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Study of Heavy Truck S-Cam, Enhanced S-Cam, and Air Disc Brake Models Using NADS

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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 three braking systems used in this study are the standard S-cam, the enhanced S-cam (larger drums and shoes), and the 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. In the noncollision runs additional performance measures were also evaluated, including stopping distances, braking distances, brake pedal forces and decelerations.

The results of this study show that the drivers who used either the air disc brakes or the enhanced S-cam brakes had fewer collisions in the emergency scenarios than those drivers using standard S-cam brakes. The fundamental result this research validated is that reducing heavy truck stopping distance has strong potential to decrease the number and severity of crashes in situations requiring emergency braking.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
in	inches	2.54	centimeters	cm
ft	feet	30.48	centimeters	cm
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.45	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar
psi	pounds per $inch^2$	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (°F - 32)	Celsius	°C

Approximate Conversions to English Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.39	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.62	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per $inch^2$	psi
kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (°C) + 32°F	Fahrenheit	°F

NOTE

REGARDING COMPLIANCE WITH

AMERICANS WITH DISABILITIES ACT SECTION 508

For the convenience of visually impaired readers of this report using text-to-speech software, additional descriptive text has been provided within the body of the report for graphical images to satisfy Section 508 of the Americans with Disabilities Act (ADA).

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EXECUTIVE SUMMARY

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.

Based on kinematics, it is reasonable to assume that if a truck can stop in a shorter distance it is more probable that the 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. This report validates this assumption through the 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 three braking systems used in this study are the standard S-cam (existing brake model), the enhanced S-cam (larger drums and shoes), and the 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 and the speed of the struck vehicle at the time of collision were recorded. From these two numbers, the effective speed of collision (delta-v) was calculated.

The four stopping emergency events were right incursion, left incursion, stopped vehicle, and stopping vehicle. These events were on a dry surface and the truck drivers were restricted from steering away from the obstacles by using concrete barriers on the shoulder, parked vehicles, and moving traffic in adjacent lanes. The events timings were designed such that in the case of the S-cam brake system the driver should bring the truck to a safe stop if he/she pushes the brake pedal to its maximum travel at the time when the incursion vehicle is first perceived. This concept provided the ability to test stopping brake effectiveness during emergency situations.

Based on the results presented in this report, the type of braking system had no statistical effect on driver behavior prior to braking. Driver behavior was assessed by studying reaction time to obstacle perception and brake pedal force.

The experiment used a validated virtual environment with high fidelity and showed systematically that professional drivers using either enhanced S-cam or air disc brake systems were better able to avoid collisions than those drivers using standard S-cam brakes. Also, drivers using air disc brakes avoided collisions more often and, in those cases where a collision occurred, had lower collision speeds than those using the enhanced or the standard S-cam brake systems.

1.0 INTRODUCTION

When heavy trucks are involved in crashes with light vehicles, it is the occupants of the light vehicle who are most often killed or seriously injured. Reducing the stopping distance of commercial vehicles should result in a decrease of both crashes and their severity. This study set up a driving simulator experiment which demonstrated that drivers of heavy trucks used more effective brakes to either avoid a collision or to collide with a significantly lower speed than they would with standard brakes.

1.1 BACKGROUND

According to the Federal Motor Carrier Safety Administration as edited by the National Highway Safety Administration (NHTSA) [1], in 2002 there were approximately 434,000 heavy trucks involved in police reported crashes; 4,542 of them resulted in fatalities. Seventy-nine percent of the fatalities were occupants of other vehicles.

NHTSA believes that reducing the FMVSS 121 (49 CFR Part 571) minimum stopping distance by twenty to thirty percent will result in saving a significant number of lives [1]. 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, then fewer crashes will result. Based on kinematics, it is reasonable to assume that 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, there could be situations where improved brakes may have little or no effect on avoiding a collision or reducing the delta speed of a crash.

The primary objective of this study was to provide test data that demonstrates the effectiveness of improved brakes on heavy trucks. This test addressed whether shorter stopping distances reduce the number and severity of certain types of heavy truck crashes.

1.2 APPROACH

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

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

The simulator scenarios were primarily based on those used in previous NHTSA Electronic Stability Control (ESC) research [2]. All simulated roads were 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 were 12 feet (3.7 m) wide, there were 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 was 11.5 feet (3.51 m) wide. Beyond the shoulder, there was an additional 75 feet (23 m) of drivable terrain (see Figure 1.1). The scenarios took place on dry pavement. The virtual environment reflected conditions consistent with the pavement. In particular, the scene was clear and the pavement appeared 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). Stopping distance was reduced by 17% and 30% when the standard S-cam brake system was replaced by the enhanced S-cam and disc systems respectively.

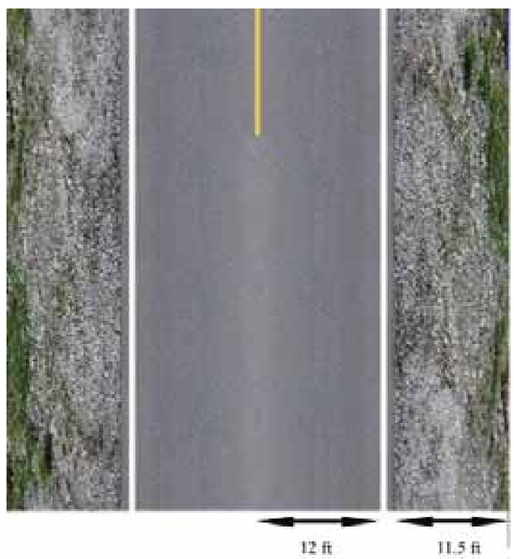

Figure 1.1 - Road Geometry

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. The population of commercial vehicle drivers is comprised of mostly males, but 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; the fourth 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, stopping distance, reaction time to event start, and average deceleration. Other behaviors were tabulated such as if the driver braked, steered, and/or accelerated.

1.3 SCENARIO DESIGN

To understand the effectiveness of heavy truck improved 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 were presented to each participant as individual drives. Each participant drove all 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 could stop without hitting the target vehicle, if the brakes were applied immediately. The scenarios conflict events were:

1.3.1 Right Incursion

The goal of this event was to force the driver to apply brakes to avoid colliding with oncoming traffic. A vehicle that pulls out of a hidden driveway attached to a roadside farmhouse combined with carefully timed oncoming traffic created the conditions for such a maneuver (Figure 1.2). The driver approached a driveway that can hide a vehicle. The driver was motivated via monetary incentives to maintain the speed limit of 55 mph (89 kph). Parked vehicles on both shoulders prevented the driver from steering to avoid the oncoming traffic. When the driver was four seconds from arriving at the driveway location, the hidden parked vehicle pulled out from the right and stopped, blocking the right lane. Drivers who could not stop within the available distance would collide with the white incursion vehicle, the green oncoming car, the gray oncoming car, or the parked truck on the left shoulder.

1.3.2 Left Incursion

The goal of this event was to force the driver to react to an incursion from the left and to brake suddenly while traveling at highway speed. The driver was on a two-lane rural highway crossing a heavily wooded area with frequent oncoming traffic (Figure 1.3). The posted speed limit was 55 mph (89 kph) and the driver was motivated via monetary incentives to maintain speed. There were several parked vehicles on both shoulders. As the driver approached the location of the event, one of the oncoming vehicles was tasked to arrive at the event location at a fixed relative position to the driver. Oncoming traffic approached a parked vehicle on the shoulder opposite to the driver's side. That parked vehicle began moving and cut off the oncoming traffic which was then forced to steer into the driver's lane. The oncoming traffic would enter the driver's lane at a fixed time-distance, 8 seconds away from the driver. Concrete barriers were placed on the right side so that the driver would not steer to the shoulder. If the driver could not stop within the available distance, the driver would collide with the oncoming red SUV, oncoming traffic in the left lane, or the concrete barriers.

1.3.3 Stopped Vehicle

The goal of this event was to force the driver to react to an obscured stopped vehicle on the highway. The driver was on a 4-lane rural highway traveling at the posted speed limit of 70 mph (110 kph) (Figure 1.4). There was a steady stream of traffic in the adjacent lane as well in the oncoming lanes. Once the driver achieved the posted speed limit, a delivery truck sped past, made a right lane change into the driver’s lane, and became the lead vehicle as well as the obscuring vehicle. The lead vehicle maintained a distance of 400 ft (122 m) in front of the driver. When the participant was 610 ft (186 m) from a stopped vehicle, the lead vehicle made a lane change into the stream of traffic in the adjacent lane revealing the stopped vehicle. The driver could collide with the stopped vehicle, traffic traveling in the same direction in the adjacent lane, or oncoming traffic in the far lanes. Because this was the most severe stop, it was always the last scenario for each driver.

1.3.4 Stopping Vehicle

The goal of this event was to force the driver to react to an abruptly stopping lead vehicle while traveling at 55 mph (89 kph). There was a continuous flow of oncoming traffic throughout the event and there were barricades and construction vehicles parked along the right side of the road. These barricades and parked vehicles constrained the driver from steering off-road during the braking event (Figure 1.5). The driver was on a two-lane rural highway crossing a heavily wooded area with frequent oncoming traffic. The posted speed limit was 55 mph. As the driver was moving along, a vehicle approached the truck from behind. As the driver cruised along, the following vehicle made a lane change and overtook the truck. It entered the driver’s lane and maintained a distance of 132 ft (40 m) for approximately 2100 ft (640 m) before it decelerated at the rate of 0.75 g to a complete stop. The driver was precluded from steering via construction barriers on the edge of driver’s lane and oncoming traffic in the adjacent lane. A collision could happen with the stopping green lead vehicle, oncoming traffic, or the concrete barriers.

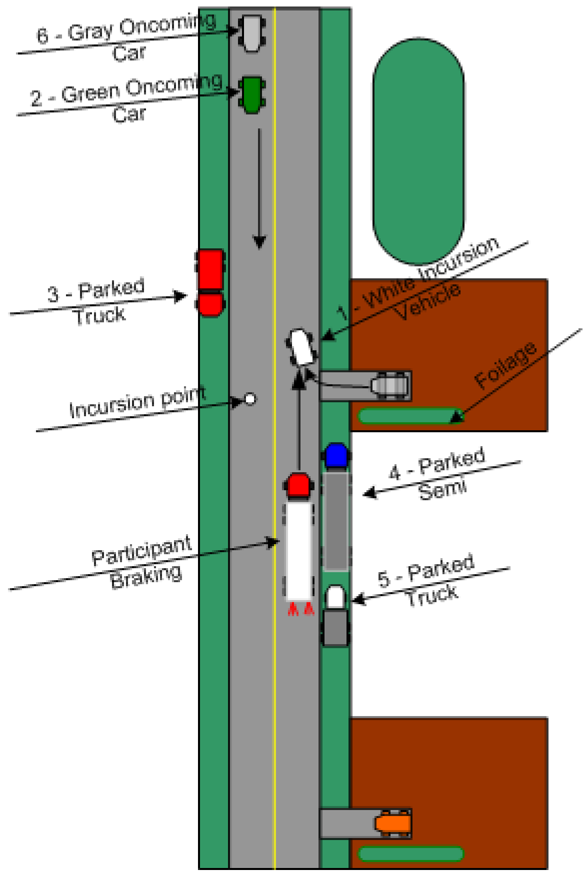

Figure 1.2 - Right incursion

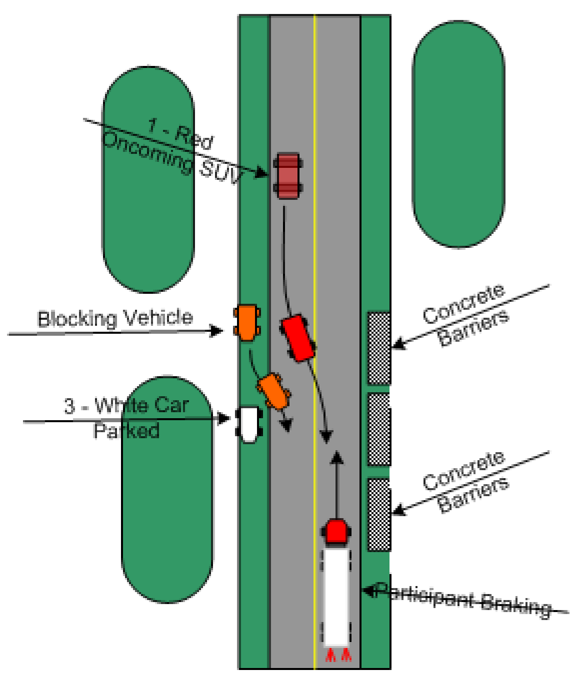

Figure 1.3 - Left incursion

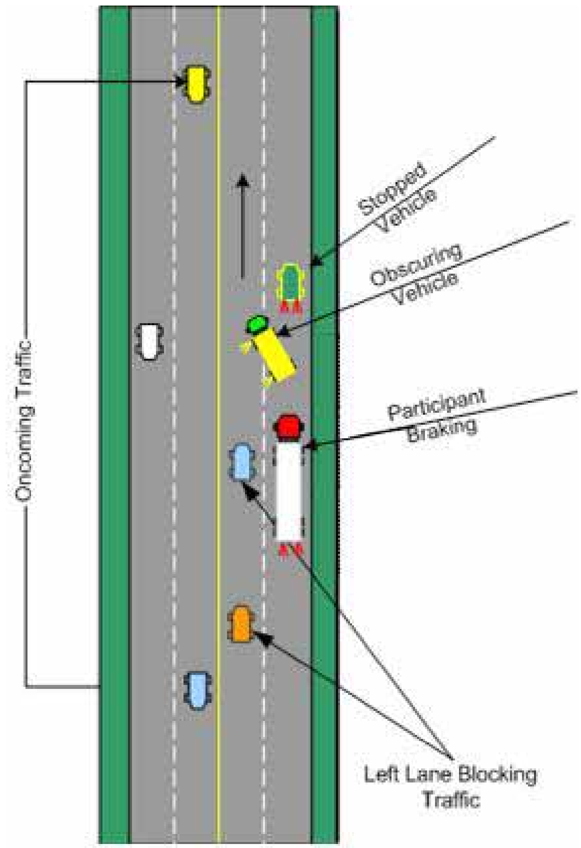

Figure 1.4 - Stopped vehicle

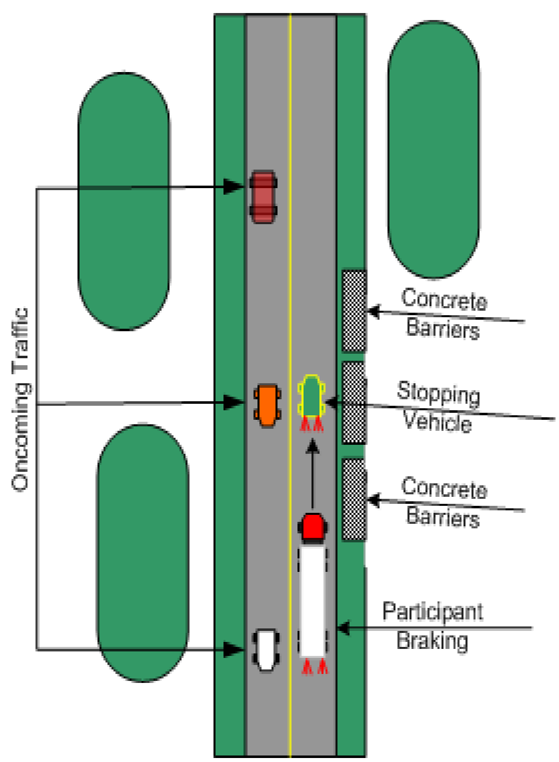

Figure 1.5 - Stopping vehicle

2.0 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.

2.1 SIMULATOR

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, which provides 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 9 degrees of freedom as shown in Figure 2.1. 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 driven controls and displays inside the cabs are electronically and mechanically active (Figure 2.2). 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 2.3). 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 360-degree field-of-view, including the rearview mirror images. The driving scene is 3-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), 3-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. The visual display timing is real time. The time delay between the driver input and the visual display is less than 50 milliseconds. 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 360-degree 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 driver's 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 2.4). 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 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 2.5 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 axle mode, 10-12 Hz frequencies are related to cab modes, and the 17-25 Hz frequencies are related to engine and power train modes.

A manual transmission with low and high gear range selection was used for this study (Figure 2.6). Before drivers were engaged in the scenarios, they were given ample time (about twenty minutes) to drive and get familiar with the transmission system. Drivers demonstrated different skill levels; however, none of the scenarios involved in this study required transmission shifting during the braking event.

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, 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 speeds and provided the data to NADS to be displayed in real time and coordinated with the engine speed.

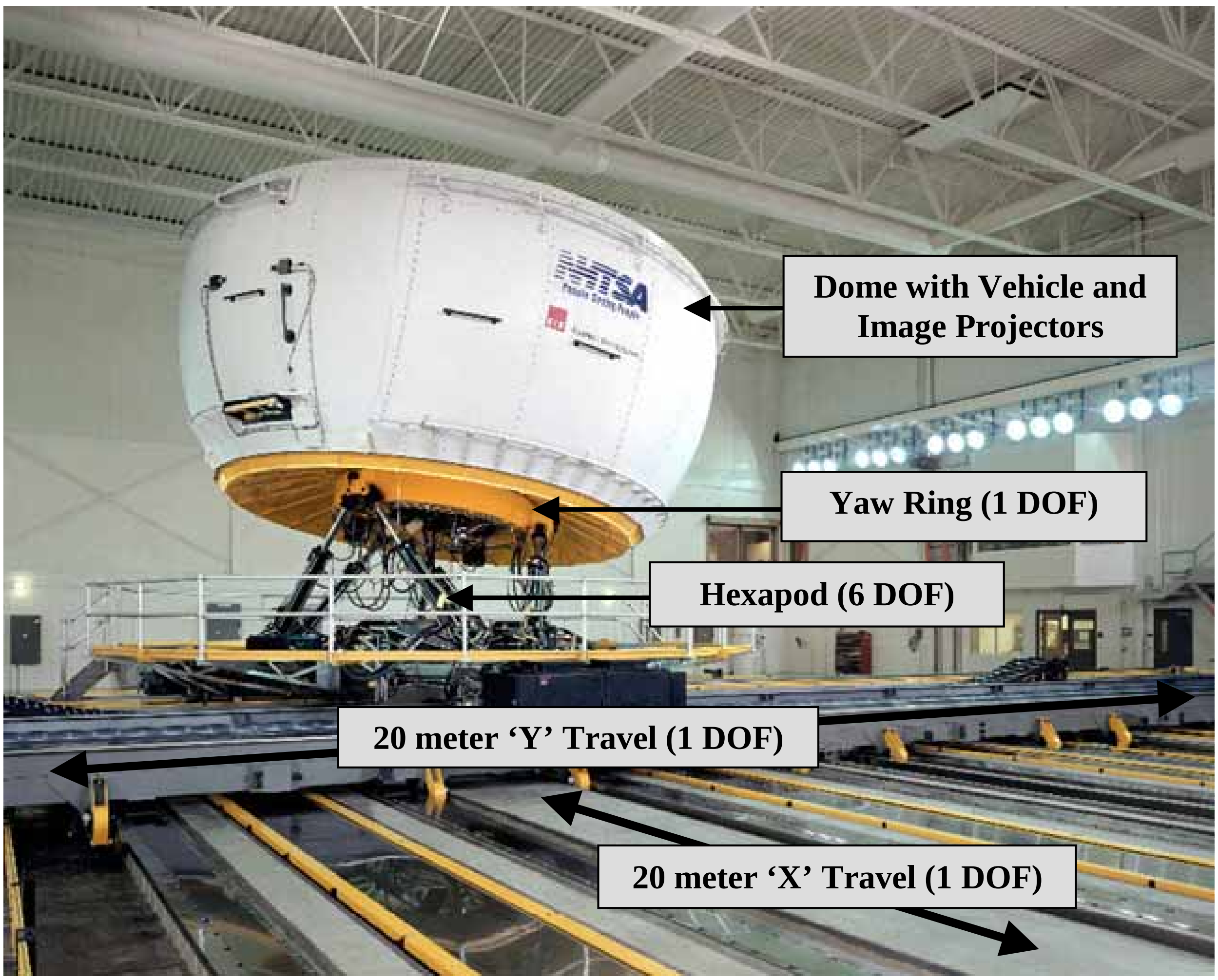

Figure 2.1 - National Advanced Driving Simulator (NADS)

Figure 2.2 - Freightliner cab interior

Figure 2.3 - Truck cab in the NADS dome

Figure 2.4 - Truck cab showing vertical actuator for vibration cues

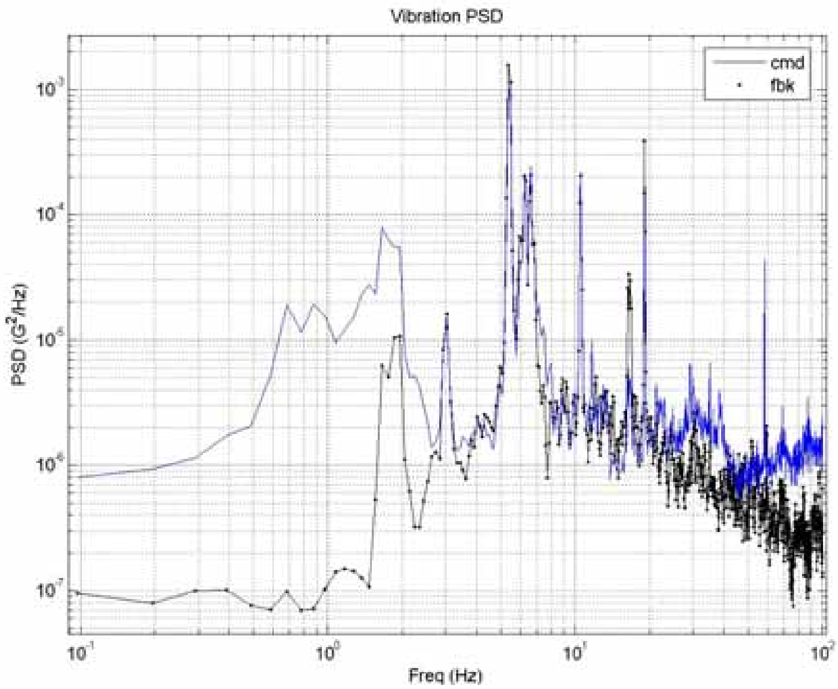

Figure 2.5 - Vibration power spectrum measured on the NADS cab (commanded and measured)

Figure 2.6 - Truck cab shifting

2.2 VEHICLE DYNAMICS AND BRAKE SYSTEM MODELS

The NADS vehicle dynamics computer simulation (NADSdyna) determined vehicle motions and control feel conditions in response to driver control actions, road surface conditions, and aerodynamic disturbances. Vehicle responses were 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 [3, 4]. Appendix C contains additional information on the S-cam, enhanced S-Cam, and air disc brake models developed for this study. Appendix D contains additional information regarding the measurement and modeling of the cab vibrations.

The torque characteristics of commercial vehicle brakes have been studied by numerous investigators. A brake model formulation 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 yet been achieved. Recent research has modeled 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 2.7).

The objective of this research was to study the functional effects of three different brake configurations. 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 S-cam brakes, 256 ft (78.0 m) for enhanced S-cam brakes, and 215 ft (65.5 m) for air disc brakes (as shown in Figure 2.8). This is a reduction of stopping distance of 17% and 30% if the standard S-cam brake system is replaced with the enhanced S-cam and disc systems respectively. In this study all these systems were integrated into the same tractor-trailer model [9].

Information on the NADS data and video collected during this study are contained in Appendix E. Appendix F contains a report of a consultants' visit to NADS prior to this study. This report contains a review of NADS subsystems with particular emphasis on the NADS control feel steering and braking systems (CFS).

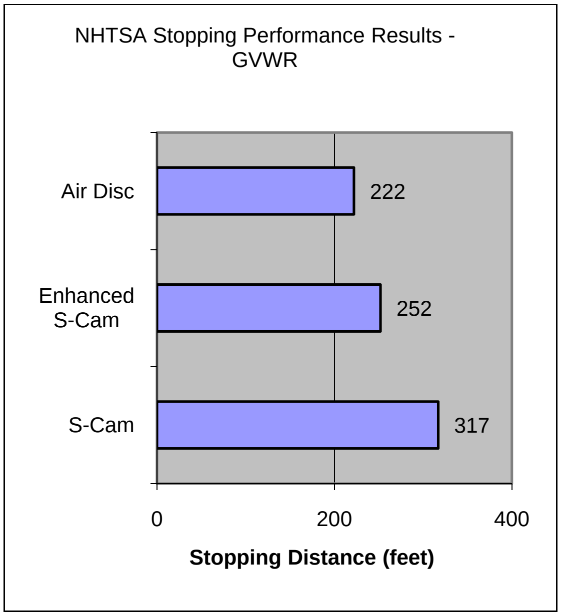

Figure 2.7 - Brake performance measured by VRTC for a typical tractor-trailer with different brakes

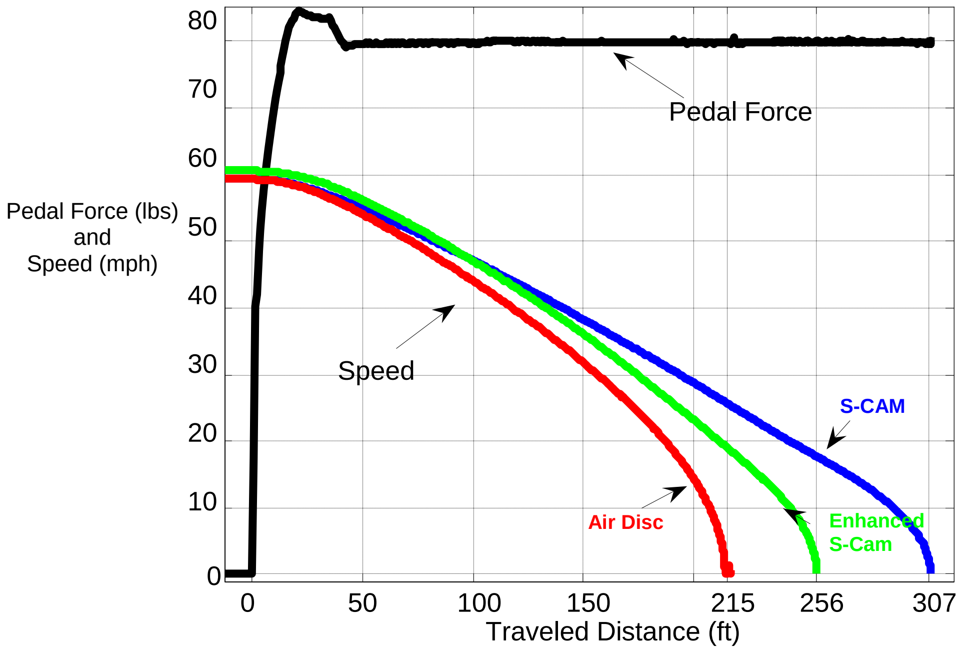

Figure 2.8 - Brake performances on NADS

3.0 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.

Appendix B contains a more detailed description of the simulator study protocol. This protocol contains an overview description of each of the three brake systems used in this study.

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.

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.

4.0 DATA REDUCTION

Each event was divided into six segments using seven different time points. These time points were T0 (trigger activated) through T6 (event completion), and they are defined in Table 4.1. T1 was defined differently for each event (see Table 4.2). Event completion at T6 was determined by evaluating several conditions, described in Table 4.3. The condition that was met first was used to set T6. This condition was called endCond.

Table 4.1 Definition of event time points

Time	Description
T0	T0 was when the subject activated the event trigger
T1	T1 was when the driver can first perceive the beginning of the event (see Table 4.2)
T2	T2 was the initiation of accelerator pedal release (when the current accelerator pedal position is less than 90% of the mean pedal position over the last 1 second)
T3	T3 was the completion of accelerator pedal release (when accelerator pedal position dropped below 5% of the full pedal position range)
T4	T4 was the initiation of brake pedal depression (when brake pedal force exceeded 2.0 pounds)
T5	T5 was the application of maximum brake pedal force
T6	T6 was the completion of the braking event
endCond	Condition used to determine T6 (see Table 4.3)

Table 4.2 Definition of T1 for each event

Event	Definition
Right	When the corner of the incursion vehicle first becomes visible from behind the occlusion vehicle
Left	When the oncoming vehicle began its lane change into the subject's lane
Stopped	When the lead vehicle begins the lane change that reveals the stopped vehicle
Stopping	When the lead vehicle begins to decelerate

Table 4.3 Conditions which defined the end of the event

endCond	Definition
1	Subject stopped (velocity is < 0.1 ft/s)
2	Subject acceleration averaged over 1 sec was greater than -0.5 ft/s^2 after braking response began
3	Right incursion vehicle stopped (The stopping of the incursion vehicle after it had entered the driving lane occurred instantaneously so the end of the event is defined immediately before this occurred)
4	None of the other conditions met; use the end of the data file

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 wheel angle at each Ti,
- reaction time between events,
- braking distance from T4 to T6,
- total stopping distance from Tl 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 Tl to T6,
- time to collision at Tl (assuming driver's speed does not change before co1lision occurrence),
- distance to collision object at Tl,
- 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 Ti,
- articulation angle at each Ti,
- maximum articulation angle,
- time of maximum articulation angle from T1,
- tractor accelerations in x, y, and z directions at each Ti,
- trailer accelerations in x, y, and z directions at each Ti,
- tractor yaw rate at each Ti,
- and trailer yaw rate at each Ti.

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.

5.0 RESULTS

One of the main performance measures for the testing was the number of crashes (collisions) that occurred for each brake type and scenario. For those simulator runs that resulted in crashes, the truck collision speed in the crash was also evaluated as a performance measure of crash severity. In addition to crash occurrences and crash severity, each event was analyzed separately using a similar statistical approach based on comparing drivers' reaction times, speeds at the onset of the braking, stopping distances, braking distances, mean and maximum brake pedal forces, and mean and maximum decelerations.

The hypothesis of this experiment was that there were more collisions (and with higher collision speed) with the S-cam brakes than with the other two systems. Truck collision speed is an indication of the collision severity; higher speeds indicate higher kinetic energy and consequently, higher severity collisions. Collision delta speed that is usually used in analyzing crash severity is the truck collision speed minus the speed of the vehicle (or obstacle and in this case is zero). The higher the truck collision speed the higher the delta speed.

After the experiment was completed, a problem with trigger event was discovered in the stopped event scenario. In 14 of these runs, the trigger was delayed such that the driver was too close to the leading vehicle to have enough time to brake effectively to avoid a collision. These runs were eliminated from the analysis leaving 94 runs for the stopped event scenario.

Table 5.1 summarizes the number of collisions that occurred with the incursion vehicles during each scenario for each brake type. There were 108 subjects in this study, which were divided into 3 groups of 36 subjects, each group assigned to a different brake type. Each subject drove all 4 scenarios. Table 5.1 includes the number of collisions that occurred for each scenario and for each brake type. The right incursion scenario resulted in only 3 collisions, the left incursion resulted in 28 collisions, the stopped event resulted in 37 collisions, and the stopping event resulted in 43 collisions. Clearly the right incursion scenario is less likely to result in a collision and the stopped and stopping scenarios are most likely to result in a collision. Comparing these numbers to real world data [10], the right incursion event occurred in 0.5% of all heavy truck multivehicle crashes, the left incursion 4.5%, the stopped event 4.2%, and the stopping event 2.9%. Table 5.1 indicates that more collisions with the incursion vehicles occurred with the S-cam brakes (51 collisions) than the other brake types. The total number of collisions for the enhanced S-cam brakes (31 collisions) is greater than those for the air disc brakes (29 collisions).

Table 5.1 Summary of number of collisions with incursion vehicles

	S-Cam	Enhanced S-Cam	Air Disc	Total Collisions per Scenario
Right Incursion	2	1	0	3
Left Incursion	13	4	11	28
Stopped Event	14	17	6	37
Stopping Event	22	9	12	43
Total Collisions per Brake Type	51	31	29	111

Table 5.2 contains a summary of the collisions by percentage of the total number of runs for each condition. The 108 drivers each drove 4 scenarios resulting in a total of 418 runs (after eliminating the 14 problem runs from the stopped event). Therefore, the 111 collisions represent 26.6% of the total number of runs.

Table 5.2 Summary of collisions by percentage of total runs

	S-Cam	Enhanced S-Cam	Air Disc	Total Collisions per Scenario
Right Incursion	5.6%	2.8%	0.0%	2.8%
Left Incursion	36.1%	11.1%	30.6%	25.9%
Stopped Event	43.8%	56.7%	18.8%	39.4%
Stopping Event	61.1%	25.0%	33.3%	39.8%
Total Collisions per Brake Type	36.4%	22.5%	20.7%	26.6%

Figures 5.1 and 5.2 show bar graphs representing the total number of collisions per brake type and for each brake type and scenario, respectively. These are graphical representations of the data provided in Tables 5.1 and 5.2.

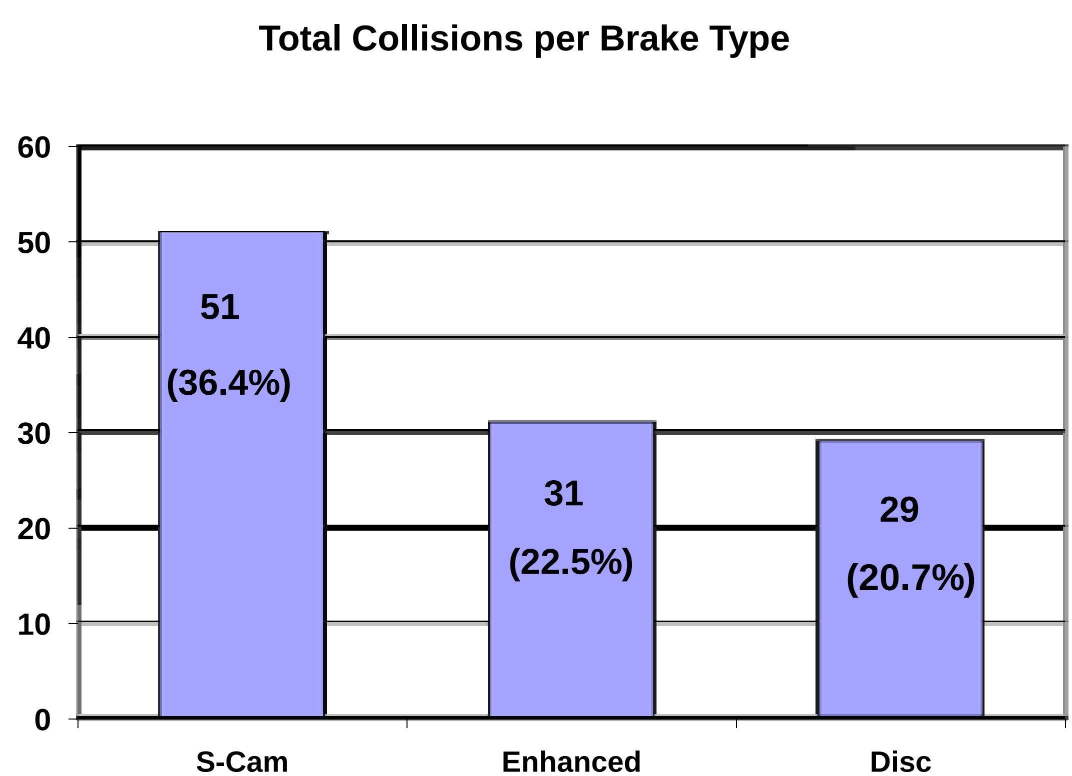

Figure 5.1 - Total number of collisions per brake type

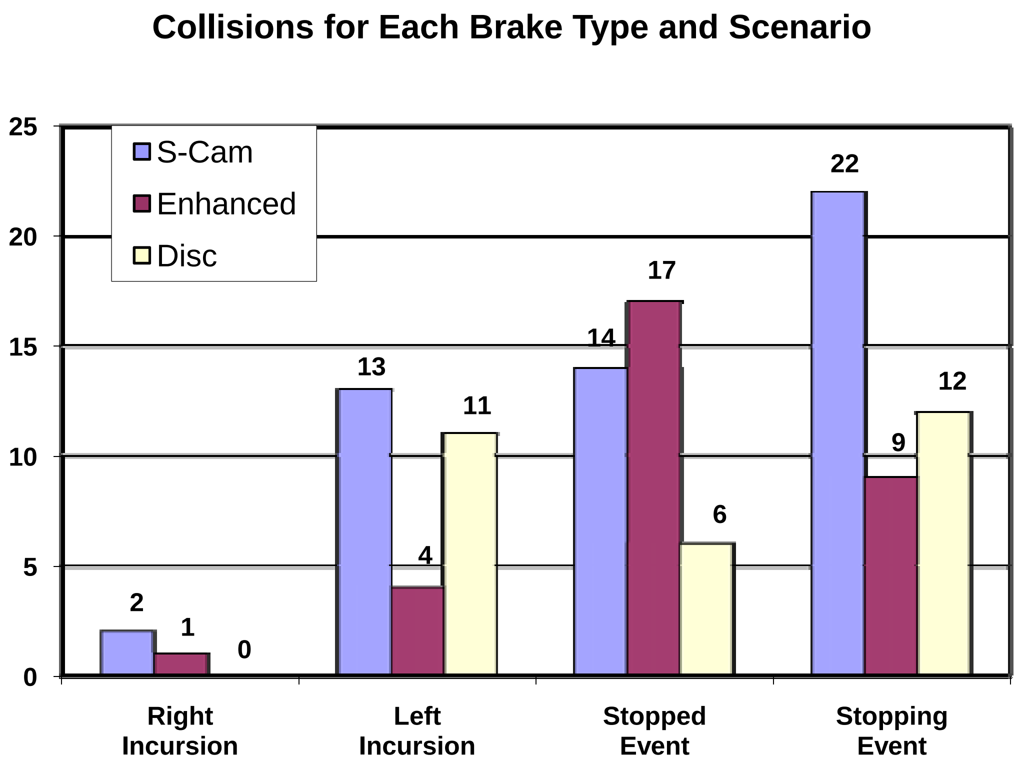

Figure 5.2 - Total number of collisions for each brake type and scenario

Table 5.3 contains mean collision speeds and the difference in vehicle speeds between the striking vehicle and the struck vehicle (delta-v) for all three brake types that occurred during the left incursion, stopped event, and stopping event, whereas Figure 5.3 is a bar graph representation of this data. Delta-v can be used to determine the severity of injury for occupants in the struck vehicle. The right incursion mean collision speed data are not included in this table and graph, as there were only three collisions during the right incursion so a comparison of the mean collision speeds for this case would be meaningless. The left incursion results in a head-on collision; that is why delta-v is larger than the collision speed. In the last two scenarios, the struck vehicle was either stopped or moving in the same direction as the truck. The rightmost column of Table 5.3 contains the p-value determined from the multi-factor analysis of variance (ANOVA) used to compare the means of the observations. P is the probability that the type of brake system has no effect on the variable. A p-value near zero suggests that at least one sample mean is significantly different from the other sample means. Specifically, a p-value less than or equal to 0.05 indicates a statistically significant difference attributed to the type of brakes.

Table 5.3 Mean collision speed and mean delta-v for collisions with struck vehicles (mph)

	S-Cam	Enhanced S-Cam	Air Disc	P
Left Incursion	24.2 (38.7)	23.3 (37.6)	17.2 (31.4)	0.27
Stopped Event	32.0 (32.0)	25.4 (25.4)	23.4 (23.4)	0.02
Stopping Event	23.0 (23.0)	18.9 (18.9)	15.7 (15.6)	0.07

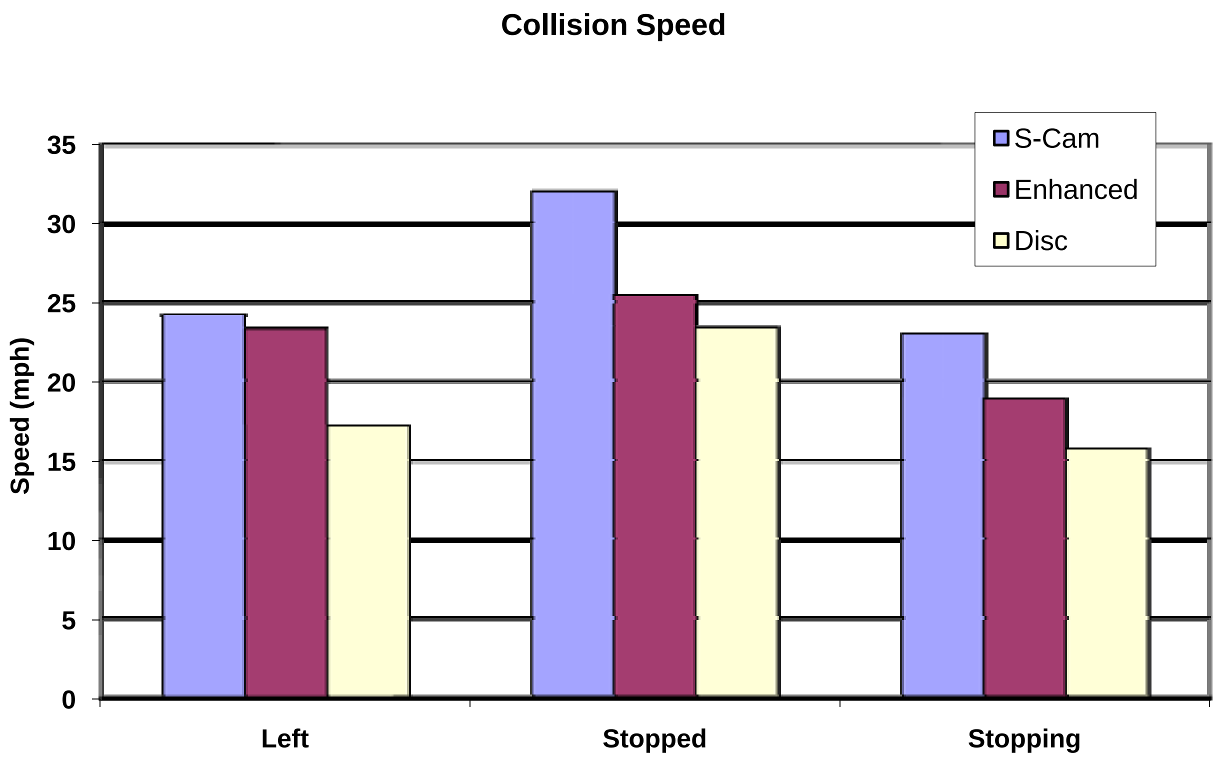

Figure 5.3 - Mean collision speed

The mean collision speeds and the mean delta-v are highest with the S-cam brakes. For the left incursion and the stopping event, the mean collision speed of the three different brake types is not significantly different (at 95-percent confidence), although the trend shows a reduction in collision velocity from S-cam to enhanced S-cam to air disc brakes. For the stopped scenario, there is a statistically significant difference in the mean collision speeds.

Figures 5.4, 5.5, and 5.6 contain comparison graphs showing the mean values and 95% confidence intervals on the mean values for each brake type mean collision speed for the left incursion, stopped event, and stopping event, respectively. Confidence intervals were calculated using the Tukey-Kramer multiple comparison method on the previously calculated ANOVA results. In these mean comparison graphs, if the confidence intervals on a pair of mean values do not overlap, there is 95% confidence that the mean values are different. For the stopped (Figure 5.5) scenario, the bands of the S-cam and enhanced S-cam brakes do not overlap. This implies that the difference in collision velocity is statistically significant. For both the stopped (Figure 5.5) and the stopping (Figure 5.6) scenario, the confidence band for the standard S-cam and the air disc brakes just barely overlap. Whereas this implies that the mean collision speeds do not differ significantly (at 95% confidence), an increase in the number of samples would likely make this difference between the two brake types significant.

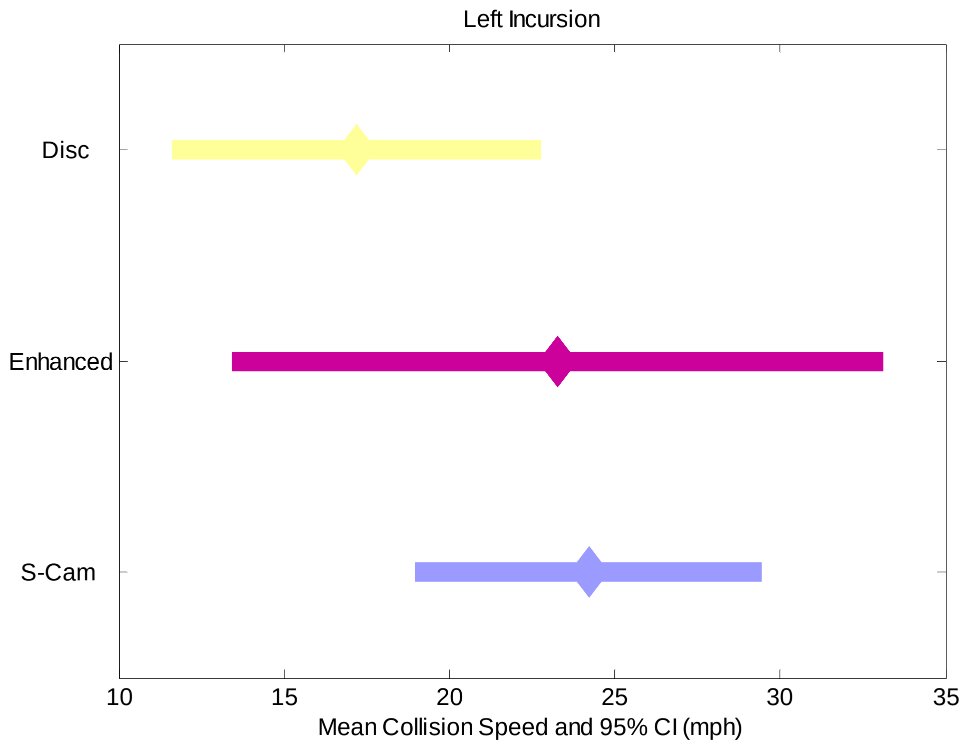

Figure 5.4 - Left incursion mean collision speed

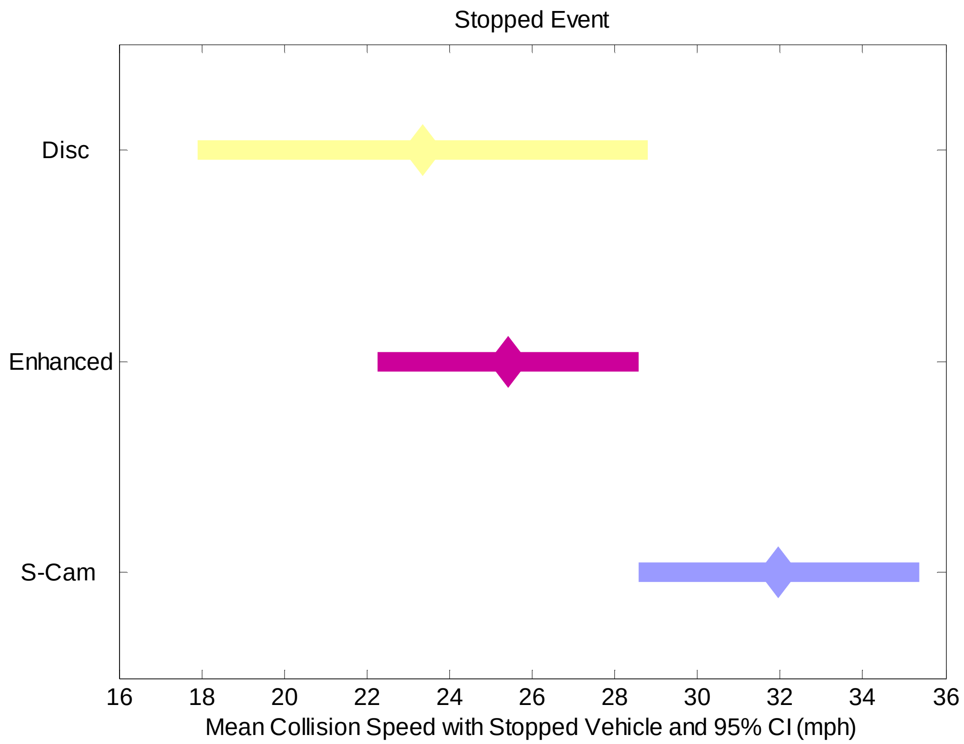

Figure 5.5 - Stopped event mean collision speed

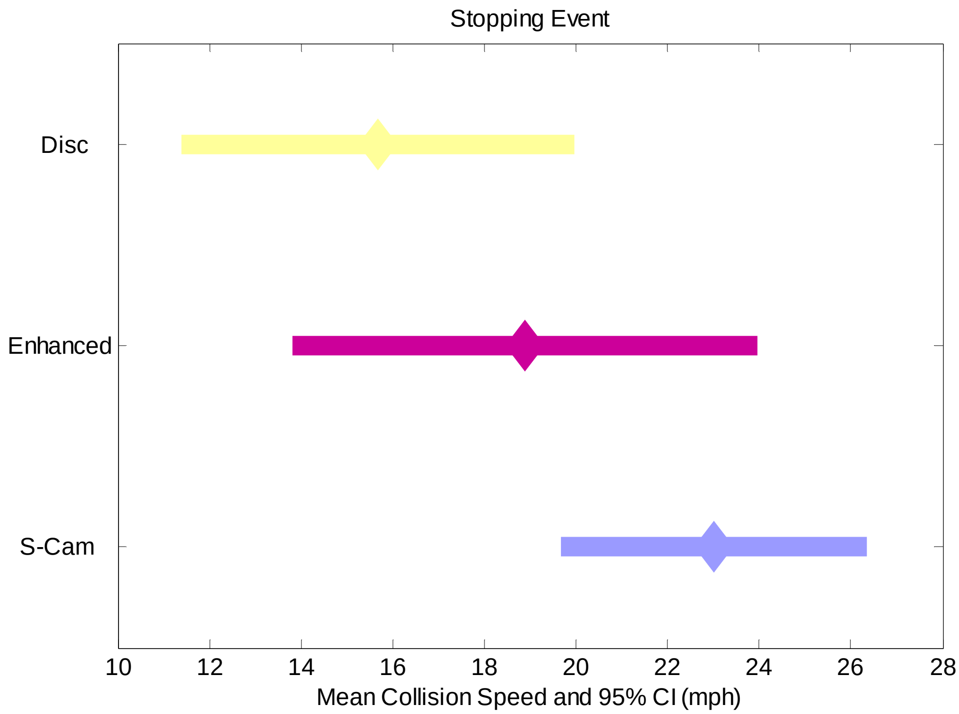

Figure 5.6 - Stopping event mean collision speed

Table 5.4 summarizes the number of non-collision events analyzed for each brake type and scenario. Except for the stopped event, the number of non-collisions per scenario is equal to the total number of runs for each scenario (108) less the number of collisions with the incursion vehicles. During the stopped event scenario, a total of 5 collisions (1 with S-cam brakes, 1 with enhanced S-cam brakes, and 3 with air disc brakes) occurred with objects other than the incursion vehicle. As explained above, only 94 runs were analyzed for this scenario.

The second row of Table 5.4 contains the number of runs during each scenario that were excluded from the analyses because the speed at the onset of the event was not within 10 mph of the target speed (nominal entry speed). Because braking and stopping distances are directly related to vehicle speed, runs in which the speed at the onset of braking differ greatly from the target speed were eliminated to avoid biasing the data. The range of 10 mph was chosen to keep the onset speeds clustered without eliminating too many of the runs, which would weaken the statistical analysis of the results. A total of 5 non-collision runs were excluded from the analyses as a result of being speed outliers.

In an effort to generate meaningful performance measures, it was necessary to analyze results from comparable simulator runs. Table 4.3 lists the end conditions that were used to define the end of the scenario events. To meaningfully analyze braking and stopping distances, brake pedal forces, and decelerations it was necessary to consider runs that stopped under the same end condition. Only runs that were terminated by end condition (endCond) 1 (vehicle was braked to a stop) were included in the non-collision analyses. The last three rows of Table 5.4 indicate the number of S-cam, enhanced S-cam, and air disc brake runs that were included in the analyses for each scenario.

Table 5.4 Summary of non-collision runs used in non-collision analyses

	Right Incursion	Left Incursion	Stopped Event	Stopping Event
Number of Non-Collisions	105	80	52	65
Number of Speed Outliers (Not Within 10 mph of Target Speed)	3	1	0	1
Number of Non-Collisions with Speed OK	102	79	52	64
Number of Non-Collisions with Speed OK and with endCond = 1	49	56	32	48
Number of S-Cam Included in Analyses	14	16	9	9
Number of Enhanced S-Cam Included in Analyses	21	23	9	21
Number of Air Disc Included in Analyses	14	17	14	18

To reliably compare the three brake systems for each braking event scenario, it is necessary to evaluate driver performance characteristics to make sure that the drivers performed similarly in the scenarios regardless of which brake type they were using. Driver reaction time and vehicle speed at braking onset were the performance characteristics evaluated. Driver reaction time is defined here as the time from event onset (T1) to the time when braking started (T4).

Figures 5.7-5.10 contain box plot graphs of the driver reaction times for each scenario, whereas Figures 5.11-5.14 contain box plot graphs of vehicle speed at braking onset for each scenario. For each box plot graph, the results for the individual brake types are displayed using box and whisker plots. The lower and upper lines of each "box" are the 25th and 75th percentiles of the sample. The distance between the top and bottom of the box is the inter-quartile range. The line in the middle of the box is the sample median. If the median is not centered in the box, this is an indication of skewness in the data sample.

The "whiskers" are lines extending above and below the box. They show the extent of the rest of the sample (unless there are outliers). If there are no outliers, the maximum of the sample is the top of the upper whisker. The minimum of the sample is the bottom of the lower whisker. By default, an outlier is a value that is more than one and a half times the inter-quartile range away from the top or bottom of the box. Outliers are indicated by a "+" symbol. Outlier points are results of variations in driver perception and/or reactions and responses.

The notches in the box are a robust graphic confidence interval about the median of a sample. A side-by-side comparison of two notched box plots provides a graphical way to determine which groups have significantly different medians. For boxes whose notches do not overlap, one can conclude, with 95% confidence, that the true medians do differ. This is similar to a one-way analysis of variance, except that the latter compares means.

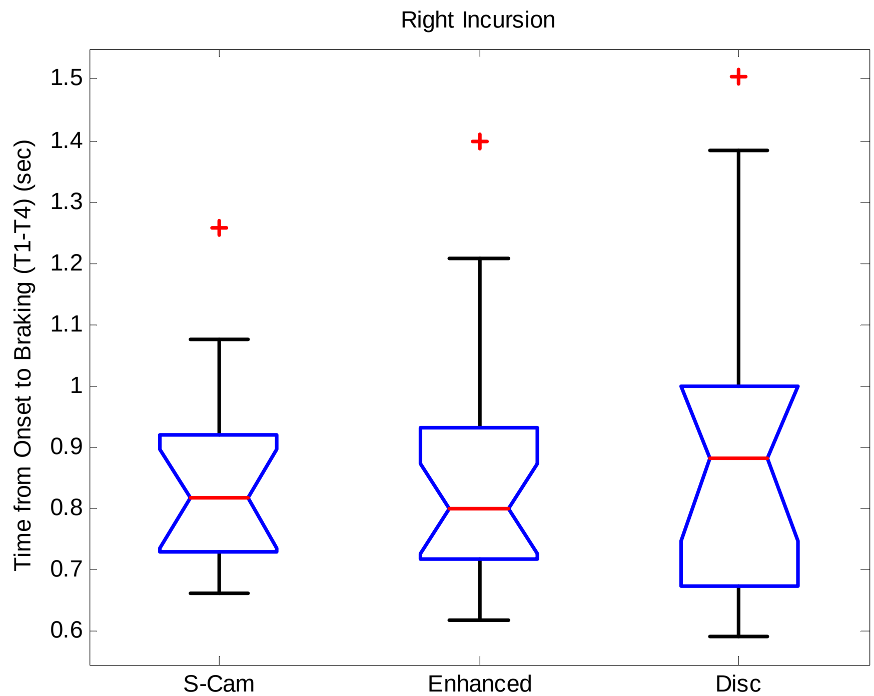

Figure 5.7 - Reaction times during right incursion scenarios

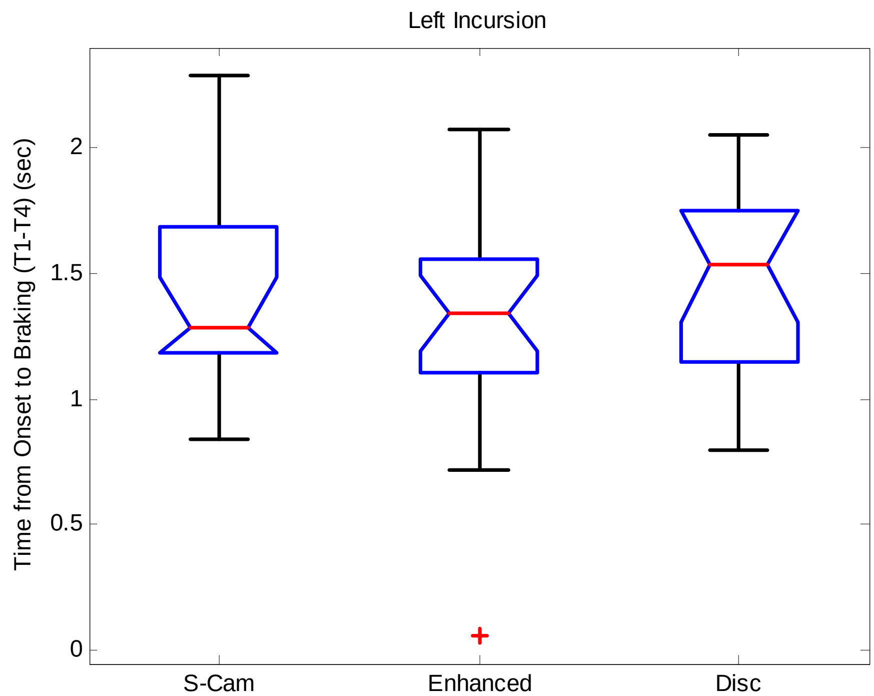

Figure 5.8 - Reaction times during left incursion scenarios

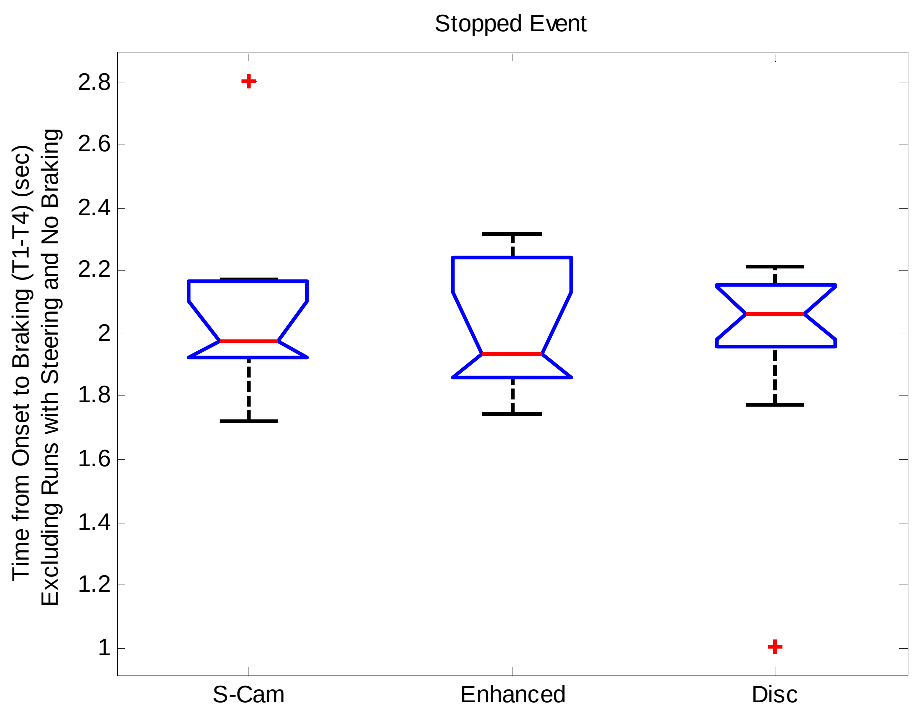

Figure 5.9 - Reaction times during stopped event scenarios

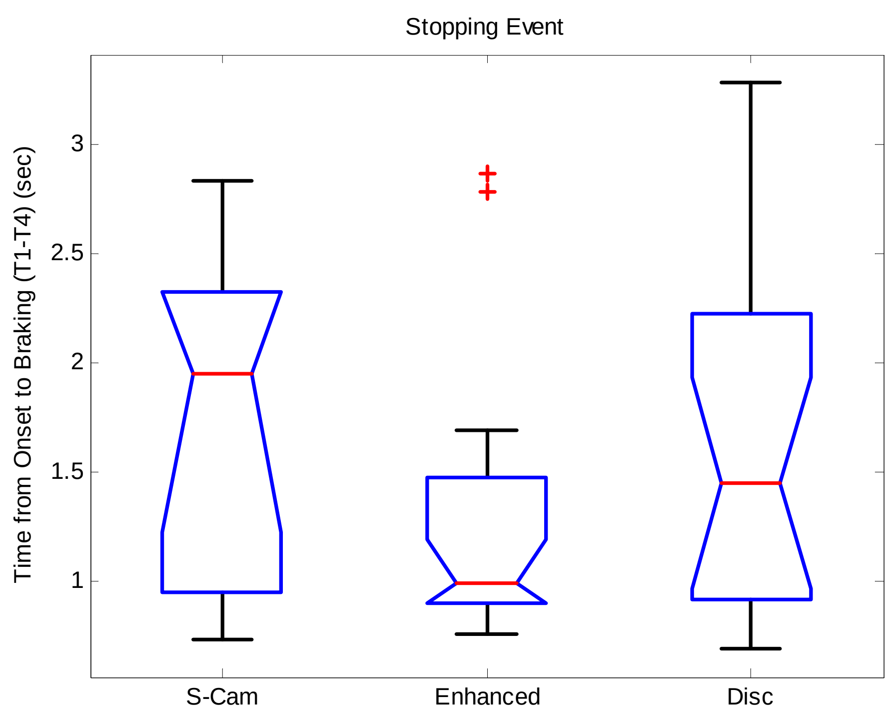

Figure 5.10 - Reaction times during stopping event scenarios

Figures 5.7, 5.8, and 5.9 indicate that the reaction time median values do not differ significantly. The notches in the boxes overlap for the three scenarios. Figure 5.10 shows a significant difference in the median reaction times between the S-cam and the enhanced S-cam brakes for the stopping event scenario. The authors do not have an explanation of why this would be the case, other than the fact that the reaction time for the enhanced S-cam brake system is very skewed (as shown by the median value very close to the bottom (lower quartile) of the box plot). The analysis of the mean value of reaction time (discussed below) shows no statistical difference in reaction times among drivers of the three systems. There is not a significant difference in median reaction times between the enhanced S-cam and the air disc brakes or between the air disc and the standard S-cam brakes.

Table 5.5 contains mean time from event onset to braking (reaction times) for all three brake types that occurred during the left and right incursion, stopping event, and stopped event. The P-values in the last column show no statistical difference between brake types. Figure 5.11 is a graphical representation of this data set.

Table 5.5 Mean time (sec) and number of tests from event onset to braking (Time from T1 to T4)

	S-Cam	Enhanced S-Cam	Air Disc	P
Right Incursion	0.85 (14)	0.86 (21)	0.90 (14)	0.81
Left Incursion	1.40 (16)	1.29 (23)	1.50 (17)	0.29
Stopped Event	2.08 (9)	2.01 (9)	1.98 (14)	0.73
Stopping Event	1.72 (9)	1.27 (21)	1.62 (18)	0.19

The p-values shown on Table 5.5 and Figure 5.11 suggest that the driver reaction time mean values for each scenario are statistically similar and the drivers’ perceptions of the events happened around the same time from event initiations. This is the same thing that box plots showed for the median values. The average reaction times for the drivers are statistically similar across the brake types for all four scenarios. That is, drivers for the S-cam, enhanced S-cam, and air disc brakes perceived the obstacles with no significant variations.

Figures 5.12-5.15 indicate that the vehicle speed at braking onset median values do not differ significantly for the right incursion, left incursion, and stopped event. In the case of the stopped event shown in Figure 5.14, it appears that the box notches for the S-cam and air disk brake types do not overlap. This indicates that there is 95% confidence that the true medians for these cases do differ. However, Table 5.6 indicates that the mean values for all three brake types do not differ. In the case of the stopping event shown in Figure 5.15, the box notches for the S-cam and enhanced S-cam brake types do not overlap. Again, this indicates that the there is 95% confidence that the true medians for these cases do differ. Table 5.6 indicates that this is also true for the mean values. The authors have no explanation for this, but the fact that these two medians differ appears to have no impact on the performance measures analyzed and presented later in this report. In fact, if the S-cam group had lower speeds at braking onset, this would reduce the group's stopping distance. This is shown not to be true later in this chapter. Table 5.6 and Figure 5.16 contain results for mean speed at braking onset.

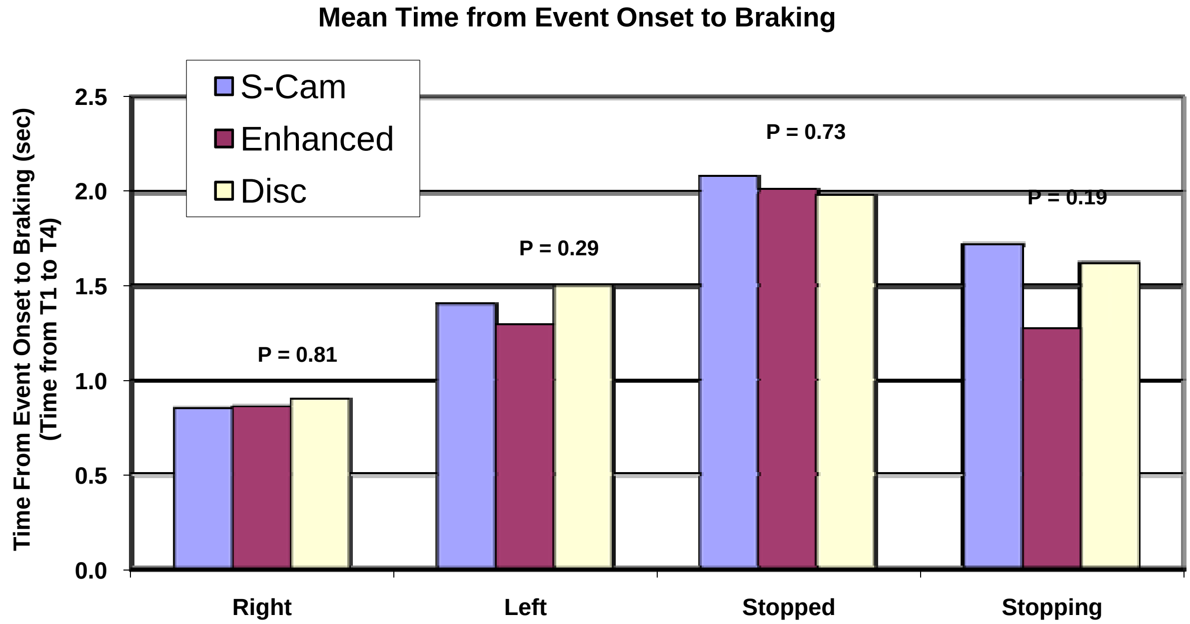

Figure 5.11 - Mean time from event onset to braking (reaction time)

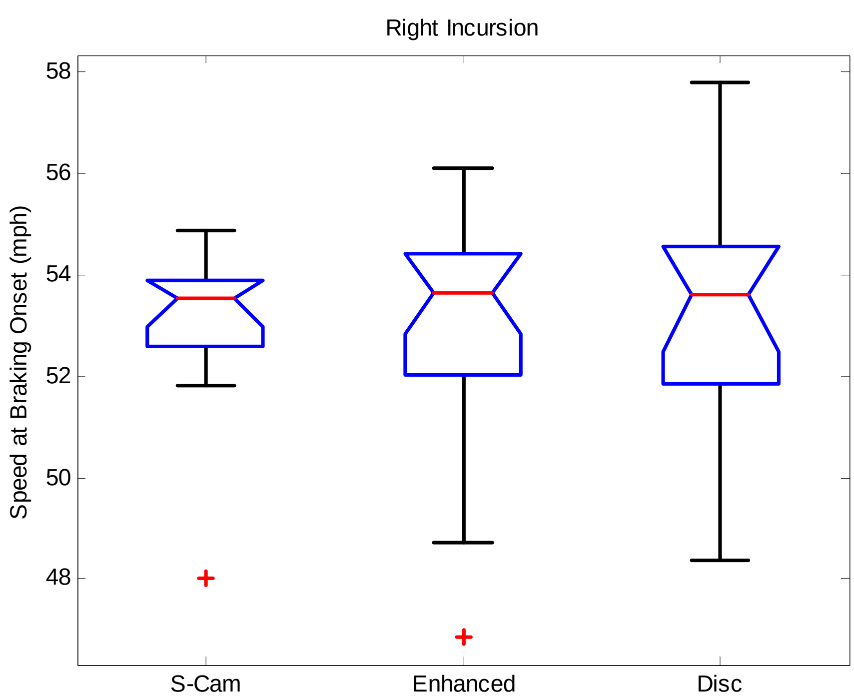

Figure 5.12 - Speeds at braking onset during right incursion scenarios

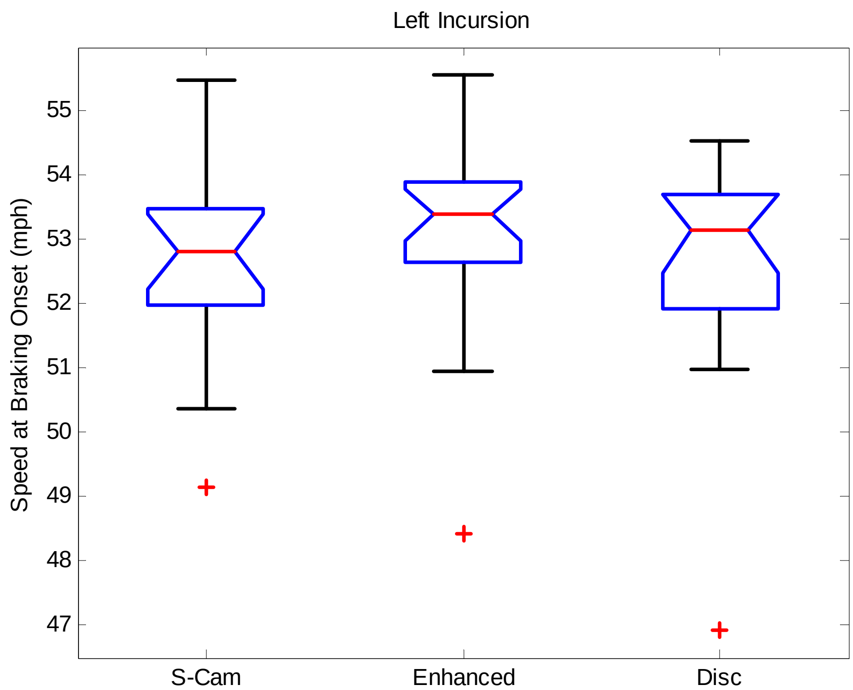

Figure 5.13 - Speeds at braking onset during left incursion scenarios

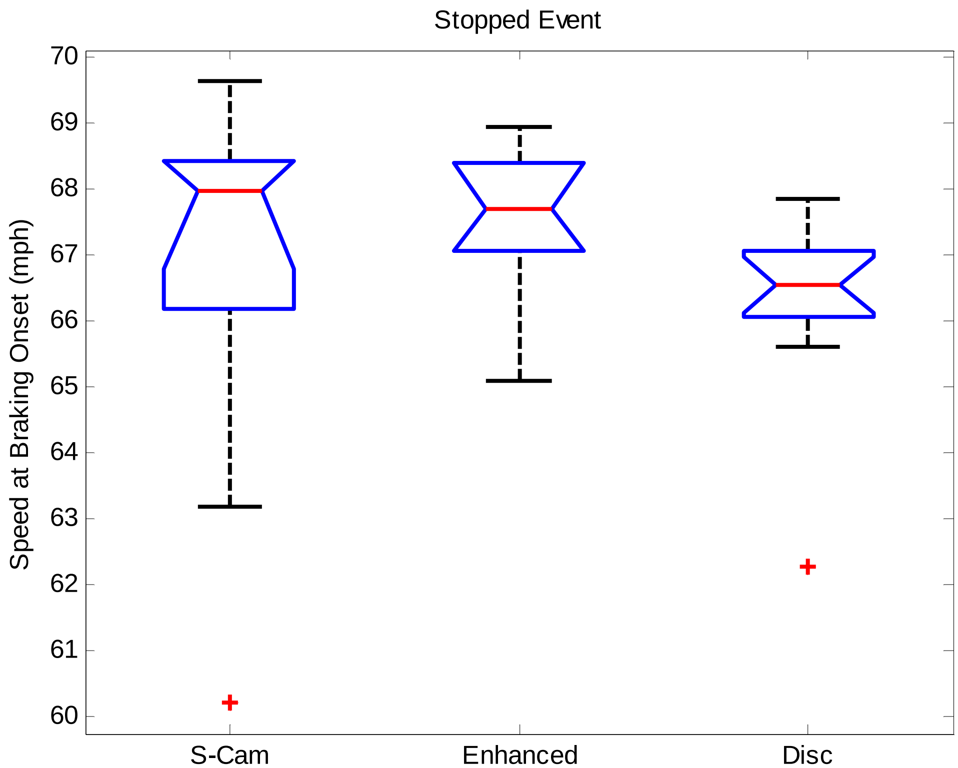

Figure 5.14 - Speeds at braking onset during stopped event scenarios

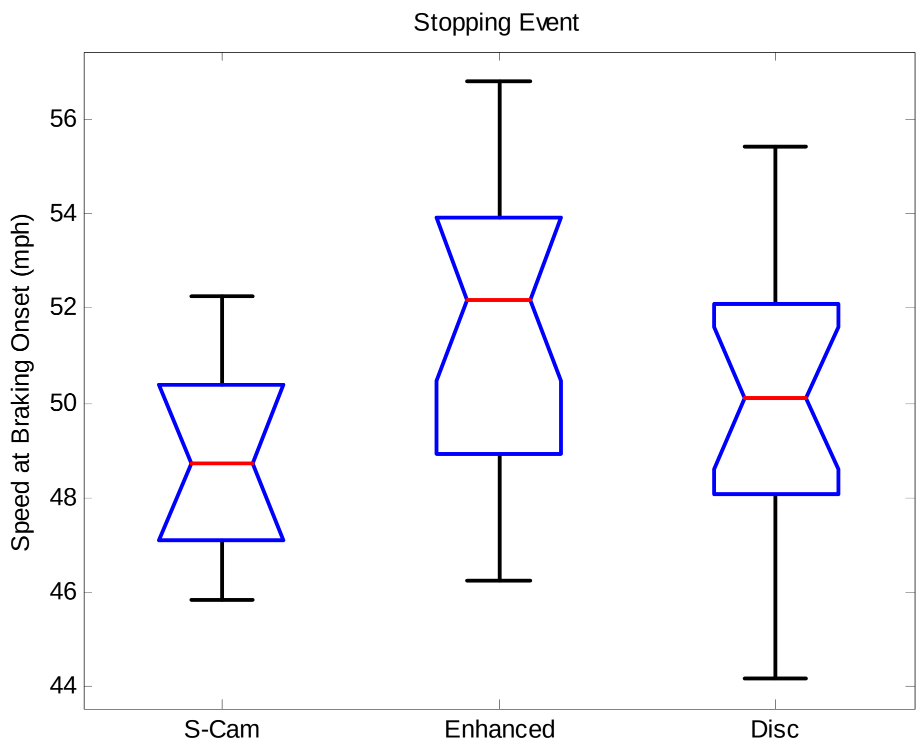

Figure 5.15 - Speeds at braking onset during stopping event scenarios

The p-values shown of Table 5.6 and Figure 5.16 suggest that the speed at braking onset mean values are not significantly different for the right incursion, left incursion, and stopped event; but are significantly different for the stopping event. This too is the same thing that box plots showed for the median values. Post hoc analysis revealed that the mean speed at braking onset was statistically significantly lower in the scenarios using standard S-cam brakes than those using enhanced S-cam brakes. As stated earlier, this difference did not affect the braking distance results.

Table 5.6 Mean speed (mph/kph) and number of tests at braking onset

	S-Cam	**Enhanced S-Cam**	**Air Disc**	**P**
Right Incursion	53.1 / 85.4 (14)	52.9 / 85.2 (21)	53.4 / 85.9 (14)	0.84
Left Incursion	52.6 / 84.6 (16)	53.1 / 85.4 (23)	52.6 / 84.7 (17)	0.54
Stopped Event	66.8 / 107 (9)	67.5 / 109 (9)	66.4 / 107 (14)	0.43
Stopping Event	48.9 / 78.6 (9)	51.8 / 83.4 (21)	50.0 / 80.5 (18)	0.01

Tables 5.7 and 5.8 show mean values and p-values for stopping distance and braking distance, respectively, for each scenario and brake type. Figures 5.17 and 5.18 contain bar graphs of

stopping distance and braking distance. The stopping distance is the distance traveled from the onset of the event (at time T1) to the stopping point (at time T6). The braking distance is the distance traveled from the onset of braking (at time T2) to the stopping point (at time T6).

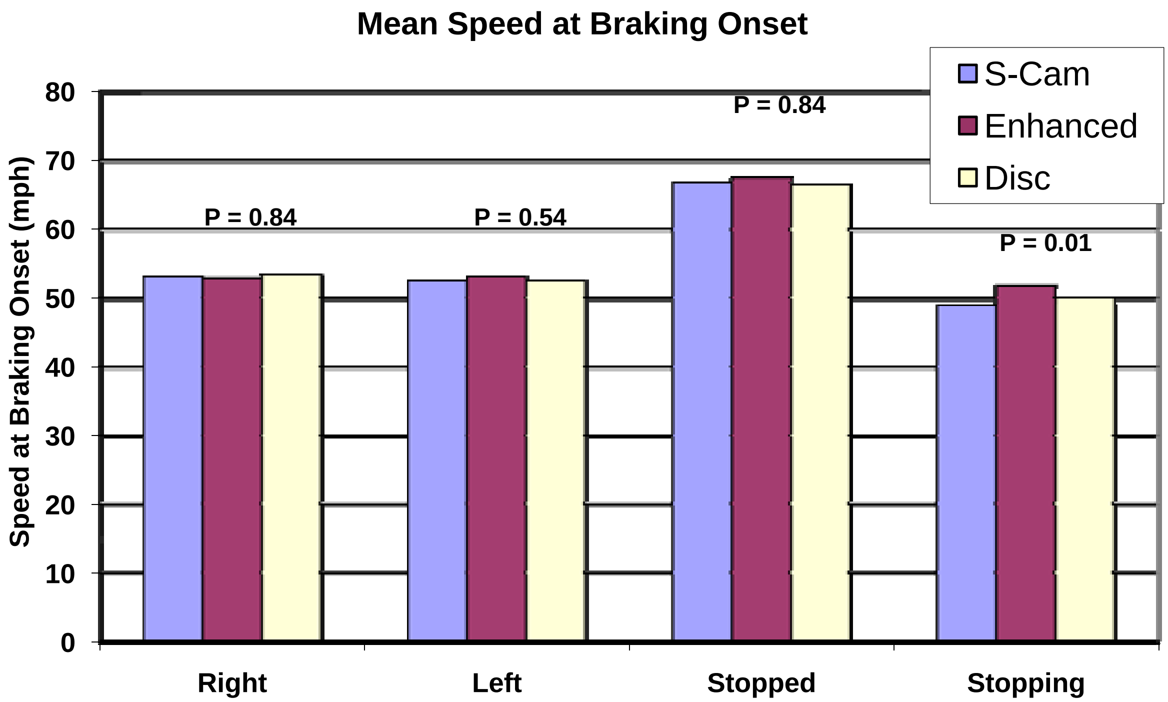

Figure 5.16 - Mean speed at braking onset

Table 5.7 Mean stopping distance (distance traveled from T1 to T6) (ft / m)

	S-Cam	Enhanced S-Cam	Air Disc	P
Right Incursion	282 / 85.9.0	249 / 75.8	251 / 76.6	0.01
Left Incursion	334 / 102	303 / 92.4	317 / 96.5	0.11
Stopped Event	724 / 221	571 / 174	496 / 151	< 0.01
Stopping Event	319 / 97.3	279 / 85.0	287 / 87.5	0.09

Table 5.8 Mean braking distance (distance traveled from T4 to T6) (ft / m)

	S-Cam	Enhanced S-Cam	Air Disc	P
Right Incursion	216 / 66.0	183 / 55.7	181 / 55.3	< 0.01
Left Incursion	227 / 69.2	203 / 61.8	201 / 61.3	< 0.01
Stopped Event	521 / 159	373 / 114	303 / 92.4	< 0.01
Stopping Event	198 / 60.3	185 / 56.3	172 / 52.3	0.03

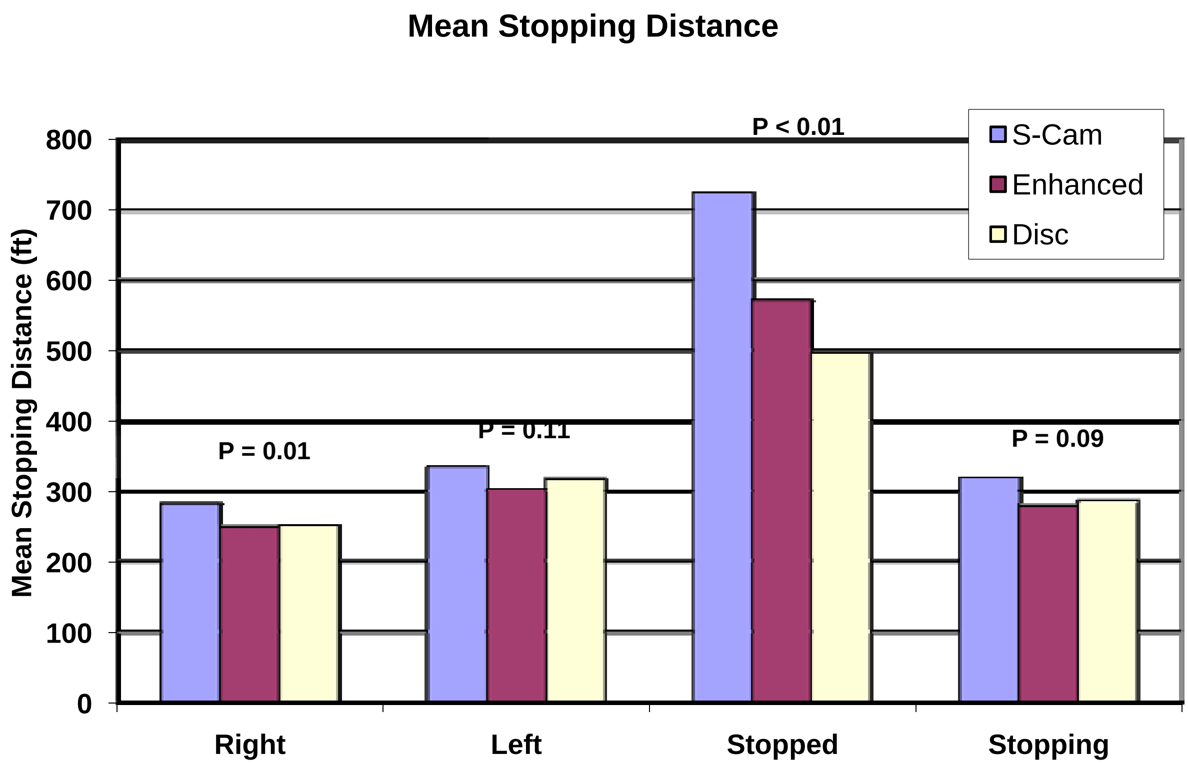

Figure 5.17 - Mean stopping distance

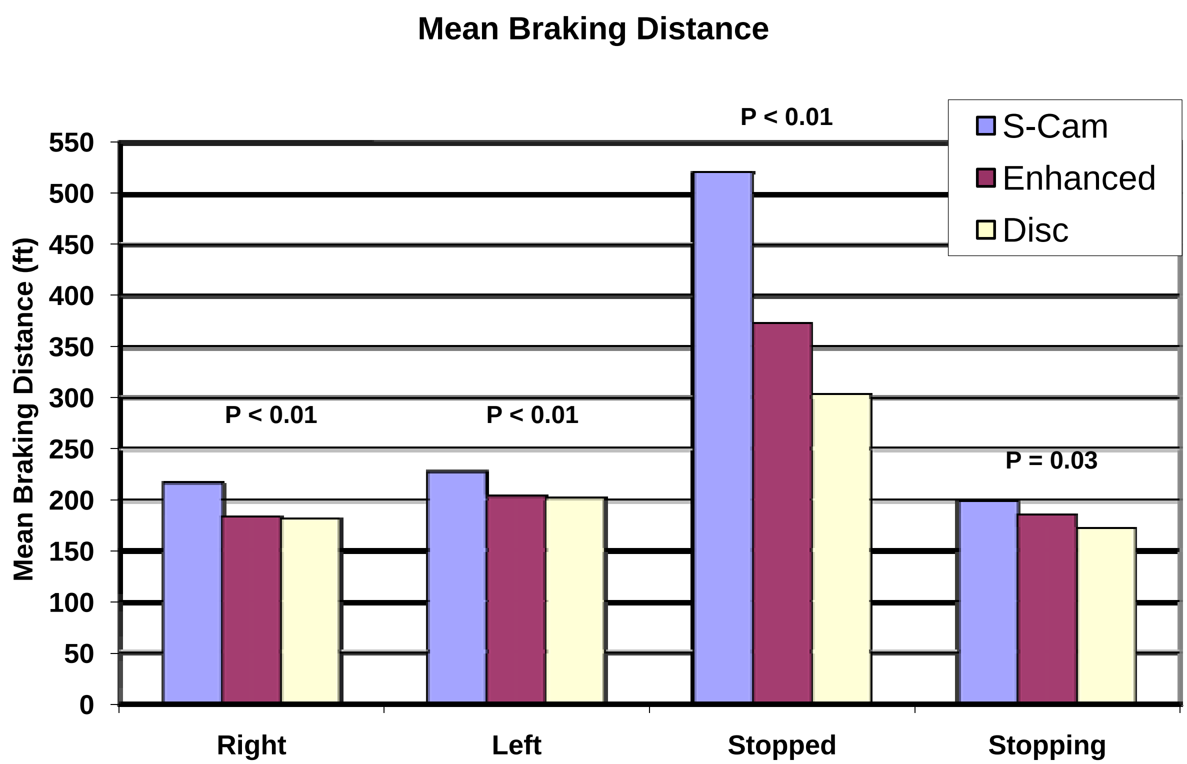

Figure 5.18 - Mean braking distance

The p-values for the stopping distances are similar to the braking distances for the right incursion and stopped event. The p-values for the left incursion and stopping events are not as low for the stopping distance as they are for braking distance. However, the trends in stopping distance are similar to the trends in braking distance.

The p-values for the braking distances indicate that the mean braking distance of at least one brake type differ significantly from the other brake types. The mean braking distance for the S-cam brakes is greater than for the other two brake types (Figure 5.18). The box plots for these tests (see Appendix A) show that the braking distance of the S-cam is statistically significantly longer than those of the enhanced S-cam and air disc brake types, except in the stopping vehicle scenario, where the braking distance of the S-cam brake was statistically significantly longer than only that of the air disc brake (confirmed by 95% confidence intervals). The braking distances for the enhanced brakes are similar to the braking distances for the air disc brakes except for the most severe scenario; the stopped event (in which case the air disc brakes had both a shorter stopping and braking distance).

Appendix A contains box plot graphs of stopping distance and braking distance, as well as the other performance measures of mean brake pedal force, maximum brake pedal force, mean deceleration, and maximum deceleration.

The drivers' braking efforts were compared for the three brake types 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 the standard S-cam system. The mean values and p-values of the mean brake pedal force (Table 5.9 and Figure 5.19) and maximum brake pedal force (Table 5.10 and Figure 5.20) were evaluated. In the cases of the left incursion and the stopping events, there was a statistically significant difference in mean brake pedal force. For the left incursion scenario, the mean brake pedal force was statistically significantly lower for the air disc brake than for the standard S-cam. For the stopping event scenario, the mean brake pedal force was statistically significantly lower for the air disc brake than for the enhanced S-cam. The authors believe this is due to the drivers with disc brakes easing off the brake pedal when they realized that a collision was no longer a threat. There was no statistical difference in maximum brake pedal force.

Table 5.9 Mean of mean brake pedal force (Mean Force from T4 to T6) (lb / N)

	S-Cam	Enhanced S-Cam	Air Disc	P
Right Incursion	75.4 / 335	70.8 / 315	67.0 / 298	0.11
Left Incursion	71.4 / 317	66.1 / 294	60.8 / 270	0.02
Stopped Event	74.5 / 331	77.0 / 343	70.9 / 315	0.27
Stopping Event	70.3 / 313	71.5 / 318	62.0 / 276	0.03

The mean values and p-values of the mean deceleration (Table 5.11 and Figure 5.21) and maximum deceleration (Table 5.12 and Figure 5.22) indicate that one of the means for mean deceleration and maximum deceleration was significantly different than at least one of the other two brake types. Examination of the box plots for these variables (Appendix A) reveals that S-cam value is statistically significantly lower than that of the other two brake types. The trends in the mean and maximum deceleration results are similar. The disc brakes provided the highest decelerations in all cases; even though the mean and maximum brake pedal forces were lower in nearly all cases. As a result of braking capability, drivers with air disc brakes experienced the fewest number of collisions, the lowest collision speeds, and the shortest mean braking distance.

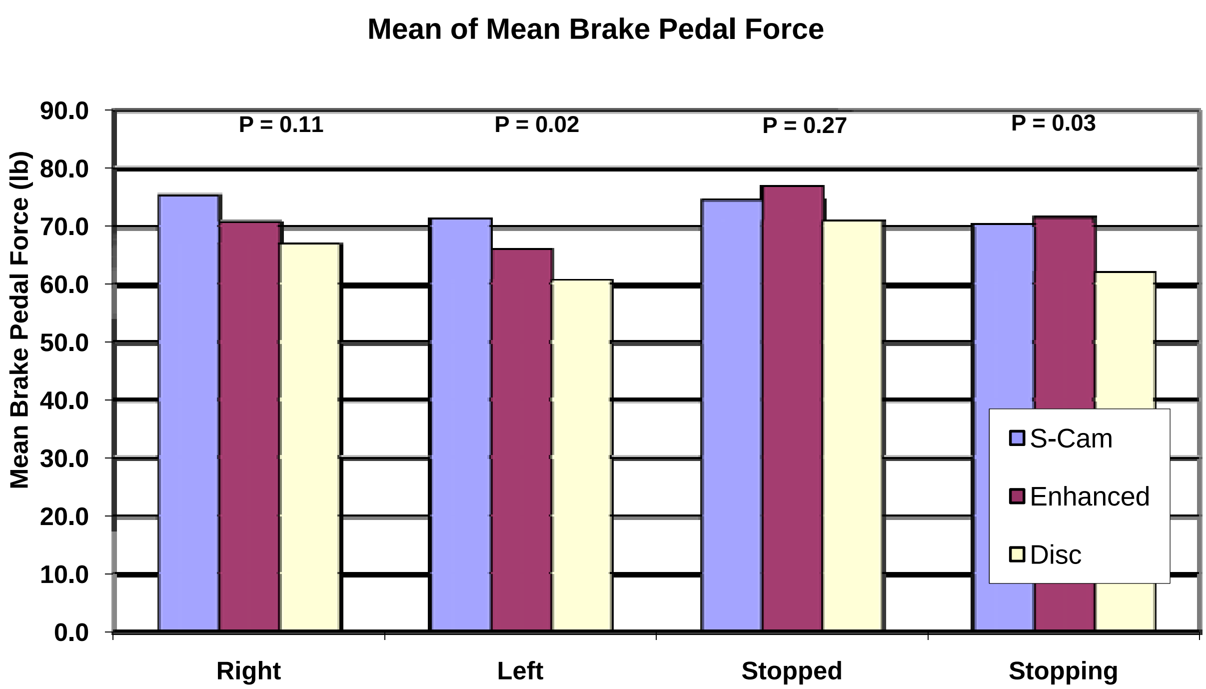

Figure 5.19 - Mean of mean brake pedal force

Table 5.10 Mean of maximum brake pedal force (lb / N)

	S-Cam	Enhanced S-Cam	Air Disc	P
Right Incursion	82.4 / 366	81.7 / 363	82.1 / 365	0.48
Left Incursion	81.5 / 363	82.0 / 365	78.8 / 350	0.07
Stopped Event	82.7 / 364	82.5 / 367	81.1 / 361	0.14
Stopping Event	83.3 / 370	81.2 / 361	79.5 / 354	0.24

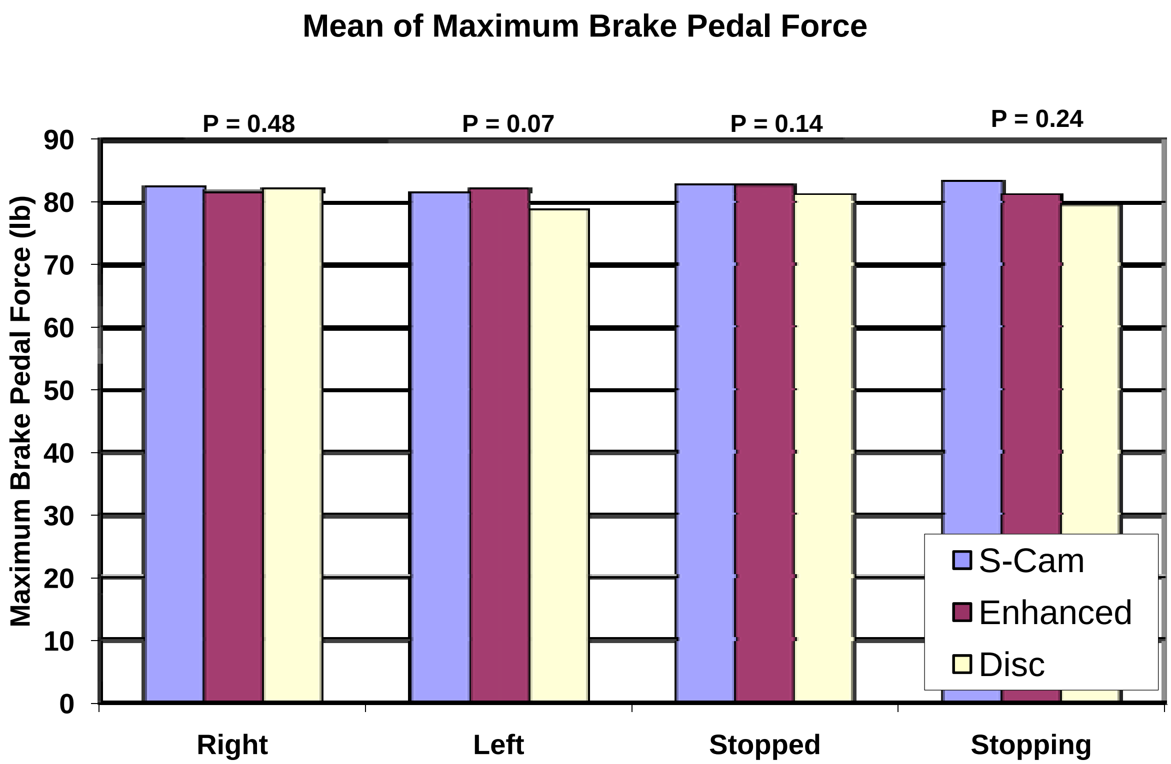

Figure 5.20 - Mean of maximum brake pedal force

Table 5.11 Mean of mean deceleration (g)

	S-Cam	Enhanced S-Cam	Air Disc	P
Right Incursion	-0.42	-0.51	-0.53	< 0.01
Left Incursion	-0.41	-0.48	-0.50	< 0.01
Stopped Event	-0.24	-0.34	-0.45	< 0.01
Stopping Event	-0.41	-0.51	-0.52	< 0.01

Table 5.12 Mean of maximum deceleration (g)

	S-Cam	Enhanced S-Cam	Air Disc	P
Right Incursion	-0.52	-0.66	-0.67	< 0.01
Left Incursion	-0.51	-0.63	-0.65	< 0.01
Stopped Event	-0.51	-0.63	-0.65	< 0.01
Stopping Event	-0.52	-0.65	-0.66	< 0.01

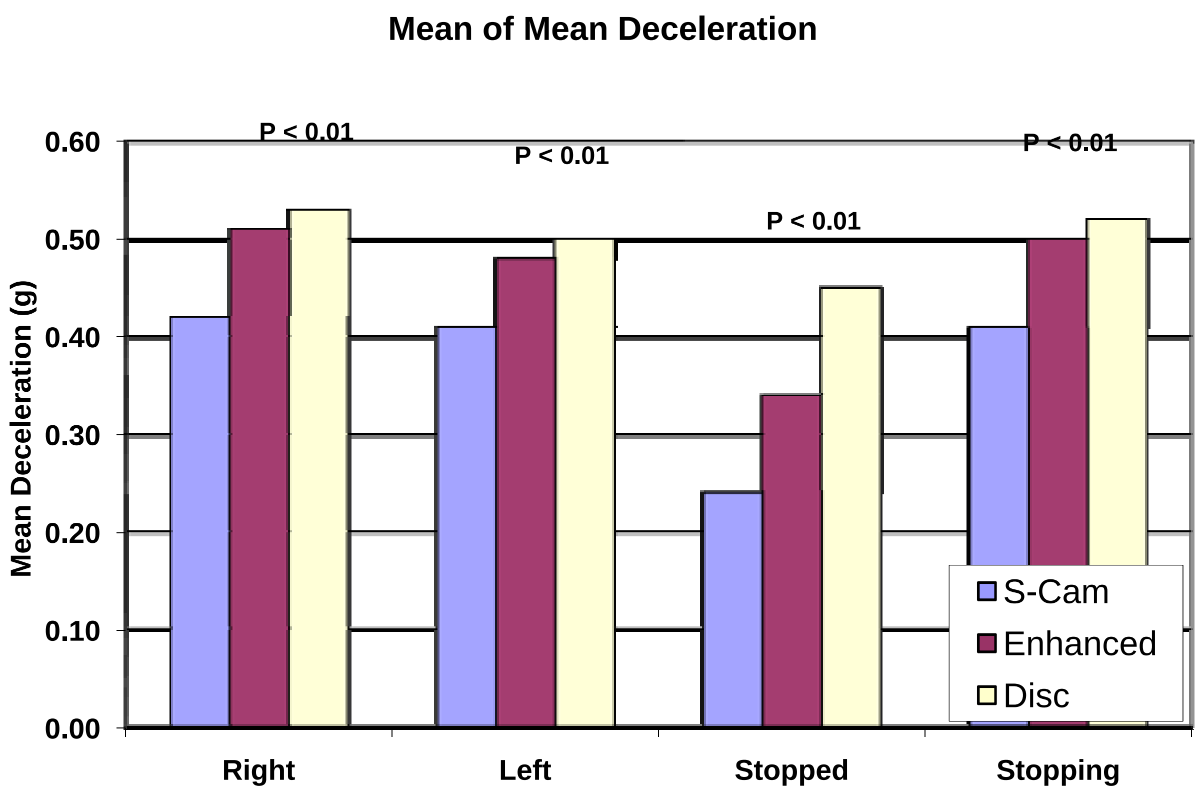

Figure 5.21 - Mean of mean deceleration

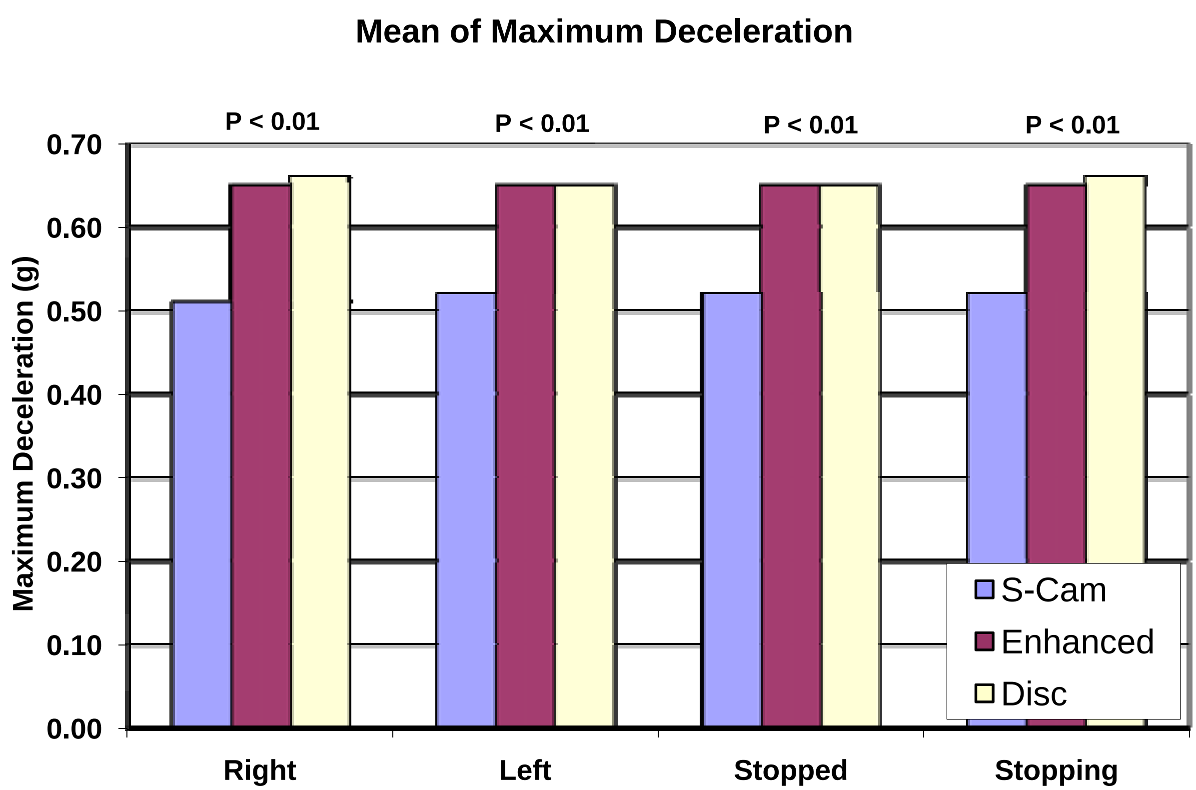

Figure 5.22 - Mean of maximum deceleration

6.0 CONCLUSIONS

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 crash severity is valid.

Except for the speed at braking onset during the stopping event scenario, the type of braking system had no statistically significant effect on driver behavior prior to braking. Drivers' braking efforts measured through brake pedal forces, truck speeds at the onset of braking during three of four events, and reaction times of scenario perceptions were statistically similar; and revealed that the type of braking system had no statistically significant effect on driver behavior prior to braking. A comparison of mean values of these three variables suggested with high confidence (95%) that the reduction in collisions were the result of better stopping performance rather than drivers' braking behavior.

The experiment showed that professional drivers using either the enhanced S-cam or air disc brake systems were better able to avoid collisions than those drivers using the standard S-cam brakes. Although there were not enough samples to provide statistical significance, the trend in the data indicates that those drivers using the enhanced S-cam and air disc brakes had fewer collisions than those using the standard S-cam brakes. The data showed that the ratio of collisions to total number of drives for the standard S-cam system is 36%, 23% for the enhanced S-cam, and 21% for the air disc brake. For the most severe event (the stopped event at 70 mph), the ratio of collision to the total number of runs for the air disc system is 19%, whereas it is 44% and 57% for the standard S-cam and enhanced S-cam systems respectively. Also, drivers using air disc brakes in this same event had reduced collision speeds compared with those using the enhanced S-cam brake system. The mean collisions speeds were 23.0 mph, 28.5 mph, and 32.0 mph for the air disc, enhanced S-cam, and standard S-cam brake systems, respectively. Collision speed is a major determinant of crash severity, and the air disc brake system lowered collision speed most effectively.

The data showed that there were more collisions with vehicles equipped with brake systems characterized by longer stopping distances, and that more crashes occurred with the standard S-cam brakes than with the other two brake types. In the case of emergency events at high speed, the disc brake system provided the safest solution.

In the cases where the driver was able to stop before crashing into the other vehicle, analysis showed that the braking distance of the standard S-cam brake was statistically significantly longer than that of the air disc brake in all four scenarios, and it was statistically significantly longer than that of the enhanced S-cam brakes in three of the scenarios. In terms of mean and maximum deceleration, in all four scenarios, the vehicle with the standard S-cam brakes did not decelerate as well as the vehicles with enhanced S-cam or air disc brakes (statistically significant in all cases).

7.0 REFERENCES

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8.0 APPENDICES

8.1 APPENDIX A: Box Plot Graphs of Performance Measures

Stopping Distance, Braking Distance, Mean Brake Pedal Force, Maximum Brake Pedal Force, Mean Deceleration, and Maximum Deceleration.

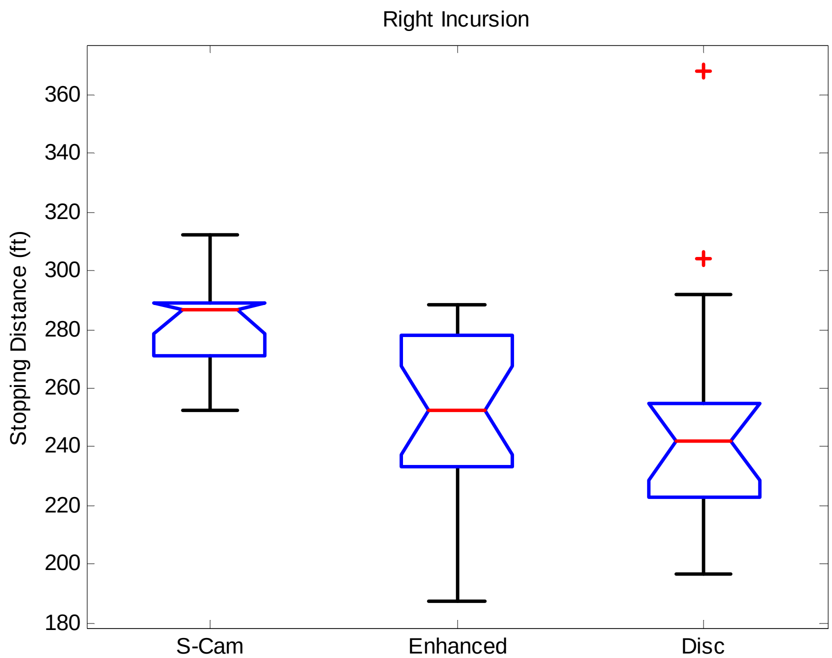


Figure A1 - Right incursion stopping distance

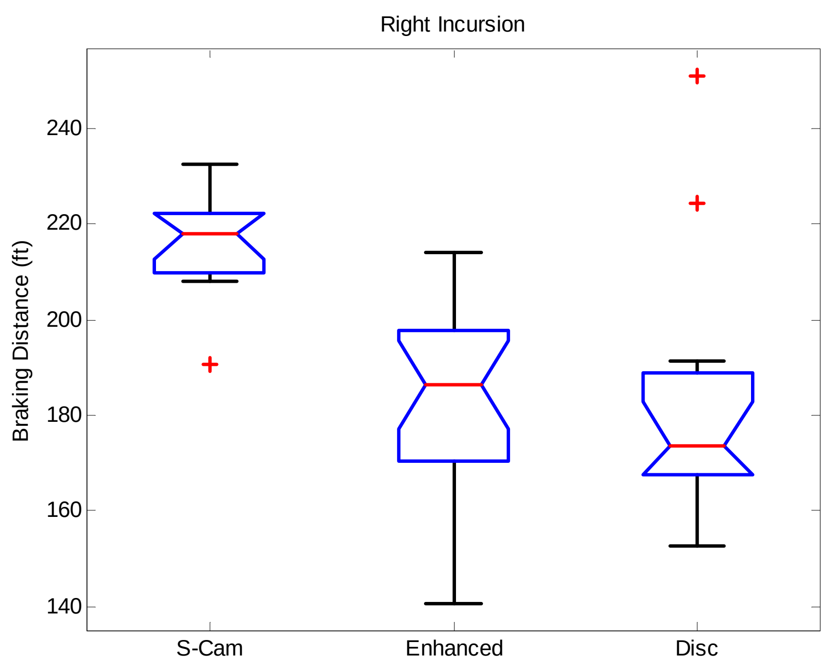


Figure A2 - Right incursion braking distance

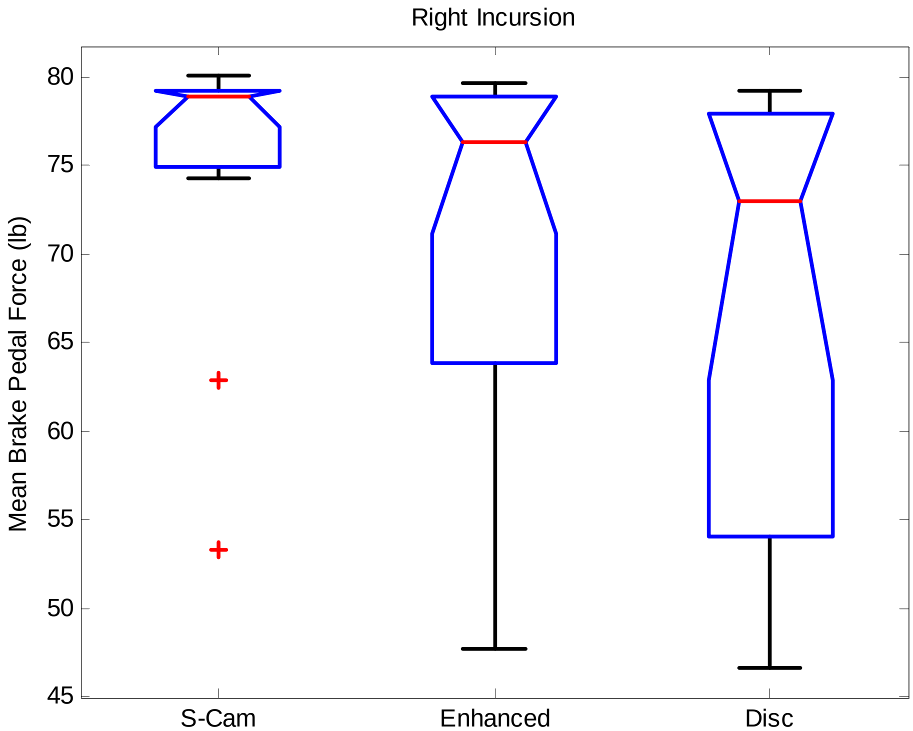


Figure A3 - Right incursion mean brake pedal force

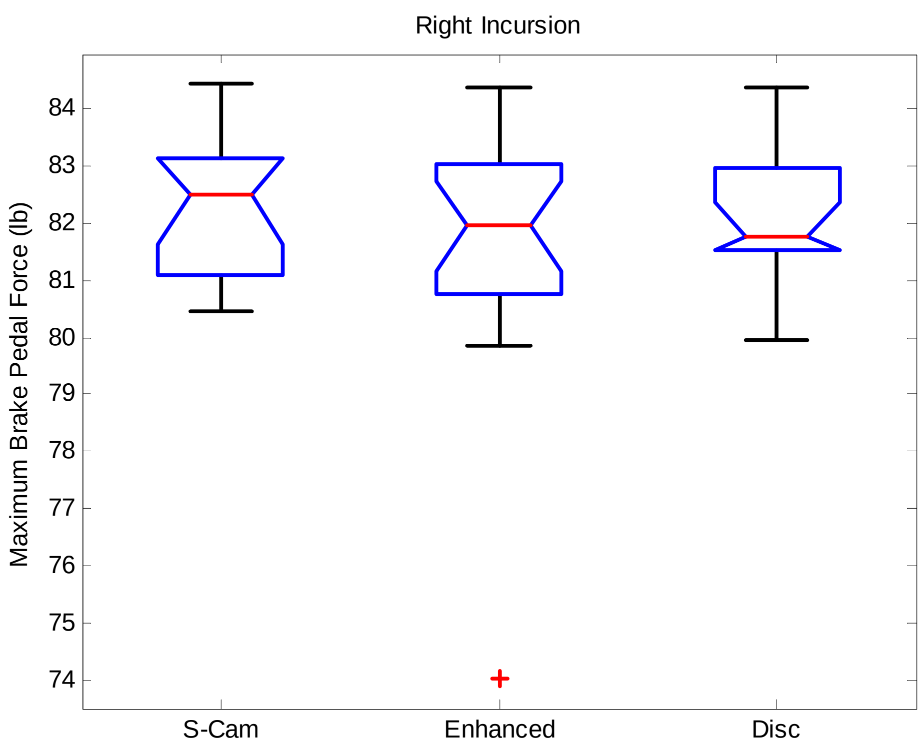


Figure A4 - Right incursion maximum brake pedal

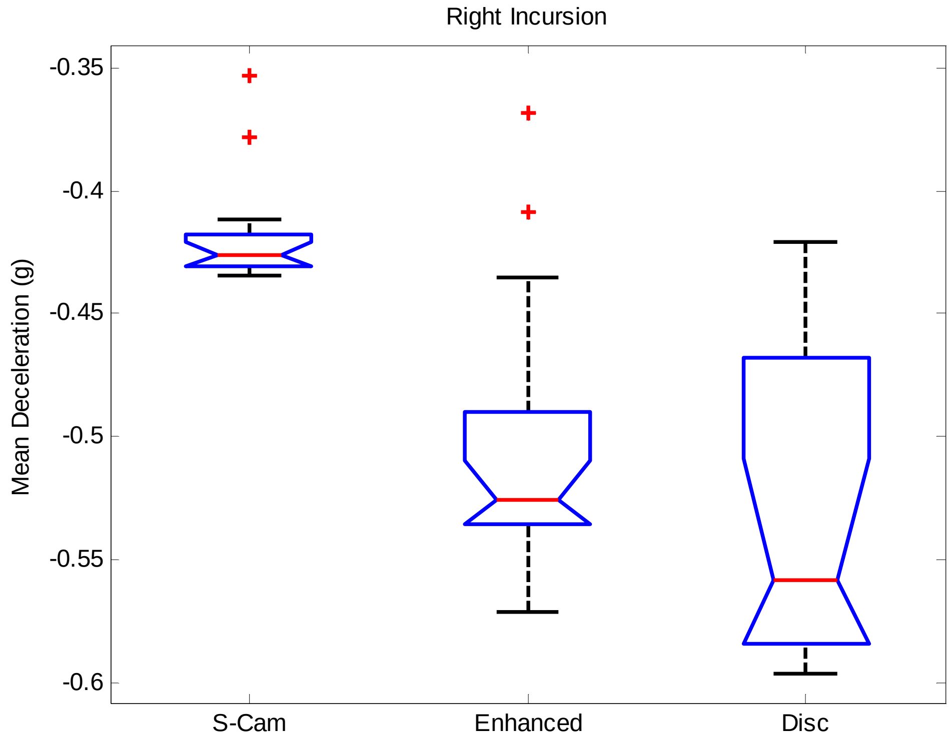


Figure A5 - Right incursion mean deceleration

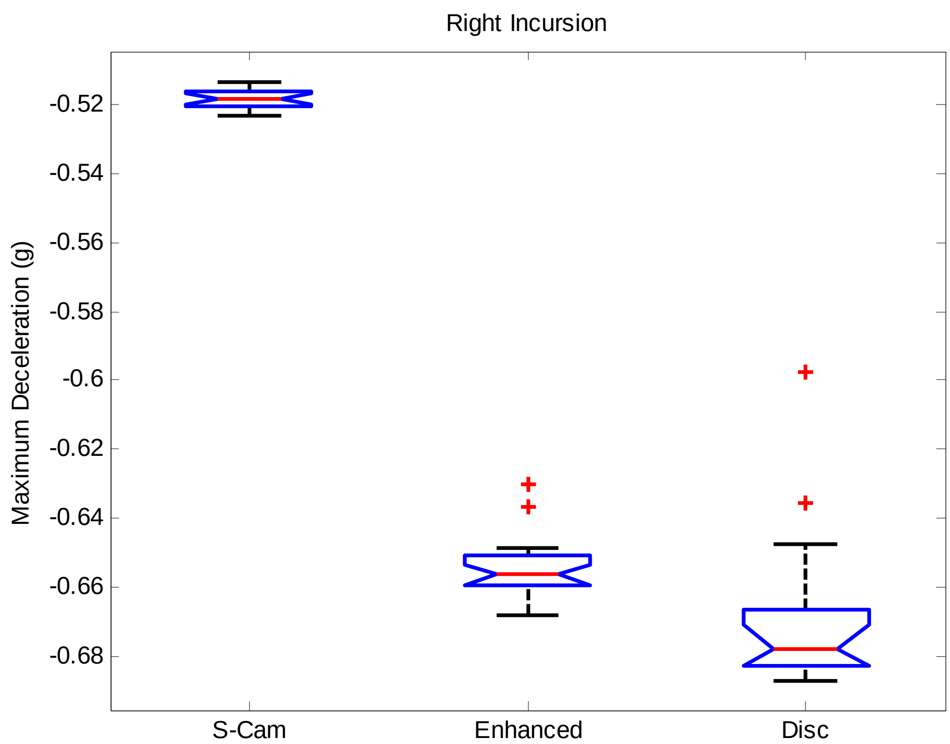


Figure A6 - Right incursion maximum deceleration

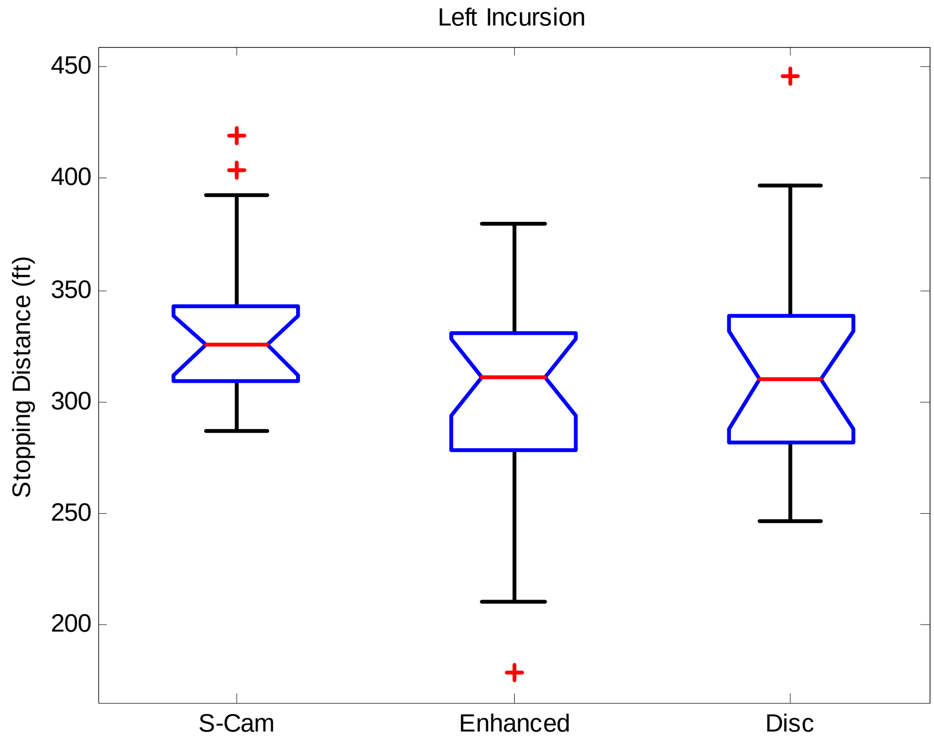


Figure A7 - Left incursion stopping distance

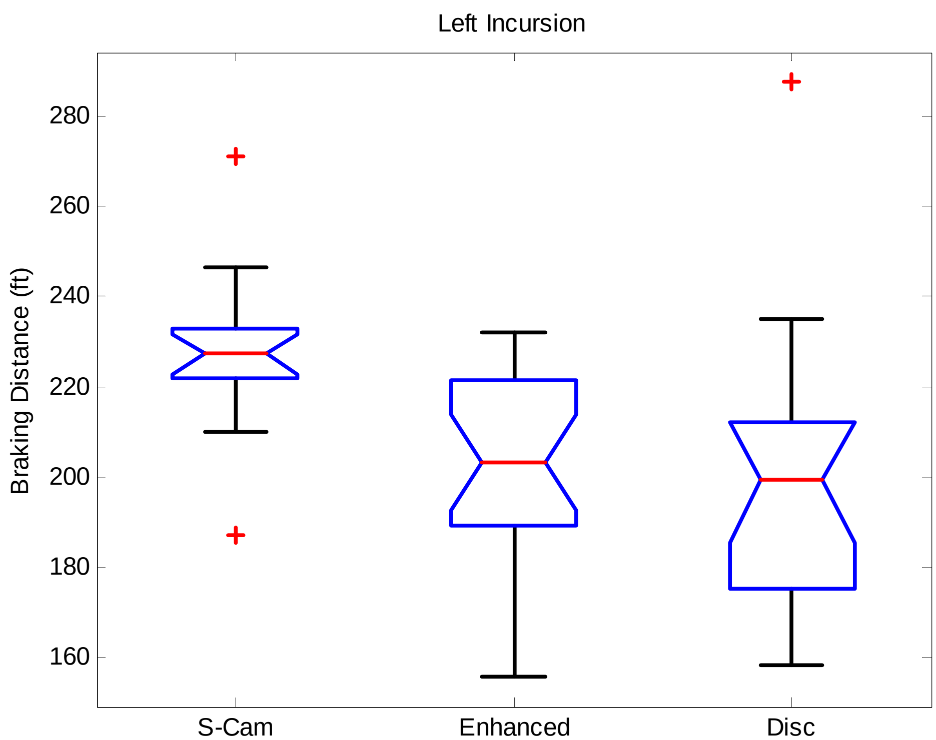


Figure A8 - Left incursion braking distance

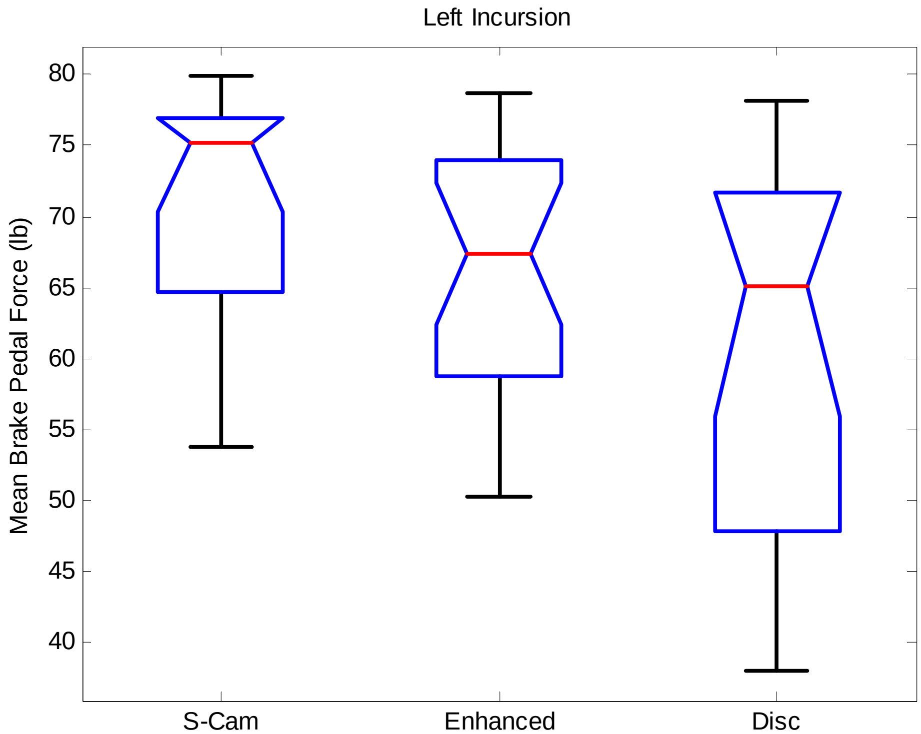


Figure A9 - Left incursion mean brake pedal force

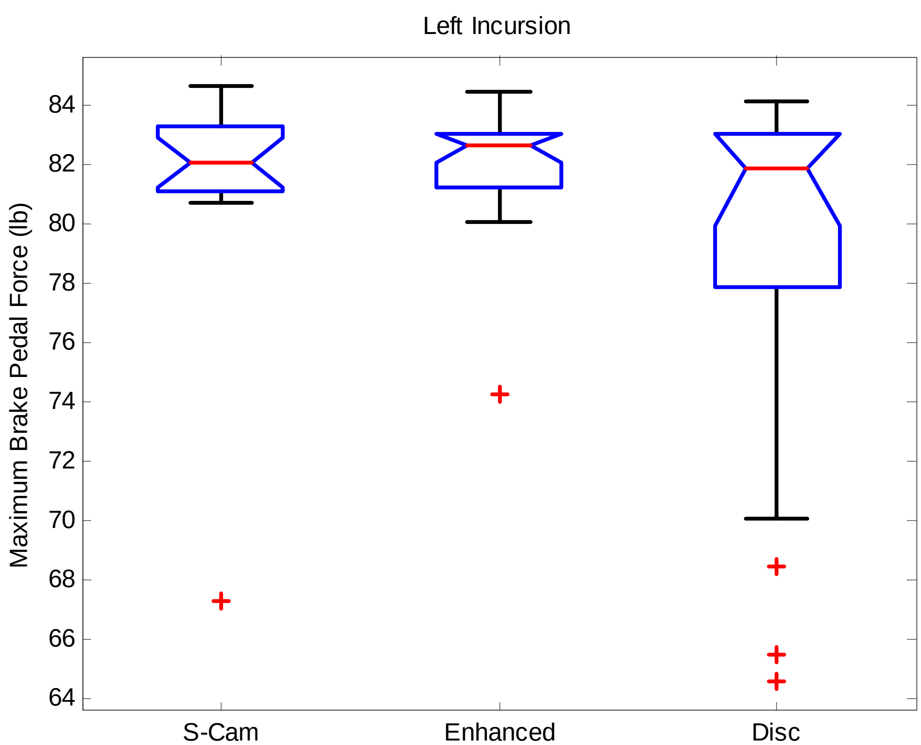


Figure A10 - Left incursion maximum brake pedal force

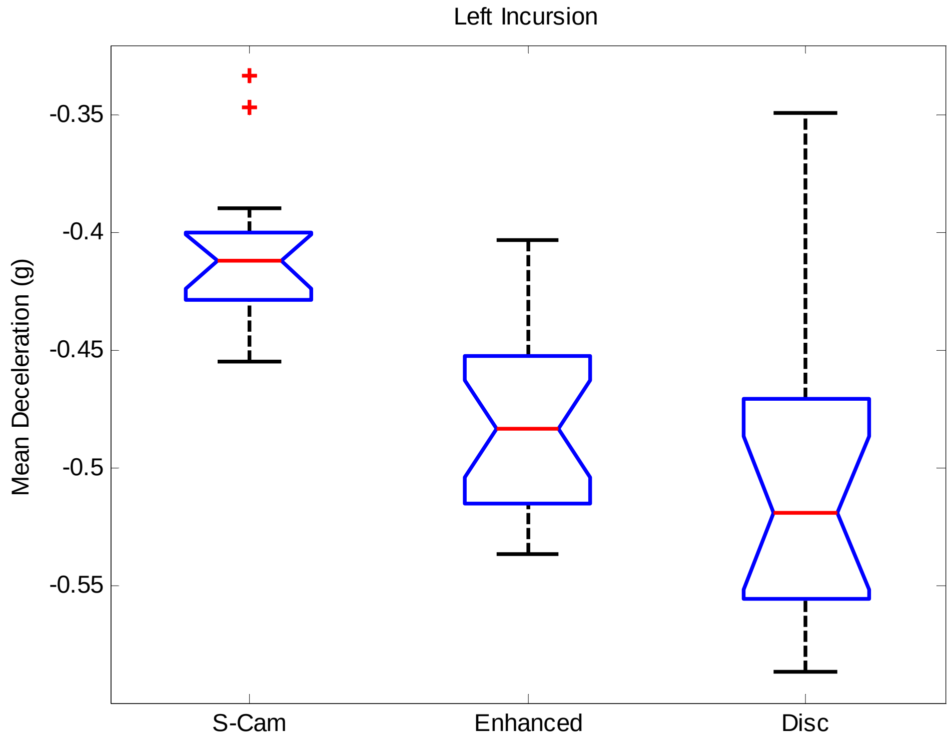


Figure A11 - Left incursion mean deceleration

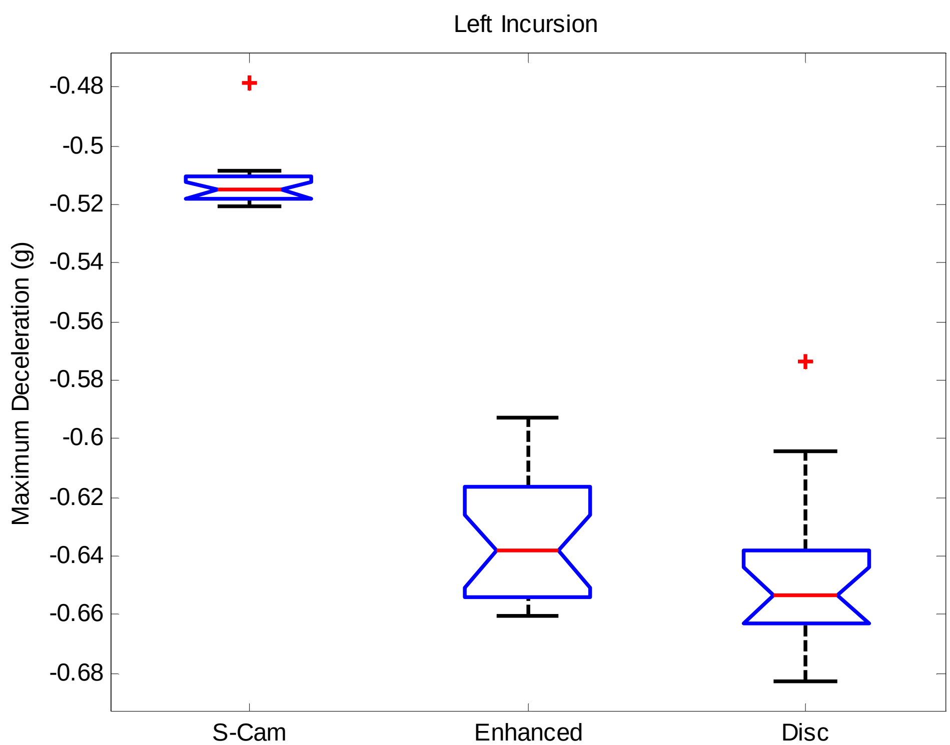


Figure A12 Left incursion maximum deceleration

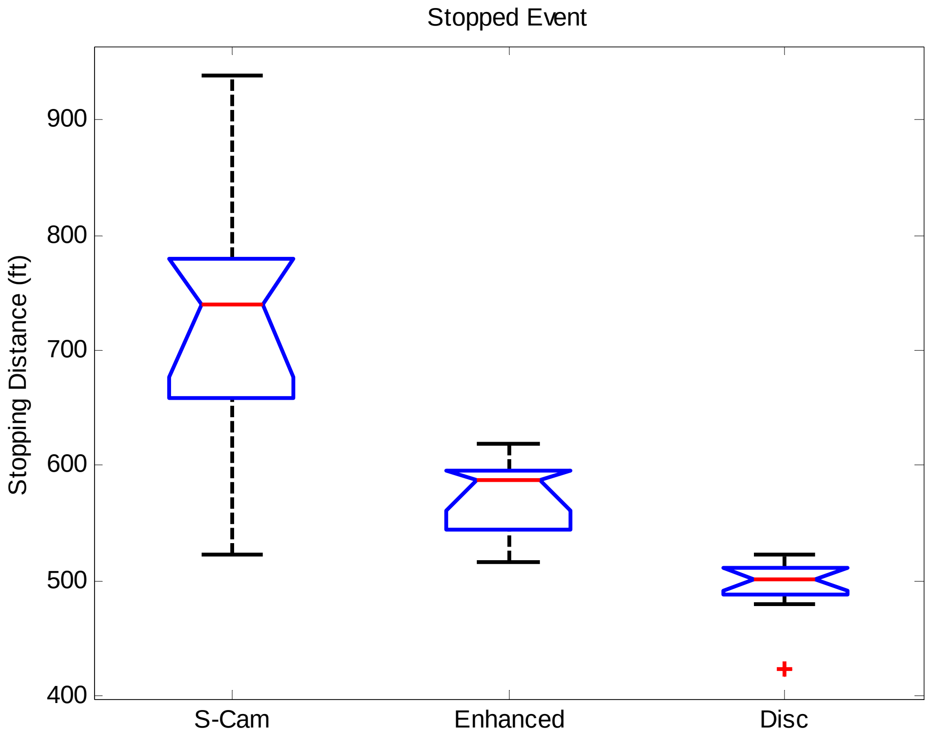


Figure A13 - Stopped event stopping distance

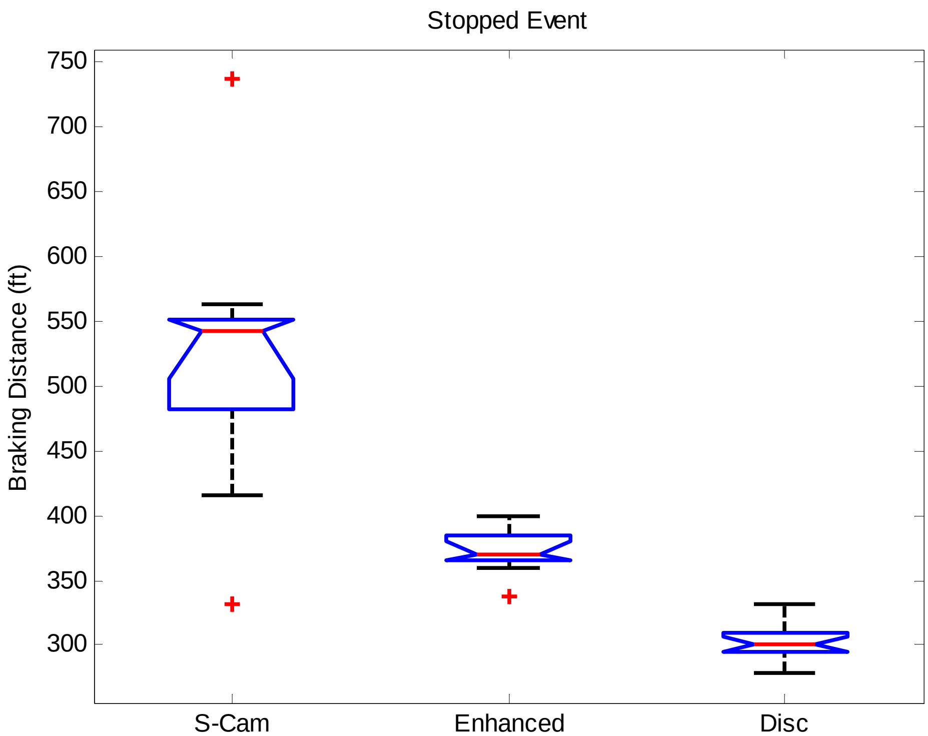


Figure A14 - Stopped event braking distance

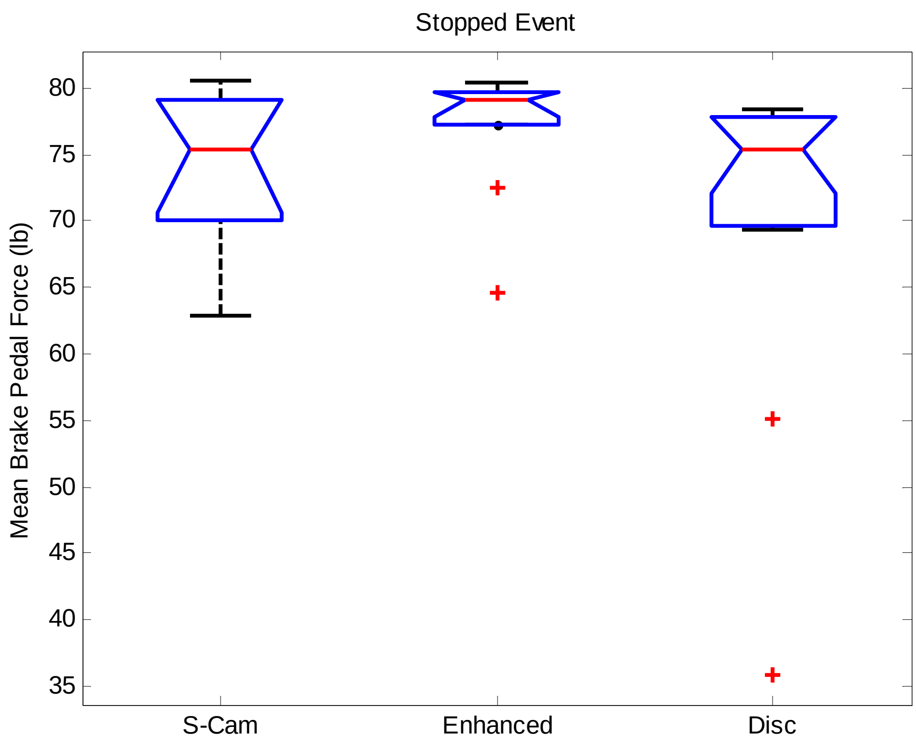


Figure A15 - Stopped event mean brake pedal force

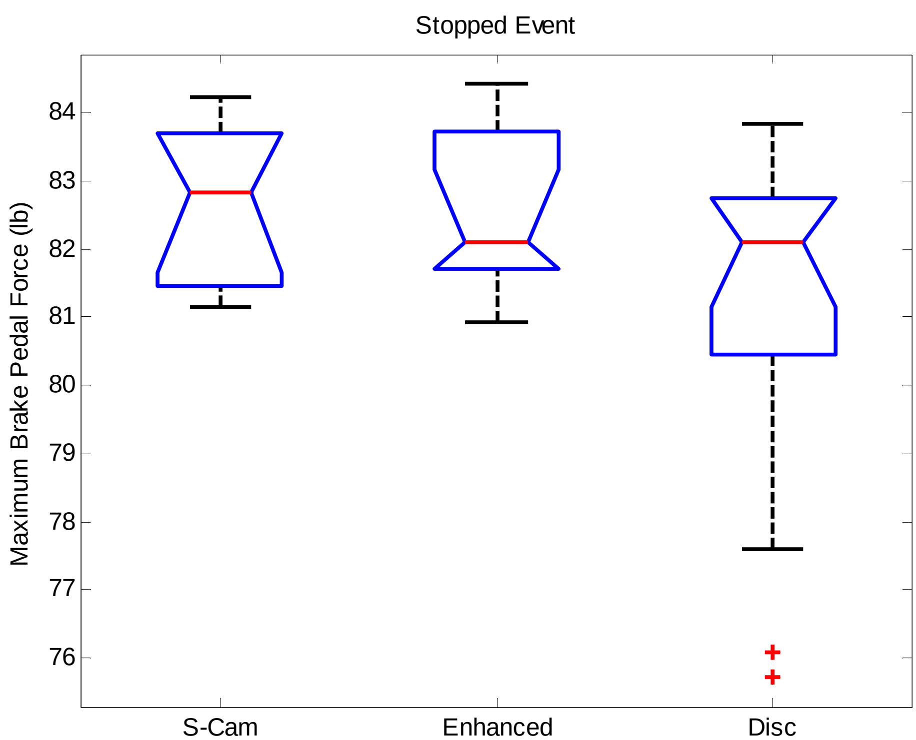


Figure A16 - Stopped event maximum brake pedal force

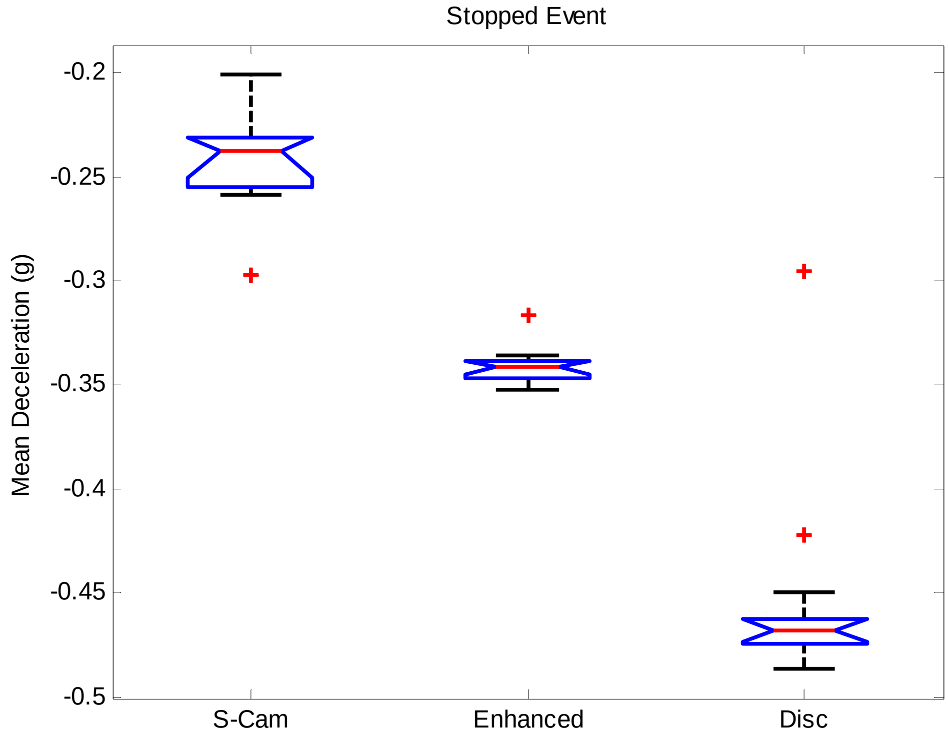


Figure A17 - Stopped event mean deceleration

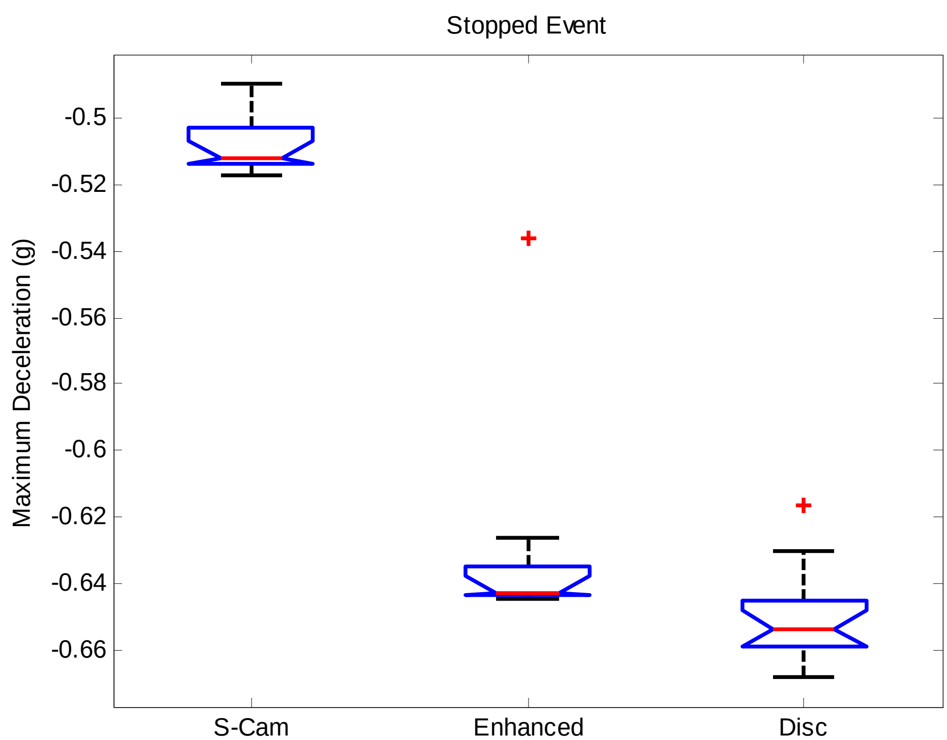


Figure A18 - Stopped event maximum deceleration

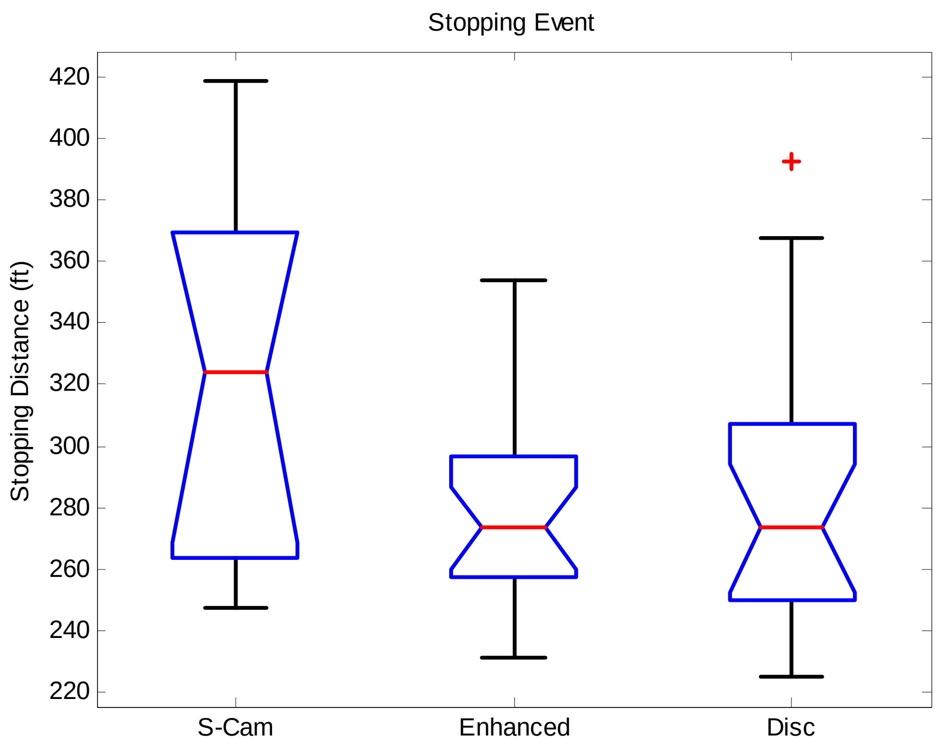


Figure A19 - Stopping event stopping distance

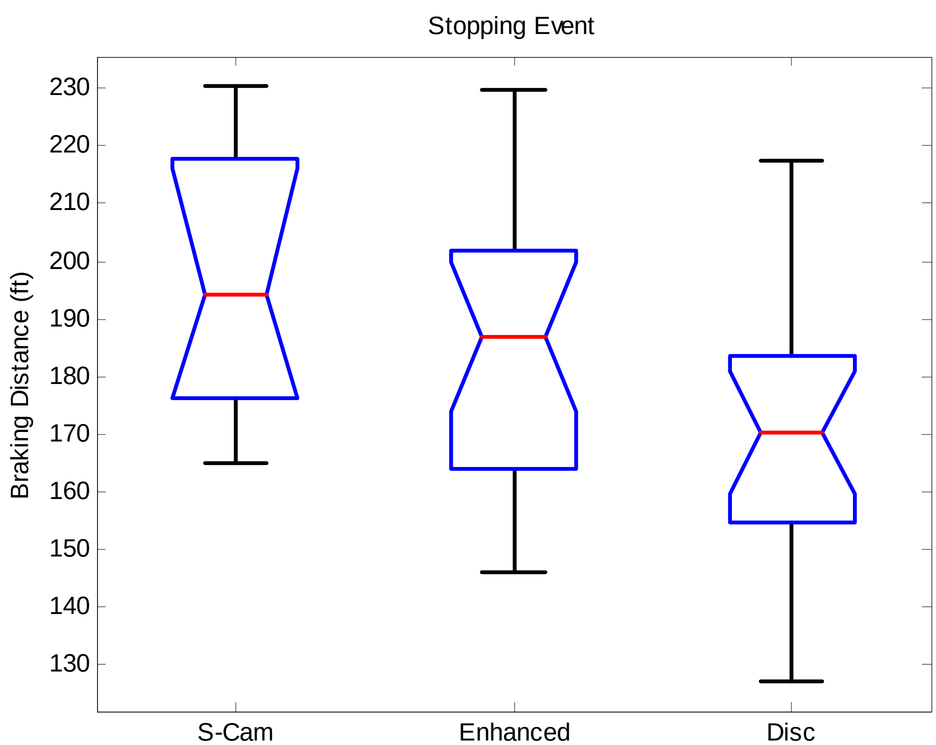


Figure A20 - Stopping event braking distance

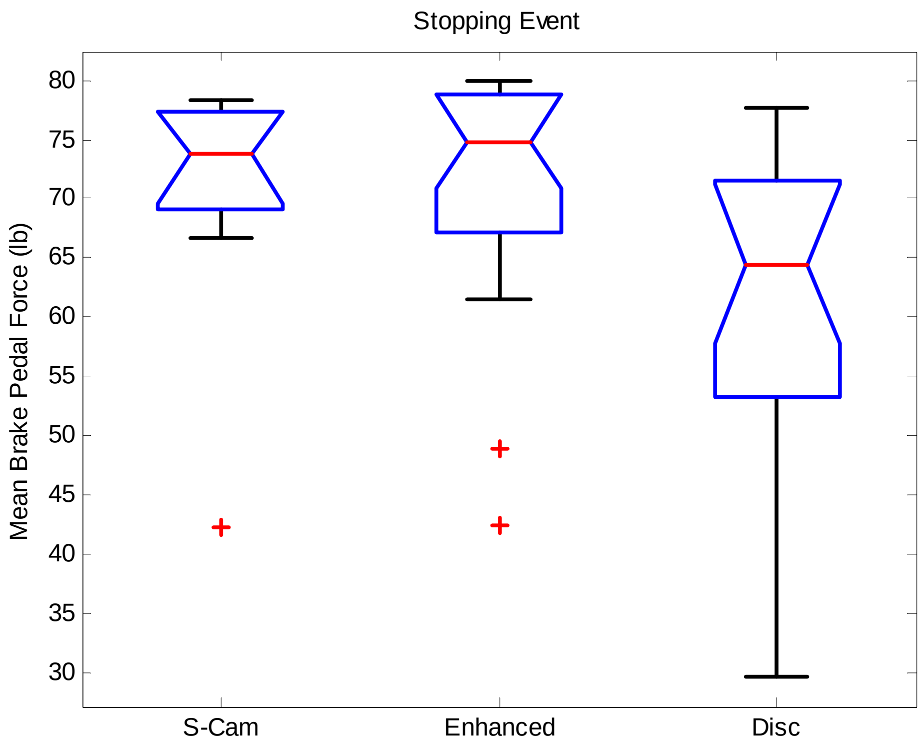


Figure A21 - Stopping event mean brake pedal force

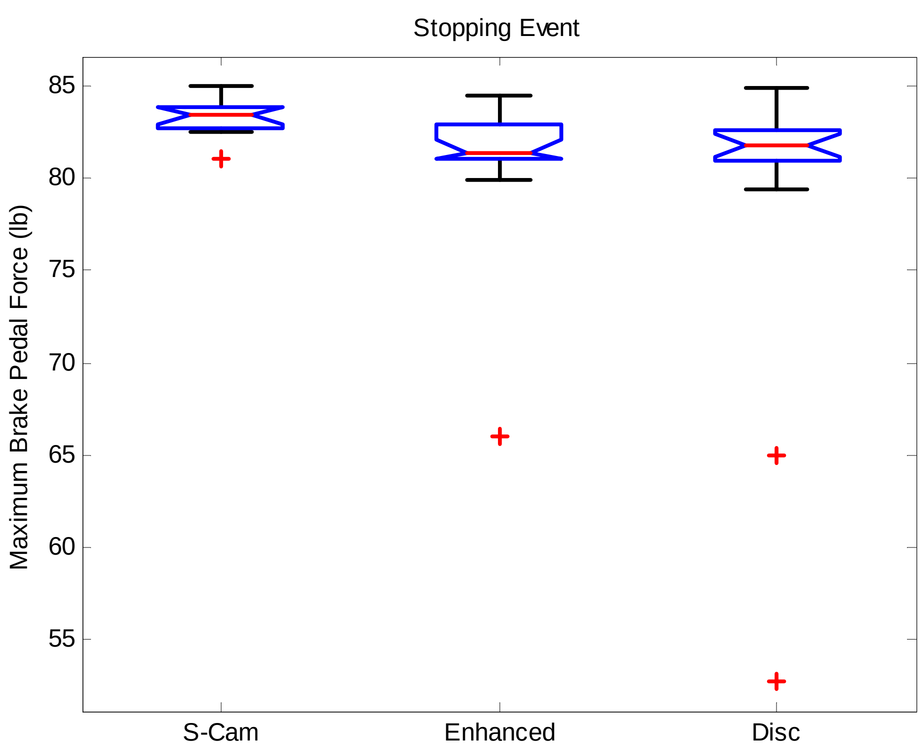


Figure A22 - Stopping event maximum brake pedal force

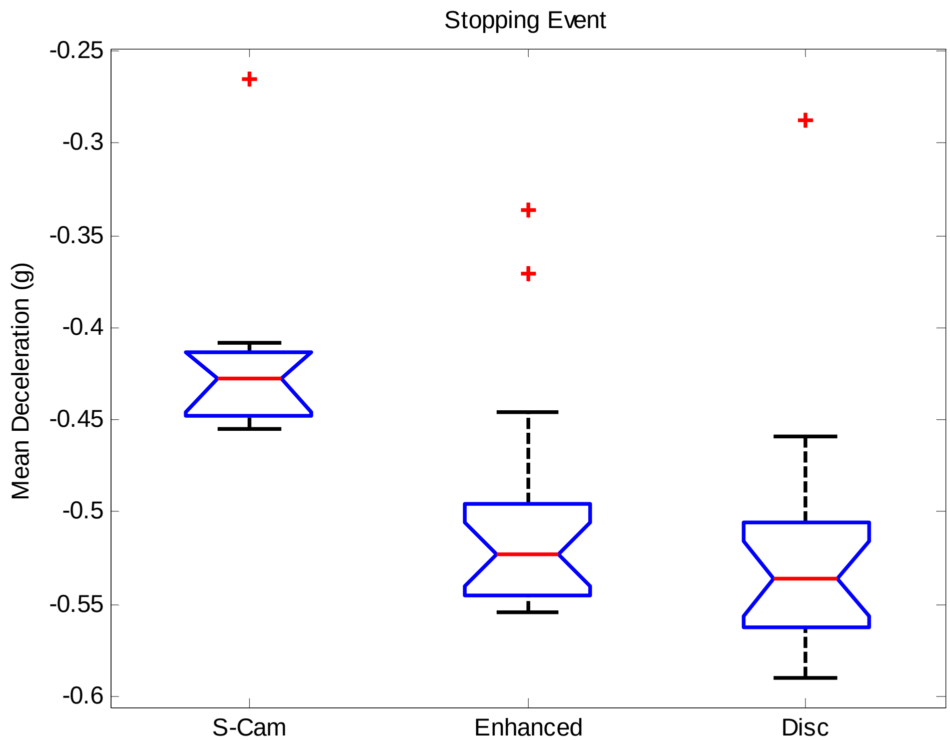


Figure A23 - Stopping event mean deceleration

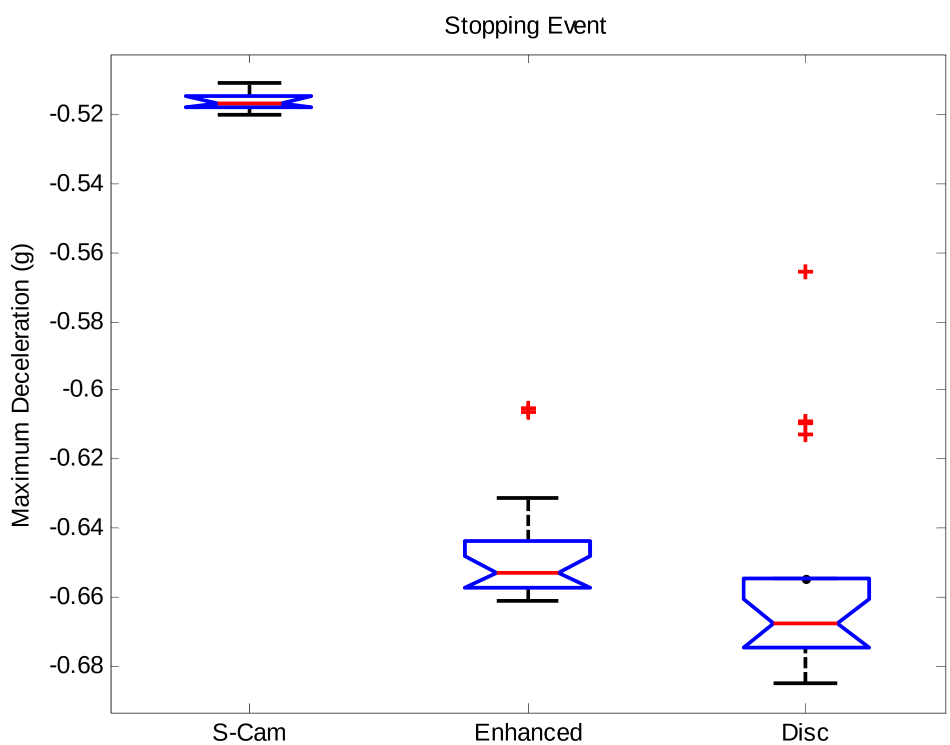


Figure A24 - Stopping event maximum deceleration

8.2 Appendix B: Simulator Study Protocol

Heavy Truck-Air Disc Brake Informed Consent Summary

Introduction

I am going to give you an overview of the research study you will be participating in today, and then I will ask you to read the Informed consent document which describes the study in detail. This document provides important information about what you will be asked to do during your visit, the risks and benefits of the study, and your rights as a research participant.

After your study visit, you will receive a copy of the Informed Consent Document for your records.

Purpose

You have been invited to participate in this study because you have:

- a valid, unrestricted, Class A Commercial Drivers License (CDL-A),
- 6 months experience,
- average at least 2000 miles per month over the last 6 months
- are in good general health, and
- are between the ages 25-55.

During your visit you will participate in a study examining the effectiveness of air disc brakes on heavy trucks.

Approximately 118 people will take part in this study.

Time Commitment

If you agree to take part in this study, your involvement will last approximately 2 hours.

What Will Happen During the Study?

Once you have completed the informed consent, we will have you complete a questionnaire regarding your driving history, demographic information, and general health status. In order to receive payment for your participation, you will complete a payment voucher. We will need to record your Social Security Number in order to process your voucher through the University.

Next you will be given eye exams that test your color vision, contrast sensitivity, and visual acuity.

Then you'll be given a brief description of brake systems that will be used in this study. You have the opportunity to earn incentive pay based on your driving performance. Research staff will explain the incentive system before you enter the simulator.

You then will be escorted to the simulator, where you will be briefed on the simulator cab, and on the drives you'll complete as part of this study. An experimenter sits in the back seat of the cab to ensure your safety while driving and exiting the simulator.

You will be asked to complete a practice drive and four study drives. Your drive time in the simulator will last approximately 1 hour. Afterward, you will be asked to complete additional questionnaires about your experience in the simulator.

"Tell me what we are asking you to do today?" Clarify misunderstandings the participant may have regarding their participation in the study.

While you drive, researchers collect 2 types of data:
Engineering data is collected from sensors that measure vehicle operation, motion, and driver actions.
Video data is collected using small cameras inside and outside the cab. This helps us understand your driving performance. (For example if the engineering data documents that a steering maneuver was performed, the video recording data will show what conditions led to that maneuver)

Views recorded include: your face and hands on the steering wheel, the road scene, the foot pedals, and a view from outside the cab (show still picture). Data is recorded onto storage media for analysis by research staff.

We will keep your name and information about you on file. This is primarily for recruitment purposes, but occasionally we contact participants in order to follow-up on data collected during their original study visit.

Agreeing to participate in this study does not obligate you to participate in future studies.

Risks
The risks involved in participating in this study are minimal.

You may experience discomfort associated with simulator disorientation. This is very rare and we do not expect this to happen to you today. You may quit driving at any time if you experience any discomfort.

In the rare event that the simulator's normal exiting procedure is not available, you will be assisted down a small ladder and escorted to a participant waiting room.

For more details about these risks, please refer to your Informed Consent Document.

Benefits
You may not benefit personally from being in this study. However, we hope that other people might benefit from this study by gaining useful information regarding braking technologies that reduce the number and severity of certain types of heavy truck crashes.

Additionally, many participants find driving in a simulator of this type to be an exciting and unique experience.

Costs
There is no cost to you for enrolling in this study. You will be compensated a base pay of $30 per hour of participation which is expected to take approximately 2 hours. In addition to your base pay, you will have the opportunity to earn an additional $12 incentive pay based on your driving performance. Most drivers earn some amount of incentive pay, but it is not expected that you will earn the full amount.

Funding
The National Highway Traffic Safety Administration (NHTSA) is funding this study. The University of Iowa is receiving payments from them to support the activities that are required to conduct the study.

Confidentiality
We will keep your participation in this research study confidential. We take several steps to protect your identity. You are assigned a research number that our staff uses during data collection, analysis, and reporting. If we write a report or article about this study, we typically describe the study results in a summarized manner.

Video image data and associated audio data may be publicly released, either separately or with the appropriate engineering data. This is typically done for scientific, educational, outreach, legislative, or research purposes. Examples include use of data:

- in a presentation of study findings at a professional conference,
- in a production for local media,
- in an interactive display on driver safety at a local mall, or
- in support of proposed legislation.

Video is usually presented in short clips to illustrate study findings. Often video used in TV segments are of NADS staff rather than study participants, in order to not disrupt data collection.

Voluntary
Your participation is voluntary. You may choose not to take part at all, or if you decide to be in this study, you may stop participating at any time. Under certain circumstances, your participation may end without your consent.

Video Data Release Statement
In the Informed Consent Document, you will be asked to grant permission to release your video data.

Questions
The research team is here to address your concerns and answer questions during your visit.

Do you have any questions?

The truck you will be driving today has an 18-speed transmission without electronic engine control. A liberal amount of slipping the clutch is required to get the truck moving and up to speed. The trailer will be fully loaded. This document describes the three braking systems used in this study (one of which will be used on the truck you drive today) as well as the shifting pattern for an 18-speed transmission.

Vented Air Disc Brakes

Vented air disc brakes are newly developed for the North American market; they are found on some emergency or specialty heavy trucks and are optional on over-the-road trucks. Disc brakes supply mechanical force to the brake via a pneumatic chamber that converts the air pressure into a linear force. Brake output can be "tuned" by using brake chambers of various sizes.

Steer and Drive Axle:

The following foundation brake configurations are used for vented air disc brakes:

Steer axle: 16.9" diameter. Ventilated air disc rotor, sealed caliper, typically a 20-sq.-in. chamber, no slack adjuster

Drive axle: 16.9" diameter. Ventilated air disc rotor, sealed caliper, typically a 24-sq.-in. chamber, no slack adjuster

Stopping Distance at 75 mph: 371 ft.

S-Cam Drum Brakes

S-cam drum brakes have been used in North America for several decades and currently make up over 90% of the heavy vehicle brakes in the fleet. S-cam drum brakes supply mechanical force to the brake via a pneumatic chamber that converts the air pressure into a linear force. Brake output can be "tuned" by using brake chambers of various sizes.

Steer and Drive Axle:

The following foundation brake configurations are used for S-cam drum brakes:

Steer axle: 15" diameter x 4" wide S-cam drum brake with a 20-sq.-in. air chamber, 5.5" slack adjuster (lever arm)

Drive axle: 16.5" diameter x 7" wide S-cam drum brake with a 30-sq.-in. air chamber (larger chamber = higher air pressure-to-torque "gain"), 5.5" slack adjuster

Stopping Distance at 75 mph: 618 ft.

Enhanced S-Cam Brakes
Enhanced S-cam brakes, also known as hybrid disc brakes, employ significantly higher-output discs on the steer axle to supplement standard S-cam drums on the drive axle.

The following foundation brake configurations are used for enhanced S-cam brakes:

Steer axle (Same as vented air disc brakes): 16.9” diameter. Ventilated air disc rotor, sealed caliper, typically a 20-sq.-in. chamber, no slack adjuster
Drive Axle (Same as standard S-cam drum brakes)**:** 16.5" diameter x 7" wide S-cam drum brake with 30-sq.-in. air chamber (larger chamber = higher air pressure-to-torque "gain"), 5.5" slack adjuster

Stopping Distance at 75 mph: 553 ft.

Steer Axle:

Vented Air Disc Brake

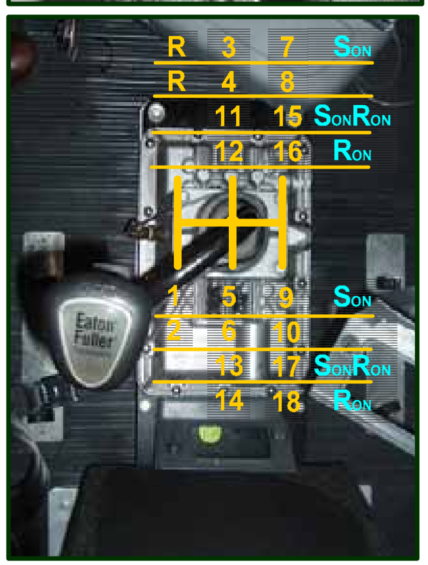
Drive Axle: Standard S-Cam Drum Brake

Shifting pattern for an 18-speed transmission

Flip grey toggle button (SON) clockwise to turn splitter on.

Flip black switch (RON) up to turn the range on.

Follow this pattern for an 18-gear transmission.



8.3 Appendix C: S-cam, Enhanced S-Cam, and Air Disc Brake Models

The S-cam and disc brake characteristics were measured at the brake-dynamometer at VRTC. The brake torque (T_b) is fitted using polynomial functions. The models were adopted from the work of Al Dunn[1]. The brake torque formulation is provided by equation (C1) and plotted at different speeds versus chamber brake pressure, Figure C1.

$$T_b = \begin{cases} 0 & 0 \le \mathrm{P_c} \le P_{p0} \\ \displaystyle\sum_{i=0}^{2} C_i \left(P_0\right)^i \frac{P_c}{P_0} & P_{p0} \le \mathrm{P_c} \le P_0 \\ \displaystyle\sum_{i=0}^{2} \left(\sum_{j=0}^{2} c_{ij} V_{hub}^{\,j} \right) \left(P_c\right)^i & P_0 \le \mathrm{P_c} \le P_{res} \end{cases} \qquad \text{(C1)}$$

Where P_{p0} is the break pressure when the system does not activate, P_0 is the brake pressure where the speed effect is negligible, P_c is the acting pressure, V_{hub} is the hub speed, and C_i's are polynomial coefficients.

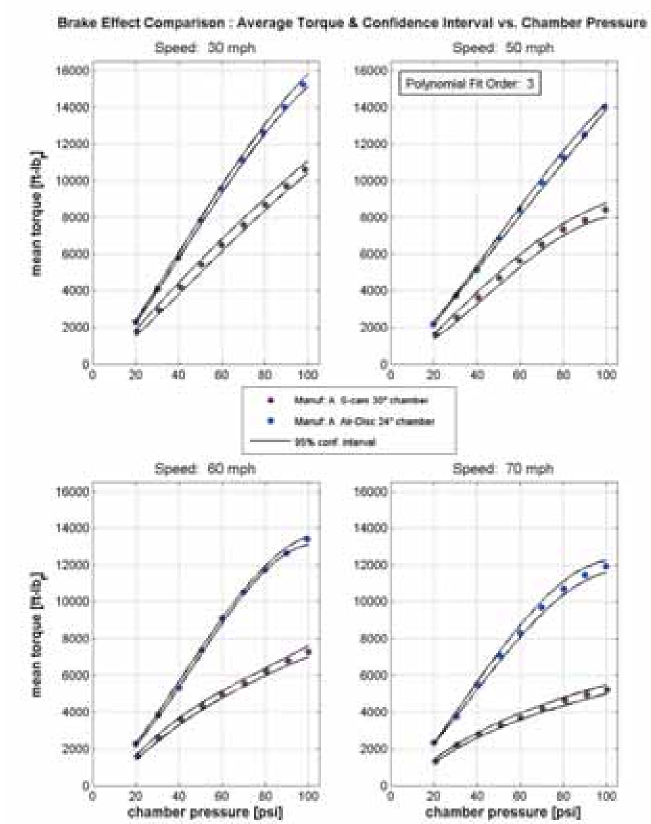


Figure C1. - Brake torque versus chamber pressure for air disc and S-cam brakes

[1] Ashley Dunn, *Jackknife Stability of Articulated Tractor Semitrailer Vehicles with High-output Brakes and Jackknife Detection on Low Coefficient Surfaces*, Ph.D. Dissertation, The Ohio Sate University, 2003

Brake line pressure buildup is modeled as a first-order differential equation with time constants determinant from effective heat coefficients. Brake torque-line pressure hysteresis characteristics are frequently encountered in heavy truck air brake systems, but may not be of significance under low level or normal braking conditions. Large hysteresis can be important under emergency braking conditions where ABS cycling is involved; it can lead to significant reduction in braking performance[2]. Disc brakes exhibit significantly lower hysteresis levels than S-cam brakes as shown by VRTC measurements.

During braking, the kinetic and potential energies of a moving vehicle are converted into thermal energy through friction in the brakes. For a tractor-trailer driving downhill, the driver may need to apply continuous braking in order to maintain a constant speed. If the brakes of a heavy truck are applied for a long time down a steep slope, the brakes loose effectiveness due to excessive temperature. This phenomenon is called brake fade. The NADS heavy truck brake system uses the following generic fade model[3] based on an energy balance at the brakes:

$$T(t+\Delta t)=\left(T(t)-T_{\infty}-\frac{4.628T_{rq}\omega}{hA_r}\right)\exp\left(\frac{-hA_r}{3600m_c}\Delta t\right)+T_{\infty}+\frac{4.628T_{rq}\omega}{hA_r} \qquad \text{(C2)}$$

Where,

$T(t)$	: brake temperature *(°F)*
T_{∞}	: temperature of the environment *(°F)*
T_{rq}	: brake torque *(ft-lb)*
ω	: wheel rotational speed *(rad/sec)*
hA_r	: equivalent heat transfer coefficient (*BTU/(h °F)*)
mc	: effective brake mass specific heat *(lb BTU/°F)*
t	: time *(sec)*
Δt	: time step *(sec)*

Textbooks on heat transfer provide a large number of empirical equations for the convective heat transfer coefficients for a variety of test conditions and geometries. These conditions usually apply to discs or drums not disturbed by tires and other wheel components. Road test data obtained from testing heavy vehicles equipped with drum brakes indicate that the convective heat transfer coefficient may be expressed by a functional relationship as follows:

$$hA_r = k_0 + k_1 u \qquad \text{(C3)}$$

Where *u* is vehicle speed in ft/sec and k_0 and k_1 are coefficients that can be estimated experimentally. These coefficients for tractor-trailer S-cam brakes were estimated to be:

$$k_0 = 50 \ \ BTU/(h\,°F)$$

[2] Johnson, L.K., Fancher, P.S., and Gillespie, T.D. , "An Empirical Model for the Prediction of the Torque Output of Commercial Vehicle Air Brakes." Highway Safety Research Institute, University of Michigan, Report No> UM-HSRI-78-53, 1978
[3] Rudolf Limpert, *Brake Design and Safety*, Society of Automotive Engineers, Inc., ISBN 1-56091-261-8, 1992

$k_1 = 1.5\ BTU\ sec/(h\,°F\ ft)$

$m_c = 0.813\ BTU/°F$

The time constant for the heating/convective-cooling effect is:

$$\tau = \frac{3600 m_c}{h A_r} = \frac{3600 m_c}{k_0 + k_1 u} \quad \text{(sec)} \tag{C4}$$

The effective brake torque is obtained from reducing the applied brake due to heat effects as follows:

$$Brake\_effective = Brake\_applied \times \left(1 - F\left(T(t) - T_\infty\right)\right) \tag{C5}$$

In equation C5 $F(\ )$ is a function that relates brake torque reduction to temperature increase. This function is defined using cubic spline interpolation of a lookup table of brake effectiveness versus temperature reading. The curve is estimated from dynamometer measurements at VRTC. We should note also that brake fades are not large during emergency stopping on straight roads, and the disc brakes have very low fade effects when compared to S-cam brakes. For the disc brakes the fade reduction factor was decreased significantly. The brake parameters were set such that severe braking from 60 mph provides a stopping distance of 307 feet for standard S-cam brakes, 256 feet for enhanced S-cam brakes, and 215 feet for air disc brakes.

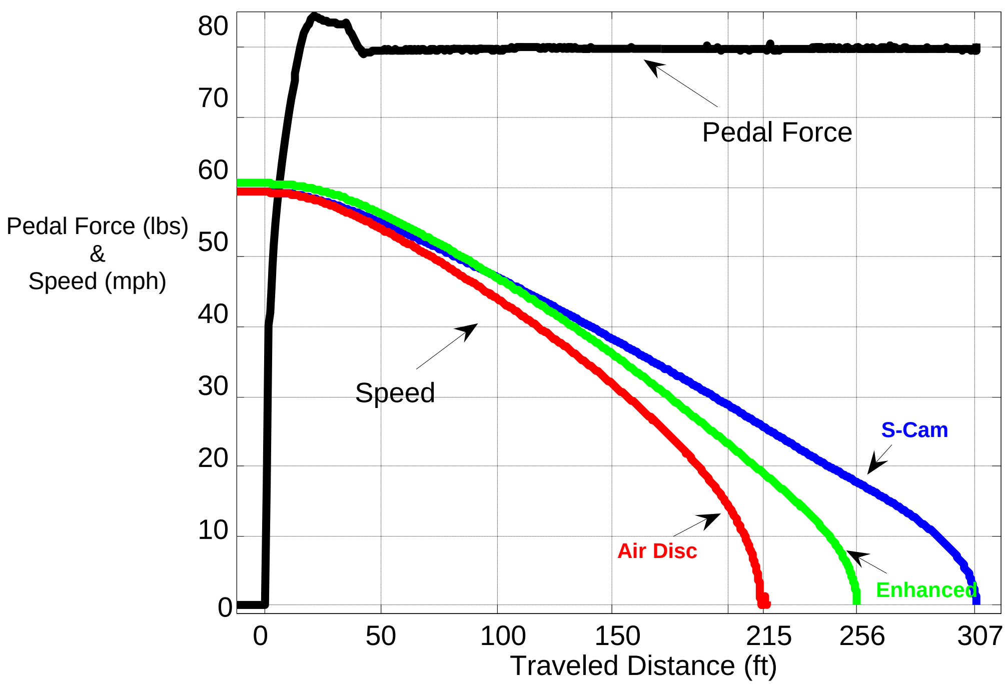


Figure C2. - Stopping distance performances

8.4 Appendix D: Heavy Truck Cab Vibration Measurements

Measurements:

The purpose for the vibration measurements is to provide information regarding the fundamental frequencies and magnitudes associated with the vibration feel inside the cab. Information from the tests was used to actuate the four vertical vibration actuators located inside the NADS simulator dome.

Measurements of vehicle speed, engine RPM, and vertical acceleration within the cab were made with a sampling frequency of 200 Hz. Four accelerometers were mounted in the cab to measure vertical accelerations on the cab floor, dashboard, beneath the driver's seat, and on the steering wheel. The data collected was analog low-pass filtered to 50 Hz. Eight data segments were collected for a 1-minute duration each, for which the test driver maintained constant engine RPM levels of 800, 1000, 1200, 1400, 1600, 1800, 2000, and maximum RPM.

Results:

The vibrations were modeled with harmonic functions to emulate the measured power spectrum. Series of harmonic functions were developed to represent different RPM levels as shown on Figure D1. The harmonic functions are formulated as follows,

$$F = mass\sum_{i=1}^{n} A_i \sin\left(2\pi f_i * time\right) \tag{D1}$$

The mechanical range of the vibration actuators is limited to 25 Hz which is sufficient to model the most important measured fundamental frequencies. These frequency modes are at 2 Hz for tractor-trailer sprung mass/spring modes, 5-7 Hz for axle modes, 10-12 Hz for cab modes, and 17-25 Hz for engine and powertrain modes.

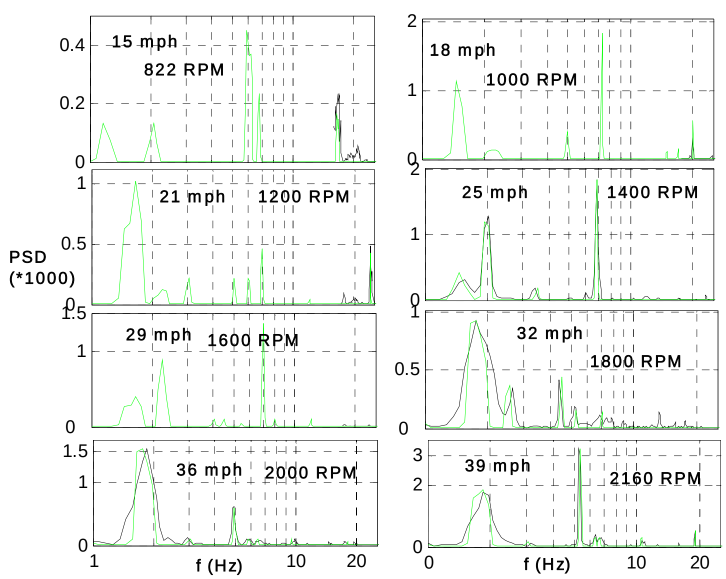


Figure D1 - Power spectrum of measured (driver seat) and modeled harmonic vibrations

8.5 Appendix E: Simulator Data

The data collection requirements for the simulator are listed in the following table.

CSSDC = Change State Signal Data Collection, and indicates that data is collected only when the state changes.

Table E1 Collected *daq* variables

Definition	NADS Variable Name	Units	Collection Freq
Accelerator pedal position	CFS_Accelerator_Pedal_Position	Normalized value between 1 and 0	240 Hz
Auto Transmission Mode *Note - The use of "CFS_Transmission_Gear" and "CFS_Auto_Transmission_Mode" are mutually exclusive for one cab.	CFS_Auto_Transmission_Mode	-2 = Park -1 = Reverse 0 = Neutral 1 = First 2 = Second 3 = Drive 4 = Overdrive	CSSDC
Brake pedal force	CFS_Brake_Pedal_Force	Pounds	240 Hz
Brake pedal position	CFS_Brake_Pedal_Position	Radians of actuator movement	240 Hz
Steering wheel angle	CFS_Steering_Wheel_Angle	Degrees	240 Hz
Steering wheel angle rate	CFS_Steering_Wheel_Angle_Rate	Degrees/sec	240 Hz
Steering wheel torque	CFS_Steering_Wheel_Torque	Foot-pounds	240 Hz
Transfer case mode	CFS_Transfer_Case_Mode	1 = 2H 2 = 4H 3 = Neutral 4 = 4L Generally defaults to 3 but hardcoded to 1 for CTB	CSSDC
Transmission Gear *Note - The use of "CFS_Transmission_Gear" and "CFS_Auto_Transmission_Mode" are mutually exclusive for one cab	CFS_Transmission_Gear	-1 = Reverse 0 = Neutral 1 = First 2 = Second 3 = Third 4 = Fourth 5 = Fifth 6 = Sixth 7 = Seventh 8 = Eighth 9 = Ninth 10 = Tenth 11 = Eleventh 12 = Twelfth 13 = Thirteenth 14 = Fourteenth 15 = Fifteenth 16 = Sixteenth 17 = Seventeenth 18 = Eighteenth 19 = Nineteenth 20 = Twentieth	CSSDC
Cruise Control state	CIS_Cruise_Control	0 – Not available 1 – off 2 – On 3 – Set/Accel 4 – Resume 5 - Coast	CSSDC
Car horn	CIS_Horn	1 – off 2 - on	CSSDC
Turn signals	CIS_Turn_Signal	1 – no turn signal on 2 – left turn signal on 3 – right turn signal on 4 – hazard signals on	CSSDC

Definition	NADS Variable Name	Units	Collection Freq
Angular velocity commanded at the head point	MIF_Head_Point_Angular_Velocities	Degrees/sec	120 Hz
Specific forces commanded at the head point	MIF_Head_Point_Specific_Forces	G's	120 Hz
Left front vibration acceleration, commanded	MIF_LF_Vibr_Accel_Zdd	G's	120 Hz
Left rear vibration acceleration, commanded	MIF_LR_Vibr_Accel_Zdd	G's	120 Hz
Right front vibration acceleration, commanded	MIF_RF_Vibr_Accel_Zdd	G's	120 Hz
Right rear vibration acceleration, commanded	MIF_RR_Vibr_Accel_Zdd	G's	120 Hz
Achieved head point angular velocity	MTS_Head_Point_Angular_Velocities	Degrees/sec	120 Hz
Achieved head point specific forces	MTS_Head_Point_Specific_Forces	G's	120 Hz
Left front vibration acceleration, Feedback	MTS_LF_Vibr_Accel_Zdd	G's	120 Hz
Left rear vibration acceleration, Feedback	MTS_LR_Vibr_Accel_Zdd	G's	120 Hz
Position Commanded – Hexapod Pitch	MTS_Pos_Cmd_Hex_Pitch	Degrees	120 Hz
Position Commanded – Hexapod Roll	MTS_Pos_Cmd_Hex_Roll	Degrees	120 Hz
Position Commanded – Hexapod X	MTS_Pos_Cmd_Hex_X	Inches	120 Hz
Position Commanded – Hexapod Y	MTS_Pos_Cmd_Hex_Y	Inches	120 Hz
Position Commanded – Hexapod Yaw	MTS_Pos_Cmd_Hex_Yaw	Degrees	120 Hz
Position Commanded – Hexapod Z	MTS_Pos_Cmd_Hex_Z	Inches	120 Hz
Position Commanded – Turntable	MTS_Pos_Cmd_TT	Degrees	120 Hz
Position Commanded – X Crossbeam	MTS_Pos_Cmd_X_Crossbeam	Inches	120 Hz
Position Commanded – Y carriage	MTS_Pos_Cmd_Y_Carriage	Inches	120 Hz
Position Feedback – Hexapod Pitch	MTS_Pos_Feedback_Hex_Pitch	Degrees	120 Hz
Position Feedback – Hexapod Roll	MTS_Pos_Feedback_Hex_Roll	Degrees	120 Hz
Position Feedback – Hexapod X	MTS_Pos_Feedback_Hex_X	Inches	120 Hz
Position Feedback – Hexapod Y	MTS_Pos_Feedback_Hex_Y	Inches	120 Hz
Position Feedback – Hexapod Yaw	MTS_Pos_Feedback_Hex_Yaw	Degrees	120 Hz
Position Feedback – Hexapod Z	MTS_Pos_Feedback_Hex_Z	Inches	120 Hz
Position Feedback – Turntable	MTS_Pos_Feedback_TT	Degrees	120 Hz
Position Feedback – X Crossbeam	MTS_Pos_Feedback_X_Crossbeam	Inches	120 Hz
Position Feedback – Y carriage	MTS_Pos_Feedback_Y_Carriage	Inches	120 Hz
Right front vibration acceleration, Feedback	MTS_RF_Vibr_Accel_Zdd	G's	120 Hz
Right rear vibration acceleration, Feedback	MTS_RR_Vibr_Accel_Zdd	G's	120 Hz
Increments every time the Audio trigger fires	SCC_Audio_Trigger	Integer, begins simulation at 0	CSSDC
Bit mask of Audio and Visual states	SCC_DynObj_AudioVisualState	2 integers	60 Hz
Scenario object's color index	SCC_DynObj_ColorIndex	Integer 1 - 5	60 Hz
Cved IDs of Scenario Objects	SCC_DynObj_CvedId	Integer ≥ 0	60 Hz
Indicates how many valid objects in SCC_DynObj Array	SCC_DynObj_DataSize	Integer	60 Hz
Scenario object's HCSM Type	SCC_DynObj_HcsmType	Integer	60 Hz
Headings of Scenario Objects	SCC_DynObj_Heading	Degrees	60 Hz
Name of scenario object	SCC_DynObj_Name	Array of char	60 Hz
Position of scenario object	SCC_DynObj_Pos	Feet	60 Hz
Roll and Pitches of Scenario Objects	SCC_DynObj_RollPitch	Degrees	60 Hz
Sol IDs of Scenario Objects	SCC_DynObj_SolId	Integer ≥ 0	60 Hz
Velocities of Scenario Objects	SCC_DynObj_Vel	Ft/s	60 Hz

Definition	NADS Variable Name	Units	Collection Freq
Lead vehicle follow data	SCC_Follow_Info	An array of 9 floats 1st - identifier of object -1 if none or error 0 if no ownvehicle 2nd - distance to lead vehicle (in feet) 3rd - bumper-to-bumper time to lead vehicle (in seconds) 4th - bumper-to-bumper distance to lead vehicle (in feet) 5th - time-to-collision (in seconds) 6th - lead vehicle velocity (ft/s) 7th – x coordinate of lead vehicle 8th – y coordinate of lead vehicle 9th – z coordinate of lead vehicle	120 Hz
Deviation from center of lane	SCC_Lane_Deviation	Feet	120 Hz
Array of 5 floats	SCC_LogStreams	1st float (Logstream1), 0 – 4, scenario specific value relating to closeness of driver to event. See section 0 for details on this LogStream. 2nd float (Logstream2), 0 or 1 0 = incentives off 1 = incentives on	60 Hz
Over speed limit accumulation	SCC_Over_Speed_Limit	Integer >= 0	60 Hz
Pitch of the driver, in scenario coordinates.	SCC_Scen_Pos_Hex_Pitch	Degrees	CSSDC
Roll of the driver, in scenario coordinates.	SCC_Scen_Pos_Hex_Roll	Degrees	CSSDC
X position of the driver, in scenario coordinates.	SCC_Scen_Pos_Hex_X	Feet	CSSDC
Y position of the driver, in scenario coordinates.	SCC_Scen_Pos_Hex_Y	Feet	CSSDC
Yaw of the driver, in scenario coordinates.	SCC_Scen_Pos_Hex_Yaw	Degrees	CSSDC
Z position of the driver, in scenario coordinates.	SCC_Scen_Pos_Hex_Z	Feet	CSSDC
Turntable position of the driver, in scenario coordinates.	SCC_Scen_Pos_TT	Degrees	CSSDC
Crossbeam position of the driver, in scenario coordinates.	SCC_Scen_Pos_X_Crossbeam	Inches	CSSDC
Cariage position of the driver, in scenario coordinates.	SCC_Scen_Pos_Y_Carriage	Inches	CSSDC
Total number of increments collected at 60 Hz	SCC_Total_Speed_Limit	Integer >= 0	60 Hz
Under speed limit accumulation	SCC_Under_Speed_Limit	Integer >= 0	60 Hz
Signal sent to mirror	SCC_Warning_Lights	0 – no warning 1 – left mirror warning 2 – right mirror warning 3 – both mirror warning	CSSDC
Within speed limit accumulation	SCC_Within_Speed_Limit	Integer >= 0	60 Hz
Type of surface the tire is upon	TPR_Surface_Tire_Friction_Ind	0 – intersections and drivable off-road 14 – road 20 - shoulder	CSSDC
	TPR_Tire_Surf_Type		240 Hz
	TPR_Tire_Surf_Obj_Type		240 Hz

Definition	NADS Variable Name	Units	Collection Freq
Flag to enable/disable ABS system	VDS_ABS_Operating_Flag	0 – ABS system disabled 1 – ABS system enabled	CSSDC
Acceleration pedal position backdrive	VDS_Acc_Pedal_Pos_Backdrive	NA	240 Hz
The type of brake currently in use by the dynamics	VDS_Brakefile_Name	Standard.inp – S-Cam brakes Enhanced.inp – Hybrid brakes Disc.inp – Air disc brakes	
Chassis CG Acceleration	VDS_Chassis_CG_Accel	Feet/sec*sec	240 Hz
Chassis CG angular velocity	VDS_Chassis_CG_Ang_Vel	Deg/sec	240 Hz
Chassis CG orientation	VDS_Chassis_CG_Orient	degrees	240 Hz
Chassis CG position	VDS_Chassis_CG_Position	feet	240 Hz
Chassis CG velocity	VDS_Chassis_CG_Vel	mph	240 Hz
Add to master table	VDS_Curr_Gear		
Output flag, indicates whether ABS is active or not.	VDS_ESP_ABS_ACTIV_FLAG	0 – Not active 1 - Active	CSSDC
Output flag, indicates whether ESC is active or not.	VDS_ESP_ACTIV_FLAG	0 – Not active 1 – Active	CSSDC
Output – Brake pedal drop flag	VDS_ESP_BRAKE_PEDAL_DROP_FLAG	0 – No action 1 – Lower brake pedal to simulation active booster	CSSDC
Output – Brake pedal vibration flag	VDS_ESP_BRAKE_PEDAL_VIB_FLAG	0 – No action 1 – Vibrate brake pedal to simulate feedback	CSSDC
Output – Fault detected flag	VDS_ESP_FAULT	0 – No fault 1 – Fault detected, system shut down	CSSDC
Inputted value, set by run's RCM file, enables/disables ESC.	VDS_ESP_Flag	0 – ESC System disabled 1 – ESC System enabled	CSSDC
Output flag, indicates whether the traction control portion of ESC is active, or not.	VDS_ESP_TRACT_CNTRL_FLAG	0 – Not active 1- Active	CSSDC
Inputted variable – type of ESC	VDS_ESP_Type	1 – Engine torque 2 – Axle torque	CSSDC
Eye point orientation in global coordinate system	VDS_Eyepoint_Orient	Degrees	240 Hz
Eye point position in global coordinate system	VDS_Eyepoint_Pos	feet	240 Hz
Angular velocity of head point	VDS_Head_Pt_Angular_Vel	Deg/sec	240 Hz
Head point specific forces	VDS_Head_Pt_Specific_Force	G's	240 Hz
Output – Light lamp on instrument panel	VDS_LAMP_FLAG	0 – System not active 1 – System active	CSSDC
Wheel torque due to external forces	VDS_Load_Torque	Foot-pounds	240 Hz
Number of grids used for each contact patch	VDS_Num_Grids	NA	CSSDC
Number of tires on vehicle	VDS_Num_Tires	0 -10	240 Hz
Commanded Steering Wheel Torque	VDS_Steering_Torque_Backdrive	Foot-pounds	240 Hz
The tire/terrain contact location	VDS_Tire_Ground_Contact	ft	240 Hz
Tire rotational velocity	VDS_Tire_Rot_Vel	Degrees/sec	240 Hz
Tire slip angle	VDS_Tire_Slip_Angle	Degrees	240 Hz
Tire slip ratio	VDS_Tire_Slip_Ratio	0 – 1 norm	240 Hz
Tire weight on wheels	VDS_Tire_Weight_On_Wheels	Pound force	240 Hz
Trailer CG Acceleration	VDS_Trailer_CG_Accel	Feet/sec*sec	240 Hz
Trailer CG angular velocity	VDS_Trailer_CG_Ang_Vel	Deg/sec	240 Hz
Trailer CG orientation	VDS_Trailer_CG_Orient	Degrees	240 Hz
Trailer CG position	VDS_Trailer_CG_Position	Feet	240 Hz
Trailer CG velocity	VDS_Trailer_CG_Vel	Mph	240 Hz
Add to master doc	VDS_Veh_Dynamic_Pres		240 Hz
Engine revolutions per minute	VDS_Veh_Eng_RPM	Rpm	240 Hz
Engine torque	VDS_Veh_Eng_Torque	Foot-pounds	240 Hz
Vehicle heading	VDS_Veh_Heading	Degrees	240 Hz
Vehicle speed	VDS_Veh_Speed	Mph	240 Hz
Transmission revolutions per minute	VDS_Veh_Trans_RPM	Rpm	240 Hz
Commanded Vibration Forces	VDS_VibrForce	G's	240 Hz
Heading angle of wheel	VDS_Wheel_Center_Heading	Degrees	240 Hz
Translational velocity of wheel center	VDS_Wheel_Center_Velocity	Ft/sec	240 Hz
Wheel spin	VDS_Wheel_Spin	Rad/sec	240 Hz

Definition	NADS Variable Name	Units	Collection Freq
Rotational position of tire, in radians	VDS_Wheel_Spin_Angle	Rad	240 Hz
Road wheel angle	VDS_Wheel_Steer_Angle	Rad	240 Hz
Add to master doc	VVS_Horn_Sound		240 Hz
ESC on icon	VVS_Right_Warning_Light	1 – off, 2 - on	CSSDC
Speedometer backdrive	VVS_Speedometer_Backdrive	Mph	240 Hz
Add to master table	VVS_Starter_Sound	Na	240 Hz

Video Data

Video collection took place for the duration of each run and consists of two different video streams. Note that video collection started at the same time the NADS entered the "RUN" state, which coincided with the time that the participant was able to drive. Video collection ended 10 seconds after the operator stopped the simulator, or when an abort, emergency stop, or fire stop signal was generated by any of the NADS or NADS facility subsystems. This means that no video was collected while the simulator was transitioning to the start position or between scenarios.

Stream 1

Stream 1 consisted of the quad split. There was also a recording of it, in mpeg format, on the hard disk. For the mpeg recording, each run was recorded to a different file. There was also a recording of it to digital video tape. Figure E1 shows an example of stream 1, whereas Figure E2 shows the configuration settings for the MPEG recordings.

Figure E1 - Example of quad split

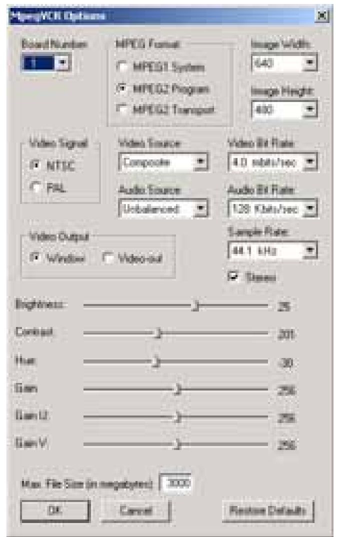


Figure E2 - MPEG VCR settings

Quad split

The quad split's four different views, and their orientation within the screen, are listed below:

a) Upper left: In-cab face camera
b) Upper right: In-dome forward view
c) Lower left: Feet
d) Lower right: In-cab over shoulder

Quad Split Text Overlay

The text overlay appears in the lower right quadrant of the quad split and is shown below, in Figure E3. Items in bold appear verbatim; other items reflect simulator variables as explained below. Whereas variable names are arbitrary, their length indicates the space that will be allowed for that variable on the overlay.

Note that the first line of numbers and the column of numbers on the left will not appear on the overlay; they exist to help determine the lineup of the text and variables of the overlay system.

 12345678901234567890
1
2
3BRAKECONDITIONNNN
4**DiscBrake_Main**
5RUNNAMERUNNAMERUN
6MM/DD/YY HH:MM:SS
7**V:** VVVVV **SA:**STEER
8**BP:**BRAKE **AP:**ACCL
9FRAMENUM**D:**DISTFT

Figure E3 - Text overlay

Table E2 Text overlay variable description

Variable	Meaning
BRAKECONDITIONNNN	The type of brake being used: Standard.inp means S-Cam brakes Enhanced.inp means Enhanced S-Cam brakes Disc.inp means Air disc brakes
RUNNAMERUNNAMERUN	The run's name
MM/DD/YY	Date
HH:MM:SS	Time
FRAMENUM	The frame number
VVVVV	The participant's velocity, in miles per hour
STEER	The steering wheel, angle in degrees
BRAKE	The brake pedal force, in pounds
ACCL	The gas pedal displacement, as a normalized value between 0 and 1
DISTFT	The distance to the vehicle in front of the driver, in feet

Stream 2

Stream 2 was the in-dome, forward view. It was recorded, in mpeg format, onto the hard disk, with each run being recorded to a different file. An example of the stream is shown in Figure E4, and the recording settings are shown in Figure E2.

Figure E4 - Example of forward view

Stream 3

Stream 3 was the quad split. It was recorded, in mpeg format, onto the hard disk, with each run being recorded to a different file.

Stream 4

Stream 4 was the in-dome, forward view. It was recorded, in mpeg format, onto the hard disk, with each run being recorded to a different file.

Details on LogStream1

For all scenarios, LogStream1 started out at 0 and was given a higher value the closer the driver gets to the event. After the event, if the driver hadn't lost control, the LogStream went to 3 or 4. Following are specifics on each scenario.

Table E3 LogStream1 values

Scenario	LogStream1 values
Stopped.scn	0 – at start 1 – set by same trigger that creates event
Stopping.scn	0 – at start 1 - set by same trigger that creates event
RightIncursion.scn	0 - at start 1 – set by Time to Arrival Trigger, same trigger that creates incursion vehicle. 2 - 260 feet beyond incursion driveway
LeftIncursion.scn	0 - at start 1 – set by Time to Arrival Trigger, at the same time as the incursion DDO is created. 2 – set by Time to Arrival Trigger, at the same time as the trigger starts the oncoming ADO to swerve into driver's lane. 3 – 325 feet back from parked DDO location.

Appendix F: Evaluation Of The Integration Of A Heavy Truck Model Into The National Advanced Driving Simulator (NADS)

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August 2006

An on-site review of the heavy truck cab integration into NADS was conducted on Wednesday and Thursday, July 19 and 20, 2006. The following items were reviewed.

1) Steering Feel and Vehicle Lateral Response

This section includes:

- Confirmation of Steering Torque/Angle Relationships
- Confirmation of Appropriate Steering System Lash
- Confirmation of CFS Steering Angle Throughput
- Confirmation of CFS Steering Torque Throughput
- Subjective Evaluation of Lane Change and Handling Stability

The relationship between steering torque and steering angle was directly measured in the heavy truck cab using a handheld spring scale and a circle template. The comparable NADS CFS variables (CFS_Steering_Wheel_Torque and CFS_Steering_Wheel_Angle) were recorded simultaneously with the direct measurements. The NADS staff reported that they had replaced and calibrated the steering torque sensor on the heavy truck CFS prior to this evaluation. Figure F1 shows that the direct measurements and CFS variables match fairly well over the range of turning the steering wheel 360 degrees in either direction. The CFS variables are limited to be around 6.25 ft-lb. This is a reasonable level of maximum torque, and it is in line with values measured at VRTC for the actual Volvo-GM heavy truck. The U-shaped characteristic curve is typical of a power-assisted steering system.

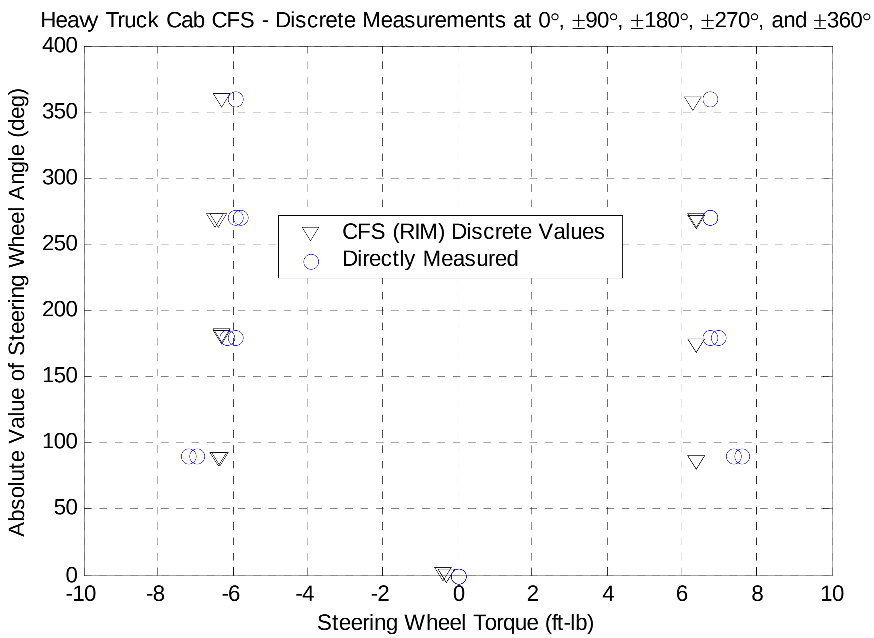

Figure F1 - Direct and CFS Measurements of Discrete Steering Properties

Following the discrete measurements, a continuous sweep of steering through positive and negative 360 degrees was conducted. Figure F2 contains time domain CFS steering data from this test, and Figure F3 shows the steering characteristic curve from this test superimposed over the discrete data (Figure F1). The CFS steering torque and angle measured during the continuous sweep test match the data collected during the discrete position test.

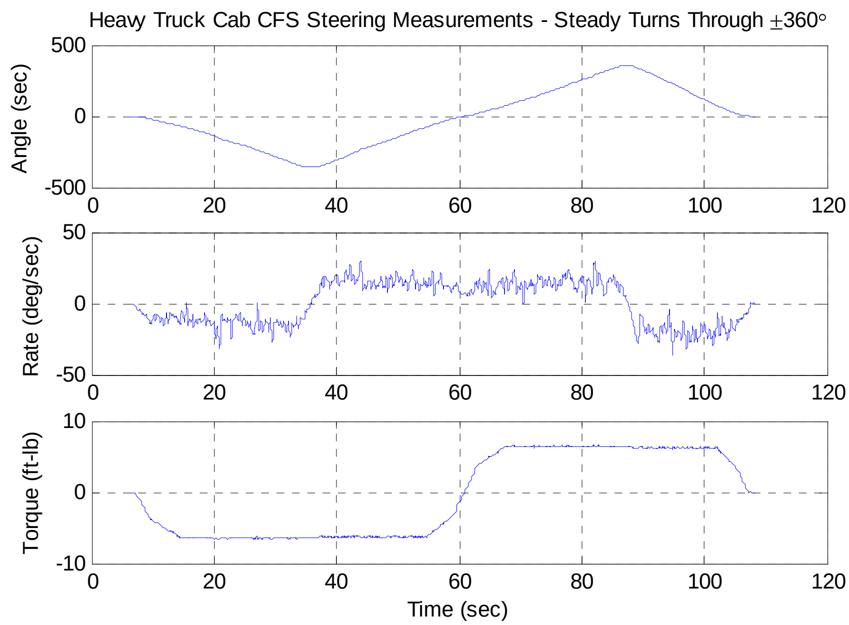

Figure F2 - Time Domain Steering Data from ±360° Steering Sweep

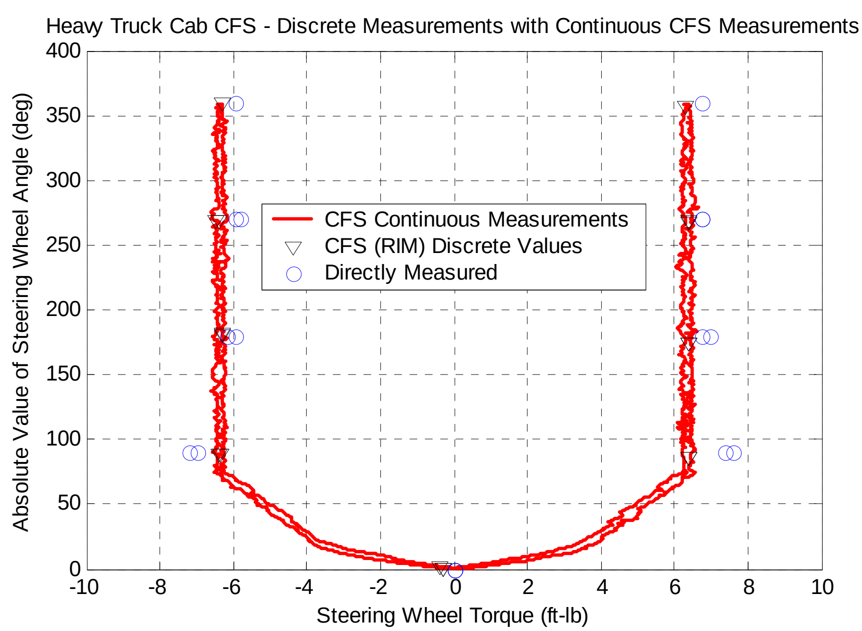

Figure F3 - Continuous CFS Steering Data with Discrete Measurements

To evaluate the on-center steering characteristics of the NADS heavy truck, lower values of discrete steering torque inputs were applied, and the torques and angles were directly measured as before. Figure F4 contains results from the NADS truck cab on-center steering characterization. These values compare very well with measurements made from the continuous steering sweep test, and with the steering characteristic curve measured using VRTC's Volvo-GM heavy truck.

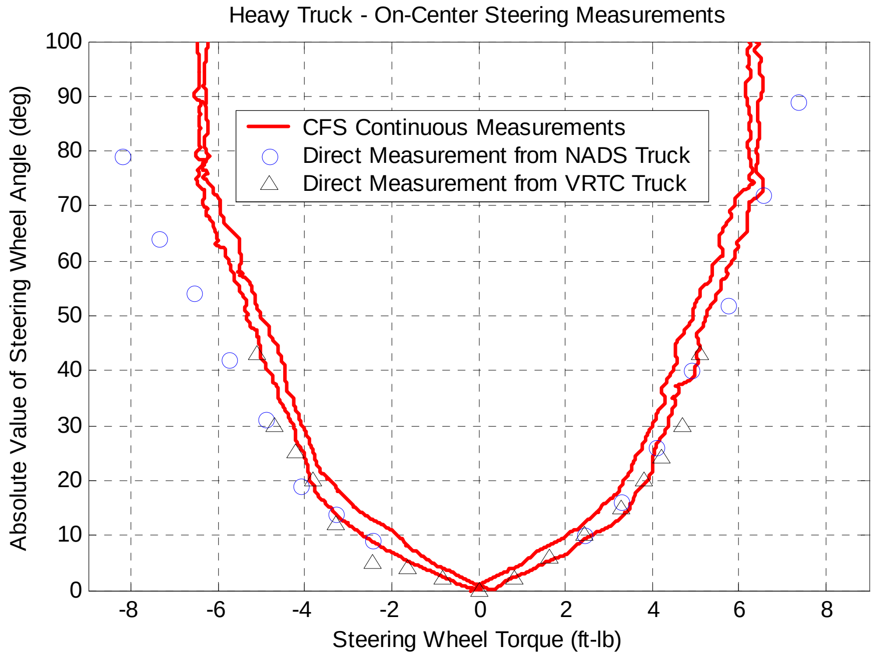

Figure F4 - NADS Heavy Truck On-Center Steering Confirmation

Figure F5 contains steering wheel angle, rate, and torque responses during 90-degree turn and release maneuvers. These tests were conducted to evaluate the free response of the steering wheel. After being released from 90 degrees, the steering wheel returned to its steady-state condition within 0.6 seconds for both the right steer and left steer directions. The responses after the releases did not overshoot, and the graphs indicate that the steering system response is nearly critically damped. The time response and damping of the NADS heavy truck steering is a close representation of the steering response of VRTC's Volvo-GM heavy truck.

Figure F6 is a graph showing CFS steering angles plotted against the measured input steering angles. The graph shows close correlation between the CFS and actual angles, with the greatest difference being less than one degree.

The lash or free play in the NADS heavy truck steering was also evaluated. The steering wheel returned to 1 to 2 degrees when released from 15 degrees. The desired, modeled free play is 2 degrees, so this response is quite good. Also, as before, the steering response was noted to behave as a critically damped system.

The results of the tests to evaluate the NADS heavy truck steering confirmed that the steering torque and angle relationships are being modeled and implemented correctly. The NADS staff made the necessary hardware and software modifications to correctly model the heavy truck steering behavior, including the power assisted steering and on-center characteristics. The tests conducted also confirmed that the correct values for steering torque and angle are being throughput on the CFS, and that the steering system lash (free-play) on the NADS heavy truck is appropriate. Finally, the steering feel of the NADS heavy truck, evaluated during lane change and other handling maneuvers, was found to be subjectively quite good. The responsiveness, damping, and overall gains of the steering system are representative of the steering system on an actual heavy truck.

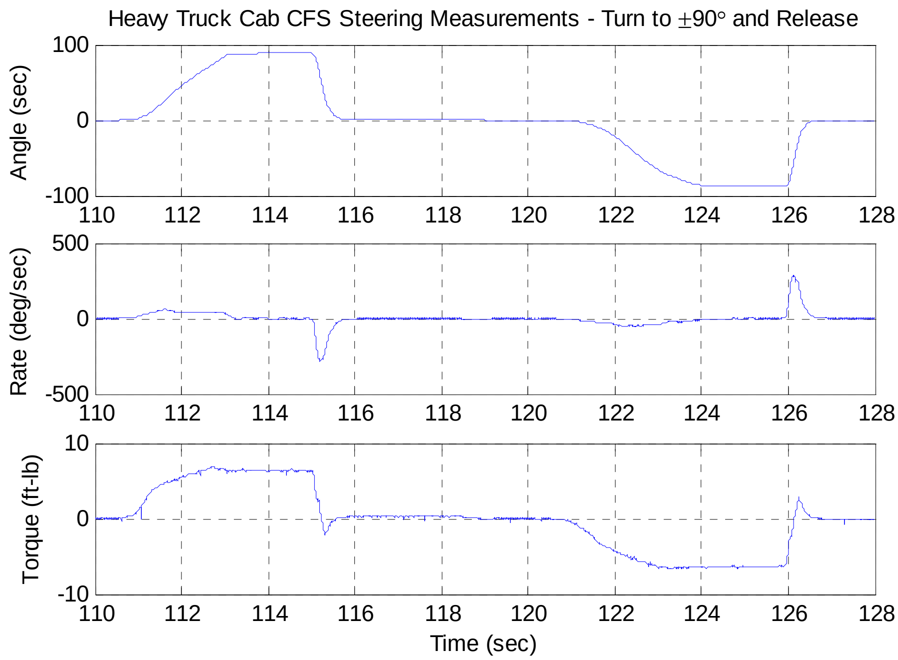

Figure F5 - NADS Heavy Truck Steering Free Response

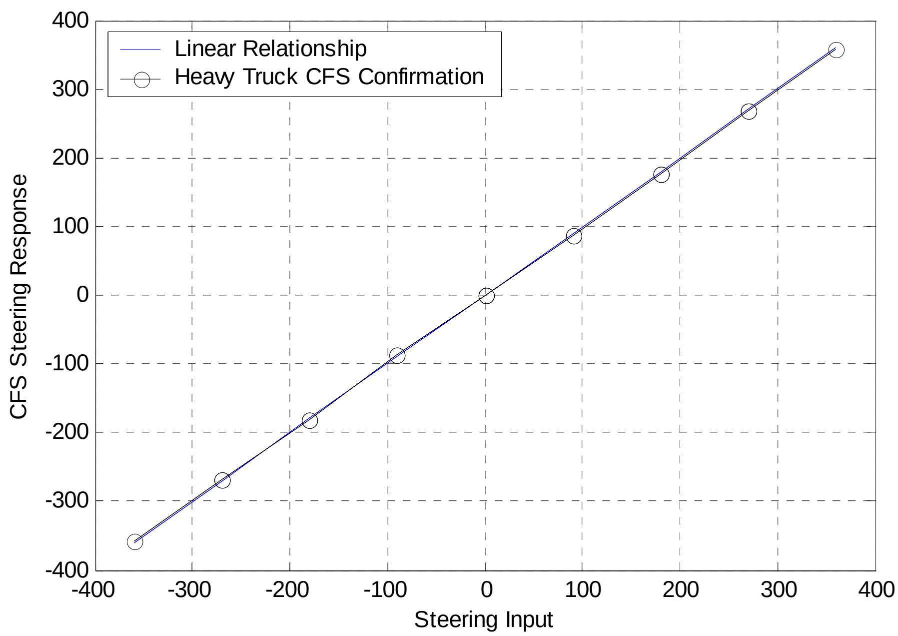

Figure F6 - Confirmation of NADS Heavy Truck Steering Angle

2) Braking System Feel and Vehicle Longitudinal Response

This section includes:

- Confirmation of CFS Brake Pedal Force Throughput
- Confirmation of Stopping Distances for Disk, Hybrid, and S-Cam Brakes

The NADS staff reported that they had recently calibrated the heavy truck CFS brake force sensor (since VRTC's June 2006 visit when the brake force was being scaled within NADSdyna). Correct calibration of the actual force sensor means the CFS brake pedal force is correct. As it should be, the CFS brake force is now being used directly as it is fed as input into NADSdyna.

Figure F7 is a graph of vehicle speed and brake pedal force as a function of distance traveled. This representative run was made with disk brakes modeled on the NADS heavy truck. The stopping distance is very close to the desired stopping distance from 60 mph, which is 215 feet. The stopping distance confirmation maneuvers performed involved very hard brake pedal applications. The brake pedal force on Figure F7 shows that full NADS heavy truck braking was applied. The CFS brake pedal force sensor for the heavy truck records a maximum of 80 lb. This value of 80 lb is also the maximum value of brake force used in the NADSdyna model, and it is very close to the pedal force on the actual Volvo-GM heavy truck that results in maximum brake pressure. The brake pedal force trace in Figure F7 substantiates that the CFS brake pedal force is correct. Stopping distances from 60 mph were also confirmed for the hybrid brake model (in the range of 256 ft) and S-cam brake model (in the range of 307 ft).

Overall, the NADS heavy truck brake system fidelity is very good. The mechanical and pneumatic system in place in the CFS of the heavy truck does a great job of representing the characteristics of the pneumatic braking system of an actual heavy truck. The brake pedal travel on the cab is appropriate and feels like an actual heavy truck brake pedal.

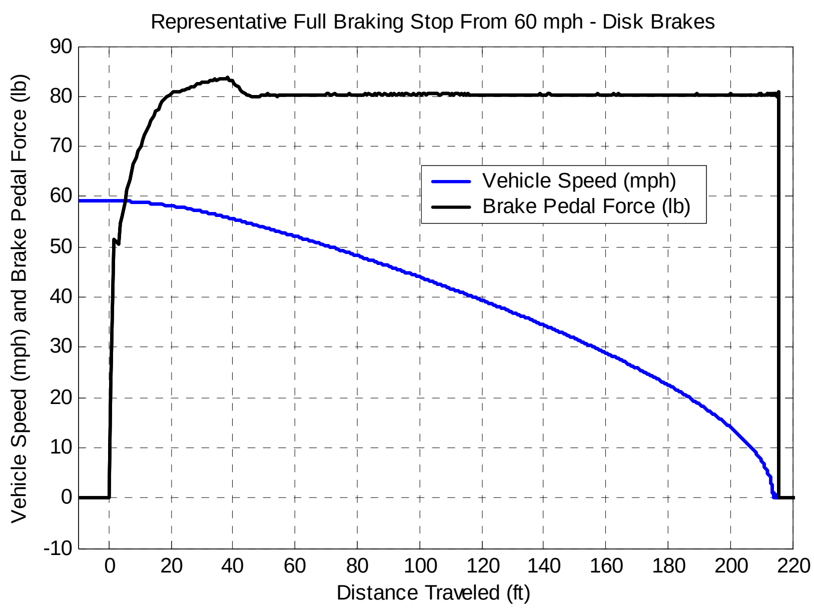

Figure F7 - Results from Full Braking Stop from 60 mph Using Disk Brakes

3) Gear Shift Fidelity

This section includes:

- Clutch Fidelity
- Review of Audio Fidelity
- Throttle (Powertrain) Fidelity and Longitudinal Performance

The NADS heavy truck gear shifting characteristics are quite similar to the actual Volvo-GM truck at VRTC. The shifting patterns are identical, and required shifting efforts are quite similar between the actual and simulator vehicles. The NADS cab exhibits appropriate lack of gear engagement “grinding”, and engagement tolerances are appropriately synchronized with engine RPM and vehicle speed.

Engine audio has been added since VRTC’s visit in June. Being able to “hear” the engine speed improved shifting realism as well as shifting ease. The engine sounds are good and they are well synchronized with engine RPM. Also, the volume of the engine audio was determined to be good (with the cab windows closed).

During this evaluation, the adjustable “ease-of-shifting” parameter setting was set to 0.5. (with 1.0 being the most difficult). This setting provided for somewhat easier shifting than when the parameter was set to 1.0. The current plan is to use 0.5 for the pilot study, which should provide for good shifting realism and not make it too difficult for the driver to shift.

The NADS heavy truck clutch response is very similar to the clutch response in the VRTC Volvo-GM heavy truck. Clutch engagement and disengagement both occurred near the clutch midstroke. Also, the force required for clutch application in the NADS heavy truck is appropriate.

The throttle displacement and resistance on the NADS heavy truck are good, and the truck’s acceleration performance is subjectively good as well.

4) Visual Review

This section includes:

- Review of General Visual Scenes
- Review of Project-Specific Scenarios

There were several problems with the visual scenes identified in June while working on the SDM, such as trees having rectangular, planar frames; yellow center lane markings changing color or intensity; and a database vehicle with disoriented tires. Prior to the July evaluations, the NADS staff worked on fixing these problems, and none of these visual database problems were noticed when the heavy truck was driven in the NADS. Also, there was some occasional "jitter" in ADO vehicles and the trailer object in the SDM, but none was noticed in the NADS.

All four of the project specific scenarios seem good. The timing of each of the events appears to be as designed, and the level of scenario detail and the "realism" associated with each scenario is appropriate. One of the scenarios includes concrete barriers positioned parallel to the roadway. The barriers were positioned directly on the edge of the travel lane. The proximity of these barriers could cause drivers to slow down and move to the left of the lane. A decision was made to move the barriers slightly off the road to avoid this potential problem.

At the time of this evaluation, NADS staff had not completed their adjustments to the rear view projections to compensate for the locations of the side mirrors. Unlike for a passenger vehicle, for the heavy truck the side mirrors need to reflect portions of the rear of the trailer. The reflected "eyepoint" of the side mirrors is further removed form the driver's actual eyepoint than in a passenger vehicle. Also, in the heavy truck, the driver was no rear window and no rearview mirror. NADS staff will need to complete tuning these adjustments prior to the heavy truck pilot study.

Another visual issue unique to the heavy truck is that the back of the heavy truck cab structure blocks portions of the images from one or more of the rear projectors. This results in a rectangular blacked-out image that can be seen in the side mirrors. This is unnatural and it will possibly be distracting to some subjects. The NADS staff was agreed to look into possibly removing portions of the heavy truck cab structure to alleviate some of this problem.

5) Motion Fidelity

This section includes

- Review of Motion Fidelity
- General Overall Drivability

The NADS staff reported that their preliminary heavy truck runs on the NADS prior to July 19, 2006 contained a steady, low frequency (less than 2 Hz) vertical motion. Review of NADSdyna runs made without motion revealed that there was a steady oscillatory component of vertical acceleration present, even when the vehicle was at zero speed. Oscillations of this type can occur in numerical simulations that are too lightly damped, which was the case here. The value for tire vertical damping (parameter td in the tire data file) that was being used in NADSdyna was too small. There was no testing done to evaluate the heavy truck tire damping, so the initial value used (10,000 N/(m/sec)), roughly five times the value used for passenger vehicle tires, was based on the fact that the tire vertical stiffness for a heavy truck tire is about five times greater than the vertical stiffness of a typical passenger car tire. Increasing the tire damping to 50,000 N/(m/sec) eliminated the numerically generated vertical oscillations. However, review of NADSdyna results from tests conducted during the evaluation period indicated that the value of 50,000 N/(m/sec) was too high. Using this value resulted in improper "settling" of NADSdyna as indicated by incorrect static load distribution among the trailer tires. Subsequent NADSdyna runs using a value for tire vertical damping of 20,000 N/(m/sec) provided good results with no vertical oscillations and with correct static load distribution.

The NADS motion fidelity while driving through the heavy truck scenarios was good. All motion runs made during the evaluation period were conducted with the tire vertical damping set to 50,000 N/(m/sec). However, using the revised value of 20,000 N/(m/sec) should not affect the motion, as the numerical vertical oscillations are not present in NADSdyna using either value for vertical tire damping.

The overall heavy truck simulation experience in the NADS is very good. Having motion, a larger field of view than the SDM provides, and having engine noise all enhanced the driving experience beyond previous heavy truck experiences in the SDM. Adding high frequency vibrations should further improve the realism of the heavy truck simulations.

6) Review of Cab Vibrations via High Frequency Actuators

Heavy truck cab vibrations, which will be simulated primarily with the high frequency actuators, had not yet been implemented at the time of this evaluation. Subsequently, VRTC completed the heavy truck cab vibration measurements and provided NADS staff with a vehicle and engine speed dependent model for cab vibrations. The plan is to add these modeled vibrations to the NADSdyna vertical acceleration of the chassis. This way, the low frequency components of vertical acceleration will be handling by hexapod motions and the high frequency actuators will handle the high frequency components. This should work well, but it needs to be implemented and evaluated prior to the pilot study.

7) Low Speed Dynamics and Stopping Stability

Considerable effort has gone into the NADSdyna modeling of tire forces in the road plane as a vehicle slows to a stop. These forces must react to hold the vehicle in a steady stopped position. The NADSdyna low speed tire models work very for four wheeled vehicles, but they have not been thoroughly evaluated or tuned for 18 wheel vehicles.

During complete stops with the heavy truck there are small but perceivable transients in the vehicle motions. These transients are dependent on the severity of the stop, on the steer angles of the front wheels, and on the slope and grade of the road. The transients are evident in the visuals as small flutters of the visual scene, but they are not noticeable in the motion, probably because the specific forces generated from stopping mask them. It is likely that subjects will not perceive these stopping transients, because their magnitudes are small and they are not unlike the transients one might expect in a normal stop of a heavy truck. With the high frequency actuators active, the stopping transient issue will likely become even less noticeable. Nonetheless, attention should be paid to determine whether or not the pilot study subjects perceive of or react to these stopping transients.

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