

Braking Behavior of Truck Drivers in Crash Imminent Scenarios

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ABSTRACT

Dynamic Brake Support (DBS) is a safety system that has been applied to various passenger cars and has been shown to be effective at assisting drivers in avoiding or mitigating rear-end collisions. The objective of a DBS system is to ensure that the brake system is applied quickly and at sufficient pressure when a driver responds to a collision imminent situation. DBS is capable of improving braking response due to a passenger car driver's tendency to utilize multi-stage braking.

Interest is developing in using DBS on commercial vehicles. In order to evaluate the possible improvement in safety that could be realized through the use of DBS, driver braking behavior must first be analyzed to confirm that improvement is possible and necessary. To determine if this is the case, a study of the response of truck drivers' braking behavior in collision imminent situations is conducted. This paper presents the method of evaluation and results.

Data was drawn from a prior NHTSA simulator study and showed that many drivers exhibited multi-stage braking during four different imminent crash scenarios. Results from analysis indicate that a DBS system capable of detecting and intervening at the most conservative level of multi-staging presented could be successful in assisting drivers in avoiding or at minimum mitigating 30% of the collisions presented in this document. Further opportunities for assisting drivers based on reducing brake application time are also shown to exist. These results suggest that a DBS system may be valuable for heavy vehicles.

CITATION: Every, J., Salaani, M., Barickman, F., Elsasser, D. et al., "Braking Behavior of Truck Drivers in Crash Imminent Scenarios," *SAE Int. J. Commer. Veh.* 7(2):2014, doi:10.4271/2014-01-2380.

INTRODUCTION

Motivation

Rear-end crashes accounted for 19.9% of all police reported heavy truck crashes based on General Estimates System data published in 2004 [1]. In these collisions the heavy truck was the striking vehicle in 60% of cases.

Based on these statistics, it is believed that a means of mitigating or avoiding frontal collision in heavy vehicles through electronically assisted braking like Dynamic Brake Support

(DBS) systems could have significant safety benefits. Such systems are currently available in the passenger car market, but have not yet been applied to heavy vehicles. The evaluation of the braking behavior of commercial vehicle drivers, during crash-imminent situations, should provide insight into whether the addition of such a system could be used to reduce the incidence and severity of frontal crashes involving heavy vehicles.

Background

The widespread application of ESC (Electronic Stability Control) systems, as mandated by the US, European Union, and other parts of the world for light vehicles, has provided the building blocks for a wide variety of brake control systems. Recently, sensors that detect moving vehicles and road obstacles have been developed and applied in systems such as Advanced Cruise Control (ACC) with braking and Forward Collision Warning (FCW). ACC systems are capable of maintaining a preset headway between the lead and following vehicles by automatically regulating the following vehicle's throttle and brakes. ACC systems are commercially available for light vehicles as well as heavy trucks, and are available to be purchased as a safety package option across most vehicle classes. FCW systems alert drivers to situations in which a frontal collision, with a lead vehicle or object, could occur in the absence of driver intervention. FCW systems monitor lead vehicle position and velocity, typically using radar, and are available as optional equipment on light vehicles and heavy trucks.

From a technical hardware requirement, any vehicle equipped with an ACC or FCW system is capable of detecting when a frontal collision is likely to occur. Vehicles with ACC can also assist the driver in applying emergency braking to avoid a collision or mitigate crash severity. Such automated emergency braking systems are known as Dynamic Brake Support (DBS) technology. These systems are already available in the passenger car market for luxury vehicles and for many lower vehicle classes. Moreover Collision Imminent Braking (CIB) systems for heavy vehicles are currently available and that would address crashes where drivers did not brake at all.

The rationale for the necessity of DBS technology is that many drivers do not apply maximum braking capacity when the danger is initially perceived; they initially brake at a level below the maximum and then apply significantly more braking prior to impact. A NHTSA study [2] that examined drivers' collision avoidance behavior using conventional and Antilock Brake Systems found that light vehicle drivers typically exhibit multi-stage braking behavior in response to potential frontal crash conflicts. Most subjects initially applied the brake moderately and then hesitated momentarily, holding the brake pedal steady at a moderate application level. If the subject then perceived that the threat could not be avoided by a moderate brake application, they then continued to full brake application.

DBS technology actively increases the amount of braking provided by the driver in an effort to avoid a frontal crash. If the driver has applied force to the brake pedal, DBS uses forward-looking sensor data, provided by technologies such as RADAR, LIDAR, and video cameras to assess the potential for a frontal crash. Should DBS ascertain a crash is likely (i.e., the sensor data indicates the driver has not applied enough braking to stop prior to reaching an object in front of the vehicle), DBS automatically intervenes. Although the manner in which DBS is implemented differs among vehicle

manufacturers, the objective of the interventions is largely the same: to supplement the driver's commanded brake input by increasing the output of the foundation brake system earlier in time. In situations where DBS intervenes, the increase in brake force may allow the driver to avoid the collision, but should at least mitigate the severity of the collision.

Similar to passenger cars, DBS systems could be added to heavy vehicles because the building blocks for such technologies already exist as part of the existing adaptive cruise control and forward collision warning systems.

Method

The main question that arises in discussing the implementation of DBS on heavy vehicles is: do commercial vehicle drivers typically apply adequate brake force in sufficiently short time when presented with collision imminent situations? To answer this question, commercial vehicle drivers' behavior during crash imminent scenarios was analyzed.

The availability of accident and field research data for crash scenarios involving heavy vehicles is very limited. Therefore, the data used is from a NHTSA National Advanced Driving Simulator (NADS) research project [3] designed to study the effect of reducing heavy truck stopping distance on the number of crashes and their severity. This study was conducted to support the rule making efforts in reducing the Federal Motor Vehicle Safety Standard No. 121 (FMVSS 121) air braked truck minimum stopping distance requirements. Three air braking systems were used; standard S-cam, enhanced S-cam (larger drums and shoes), and an air-actuated disc brake system. A test group 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 four stopping emergency events were right incursion, left incursion, stopped vehicle, and stopping vehicle. These events were simulated 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 were timed such that with a typical S-cam brake system that met 2004 FMVSS 121 stopping distance requirements, the driver could bring the truck to a safe stop if he/she pushed the brake pedal to its saturation pressure at the time when the incursion vehicle was first perceived.

The results of NHTSA's study [3] showed that the type of braking system had no statistically significant effect on driver behavior prior to braking. Drivers' braking efforts measured through pedal forces and reaction times of scenario perceptions were found to be statistically similar. The results validated the theory that; reducing heavy truck stopping distance has strong potential to decrease the number and severity of crashes in situations requiring emergency braking, given that the operators' reaction time, control behavior, and

their perceptions of available stopping distance remain constant. For further explanation of the scenarios presented to the subjects the reader is referred to [Appendix B](#).

[Table 1](#) includes the number of collisions that occurred for each scenario and each brake type. The right incursion scenario is less likely to result in a collision and the stopped and the stopping event scenarios are more likely to result in a collision. Comparing these numbers to real world data [4], 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 2](#) contains mean collision speeds and the differences in vehicle speeds between the striking vehicle and the struck vehicle (delta-v) for all the brake types that occurred during the left incursion, stopped event, and stopping event. The right incursion data was not included because there were only three collisions, and a comparison of the mean speeds for this case would be meaningless. The left incursion results in a head-on collision; that is why the collision speed is less than delta-v.

[Table 1. Summary of number of collisions with incursion vehicles](#)

	S-Cam	Enhanced S-Cam	Air Disc	Total Collisions
Left Incursion	11	4	11	26
Right Incursion	2	1	0	3
Stopping	22	9	12	43
Stopped	14	17	6	37
Total Collisions per Brake Type	49	31	29	109

The data from this NHTSA's study showed that the ratio of collisions to total number of drivers for the standard S-Cam system is 38.6%, 23.7% for the enhanced S-CAM, and 23.0% for the air disc brake. For the most severe event (the stopped at 70 mph), the ratio of collision to the total number of runs for the air disc system is 24.0%, whereas it is 56.0% and 58.6% for the standard S-Cam and enhanced S-Cam respectively. Also, drivers using air disc brakes in this event had reduced collision speeds compared with those using the S-Cam and enhanced S-Cam.

[Table 2. Mean collision speed and \(mean delta-v\) for collisions with struck vehicles \(mph\)](#)

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

The current study's data analysis did not address the same metrics evaluated during the earlier research. However, the same data from the four crash imminent scenarios was analyzed in the current work to determine driver braking behavior metrics and evaluate the possibility for using DBS to assist in reducing rear-end crashes.

The objective of this study was to evaluate heavy truck CDL-licensed drivers' braking behavior from the time of danger perception up to maximum braking efforts. The analysis is based on three main concepts: peak brake pressure, application time from brake initialization to when peak brake pressure is reached, and if brake application was performed in multiple stages.

In order to ensure that the data being analyzed only consisted of the test subjects' response to the presented scenario, each dataset was truncated, so that only the desired time frame was evaluated. Each dataset was specified to start when the scenario began. The end point for the dataset was triggered by one of two events: first, if a driver was involved in a collision; and second, if the driver achieved a complete stop. If neither of these events were triggered the end of the dataset evaluated was the end of the parent dataset. This typically occurred in situations in which a driver slowed significantly prior to the occurrence of a collision and then allowed the vehicle to coast at a slow speed.

In evaluating the datasets to determine whether or not a collision had occurred, it was found that some datasets were incomplete. In these datasets the reported data for the distance between the subject vehicle and scenario vehicles was not recorded correctly. Datasets in which this occurred were removed from the population of datasets used for this analysis. Also, in some datasets it was discovered that the driver did not apply a brake force exceeding two pounds at any point during the test. Two of such runs were also removed from the population analyzed. The resulting population of datasets is presented in [Table 3](#).

[Table 3. Population distribution of datasets analyzed](#)

Distribution of Valid Dataset Population		
Scenario	Brake System	Total Tests
Left Incursion	S-Cam	32
	Enhanced S-Cam	33
	Disc	34
Right Incursion	S-Cam	34
	Enhanced S-Cam	33
	Disc	31
Stopping	S-Cam	36
	Enhanced S-Cam	36
	Disc	36
Stopped	S-Cam	25
	Enhanced S-Cam	29
	Disc	25
Totals		384

BRAKING METRICS

Peak Brake Pressure

The brake pressure considered is the control input to the brake system (treadle pressure). The pressure is set using a valve that is attached to the brake pedal and reaches saturation once a given pressure is reached. The NADS pneumatic brake pressure model is set to saturate at 100 psi; this level replicates the reservoir pressure for braking in heavy vehicles. Once brake system saturation is reached, any additional force applied to the brake pedal does not increase the system pressure, and in turn does not increase the level of braking. Because of this saturation, it was decided to identify the braking peak based on system pressure, rather than brake pedal force, as it is more directly related to the applied brake torque.

Two metrics are computed for every combination of scenario and brake system: peak brake pressure and brake application time. The brake application time is defined as the time between the initialization of braking and when the brake peak is achieved. The peak brake pressure is the brake pressure recorded at the time when a brake peak is identified. The brake line pressure is computed by using the NADS brake model static curve that relates applied brake pedal to treadle pressure that activates the system. It was merely a static conversion to indicate pressure saturation, and the time to reach it. As for the remainder of the analysis in this paper, drivers' braking pauses were determined using brake pedal force, since any pause occurs before reaching saturation.

Peak Identification

The location of the peak is defined as the location of maximum pressure between the times in which the data first crosses the peak start threshold and when it crosses the peak end threshold. The definition of the initialization of braking is the first point in time after the beginning of the scenario when the applied brake force exceeds two pounds. The peak-start and peak-end thresholds are 95% and 90% of the maximum pressure recorded for the desired test, respectively. In the case that the same peak is reached at multiple points in time the point that occurs first is selected as the peak. [Figure 1](#) is a graphical example of the method of peak identification. It should also be noted that the simulated trailer was heavily loaded to reach about 80,000 lbs., and with a dry surface the ABS (Anti-Lock Brake System) did not activate for all runs.

Peak System Pressure Statistics

The mean and standard deviation of the peak system pressure were computed for each scenario and brake system in order to compare the data for all configurations. The resulting data is shown in [Table 4](#).

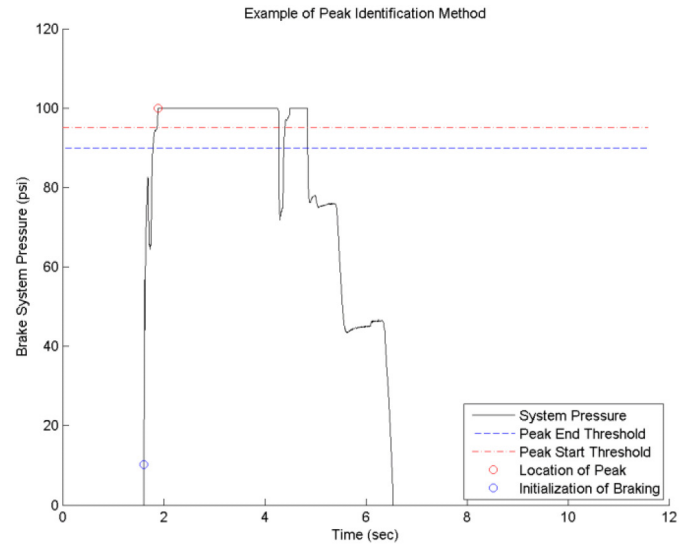


Figure 1. Example plot of method of peak identification.

The minimum mean for all datasets in [Table 4](#) is 96.1 psi which could indicate that in the majority of tests the driver achieved the brake system saturation pressure at some point during the scenario. To prove this, the data from each test was evaluated to determine if the driver had achieved brake pressure saturation. [Table 5](#) contains the results of this analysis.

Table 4. Mean and standard deviation of peak brake pressure for each combination of brake system and maneuver.

Peak Brake Pressure			
Scenario	Brake System	Mean (psi)	Standard Deviation (psi)
Left Incursion	S-Cam	97.4	9.9
	Enhanced S-Cam	96.6	14.0
	Disc	97.4	6.7
Right Incursion	S-Cam	98.1	9.8
	Enhanced S-Cam	99.7	1.5
	Disc	98.5	4.7
Stopping	S-Cam	99.4	3.0
	Enhanced S-Cam	98.1	9.2
	Disc	97.7	8.3
Stopped	S-Cam	99.5	2.7
	Enhanced S-Cam	97.8	11.3
	Disc	96.1	19.5

From [Table 5](#), the column showing the percentage of tests with saturation confirms that a majority of the drivers achieved the brake system saturation pressure. From this table, the minimum percentage is 82% and the overall average percentage for all scenarios is 92%. Based on these results, it is reasonable to conclude that a considerable majority of drivers apply sufficient brake force when confronted with a crash imminent situation.