VOLVO TRUCKS FIELD OPERATIONAL TEST: EVALUATION OF ADVANCED SAFETY SYSTEMS FOR HEAVY TRUCKS

Matthew J. Lehmer
U.S. Department of Transportation, NHTSA
Vincent Brown (Co-author)
Rob Carnell (Co-author)
Anne-Claire Christiaen (Co-author)
Nancy McMillan (Co-author)
John Orban (Co-author)
Greg Stark (Co-author)
Battelle
Robert Miller (Co-author)
URC Enterprises, Inc.
Nicholas A. Rini (Co-author)
Volvo Trucks North America
United States
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ABSTRACT

A field operational test (FOT) was recently completed to determine the potential safety benefits of advanced safety systems for heavy trucks. The safety systems in the FOT included a rear-end collision warning system (CWS), adaptive cruise control (ACC), and an electronically controlled brake system (ECBS), which included air disc brakes (ADB). These systems were developed to help reduce the frequency and severity of rear-end collisions, which accounted for 13% of all crashes involving heavy trucks in 2003.

The FOT was funded under the United States Department of Transportation (USDOT) Intelligent Vehicle Initiative (IVI) and was managed by the National Highway Traffic Safety Administration (NHTSA). The industry team that conducted the test was led by Volvo Trucks North America. Battelle performed an independent evaluation of the FOT.

This paper is a summary of the FOT and independent evaluation final reports, and includes the results of safety benefit and benefit-cost analyses based on data collected during the FOT. Driver acceptance, performance, durability, reliability, and maintenance costs of the safety technologies are also reviewed.

INTRODUCTION

This paper summarizes the results of an Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT), as well as an independent evaluation of the FOT, sponsored by the United States Department of Transportation (USDOT).

In September of 1999, the Federal Highway Administration (FHWA) initiated the FOT to determine the potential safety benefits of advanced safety systems on heavy trucks. The National Highway Traffic Safety Administration (NHTSA) managed the FOT, and it was conducted by an industry team led by Volvo Trucks North America, Inc. The team also comprised US Xpress Leasing, Inc., the fleet operator, Eaton VORAD, Eaton Bosch, and the Aberdeen Test Center, as described in [8] Volvo.

The safety systems in the FOT included a rear-end collision warning system (CWS), adaptive cruise control (ACC), and an electronically controlled brake system (ECBS), which included air disc brakes (ADB). These systems were developed to help reduce the frequency and severity of rear-end collisions. According to NHTSA General Estimates System (GES) 2003 data, rear-end collisions accounted for 13% of all crashes involving heavy trucks (including single-unit and combination trucks, GVWR over 10,000 lbs., striking another vehicle).

The objectives of the FOT were:

- Evaluate the performance of the safety systems as operated in a real-world environment
- Accelerate the deployment of the systems

- Help forge strategic partnerships in the transportation industry as a model for public-private cooperation for the development and deployment of advanced transportation safety technologies
- Assess the state-of-the-art in safety benefits analysis for vehicle-integrated advanced safety systems.

Beginning in January 2001, 100 new Volvo tractors were operated in normal revenue-generating service with US Xpress for 3 years throughout the contiguous United States. The trucks were organized into 3 fleets and equipped with the advanced safety systems as shown in Table 1 below.

Table 1.
3 Fleets, Number of Trucks, and Safety System(s) Installed

Fleet	No.	Safety System		
		CWS	ACC	ECBS/ADB
Baseline*	20			
Control	50	✓		
Test	50	✓	✓	✓

*Baseline vehicles were a 20-vehicle subset of the Control vehicles, operated for part of the FOT with the CWS display disconnected.

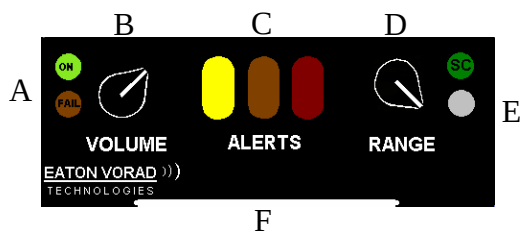
The USDOT contracted with Battelle to perform an independent evaluation of the FOT (see [1] Battelle). Specifically, the goals of the independent evaluation were:

- Estimate safety benefits
- Perform a benefit-cost analysis
- Assess driver acceptance of the new technology.

This paper is a summary of the FOT and independent evaluation final reports. It includes the results of safety benefit and benefit-cost analyses based on data collected from on-board vehicle data acquisition systems (DAS) during the FOT. Data collected from the DAS on each tractor were combined with historical crash data to perform the analyses. A known characteristic of the safety benefit calculation is that the statistical uncertainty of the estimated crash reduction rate varies as the conflict definition changes. For this reason, crash reduction calculations were performed at 3 different levels of conflict severity for 3 combinations of the safety systems. In addition, driver acceptance, performance, durability, reliability, and maintenance costs of the safety technologies are reviewed.

Description of the Technologies

Collision Warning System (CWS) – The commercially available Eaton VORAD® EVT 300 CWS was installed on all 100 of the FOT vehicles. The system transmits and receives radar signals using a forward-facing, front-end mounted radar antenna. The CPU uses the data from the antenna to determine the distance and relative speed between the host vehicle and objects in front. The system provides audible and visual alerts on the display unit (see Figure 1 below) to warn drivers of potentially dangerous situations when other vehicles are within predefined distances or closing times. This gives drivers more time to react and, hopefully, avoid a rear-end collision through avoidance maneuvers.



A: System operation indicators
B: Volume control knob & on/off switch
C: Visual alert indicators & speaker
D: Range setting knob
E: Light sensor
F: Driver ID card slot

Figure 1. Eaton VORAD® Display Unit.

Adaptive Cruise Control (ACC) – ACC utilizes conventional cruise control (CCC) and the CWS forward-facing radar in a combined function. With the system operational, no vehicle in the same lane as the host vehicle, and no target within range of the radar, the system operates like CCC by maintaining a speed set by the driver. If the radar detects a vehicle ahead of and in the same lane as the host vehicle, ACC will maintain a pre-set minimum following interval, expressed in seconds, between the lead vehicle and the host vehicle. The following interval is set using the range knob on the CWS driver display unit (see Figure 1 above). The system maintains the following interval by adjusting vehicle speed via the engine control module, thereby helping the driver avoid a situation that could lead to a collision.

The ACC system installed for this FOT was not capable of actively controlling the vehicle's brakes. ACC operation modes are illustrated in Figure 2 below.

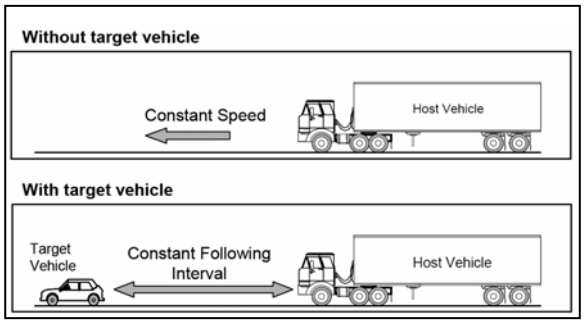


Figure 2. Operation Modes of ACC.

<u>Electronically Controlled Brake System (ECBS) with Air Disc Brakes (ADB)</u> – ECBS builds on existing antilock brake system (ABS) technology in that the air signal traditionally used by ABS to control the activation of the vehicle foundation brakes is replaced by an electronic signal. This reduces the time needed to activate the brakes, resulting in faster vehicle response time and, potentially, a shorter stopping distance. The brake torque generated at each wheel is still provided by air pressure delivered to the brake chamber, but the air pressure is applied and controlled electronically. To provide the brake control redundancy required by current Federal Motor Vehicle Safety Standards (FMVSS 121), ECBS is overlaid on a dual air-brake system, resulting in two pneumatic control circuits and one electronic control circuit (2P/1E). The ECBS used in this FOT was provided by Eaton Bosch.

During both normal and full-treadle emergency braking, ECBS can apply the brake at each wheel individually, providing:

- Improved dynamic brake force distribution, resulting in fewer ABS events and reduced pad wear
- Improved vehicle stability through wheel-by-wheel adjustment of braking in response to real-time conditions
- Improved combination vehicle brake balance and compatibility (if both the tractor and trailer are equipped).

ECBS also has self-diagnostic capabilities including lining wear and brake fade warnings.

The ECBS evaluated in the FOT included a new generation of ADB designed and provided by Volvo. In general, disc brakes are known to generate a linear, stable, and fade-resistant brake torque output. Volvo claims their latest design offers more braking capability, shorter stopping distances, and improved durability and reliability than previous designs. The ADB assembly used in the FOT is illustrated in Figure 3 below. Note that FOT vehicles not equipped with ECBS/ADB were equipped with drum brakes and standard ABS.

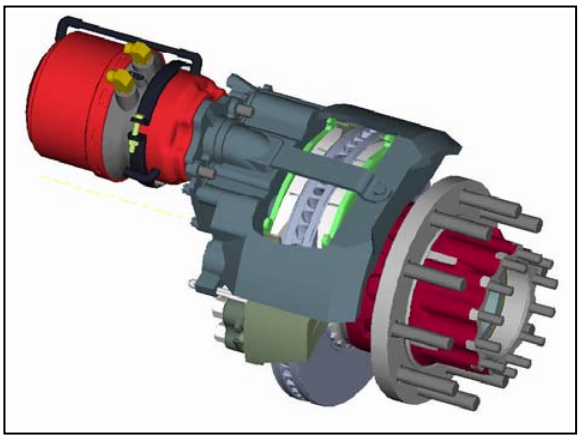


Figure 3. Air Disc Brake (ADB) and Hub Assembly.

On-Board Vehicle Data Collection

The basic locations of the advanced safety systems installed on the FOT vehicles are illustrated below in Figure 4.

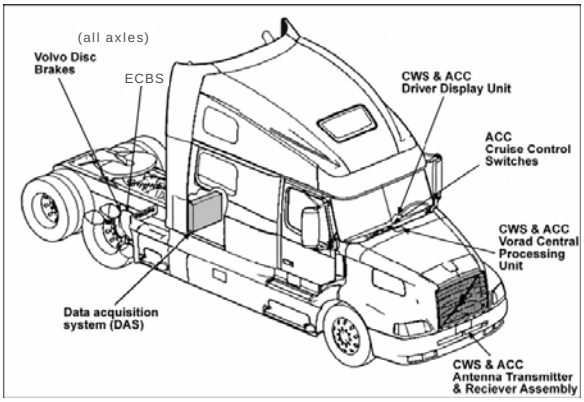


Figure 4. Installation Locations of Advanced Safety Systems and DAS.

Also shown is the location of the DAS, an on-board computer with data collection and communication capabilities. It was used to collect data from:

- J1939 and J1587 vehicle data buses
- VORAD CWS data bus
- Global Positioning System (GPS) sensor
- Steering wheel position sensor
- Biaxial accelerometer (in the DAS).

The data were stored on a solid-state flash memory card and could be transferred to a remote location wirelessly, or by removing the memory card. The

data collected were used as inputs to the safety benefits analysis, a summary of which follows.

SAFETY BENEFITS ANALYSIS

The safety benefits of the advanced safety systems were estimated using a statistical model that determined crash rates based on the frequency and severity of rear-end conflicts encountered during the FOT. The fundamental steps involved in this analysis are summarized below.

Data Reduction

Select Conflict Events – During the FOT, data were collected in 15-s time history files when specific trigger conditions were met, creating a triggered event. Conditions which triggered data collection are listed below. Trigger conditions are explained in detail in [8] Volvo.

- Longitudinal deceleration >0.25 g with brakes applied
- Lateral acceleration >0.20 g
- Kinematic motion event (an algorithm which considers lead- and following-vehicle velocity, acceleration, and relative distance)
- Time to collision <4 s
- Following interval <0.5 s
- ABS activation.

Not all triggered events represented a true conflict. These non-threatening events were identified and filtered out of the database. Non-threatening events were defined as those where:

- The lead vehicle was present for <1 s for a stopped lead vehicle, or <2 s for a moving lead vehicle
- The truck was in a curve (yaw rate >2 deg/s for 3 s) and the lead vehicle was stopped or on-coming
- The lead vehicle was in a different lane (lateral distance to target >2 ft)
- The lead vehicle crossed in front of the truck, e.g., at an intersection,
- The lead vehicle was so close to the truck that an unreasonable (>0.4 g) lateral acceleration would be required to avoid a crash
- There was no driver reaction to the event
- The lead vehicle was moving away from the following vehicle after the time of trigger.

Conflict Severity – A driving event recorded in the FOT data was considered a conflict if the event would require a "quick reaction" or "hard braking" maneuver by the driver of the following vehicle in order to avoid a collision with the lead vehicle. Most conservatively, a "quick reaction" was defined as a scenario in which the driver must brake within 1.5 s, and "hard braking" was defined as a scenario in which the driver must brake with a deceleration rate of at least 8 ft/s^2 (0.25 g) to avoid a rear-end crash. If these thresholds were exceeded the event was identified as a "conservative" conflict. If the event did not meet the most conservative threshold, it was discarded.

Three conflict threshold levels were defined in the analysis as indicated below in Table 2. Conflicts that satisfied the medium and aggressive thresholds were actually subsets of the conservative conflicts, since they also satisfied that threshold.

Table 2.
Rear-end Driving Conflict Thresholds

Threshold	Reaction Time (s)	Required Deceleration (ft/s^2)	Percent of Conflicts
Conservative	1.5	8	100%
Medium	1.0	10	24%
Aggressive	0.5	12	7%

In the analysis summarized here, the driving conflicts meeting the conservative threshold above were also required to meet a secondary criterion that they would have resulted in an actual collision if the driver had waited up to 15 s to react (See "Kinematic Analysis for Determining Lag Time" in [1] Battelle). If the driver had waited more than 15 s to react and a collision would not have occurred, the conflict was discarded. This secondary, more-restrictive requirement results in a comparison of more severe conflicts that are more likely influenced by the safety technologies, and therefore an improved safety benefits estimate.

Conflict Classification

After the data reduction steps were completed, the remaining valid conflicts were classified by conflict type. Table 3 below describes the 5 conflict types that are common among rear-end crashes recorded in GES.

Table 3.
Rear-End Conflict Types in GES

Conflict Type	Label	Description*
1	Overtaking Slower Vehicle	Truck is traveling at a constant speed, encounters a slower vehicle (at constant speed)
2	Overtaking While Slowing	Truck is decelerating, encounters another vehicle
3	Changing Lanes	Truck is changing lanes or merging, encounters a slower vehicle (at constant speed)
4	Stopped Lead Vehicle	Truck encounters a stopped vehicle in its lane
5	Slowing Lead Vehicle	Truck is traveling at a constant speed, encounters a decelerating vehicle

*GES does not differentiate between constant speed and acceleration.

These conflict types can also be defined by the kinematic conditions of the lead and following vehicles, as shown below in Table 4. Also shown is the corresponding relative frequency with which each conflict precedes a tractor-trailer rear-end crash recorded in GES, and the conflict percentage determined from analysis of the data collected in the FOT.

Table 4.
Relative Frequency of Conflict Types for Tractor-Trailer Combination Vehicles

Conflict Type	Kinematic Condition*		Relative Frequency	
	Lead Vehicle	Following Vehicle	GES	FOT
1	Constant	Constant	14%	34%
2	Constant/Decel.	Decelerating	4%	30%
3	Constant	Changed Lanes	2%	22%
4	Stopped	Constant/Decel.	40%	7%
5	Decelerating	Constant	26%	7%

*GES does not differentiate between constant speed and acceleration.

As is evident in Table 4, the relative frequencies of conflict types observed in the FOT are significantly different from the relative frequencies of conflicts preceding crashes reported in GES. One obvious reason for this difference is that, unlike the GES relative frequencies, the FOT conflict percentages are not conditional on a crash having occurred. It may be inherently easier to maneuver around a lead vehicle or object when involved in some conflict types, thereby avoiding a crash, and amounting to fewer recorded conflicts preceding crashes in GES.

These differences may also be due to variations in data processing and interpretation of the data. Conflicts defined from GES data are based on information in police reports of actual crashes, while the FOT classification is derived from kinematic criteria applied to time histories. There might also be variability in the definition of the pre-crash movements of the truck. For example, some individuals may define the event by the kinematics of the vehicles immediately before impact, while others define it by the kinematics just before evasive action was taken.

Further, it is possible that the filters used in the FOT data reduction process to remove non-threatening time histories from the pool of driving conflicts were too restrictive for some conflicts, causing valid events to be discarded. If the algorithms were biased towards a particular conflict type, intentionally or not, the recorded number of FOT conflicts could be significantly less.

Finally, it should be mentioned that the amount of FOT data collected for conflicts 4 and 5 was insufficient to complete a proper safety benefits analysis. Considering all of these differences, a decision was made to combine the 5 conflict types defined above into 3 categories as shown below in Table 5. The relative frequencies of the revised conflict categories observed in the FOT data better match the corresponding relative frequencies of conflicts preceding crashes reported in GES.

Table 5.
Re-classification of 5 Conflict Types into 3 Categories

Category	Conflict Type		Kinematic Condition of Following Vehicle	Relative Frequency	
	No.	Description		GES	FOT
1. Constant Speed: Overtaking at constant speed	1	Overtaking Slower Vehicle	Constant	40%	41%
	5	Slowing Lead Vehicle			
2. Slowing: Overtaking while slowing	2	Overtaking While Slowing	Decelerating	44%	37%
	4	Stopped Lead Vehicle			
3. Lane Change	3	Changing Lanes	Lane Change	2%	22%

Safety Benefits Equation

The number of rear-end crashes that occur each year defines the opportunities for crash reduction using any of the advanced safety systems in the FOT. The safety benefits equation (1) is used to calculate the estimated percentage of rear-end crashes that can be prevented by the safety systems. This equation was developed by NHTSA and FHWA, together with the Volpe National Transportation Systems Center (see [4][5][6] Najm and daSilva, [7] Najm). Further, application of (1) to FOT data was considered in [3] McMillan et al.

$$B = \underbrace{N_{wo} \cdot \sum_i P_{wo}(S_i \mid C)}_{\text{Number of relevant crashes (from GES)}} \cdot \underbrace{\left[1 - PR_i \cdot ER_i\right]}_{\text{Percent reduction in crashes for each conflict category}} \qquad (1).$$

where $$PR_i = \frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)} \qquad (2).$$

$$ER_i = \frac{P_w(S_i)}{P_{wo}(S_i)} \qquad (3).$$

For all equations, *wo* indicates a conflict or crash without safety systems installed, and *w* indicates a conflict or crash with safety systems installed. N_{wo} is the annual number of rear-end crashes in a particular fleet, without safety systems installed. S_i (i = 1,2,3) are the 3 rear-end driving conflicts categorized in Table 5. $P_{wo}(S_i \mid C)$ is the probability (without the safety systems installed) that driving conflict S_i precedes a rear-end crash. PR_i is the prevention ratio, and ER_i is the exposure ratio, for driving conflict S_i.

The prevention and exposure ratios are defined by (2) and (3), respectively. $P_w(C \mid S_i)$ is the probability (with safety systems installed) that a rear-end crash occurred, given that driving conflict S_i occurred. $P_{wo}(S_i)$ is the probability (without safety systems installed) that driving conflict S_i occurred.

The prevention ratio, PR, is a measure of the ability of an advanced safety system to prevent crashes after a particular driving conflict has occurred. PR <1 suggests the safety system helps the driver avoid crashes in that type of driving conflict. The exposure ratio, ER, compares the probabilities that a driver will encounter a particular driving conflict, with and without advanced safety systems. ER <1 suggests the safety system helps the driver avoid that type of driving conflict.

The safety benefits calculation is covered in detail in the FOT independent evaluation report ([1] Battelle). The results are presented in the next section.

Percent Reduction in Crashes

The prevention and exposure ratios were used to calculate the percent reduction in crashes (the term $1 - PR_i \cdot ER_i$ in the benefits equation) for each conflict category. The overall percent reduction in crashes was calculated as the weighted average of percent reduction in crashes for each category, using the relative frequency of occurrence of each conflict category in Table 5.

The percent reduction in crashes was calculated for the 3 combinations of safety systems across the 3 conflict threshold levels, as shown below in Table 6. The estimated percent reduction in crashes for each combination of safety systems was determined by comparing the estimated crash rates for drivers who used them with the corresponding rates for drivers who did not. The statistically significant result is shown in bold. A 28% reduction in rear-end crashes is associated with the deployment of the 3 systems bundled together; although the majority of this benefit (21%) appears to come from the effect of CWS.

Table 6.
Estimated Percent Reduction in Rear-End Crashes from Deployment of Advanced Safety Systems at 95% Confidence Interval (Mean ± Two Standard Errors)

Threshold	Selected Safety System(s)		
	CWS	ACC+ ECBS/ADB	CWS+ACC+ ECBS/ADB
Conservative	-1.9 ± 20.8%	9.4 ± 12.4%	7.2 ± 16.8%
Medium	20.7 ± 24.2%	12.0 ± 28.4%	**28.1 ± 21.0%**
Aggressive	25.3 ± 44.0%	9.8 ± 53.6%	29.9 ± 39.6%

These results are also illustrated graphically in Figure 5 below. Statistically significant data are hatched. Note the confidence bounds become narrower as the threshold becomes more conservative. This is because there are more driving conflicts which satisfy the conservative threshold than the medium or aggressive thresholds. This larger sample size leads to tighter confidence bounds in the safety benefits calculation.

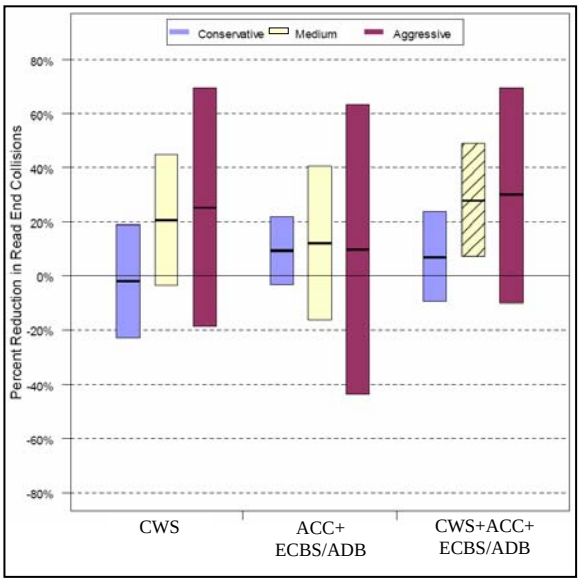


Figure 5. Estimated Percent Reduction in Rear-End Crashes from Deployment of Advanced Safety Systems at 95% Confidence Interval.

Application to Nationwide Fleet

The safety results observed in this FOT were used to estimate the benefits (reductions in crashes, injuries, and fatalities) that could be achieved if the safety systems were deployed on all 1.8 million Class-7 and Class-8 tractor-trailer vehicles nationwide. Data from the GES and the Fatality Analysis Reporting System (FARS) for the 5-year period from 1999 through 2003 were examined to determine the average annual number of trucks involved in rear-end crashes as well as the number of injuries and fatalities. Each year, the approximately 1.8 million tractor-trailer vehicles in the U.S. are involved in 23,000 rear-end crashes, resulting in:

- 12,000 associated injuries
- 304 fatalities.

Because the trucks involved in this FOT were also tractor-trailer vehicles, it is reasonable to project that, if the same safety systems (CWS + ACC + ECBS/ADB) were deployed in the 1.8-million-truck nationwide fleet, each year the technologies could prevent approximately:

- 6,500 rear-end crashes
- 3,400 injuries
- 122 fatalities.

Note that more fatalities are avoided than the 28.1% predicted in Table 6 due to the distribution of fatalities in GES among various conflict types.

Deployment of the CWS alone in the 1.8-million-truck fleet is projected to prevent:

- 4,700 rear-end crashes
- 2,500 injuries
- 96 fatalities.

BENEFIT-COST ANALYSIS

The Volvo IVI FOT independent evaluation team performed a benefit-cost analysis (BCA) to determine the net economic benefits of deploying the advanced safety systems. Following is a general, high-level analysis of all identifiable benefits and all costs at the societal level. The analysis is not targeted specifically to the motor carrier industry, truck manufacturers, or other private-sector entities. The specific hypothesis tested in the BCA is that the total cost to society of deploying and maintaining each of the safety systems is less than the combined value of all the benefits. If the hypothesis is true, the result would be a benefit-cost ratio (BCR)>1, and the deployment of the advanced safety systems would be considered economically justifiable.

Cost Assessment

Costs to deploy and maintain the advanced safety systems include one-time costs and recurring costs, as listed in Table 7 below.

Table 7.
Costs Related to Advanced Safety System Deployment

Cost	Measure
One-Time	Dollar value of capital equipment and software
	Dollar value of initial driver training
	Dollar value of start-up services, installation, consulting, administration, etc.
Recurring	Dollar value of annual operating and maintenance
	Dollar value of new/replacement driver training
	Dollar value of recurring replacement hardware

The quantitative cost information estimated to be incurred during real-world deployment and operation of the safety systems was obtained from the FOT partners and other industry sources. Specific cost information is not included in this paper, but can be found in [1] Battelle.

Cost Savings (Benefits) Assessment

The deployment of the advanced safety systems is expected to result in cost savings by avoiding

crashes. No other major cost savings to fleet operators or to society are anticipated. The benefits identified in the analysis are listed below in Table 8.

Table 8.
Cost Savings (Benefits) Related to Advanced Safety Systems Deployment

Benefit	Measure
Safety	Reduced numbers of crashes
	Crash severity
	- Change in severity
	- Effect on injury/fatality rates
	Dollar value of a crash
	Avoided fatalities, personal injury, property and infrastructure damage per crash
	Avoided costs of emergency services (police, fire, EMS) per crash
Mobility	Improved public mobility (reduced traffic delays/congestion from a crash)

It is possible that long-range savings may be realized through enhanced driver satisfaction (resulting in reduced rates of driver turnover and increased savings of funds normally devoted to recruitment, driver training, etc.), reduced insurance rates, and other benefits. These kinds of indirect savings, however, are difficult to quantify and document in an FOT and were not evaluated.

The numbers of crashes, injuries, and fatalities that could be prevented through the deployment of the advanced safety systems were estimated through statistical modeling and analysis based on national historical crash statistics, and also engineering data from the FOT. The costs associated with each crash, injury, and fatality were determined through industry literature reviews.

Two different safety system deployment options (CWS and CWS+ACC+ECBS/ADB) were modeled for all 1.8 million Class-7 and Class-8 tractor-trailer vehicles nationwide across the 3 different conflict severity thresholds (conservative, medium, and aggressive) for 2 different current cost assumptions (low and high), resulting in 12 total scenarios. Both low and high cost assumptions were made due to the wide range in current equipment and installation prices. As might be expected, industry research revealed that prices varied by supplier, manufacturer, amortization volume and timeframe, etc.

Additional scenarios were modeled with potential future reductions in capital and operating and maintenance costs (future low cost assumptions), resulting in 6 more scenarios, for a total of 18. The BCR was calculated for each in year 2005 dollars over a 20-year service window, and displayed graphically in Figure 6 below. As noted before, values of BCR>1 indicate an economic return on investment where deployment of the advanced safety systems could be justified.

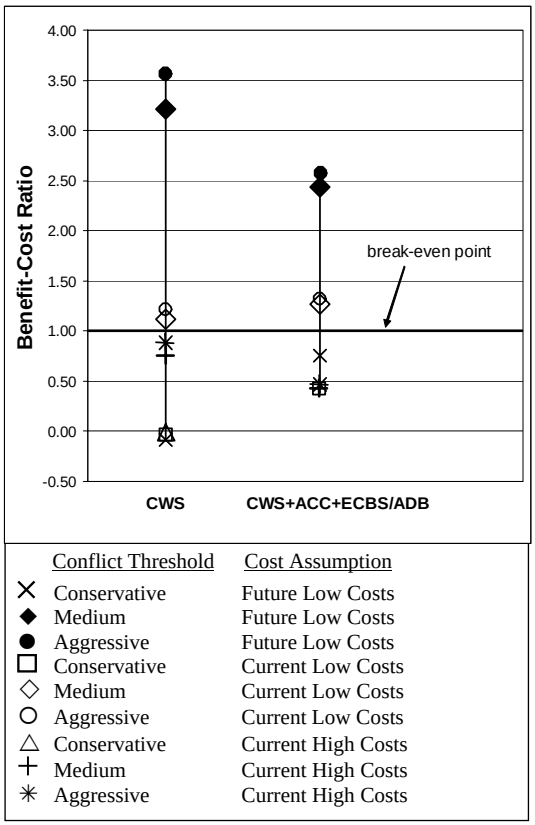


Figure 6. 20-Year Benefit-Cost Ratios Across Nationwide Fleet Using Multiple Cost Assumptions and Conflict Thresholds.

The following observations are worth noting:

- Little difference in BCR was observed between the medium and aggressive conflict thresholds.
- The only positive societal returns on investment occur if CWS or the bundled system is deployed on all tractor-trailers under the current or future low cost assumptions.

USER ACCEPTANCE

According to driver surveys, most drivers agreed that all 3 technologies helped them drive more safely and, as shown in Figure 7 below, most preferred to drive trucks equipped with these systems. Over 80% of drivers preferred trucks equipped with CWS. Many drivers reported that CWS made them more vigilant,

helped them maintain a safe following distance, and improved their reaction time and general awareness. Despite a relatively high rate of warnings from non-threatening objects, driver acceptance of CWS was high.

Over 90% of drivers preferred trucks equipped with ECBS/ADB. Drivers said they felt more secure when using the system because they did not have to apply as much pedal pressure to stop the truck. This is because ECBS controls braking using parameters monitoring vehicle deceleration. For a given brake pedal position, vehicles equipped with ECBS decelerate at a fixed rate, regardless of the load on the tractor and trailer. With a conventional braking system, however, the driver must apply more brake pressure to stop a heavier load than what is required for a lighter load. This feature of ECBS avoids the need for drivers to adjust their braking demand as a function of truck load and brake condition. The fade resistance of ADB also contributes to maintaining a constant deceleration rate.

The attitudes about ACC were mixed. About half of those interviewed said ACC helped them maintain safe following distances and improved reaction time. A few drivers reported that ACC made them more relaxed. However, some were uncomfortable with the system taking control away from the driver.

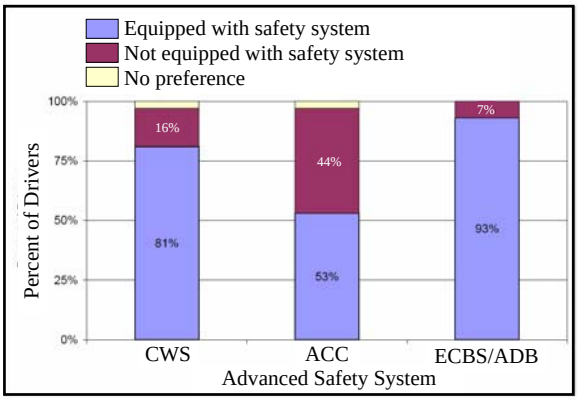


Figure 7. Drivers' Preference for Driving Trucks Equipped with Advanced Safety Systems.

Drivers were generally satisfied with the performance of all 3 systems. Most drivers did not have recommendations for improvements, but of those who did (38%), some wanted more detailed information on CWS indicators (e.g., distances associated with each warning indicator), volume controls for alerts, and better training.

PERFORMANCE SUMMARY

Analyses of the driving conditions under which these systems were used revealed that the systems were most effective at helping to avoid rear-end crashes when the truck was operating at highway speeds. It was found that drivers using CWS tended to maintain greater following distances than drivers without the system, and drivers without CWS warnings experienced more high-closing rate conflicts.

As shown in Figure 8 below, the average following distance for drivers using CWS was approximately 15 ft greater than for drivers without CWS. This finding was supported by the results of the driver interviews (discussed in detail in [2] Battelle.) Drivers using CWS along with ACC and ECBS/ADB had slightly shorter following distances than drivers with CWS alone. This may be due to increased confidence drivers had in their ability to stop with ECBS/ADB; however, there is no data to directly support this theory.

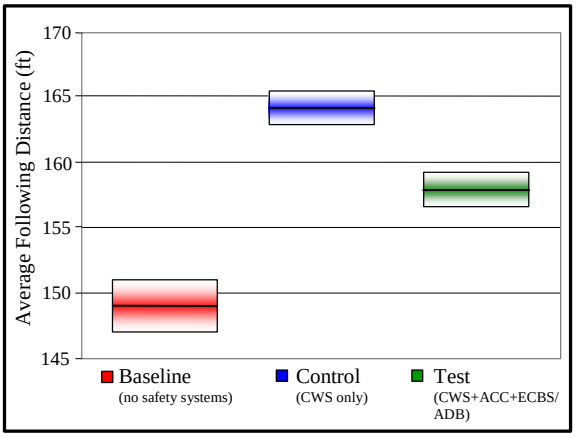


Figure 8. Average Following Distance for Each Fleet.

Baseline vehicles (no safety systems) exhibited an average of 11.9 ABS events per million miles with a time to collision less than 0.5 s. For Control vehicles (CWS only) and Test vehicles (CWS+ACC+ ECBS/ADB), the average number of ABS events was 7.9 and 2.1, respectively. Figure 9 below summarizes this data graphically. The relatively low number of ABS events for Test vehicles suggests that vehicles equipped with ECBS/ADB had a lower rate of ABS activation in hard braking events than vehicles with all-pneumatic systems; however, the effects from ECBS/ADB cannot be isolated from those of ACC in this FOT design.

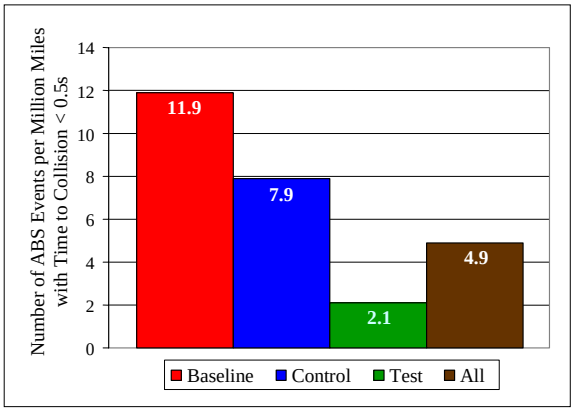


Figure 9. Number of ABS Events per Million Miles with Time to Collision < 0.5 s.

DURABILITY, RELIABILITY, AND MAINTENANCE COSTS

The average frequency of repair for CWS was 0.59 repairs per million miles of travel. Replacement parts for the radar antenna (mounted on the front bumper) accounted for most of the system repair costs, which were $475 on average per million miles of travel.

Brake system repair frequency varied by foundation brake type. The average drum brake repair frequency of 1.31 repairs per million miles was higher than the average disc brake repair frequency of 0.76 repairs per million miles. However, the average disc brake repair cost per million miles ($703) was higher than for drum brakes ($230). This was due to the relatively high cost of pre-production disc brake components and repair technician unfamiliarity with disc brake repair procedures.

The average frequency of repair per million miles was similar for ECBS (1.51) and ABS (1.31). However, the average repair cost per million miles for ECBS ($741) was higher than for ABS ($253) due to the relatively high cost of pre-production electronic control units. Replacement of the wheel speed sensor accounted for the majority of repairs for both systems.

CONCLUSION

During the 3 years of data collection in the FOT there were no major failures of the advanced safety systems. The durability, reliability, and performance of the advanced safety systems were as good as or better than comparable standard systems, demonstrating that they are ready for commercial deployment. The maintenance costs for the advanced safety systems were higher than for comparable standard systems; however, these costs are expected to decrease to a competitive level with higher production volumes.

Deployment of the advanced safety technologies is economically justifiable if CWS or the bundled system (CWS+ACC+ECBS/ADB) is deployed on the nationwide fleet of 1.8 million tractor-trailer vehicles under current or future low system cost assumptions.

A statistically significant, 28% reduction in rear-end crashes associated with the deployment of the 3 safety systems bundled together was found, although the majority of this benefit (21%) came from the effect of CWS.

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