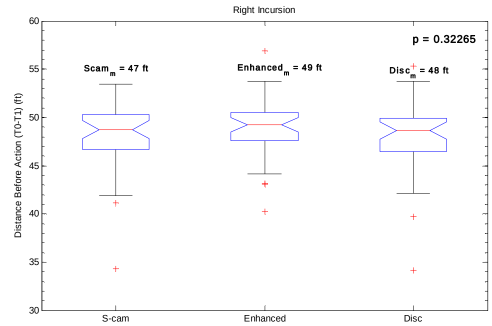

Figure 16. Right incursion drivers' distance traveled before action.

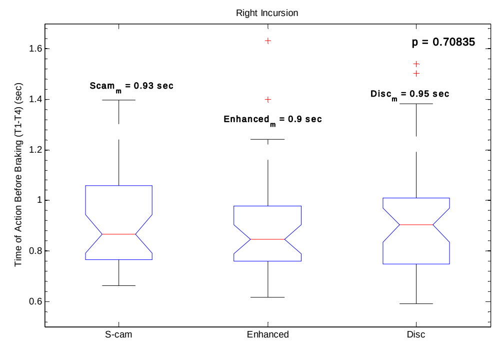

Figure 17. Right Incursion Drivers' Time to Action.

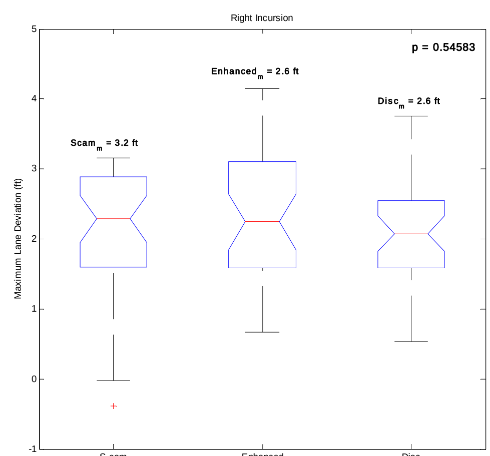

Figure 18. Right incursion drivers' lane deviation.

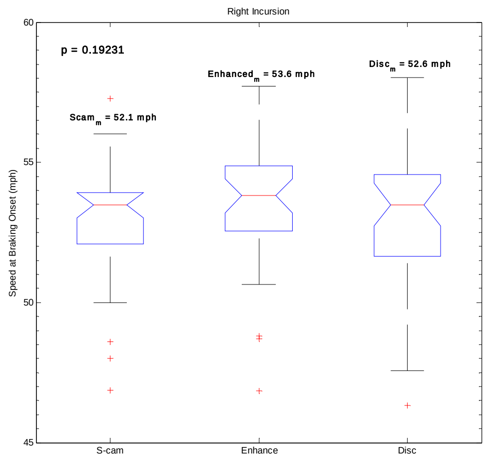

Figure 19. Right incursion drivers' speed at heavy braking onset.

Left Incursion

The left incursion analysis followed the methodology used for the right incursion, and Table 4 provides the number of crashes for each brake systems. There were fewer collisions with the enhanced and disc system than with the S-cam. Tables 5 and 6 and Figures 20 – 26 illustrate driver responses for this scenario.

Table 4.
Left Incursion Collisions

Brake Type	Collision	Speed mph (kph)	P
S-cam	**13**	**24 (38.6)**	**0.268**
Enhanced	**4**	**23 (37.0)**	
Disc	**11**	**17 (27.3)**	

Table 5.
Left Incursion Stopping Distance

Brake Type	Mean ft (m)	P
S-cam ft	**340 (103.6)**	**0.05**
Enhanced ft	**309 (94.2)**	
Disc ft	**322 (98.1)**	

Table 6.
Left Incursion Drivers' Performances Before Heavy Braking

Type	S-cam	Enhanced	Disc	P
Entry Speed mph (kph)	**53.0 (85.3)**	**53.3 (85.8)**	**52.9 (85.1)**	**0.45**
Distance before T1 ft (m)	**216 (65.8)**	**213 (64.9)**	**212 (64.6)**	**0.74**
Time of Action (T1-T4) sec	**1.461**	**1.35**	**1.62**	**0.07**
Speed Before Heavy Braking mph (kph)	**52.7 (84.8)**	**53.1 (85.4)**	**52.5 (84.5)**	**0.29**
Lane Deviation ft (m)	**2.9 (0.9)**	**2.8 (0.85)**	**2.7 (0.8)**	**0.45**

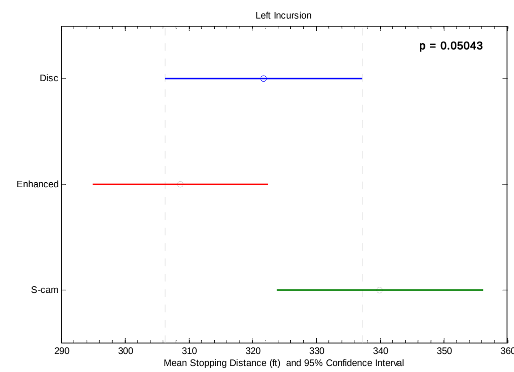

Figure 20. Left incursion stopping distance.

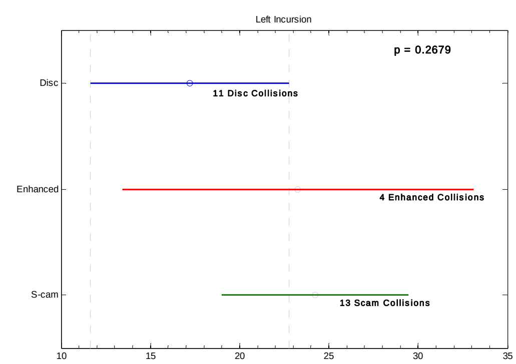

Figure 21. Left incursion collision speed.

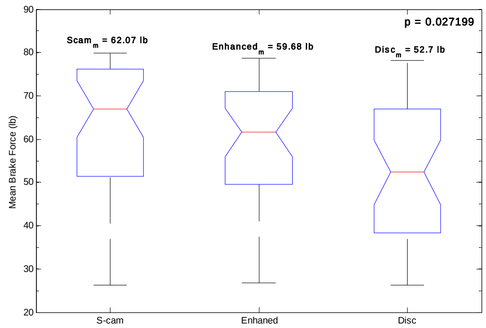

Figure 22. Left incursion drivers' braking efforts.

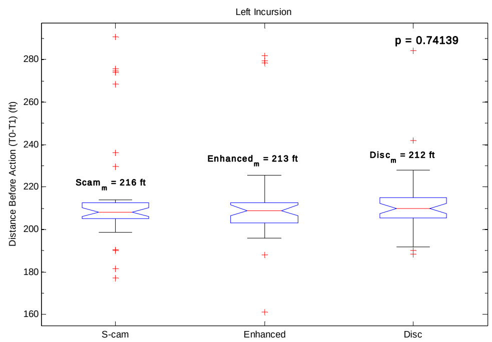

Figure 23. Left incursion drivers' distance traveled before action.

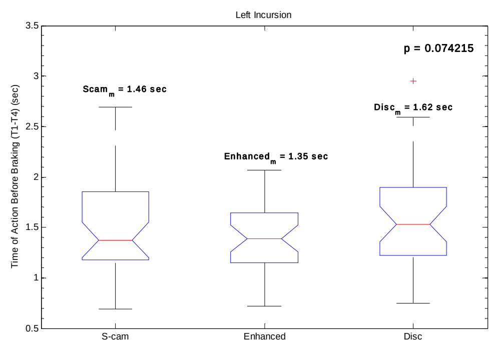

Figure 24. Left incursion drivers' time to action.

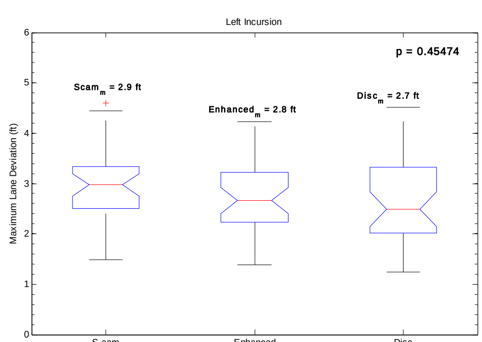

Figure 25. Left incursion drivers' maximum lane deviation.

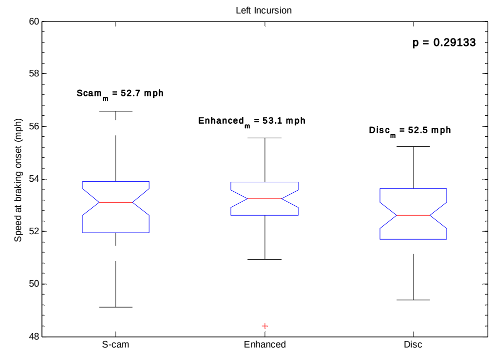

Figure 26. Left incursion drivers' speed at heavy braking onset.

Stopping Event

This event collision data are provided in Table 7 and show that there are more collisions with S-cam brakes and the collision speed is greater than with the other systems. The Enhanced and the Disc brakes are showing about the same number of collisions, with lower collision speed for the disc brakes. Tables 8 and 9 and Figures 27 – 30 illustrate driver responses for this scenario.

Table 7.
Stopping Event Collisions

Brake Type	Collision	Speed mph (kph)	P
S-cam	**22**	**23.0 (37.0)**	
Enhanced	**9**	**18.9 (30.4)**	**0.069**
Disc	**12**	**15.7 (25.3)**	

Table 8.
Stopping Event Stopping Distance

Brake Type	Mean ft (m)	P
S-cam	**336 (102.4)**	
Enhanced	**281 (85.6)**	**0.007**
Disc	**296 (90.2)**	

Table 9.
Stopping Event Drivers' Performances Before Heavy Braking

Type	S-cam	Enhanced	Disc	P
Entry Speed mph (kph)	**50.8 (81.7)**	**52.0 (83.7)**	**50.9 (81.9)**	**0.157**
Distance before T1 ft (m)	**4.8 (1.5)**	**4.8 (1.5)**	**4.6 (1.4)**	**0.285**
Time of Action (T1-T4) sec	**1.6**	**1.32**	**1.63**	
Speed Before Heavy Braking mph (kph)	**51.0 (82.0)**	**52.0 (83.7)**	**51.0 (82.0)**	**0.148**
Lane Deviation ft (m)	**2.0 (0.6)**	**2.1 (0.64)**	**2.0 (0.6)**	**0.843**

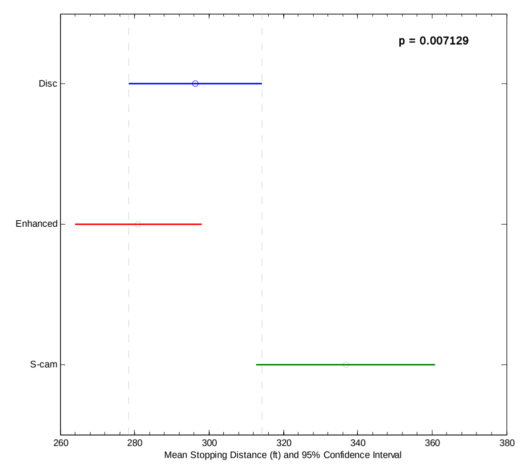

Figure 27. Stopping event stopping distance.

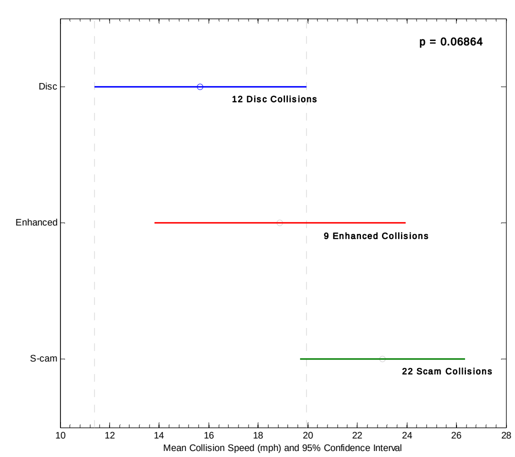

Figure 28. Stopping event collision speed.

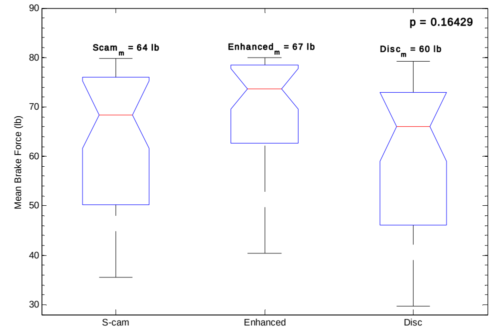

Figure 29. Stopping event drivers' braking efforts.

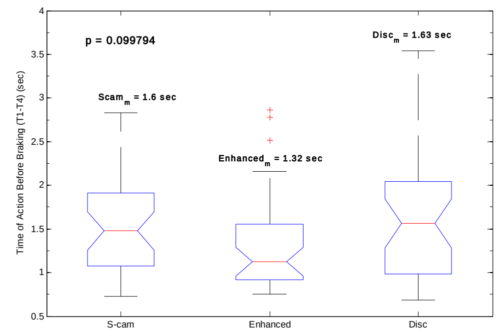

Figure 30. Stopping event drivers' time to action.

Stopped Event

This event involved driving at a high speed close to 70 mph (110 kph) and is considered to be the most severe of the three scenarios. Some drivers took evasive action by steering to the right. For those drivers who remained in their lane, the collision data listed in Table 10 show that those with the disc brake system had fewer collisions than those with the other two systems. The severity of this experiment showed that only the disc brake system was able to reduce the number of collisions significantly and the collision speed. With less braking effort, drivers with the disc brake system were able to stop within a shorter distance and had fewer collisions. Tables 11 and 12 and Figures 31 – 35 illustrate driver responses for this scenario.

Table 10.
Stopped Event Collisions

Brake Type	Collision	Speed mph (kph)	P
S-cam	**Stopped: 15 Other: 1**	**32 (51.5)**	
Enhanced	**Stopped: 22 Other: 1**	**28 (45.0)**	**0.06**
Disc	**Stopped: 7 Other: 3**	**23 (37.0)**	

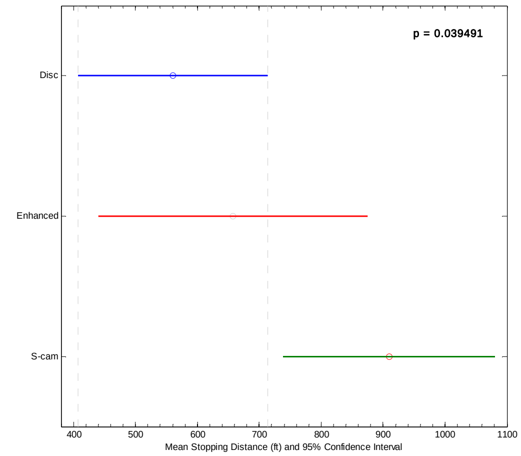

Figure 31. Stopped event stopping distance.

Table 11.
Stopped Event Stopping Distance

Brake Type	Mean ft (m)	P
S-cam	**909 (277.0)**	
Enhanced	**657 (200.2)**	**0.039**
Disc	**560 (170.7)**	

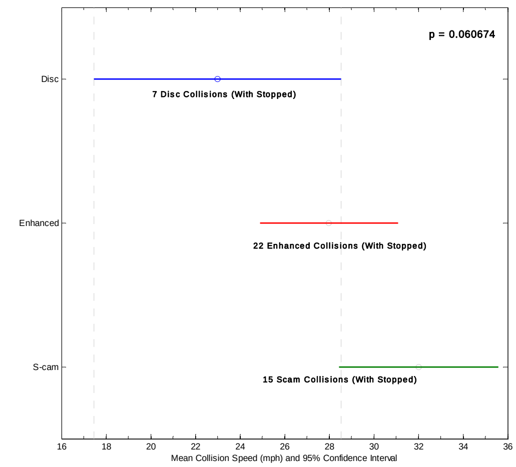

Figure 32. Stopped event collision speed.

Table 12.
Stopped Event Drivers' Performances Before Heavy Braking

Type	S-cam	Enhanced	Disc	P
Entry Speed mph (kph)	**67 (107.8)**	**68 (109.4)**	**67 (107.8)**	**0.046**
Distance before T1 ft (m)	**86 (26.2)**	**97 (29.6)**	**80 (24.4)**	**0.220**
Time of Action (T1-T4) (sec)	**3.0**	**2.2**	**3.0**	**0.520**
Speed Before Heavy Braking mph (m)	**67 (107.8)**	**68 (109.4)**	**66 (106.2)**	**0.097**
Lane Deviation ft (m)	**3.7 (1.1)**	**3.3 (1.0)**	**3.2 (0.97)**	**0.552**

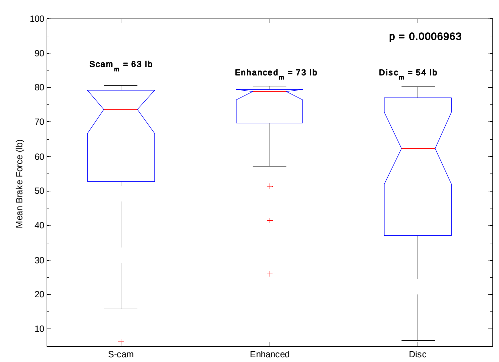

Figure 33. Stopped event drivers' braking efforts.

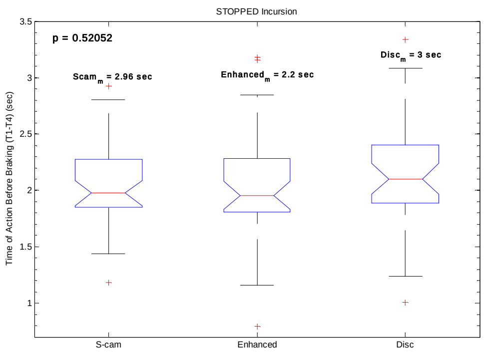

Figure 34. Stopped event drivers' time to action before braking.

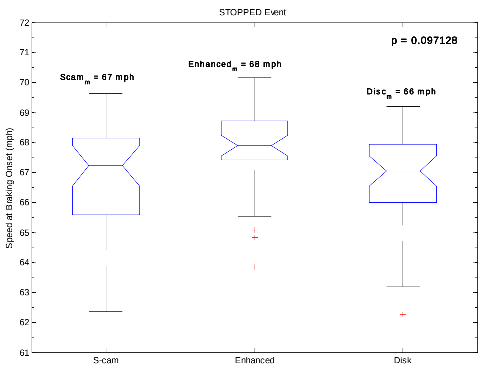

Figure 35. Stopped event drivers' speed at hard braking onset.

CONCLUSION

Based on the results presented here, the hypothesis that a brake system that provides a shorter stopping distance in an emergency braking event would reduce crashes and fatalities is valid. The type of braking system had no statistical effect on driver behavior prior to braking. The experiment used a validated virtual environment with high fidelity and showed systematically within a reasonable statistical confidence that professional drivers using either enhanced or disc brake systems were able to avoid many collisions. In an extreme emergency braking event at high speed, drivers using the disc brake system avoided collisions better or had reduced collision severity than those using the enhanced brake system.

ACKNOWLEDGEMENT

We would like to thank Elizabeth Mazzae (NHTSA) for setting up the initial guidelines for this project and for her contributions in the early phases of this project.

CONTACT

Dr. Paul Grygier
Paul.Grygier@dot.gov

REFERENCES

[1] U.S. Department of Transportation, Federal Motor Carrier Safety Administration, "Commercial Motor Vehicle Facts," http://www.fmcsa.dot.gov/facts-research/facts-figures/analysis-statistics/cmvfacts.htm, April 2005.

[2] Mazzae, E. *et al*, *The Effectiveness of ESC and Related Telltales: NADS Wet Pavement Study*, DOT HS 809 978, NHTSA (November 2005)

[3] Salaani, M. K., Grygier, P. A., Heydinger, G. J.' "Evaluation of Heavy Tractor-Trailer Model used in the National Advanced Driving Simulator," SAE Paper 2003-01-1324

[4] Salaani, M. K., Heydinger G. J., Grygier, P. A., "Heavy Tractor-Trailer Vehicle Dynamics Modeling for the National Advanced Driving Simulator," SAE Paper 2003-01-0965

[5] John Pierowicz, Jerry Robin Glenn Wilson, *National Advanced driving simulator (nads) – Utilization research*, Contract no. DTFH61-95-C-00077, Task 7, 2005

[6] NADS Professional Drivers' Evaluations, NADS Internal Documents, The University of Iowa, USA

[7] Salaani, M. K., Heydinger, G. J., Grygier, P. A., Garrott, W. R., "Transport Delay Compensation for the Image Generator used in the National Advanced Driving Simulator," IMECE2003-42975, 2003 ASME International Mechanical Engineering Congress, November 15-21, 2003 Washington, D.C.

[8] McFarland, R. E., NASA Technical Memorandum 100084, "Transport Delay Compensation for Computer-Generated Imagery Systems," Ames Research Center, 1988

[9] Salaani, M.K, Heydinger G. J, Grygier, P. A., Schwarz, C., Brown T., *Heavy Truck Air Disc Brake Study Using NADS*, US DOT report in progress.