Title

Leveraging Large-Truck Technology and Engineering to Realize Safety Gains:
Air Disc Brakes

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Foreword

The mission of the AAA Foundation for Traffic Safety is to save lives through research and education. One of major focus areas is understanding how emerging technologies can affect traffic safety. Whereas the majority of our research into emerging technologies focuses on technologies found in the cars and light trucks driven by the general public, the research described in this report examines the issue from a different perspective: What role can advanced safety technologies for large trucks play in reducing crashes, injuries, and deaths on our roads?

This is one of four reports describing the results of a comprehensive study of the benefits and costs of several advanced safety technologies for large trucks. The focus of this report is on air disc brakes. This report should be a useful reference for Federal transportation agencies, the trucking industry, and developers and suppliers of advanced safety technologies. Companion reports presenting related research on automatic emergency braking systems, lane departure warning systems, and video-based onboard safety monitoring systems for large trucks are also available.

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About the Sponsor

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Founded in 1947, the AAA Foundation for Traffic Safety is a not-for-profit, publicly supported charitable research and education organization dedicated to saving lives by preventing traffic crashes and reducing injuries when crashes occur. Funding for this report was provided by voluntary contributions from AAA/CAA and their affiliated motor clubs, individual members, AAA-affiliated insurance companies and other organizations or sources.

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List of Abbreviations and Acronyms

Acronym	Definition
AAAFTS	AAA Foundation for Traffic Safety
ADB	Air disc brakes
AIS	Abbreviated injury scale
AST	Advanced safety technology
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
CE	Cost-effectiveness
CEA	Cost-effectiveness analysis
CPI	Consumer price index
CUT	Combination unit truck
DOT	Department of Transportation
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GES	General Estimates System
GVWR	Gross vehicle weight rating
HOS	Hours-of-service
LTCCS	Large Truck Crash Causation Study
MAIS	Maximum abbreviated injury severity
MCMIS	Motor Carrier Management Information System
NHTSA	National Highway Traffic Safety Administration
NPV	Net present value
OEM	Original equipment manufacturer
OMB	Office of Management and Budget

PDO	Property damage only
PV	Present value
QALY	Quality adjusted life year
SUT	Single unit truck
VIUS	Vehicle inventory and use survey
VMT	Vehicle miles traveled
VSL	Value of statistical life

Executive Summary

In 2015, large trucks (trucks with a gross vehicle weight rating of more than 10,000 pounds) were involved in 414,958 crashes that resulted in 116,000 injuries and 4,067 fatalities (Federal Motor Carrier Safety Administration, 2016). The AAA Foundation for Traffic Safety identified the potential of several large-truck advanced safety technologies (ASTs) as promising countermeasures to reduce these crashes. Advanced safety technologies may use sensors or alerts to warn a driver of a possible collision, actively assume control of a vehicle in situations where a driver does not react to the threat of an imminent crash, or improve driver and fleet management (e.g., monitoring vehicle safety systems and drivers' hours-of-service status). Although some advanced safety technologies may be effective at preventing crashes, it is also important to know whether they are cost-effective, as this information may assist consumers in purchasing advanced safety technologies and/or government regulators in mandating their use.

The objective of this research was to provide scientifically-based estimates of the societal benefits and costs of advanced safety technologies in large trucks (i.e., the impacts an advanced safety technology may have across the entire society if implemented) in order to (1) allow the Department of Transportation to make informed decisions related to potential regulations on advanced safety technologies, and (2) promote the adoption of cost-effective advanced safety technologies to motor carriers. To accomplish this objective, an in-depth literature synthesis of 14 advanced safety technologies was completed, an expert advisory panel informed cost and benefit estimations for all advanced safety technologies (based on the literature review and their experience and knowledge), and benefit-cost analyses were performed on selected advanced safety technologies. The advisory panel recommended the following four technologies for benefit-cost analysis: air disc brakes, lane departure warning systems, automatic emergency braking systems, and video-based onboard safety monitoring systems. This report presents the results related to air disc brakes. See other AAA Foundation reports for analyses of automatic emergency braking systems, lane departure warning systems, and onboard safety monitoring systems.

Overview of Air Disc Brakes

Air disc brakes are a vehicle safety system that has garnered attention in the trucking industry and may show promise in reducing crashes and their associated injuries and fatalities. Air disc brakes have been widely adopted in Europe and are increasingly popular in the U.S. Air disc brakes are an alternative to the traditional drum brake. Although air disc brakes have been available for several decades, early adoption was slow due to the high price of early generation air disc brakes, incompatibility with drum brakes, and a number of design shortcomings (e.g., power screw with poor release, chrome-plated slide pins, brake pad attached to the brake caliper, single-piston design, and undersized brake rotors; Bendix, n.d.). Air disc brakes use air pressure on the brake chamber and an internal slack adjuster to move a power screw. This power screw applies pressure on the wheel's disc with the caliper. Air disc brakes offer reduced stopping distance, reduced maintenance, and reduced frequency of maintenance compared to traditional drum brakes.

Efficacy and Costs Associated with Air Disc Brakes

The literature review identified four studies that estimated the efficacy of large-truck air disc brakes in reducing crashes. These studies found air disc brakes may improve large-truck stopping distance by 30% and may reduce high-speed large-truck striking rear-end collisions by as much as 43.2%. It is important to note that these studies were performed before the National Highway Traffic Safety Administration's 2013 rule that mandated improved large-truck braking performance (Federal Motor Vehicle Safety Standards; Air Brake Systems, 2013). Thus, the efficacy of the current generation of air disc brakes is likely significantly lower compared to those found in the published literature (i.e., lower relative to current generation drum brakes that are also required to meet the 2013 braking performance rule). Additionally, one published report provided costs associated with air disc brakes. This report identified the costs of air disc brakes to range from $536 per vehicle (air disc brakes on only the steer axle) to $1,308 (air disc brakes on all axles).

Expert Advisory Panel

An Expert Advisory Panel convened May 17, 2016, at the AAA Foundation for Traffic Safety headquarters in Washington, D.C. This advisory panel consisted of six individuals representing various aspects of the industry, including representatives from a commercial motor vehicle carrier, a trucking insurance company, the Federal Motor Carrier Safety Administration, National Highway Traffic Safety Administration, and an air disc brakes original equipment manufacturer. The panel also included an industry safety consultant.

The purpose of this meeting was twofold: (1) to assist the research team in selecting technologies that require a benefit-cost analysis, and (2) to identify the appropriate efficacy rates and costs to be used in the benefit-cost analyses. Following this discussion, a benefit-cost analysis was recommended for air disc brakes, and upper- and lower-bound efficacy rates and costs were selected for air disc brakes.

Unlike the other advanced safety technologies, the literature review did not uncover any recent (i.e., conducted after the National Highway Traffic Safety Administration's 2013 rule) research for air disc brakes. However, the advisory panel recommended analyses for air disc brakes because effective braking is critical to preventing crashes, because the efficacy of many other advanced safety technologies relies on brakes that can minimize a large truck's stopping distance. The four studies investigating the efficacy of air disc brakes in preventing crashes were conducted prior to the improved stopping distance mandate (Federal Motor Vehicle Safety Standards; Air Brake Systems, 2013). This improvement in stopping distance for all brake systems significantly impacts the efficacy of air disc brakes when compared to other brake systems. With this in mind, the advisory panel recommended reduced efficacy rates (compared with those reported in previous research) of 10% and 15% reduction in rear-end crashes. Additionally, the advisory panel recommended a cost of $1,308 per truck (when air disc brakes are installed on all axles) based on vendor feedback and Garrott and Dunn (2007).

Benefit-Cost Analysis Methods

The benefit-cost analysis followed conventional methods used in similar studies (e.g., Hickman et al., 2013) to estimate the societal benefits and costs of implementing air disc brakes in the trucking industry. Societal benefits of air disc brakes associated with a reduction in crashes were compared to the costs of deploying air disc brakes across the entire U.S. fleet of large trucks. The benefit and cost factors considered in this study are discussed below.

Benefit Factors:
- Medical-related costs
- Emergency response service costs
- Property damage
- Lost productivity
- Monetized value of pain, and the suffering and quality-of-life decrements experienced by families in a death or injury

Cost Factors:
- Hardware purchase, installation, and financing costs
- Maintenance costs
- Replacement costs
- Costs associated with training for drivers and managers

To assess the impact air disc brakes could have on reducing crash rates (and the costs associated with the systems), national crash databases were used to identify air disc brakes' target population. These crash databases included the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES). The FARS database was used to determine the number of fatal crashes and their associated fatalities and injuries, and the GES database was used as an estimation for injury and property damage only crashes. The GES database also was used to estimate the number of injuries as a result of injury crashes. Queries were developed for crashes relevant to air disc brakes and information was extracted for different vehicle types for a period of six years (2010 to 2015).

When filtering the GES and FARS crashes, the research team carefully considered the scenarios where air disc brakes may have prevented the crash. Specifically, only large-truck rear-end crashes where the large truck struck another vehicle were selected. Additionally, the research team used the following GES/FARS variables to further limit crashes that may have been prevented by air disc brakes: pre-event movement, critical event, and first harmful event. Finally, all crashes that involved the use of alcohol or drugs by the large-truck driver were eliminated. The complete list of GES/FARS variables may be found in Appendix B.

The recommended efficacy rates were applied to 86.6% of crashes estimated to be preventable by air disc brakes, to account for vehicles with brakes that may be out of adjustment. This percentage was estimated based on the results of the Commercial Motor Vehicle Safety Alliance 2016 Operation Airbrake program inspections that found 12.4% of vehicles had brake violations (Transport Topics, 2016). The proportion of crashes potentially preventable by improved braking performance of air disc brakes was adjusted downward accordingly to account for the possibility that some proportion of trucks would have poorly maintained brakes, which would decrease the effectiveness of the air disc brakes.

Two sets of benefit-cost analyses were performed for air disc brakes. The first set of analyses included retrofitting the entire U.S. fleet of large trucks. This approach assumed all new vehicles added to the fleet would be equipped with air disc brakes and old vehicles would be retrofitted. This analysis approach represented the scenario with the most benefits but also the highest costs. The second set of analyses used an annual incremental costs analysis approach. This approach assumed all new vehicles would be equipped with air disc brakes (starting in 2018) and did not include retrofitting existing vehicles. Societal benefits were assessed over the life of the vehicle. Analyses included only class 7 and 8 (gross vehicle weight rating greater than 26,000 pounds) combination unit trucks (CUTs).

Additionally, separate analyses were performed to account for the rate of monetary discount, in the present value, of the cost and benefits in any future year. Following guidance from the Office of Management and Budget (OMB, 2003) analyses were performed using a 0%, 3%, and 7% discount rate.

Benefit-Cost Analysis Results: All Vehicles (New and Old) Equipped with Air Disc Brakes

Air disc brakes were evaluated using a low and high efficacy rate (10% and 15%, respectively) and a low, average, and high cost ($700, $1,300, and $2,020, respectively). Unlike the other advanced safety technologies, benefit-cost analyses were performed only for combination-unit trucks at the recommendation of the advisory panel. Table 1 shows the benefit-cost ratios for air disc brakes when equipping all combination unit trucks (new and existing). The analyses with benefit-cost ratios greater than 1.00, which indicate that the benefits outweigh the costs, are highlighted. For example, the first row of results in Table 1 shows the results for all large trucks using a high efficacy rate (15%) for air disc brakes. When the costs of air disc brakes are average and the discount rate is 0%, the estimated benefits of ADB are 1.39 times the estimated costs. However, when the costs of air disc brakes are high and the discount rate is 7%, the estimated benefits are 15% less than the estimated costs.

Table 1. Benefit-Cost Ratios for Air Disc Brakes Installed on Combination Unit Trucks by Efficacy Rate, Cost, and Discount Rate

	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs – High Efficacy	2.92	2.80	2.64	1.39	1.34	1.27	0.93	0.90	0.85
Only CUTs – Low Efficacy	1.67	1.60	1.51	0.79	0.76	0.72	0.53	0.51	0.49

Sensitivity analyses were performed with a higher value of a statistical life ($13,260,000) as well as a lower value ($5,304,000). Since many of the analyses indicated that air disc brakes would not be cost-effective, lowering the value of a statistical life would only make these systems less cost-effective. Thus, only the results with the higher value of a statistical life are shown below. The results with the lower value are shown in Appendix C. Table 2 shows the sensitivity analyses for retrofitting the entire U.S. fleet of combination unit trucks with air disc brakes, using the higher value of a statistical life. Using the low efficacy rate with a $13,260,000 value resulted in a benefit-cost ratio greater than 1.00 for the low- and average- cost estimates (except for an average-cost and a 7% discount rate). The high efficacy rate with a $13,260,000 value of a statistical life resulted in a benefit-cost ratio greater than 1.00 for all the cost estimates.

Table 2. Sensitivity Analyses for Retrofitting the Entire U.S. Fleet of Combination Unit Trucks with Air Disc Brakes and Using a $13,260,000 Value of a Statistical Life

	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs – High Efficacy	4.00	3.84	3.63	1.91	1.83	1.74	1.28	1.23	1.91
Only CUTs – Low Efficacy	2.29	2.19	2.07	1.09	1.05	0.99	0.73	0.70	1.09

Benefit-Cost Analysis Results: Only New Vehicles Equipped with Air Disc Brakes

Table 3 shows the benefit-cost ratios for air disc brakes when only equipping new combination unit trucks. As shown in Table 3, low-, average-, and high-cost air disc brakes were cost-effective with the high efficacy rate. However, only the low- and average-cost air disc brakes were found to be cost-effective with the lower efficacy rate.

Table 3. Benefit-Cost Ratios for Air Disc Brakes Installed on New Combination Unit Trucks by Efficacy Rate, Cost, and Discount Rate

	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs – High Efficacy	4.59	4.27	3.96	2.33	2.15	1.97	1.60	1.47	1.34
Only CUTs – Low Efficacy	2.62	2.44	2.26	1.33	1.23	1.13	0.91	0.84	0.77

Table 4 shows the sensitivity analyses for only equipping new combination unit trucks with air disc brakes using the higher value of a statistical life. The results with the lower value of a statistical life are shown in Appendix C. As shown in Table 4, only equipping new combination unit trucks with air disc brakes was cost-effective regardless of cost or efficacy rate when using the higher value of a statistical life.

Table 4. Sensitivity Analyses for Equipping All New Combination Unit Trucks with Air Disc Brakes and Using a $13,260,000 Value of a Statistical Life

	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs – High Efficacy	6.30	5.86	5.44	3.20	2.95	2.71	2.19	2.02	1.85
Only CUTs – Low Efficacy	3.60	3.35	3.11	1.83	1.69	1.55	1.25	1.15	1.05

Discussion

This report presents the scientific-based estimates of the societal benefits and costs of air disc brakes installed on combination unit trucks. Although the literature review identified efficacy rates for air disc brakes, these estimates were before the National Highway Traffic Safety Administration's 2013 mandate for improved braking performance of large trucks (Federal Motor Vehicle Safety Standards; Air Brake Systems, 2013). Thus, the advisory panel recommended using lower efficacy rates in the benefit-cost ratios to better reflect the efficacy of current ADB systems relative to other modern braking systems that also meet the new standard. Crashes were identified using 2010 to 2015 GES and FARS data sets. Additionally, estimates of the number of crashes that could potentially be prevented by air disc brakes were adjusted downward by 12.4% to account for the estimated prevalence of trucks whose brakes are out of adjustment. Benefit-cost analyses were performed using varying efficacy rates, brake costs, and discount rates.

The results showed that air disc brakes were cost-effective given a low cost of $700 and either a 10% or 15% efficacy rate. They were also found to be cost effective at an average cost of $1,300 given a 15% efficacy rate. Even at a high cost of over $2,000 air disc brakes were shown to be cost-effective with a 15% efficacy rate when only new CUTs were to be equipped with ADB. Thus, these results provide some guidance regarding the potential for installing air disc brakes on combination unit trucks. These results showed that retrofitting old vehicles would not be cost-effective unless air disc brakes can achieve a 15% efficacy rate (with a low or average cost) or the costs can be reduced from $1,300. However, these analyses do suggest that installing air disc brakes on all new combination unit trucks would likely be cost-effective if it could be accomplished at or lower than the average cost used in the analyses reported here.

Limitations

Although the analyses used to assess the benefits and costs associated with air disc brakes were comprehensive, there were several limitations, including the following:

- It is possible the efficacy rates used in this study may not represent the current functionality/effectiveness of the current generation of air disc brakes, specifically, relative to current generation drum brakes that meet the National Highway Traffic Safety Administration's 2013 brake performance rule. The research team did not find any research regarding the efficacy of air disc brakes conducted after 2013 rule. However, the advisory panel consisted of experts with knowledge of current technology performance; thus, the efficacy rates recommended by the advisory panel should represent reasonable estimates of air disc brake efficacy.
- The technology costs used in this study may differ from current costs (with costs typically decreasing over time).
- It is possible maintenance cost savings associated with air disc brakes were not adequately captured in these benefit-cost analyses; thus, the cost-effectiveness of air disc brakes may be higher or lower.
- This study used estimated crash, technology, and labor costs. It is possible that actual costs may differ, and thus impact the cost-effectiveness of air disc brakes.
- The GES only included crashes that required a police accident report. However, air disc brakes may also prevent less severe crashes. Thus, these additional benefits are not accounted for in the benefit-cost analyses.

- The real-world effectiveness against different severity crashes may differ significantly. However, data limitations excluded the use of separate efficacy estimates for this study.
- These analyses did not account for reduced litigation costs associated with reduced crashes. These may be significant cost savings that were not integrated into the analyses.
- This study assumed all vehicle systems were functioning as intended. However, this is unlikely to be seen in the real world. Specifically, anti-lock brakes and foundation brakes have a direct impact on a vehicle's ability to avoid a crash. If they are poorly maintained, the efficacy rates used in this study will be reduced.

Introduction

In 2015, large trucks (trucks with a gross vehicle weight rating [GVWR] of more than 10,000 pounds) were involved in 414,958 crashes that resulted in 116,000 injuries and 4,067 fatalities (Federal Motor Carrier Safety Administration [FMCSA], 2016). Decades of research have shown that, historically, between 87% and 92% of all U.S. crashes have resulted from driver errors or risky behaviors. For example, the Large Truck Crash Causation Study (FMCSA, 2006) found that approximately 87% of all large-truck crashes were the result of risky driving behaviors or errors. Similarly, Treat et al. (1979) found that human factors (i.e., recognition errors, decision errors, performance errors, and critical non-performances) were determined to be the probable cause in 92.6% of all crashes, and Hendricks et al. (2001) found that driver behavioral errors contributed to or caused 717 out of the 723 crashes examined in their research. Risky driving behaviors and errors include excessive speed, violations of speed limits, excessive lateral acceleration on curves, unplanned lane departures, frequent hard braking, close following distances, lateral encroachment, failure to yield at intersections, distracted driving, and general disobedience of the rules of the road, among others.

The AAA Foundation for Traffic Safety (AAAFTS), which is recognized as an industry leader in traffic safety research, identified the potential of advanced safety technologies (ASTs) to mitigate risky driving behaviors or errors, which in turn may help prevent large-truck crashes. ASTs may use sensors or alerts to warn a driver of a possible collision. ASTs may also actively assume control of a vehicle in situations where a driver does not react to the threat of an imminent crash. In addition, ASTs include devices that improve driver and fleet management by, for example, monitoring vehicle safety systems and drivers' hours-of-service (HOS) status. There are a wide variety of ASTs available for large trucks, including the following:

- Forward collision warning
- Adaptive cruise control
- Automatic emergency braking systems
- Lane departure warning systems
- Blind spot warning
- Electronic stability control
- Roll stability control
- Speed limiters
- Video-based onboard safety monitoring systems
- Kinematic-based onboard safety monitoring systems
- Vehicle-to-vehicle communication and large truck platooning systems
- Electronic logging devices
- Air disc brakes (ADB)
- Brake stroke monitoring systems

Project Objective

The objective of this research was to provide scientifically-based estimates of the societal benefits and costs of ASTs in large trucks. To accomplish this objective, an in-depth literature synthesis of 14 ASTs was completed, an expert advisory panel informed cost and benefit estimations for all ASTs, and a benefit-cost analysis (BCA) was performed on selected ASTs. The results of this study may be used by motor carriers and the Department of Transportation (DOT) to inform decisions related to the potential regulation and implementation of ASTs. These results may also be used to promote the adoption of cost-effective ASTs. Although the advisory panel recommended BCAs for four ASTs, this report only presents the information pertaining to ADB. Information about other ASTs are provided in separate AAAFTS reports.

Literature Review

The general approach taken for the literature synthesis was to identify relevant documents from the broader research literature and summarize the key information regarding the costs and benefits using a structured review format.

The major information sources for the literature review were (i) Transportation Research Information Services; (ii) U.S. government departments, such as the DOT; (iii) industry groups, such as the American Transportation Research Institute and the Owner-Operator Independent Drivers' Association; and (iv) academic journals (e.g., *Accident Analysis and Prevention* and the *Journal of Safety Research*).

All research obtained in the literature review was assessed to determine whether it contained the following detailed information: (i) a description of the ADB features, (ii) a description of the vehicles examined, (iii) the estimated benefits of ADB (e.g., reduction in crashes or costs), and (iv) the estimated costs associated with ADB (e.g., purchase, installation, and/or maintenance). Literature that did not contain information about any of these fields was eliminated from further review. Additionally, only research pertaining to large trucks was considered. Literature that only discussed the costs and benefits of ADB on light vehicles was also eliminated from further review. Each relevant document was reviewed to identify the specific ADB, vehicle type, study methodology, results related to benefits and costs, and study quality.

Some of the studies produced multiple reports, journal articles, and conference presentations (i.e., the same study was published in different journals, conference proceedings, etc.). Where possible, priority was given to a final report over journal articles and conference proceedings (which tend to provide less information). Typically, these secondary documents were removed from consideration or noted as duplicate works. In addition, the capabilities of the current generation of ADB may vary greatly compared to prior generations. Studies conducted after the year 2000 were given priority over research published prior to the year 2000.

Air Disc Brakes

Air disc brakes are a vehicle safety system that has garnered attention in the trucking industry and may show promise in reducing crashes and their associated injuries and fatalities. Effective braking is fundamental to the safety of large trucks, and ADB may improve large truck braking performance due to ease of maintenance and improved stopping distances. Air disc brakes have been widely adopted in Europe and are increasingly popular in the U.S. Air disc brakes are an alternative to the traditional drum brake. Although air disc brakes have been available for several decades, early adoption was slow due to the high price of early generation ADB, incompatibility with drum brakes, and a number of design shortcomings (e.g., power screw with poor release, chrome-plated slide pins, brake pad attached to the brake caliper, single-piston design, and undersized brake rotors; Bendix, n.d.). Air disc brakes use air pressure on the brake chamber and an internal slack adjuster to move a power screw. This power screw applies pressure on the wheel's disc with the caliper. Air disc brakes offer reduced stopping distance, reduced maintenance, and reduced frequency of maintenance.

Crash Reductions Associated with Air Disc Brakes

The literature review identified four studies that included ADB in the evaluation of crash reductions. These studies are summarized below.

Garrott and Dunn (2007) simulated the stopping distances of ADB to model their potential safety benefits using FARS data from 2000 to 2002. The authors determined the 2007 generation of air disc brakes were capable of 30% reductions in large-truck stopping distance. Garrott and Dunn (2007) concluded a 30% reduction in stopping distance could prevent 257 fatalities and 284 serious injuries (abbreviated injury scale categories 3–5). These results helped inform NHTSA's decision to require all large-truck brakes to achieve this reduction (including both drum brakes and disc brakes; Federal Motor Vehicle Safety Standards; Air Brake Systems, 2013)

Salaani, Heydinger, Grygier, and Schwarz (2010) used the National Advanced Driving Simulator to estimate the differences between S-cam drum brakes, enhanced S-cam drum brakes, and ADB. The authors collected simulator data from 108 commercial drivers to see if reduced stopping distances resulted in fewer crashes and/or lower crash severity. Four emergency scenarios were developed to simulate real-world safety-related scenarios. These scenarios included the following:

1. another vehicle suddenly entered the roadway from a hidden driveway on the right side of the road (right incursion; speed limit of 55 mph),
2. oncoming traffic performed an evasive maneuver and entered the truck's lane (left incursion; speed limit 55 mph),
3. the lead vehicle made an abrupt stop (stopping vehicle; speed limit 55 mph), and
4. a stopped vehicle in the middle of an interstate (stopped vehicle; speed limit 70 mph).

The results showed that ADB performed slightly better on right incursions, and had significantly fewer left incursions, and fewer stopping- and stopped-vehicle crashes compared to S-cam drum brakes. Furthermore, air disc brakes were the only braking system that proved effective in the stopped vehicle scenario on a highway with traffic traveling at 70 mph. Overall, ADB reduced collisions by 43.2% (51 collisions for S-cam compared with 29 collisions with ADB).

Battelle (2007) performed an independent evaluation of the Volvo Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT; Volvo Trucks North America, Inc., 2005) that included 150 large trucks. One hundred trucks were equipped with forward collision warning, adaptive cruise control, and an advanced braking system (ADB with an electronically controlled braking system), and 50 trucks served as a control group. Battelle (2007) modeled the potential safety benefits of the ASTs using the frequency of safety-critical events (SCEs) that occurred during the Volvo FOT and data from GES and FARS. Unfortunately, the authors did not provide a specific crash reduction associated with ADB, only ADB coupled with adaptive cruise control.

Similarly, Silvani, Skorupski, Stinebiser, Nicosia, and Van Order (2009) performed an independent evaluation of an FOT that tested an electronically controlled braking system and the technologies enabled by it (i.e., electronic stability control and adaptive cruise control). The FOT equipped 48 tractors and 100 trailers with ASTs for 12 months. The electronic stability control and adaptive cruise control systems were turned off for the first six months of the FOT and were turned on for the final six months. Using the data from the FOT, Silvani et al. (2009) estimated the potential safety benefits of the ASTs using GES. However, the authors did not provide specific estimates for ADB, only the reductions associated with a combined advanced braking system (including electronic stability control and adaptive cruise control).

Air Disc Brakes Costs

The literature review found one published report on the costs associated with ADB. Garrott and Dunn (2007) reported that ADB on all axles cost $1,308, and cost $536 on just the steer axle.

Literature Review Conclusions

The published literature was reviewed to identify the costs and benefits associated with large truck ADB. Appendix A provides a summary of citations for ADB. The literature review identified four studies that estimated the efficacy of large-truck ADB in reducing crashes. These studies found ADB may improve large-truck stopping distance by 30% and may reduce high speed large-truck striking rear-end collisions by 43.2%. It is important to note that these studies were performed before the National Highway Traffic Safety Administration's (NHTSA) 2013 rule that mandated improved large-truck braking performance (Federal Motor Vehicle Safety Standards; Air Brake Systems, 2013). Thus, the efficacy of the current generation of ADB is likely significantly lower compared to those found in the published literature. Additionally, one published report provided costs associated with ADB. This report identified the costs of ADB to range from $536 (ADB on just the steer axle) to $1,308 (ADB on all axles) per vehicle.

Methods

This section of the report provides an overview of the design and methods used to perform the BCAs.

Expert Advisory Panel

An Expert Advisory Panel convened May 17, 2016, at AAAFTS headquarters in Washington, D.C. The advisory panel consisted of six individuals representing various aspects of the industry, including representatives from a commercial motor vehicle carrier, trucking insurance company, FMCSA, NHTSA, and an ADB original equipment manufacturer (OEM), as well as an industry safety consultant.

The purpose of this meeting was twofold: (1) to assist the research team in selecting technologies that require a BCA, and (2) to identify the appropriate efficacy rates and costs to be used in the BCAs. Following this discussion, upper- and lower- bound efficacy rates and costs were selected for each of the four ASTs.

When determining the recommended efficacy rates and cost associated with ADB, the advisory panel prioritized recent research, real-world studies, generation of the technology, federal regulations, efficacy/cost estimates from the U.S. (due to differences in roadway infrastructure, safety culture, and crash rates), and crash reductions for specific crash types (compared with crash reductions for all large truck-crashes). Additionally, the Advisory Panel sought to be conservative in its efficacy estimates to avoid overestimating the potential benefits and cost-effectiveness of systems.

Unlike the other ASTs, the literature review did not uncover any recent (conducted after NHTSA's mandate in 2013) research for ADB. However, the advisory panel recommended analyses for ADB because effective braking is critical to preventing crashes. Thus, the effectiveness of many ASTs rely on brakes that can minimize a large truck's stopping distance, regardless of vehicle speed. The four studies investigating the efficacy of ADB in preventing crashes occurred prior to NHTSA's improved stopping distance mandate (Federal Motor Vehicle Safety Standards; Air Brake Systems, 2013). This improvement in stopping distance for all brake systems significantly impacts the efficacy of ADB when compared with other brake systems. With this in mind, the advisory panel recommended reduced efficacy rates (compared with what the previous research found) of 10% and 15% reduction in rear-end crashes. Additionally, the advisory panel recommended a cost of $1,308 when air disc brakes are installed on all axles.

Benefit-Cost Analysis Approach

The objective of deploying an AST is to reduce crashes and their associated fatalities and injuries. However, when faced with limited resources, industry stakeholders need to understand the positive and negative impacts associated with the deployment of each AST to make an informed decision. One tool often used to assist in the decision-making process is an economic analysis. An economic analysis is defined as "a systematic approach in determining the optimum use of scarce resources, involving comparison of two or more alternatives in achieving a specific objective under the given assumptions and constraints" (Business Dictionary, 2016). A BCA (a form of economic analysis) is the systematic process of calculating and comparing monetary benefits and costs for two purposes: (i) to determine if it is a sound investment (justification/feasibility), and (ii) to see how it compares with alternate projects (i.e., ranking/priority assignment; Transportation Economies Committee of the Transportation Research Board, n.d.). A cost-effectiveness analysis (CEA) is also a form of economic analysis where the benefits are not expressed in monetary gains, but in outcomes.

The process of an economic analysis involves relatively straightforward steps, as shown in Figure 1.

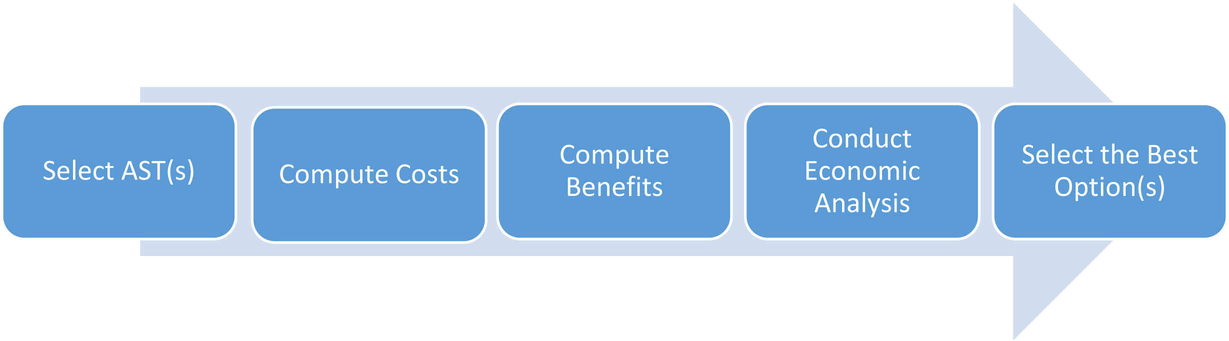

Figure 1. Economic analysis steps.

The associated AST deployment costs, benefits, and assumptions for each of the steps mentioned above are specific to the particular stakeholder group affected by the decision (i.e., carriers or society as a whole). Federal regulations require a societal BCA of an AST before any final decision is made (i.e., the impact of an AST-related regulation on all large trucks for which the regulation is being considered).

Societal benefits and costs are likely to differ from the benefits and costs for private carriers measured in the marketplace due to imperfections in analyses arising from: (i) external economies or diseconomies where actions by one party impose benefits or costs on other groups that are not compensated for in the marketplace, (ii) a monopoly power that distorts the relationship between marginal costs and market prices, and (iii) specific taxes or subsidies.

The present study focused on the evaluation of the expected societal costs and benefits originated by the deployment of ADB. This type of analysis is needed to evaluate the impact of new regulations through a regulatory analysis process (e.g., such as mandating a specific AST—in this case ADB—on trucks). Regulatory analysis requirements for the rulemaking process vary in terms of the regulating agency, rules the agency covers, and the "significant impact" of a proposed regulation. Currently, the most applied set of requirements includes those provided in Executive Order 12866 (1993), Executive Order 13563 (2011), and Office of Management and Budget (OMB) Circular A-4 (2003).

Executive Order 12866 (1993), *Regulatory Planning and Review*, requires "covered agencies" to conduct a regulatory analysis for "economically significant regulatory actions." Section 1 states,

> "In deciding whether and how to regulate, agencies should assess all costs and benefits of available regulatory alternatives, including the alternative of not regulating. Costs and benefits shall be understood to include both quantifiable measures (to the fullest extent that these can be usefully estimated) and qualitative measures of costs and benefits that are difficult to quantify, but nevertheless essential to consider. Further, in choosing among alternative regulatory approaches, agencies should select those approaches that maximize net benefit." (Executive Order 12866, 1993) Section 1 (b) states that some costs and benefits are difficult to quantify, and agencies "should propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its cost." (Executive Order 12866, 1993)

A regulatory action is classified as significant if any of four parameters are met. In most cases, the trigger criterion is when an action will have an annual effect of $100 million on the economy or adversely affect the economy as a whole or certain sectors. For the present study, the research team conducted an economic analysis for ADB, which would independently affect the economy by $100 million.

Executive Order 13563 (2011) is supplemental and reaffirms the principles of Executive Order 12866 (1993). This directs agencies to propose or adopt regulations after conducting an analysis that shows the benefits justified the costs.

Circular A-4 (OMB, 2003) was designed "to assist analysts in the regulatory agencies by defining good regulatory analysis, called either 'regulatory analysis' or 'analysis' for brevity, and standardizing the way benefits and costs of Federal regulatory actions are measured and reported" (OMB, 2003). The circular specifies that "a good regulatory analysis should include the following three basic elements: (i) a statement of the need for the proposed action, (ii) an examination of alternative approaches, and (iii) an evaluation of the benefits and costs— quantitative and qualitative—of the proposed action and the main alternatives identified by the analysis" (OMB, 2003). With regard to analytical approaches, the circular states that BCAs provide a systematic framework for identifying and evaluating the likely outcomes of alternative regulatory choices and, when possible, a major rulemaking should be supported by both types of analysis.

To comply with Circular A-4 (2003) and Executive Orders 12866 (1993) and 13563 (2011), the OMB (2003) provides guidance on the steps that need to be completed, which include the following: (i) describe the need for the regulatory action, (ii) define the baseline alternative, (iii) select the analysis period, (iv) identify alternatives, (v) identify the consequences of regulatory alternatives, (vi) quantify and monetize costs and benefits, (vii) discount future benefits and costs, (ix) evaluate non-quantified and non-monetized benefits and costs, and (x) characterize uncertainty in benefits, costs, and net benefits.

NHTSA, the federal agency that governs new vehicle standards and also has the legal authority to mandate retrofitting of trucks, is in charge of completing the steps of the regulatory analysis process for the mandatory deployment of any AST. The present study completed the same steps described in Circular A-4 by using a formal economic analysis approach (OMB, 1992; 2003).

Conceptually, two options were formulated for the deployment of ADB. The first option assumed that the agency did not issue any new rules regarding the adoption of ADB. These are the baselines against which costs and benefits were computed. The second option for ADB assumed rules were issued mandating the deployment of ADB. In addition, two sets of BCAs were performed for ADB. The first set of analyses assumed all large trucks would be equipped with ADB. In other words, these analyses assumed all new trucks would be equipped with ADB, and all old trucks would be retrofitted with ADB. The second set of analyses only assumed new trucks would be equipped with ADB. The following sections provide a brief description of the analysis period, technology and deployment costs, estimation of the target crash/injury base population, crash costs, identification of benefits as a reduction in crashes/injuries, discount rate, and expected economic indicators.

Analysis Period

According to the OMB (2003), the analysis period "should cover a period long enough to encompass all the important benefits and costs" (page 15). The time period should be long enough to consider the costs and most of the benefits in the project. Predicting the effect of state of the art of ADB is a difficult task, especially taking into account the advancements made in the fields of connected and autonomous vehicles. There was consensus among the Advisory Panel that 20 years, with a 2018 base year, would be a reasonable analysis period. Selecting 2018 as the base year allowed for a lead implementation period of two years.

Technology and Deployment Costs

The costs associated with implementing ADB include all nonrecurring costs, such as the initial cost of the equipment and initial training, along with all recurring and operational costs, such as maintenance and additional training. These costs include everything that is needed to maintain the ADB at operational levels. The cost of the installation and deployment of each ADB per truck/driver per year is computed as:

$$CADB_y = ADB_y + I_y + T_y + M_y$$

where $CADB_y$ is the total cost of installation and deployment of ADB per truck for year y; y is the year of the analysis period (0, 1, 2…n); ADB_y is the cost of the ADB for year y; I_y is the initial installation cost of the ADB for year y; T_y is the training cost for year y; and M_y is the maintenance cost for year y. It is important to note that some costs of the ADB hardware are directly related to the number of trucks where the technology will be implemented, whereas other costs (e.g., training) are related to the number of drivers.

Technology Costs

The cost of the technology is usually the most significant cost in AST implementation. This holds true for ADB.

Different costs can be included in the computation of the technology costs: research and development, manufacturing setup for mass production, compliance, and the marginal unit costs. For this report, the authors assumed these costs were built in to the initial cost of ADB (i.e., the technology provider allocated these costs over the life of the technology).

In order to minimize the impact of the cost uncertainties, the research team used three costs: low, average, and high. The average costs were those recommended by the advisory panel and generally corresponded to the most representative cost provided by the industry. For example, in the case of ADB, the lower and higher costs (including installation) reported in published literature varied between $536 (ADB for only the steer axle) and $1,308 (ADB on all axles). After careful consideration, the advisory panel recommended an ADB value of $1,300 as a base for the analysis. This cost was adopted as the average value. The lower cost and higher costs corresponded with the minimum and maximum costs estimated by the advisory panel for ADB on all axles.

The cost of ADB was related not only to the number of units produced, but also the manufacturer's experience in producing the ADB. Experience curves or learning curves can be used to estimate the potential reduction in costs as experience is gained in producing the technology. In general, one-factor learning curves are the most prevalent:

$$C_i = a\, x_i^{-b}$$

where C_i is the cost to produce the i^{th} unit, B is learning rate exponent, A is the coefficient (constant), and x_i is cumulative production or capacity through period i.

The curves represent the reduction in costs when a cumulative value of the production is reached. If a 92% learning curve is selected, it can be expected that costs are reduced 8% every time production is doubled.

Driver/Manager Training

Although training is not directly regulated, a BCA must identify all costs and benefits associated with a proposed alternative. Training the drivers, managers, and maintenance personnel on the new technology's capabilities and how to use it is not only a reasonable assumption, but a cost that cannot be disregarded. The training required when deploying a new technology can be subdivided into initial and recurrent training. The initial training is applicable when the technology is installed on the truck. The recurrent training is conducted by the carrier each time there is a new driver, manager, or maintenance personnel (or during a refresher training course). For this study, an initial training time (generally one hour) was assumed for ADB. Three factors influence the needed recurrent training in further years: the complexity of ADB, the driver attrition rate in the industry (assumed to be 100%), and the point at which the ADB becomes integrated into basic safety training. To compute the technology and deployment cost for all trucks for year *y*, the costs were multiplied by the number of trucks where ADB will be installed/replaced and the number of drivers/managers who will receive training.

Truck Population

A critical part of any BCA is the identification of the number of vehicles where the technology will be implemented. The trucking industry is as diverse in operating characteristics as it is in the services it provides. Carriers are usually classified based on the size of the fleet, type of trucks, and type of operations and commodities they haul. There is not a unique classification system for trucks. In general, agencies classify trucks by the number of axles, their carrying capacity, or GVWR. The Federal Highway Administration's (FHWA's) Vehicle Inventory and Use Survey (VIUS) classifies trucks by their GVWR. As shown in Figure 2, this classification system includes eight classes ranging from 1 to 8.

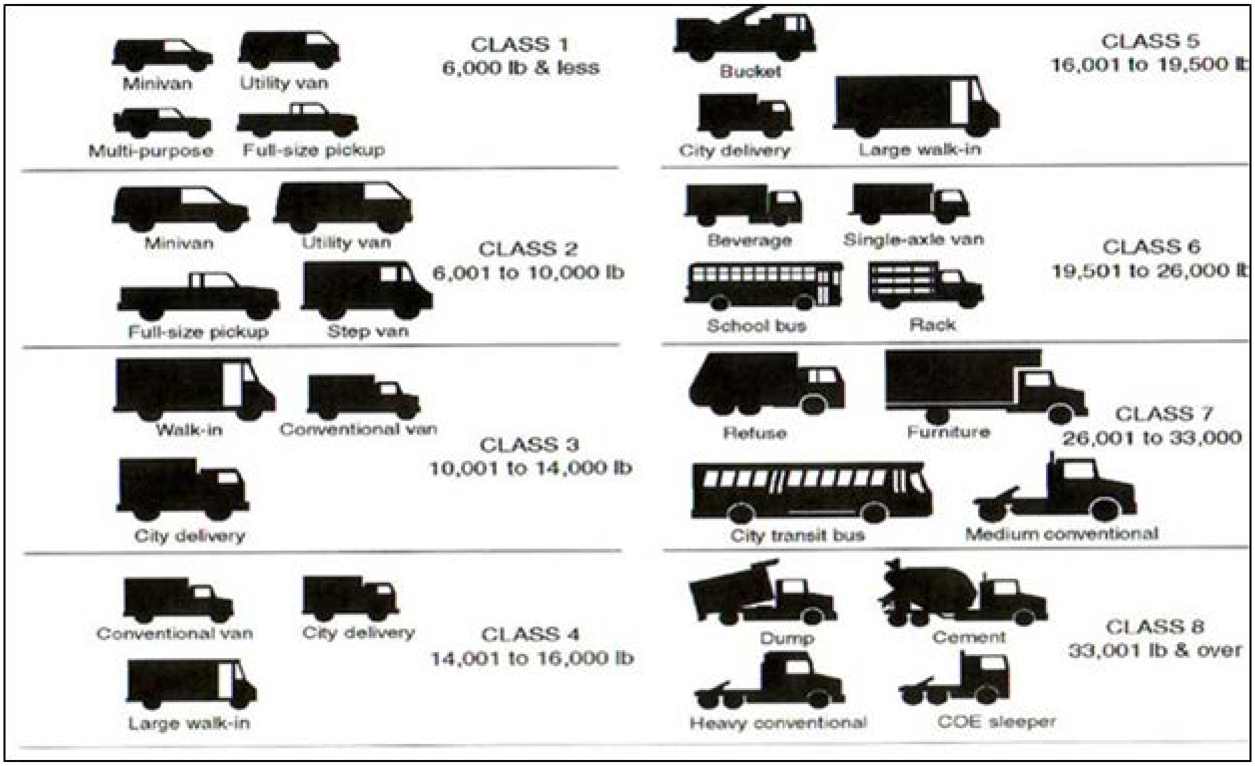

Figure 2. Truck classifications by gross vehicle weight.

Based on this classification, trucks also can be grouped as (i) "Light Duty" (class 1 and 2 vehicles), (ii) "Medium Duty" (class 3, 4, 5, and 6 trucks), and (iii) "Heavy Duty" (class 7 and 8 trucks). Per the recommendation of the advisory panel, the analyses in this study focus only on heavy-duty trucks (i.e., class 7 and 8 truck-tractor and trailers) to match the vehicle populations found in previous studies identified in the literature review.

To identify the current and future truck target population, the research team relied on three sources of information: (i) the number of vehicles registered, (ii) the number of new vehicles that entered the market, and (iii) the number of vehicle miles traveled (VMT) per year for each vehicle category. FHWA's Office of Highway Policy Information regularly publishes Table VM1 (2014), which contains information regarding the number of vehicles registered and VMT for different types of vehicles. This table classifies vehicles as light vehicles, trucks, motorcycles, and buses. Trucks are further classified as single unit trucks (SUTs) and combination unit trucks (CUTs). SUTs include all class 3 to 8 single trucks with a GWVR of more than 10,000 pounds. CUTs include all class 7 and 8 trucks with a GVWR of more than 26,000 pounds that are designed to be used in combination with one or more trailers. Table 5 shows the number of registered vehicles, the total number of VMT, and the average annual VMT for SUTs and CUTs.

Table 5. Number of Registered Vehicles, VMT, and Average Annual VMT for SUTs and CUTs (adapted from Office of Highway Policy Information, 2014)

Year	Truck Single Unit 2 axle 6 tires or more			Combination Trucks		
	Registration	VMT (millions)	Average Annual VMT	Registration	VMT (millions)	Average Annual VMT
1990	4,487,000	51,901	11,567	1,709,000	94,341	55,202
1991	4,481,000	52,898	11,805	1,691,000	96,645	57,153
1992	4,370,000	53,874	12,328	1,675,000	99,510	59,409
1993	4,408,000	56,772	12,879	1,680,000	103,116	61,379
1994	4,906,000	61,284	12,492	1,681,000	108,932	64,802
1995	5,024,000	62,705	12,481	1,696,000	115,451	68,073
1996	5,266,000	64,072	12,167	1,747,000	118,899	68,059
1997	5,293,000	66,893	12,638	1,790,000	124,584	69,600
1998	5,414,000	67,894	12,540	1,831,000	128,159	69,994
1999	5,763,000	70,304	12,199	2,029,000	132,384	65,246
2000	5,926,000	70,500	11,897	2,097,000	135,020	64,387
2001	5,704,000	72,448	12,701	2,154,000	136,584	63,409
2002	5,651,000	75,866	13,425	2,277,000	138,737	60,930
2003	5,849,000	77,757	13,294	1,908,000	140,160	73,459
2004	6,161,000	78,441	12,732	2,010,000	142,370	70,831
2005	6,395,000	78,496	12,275	2,087,000	144,028	69,012
2006	6,649,000	80,344	12,084	2,170,000	142,169	65,516
2007	8,117,000	119,979	14,781	2,635,000	184,199	69,905
2008	8,228,000	126,855	15,417	2,585,000	183,826	71,113
2009	8,356,000	120,207	14,386	2,617,000	168,100	64,234
2010	8,217,000	110,738	13,477	2,553,000	175,789	68,856
2011	7,819,000	103,803	13,276	2,452,000	163,791	66,809
2012	8,190,000	105,605	12,894	2,469,000	163,602	66,262
2013	8,126,000	106,582	13,116	2,471,000	168,436	68,165
2014	8,329,000	109,301	13,123	2,577,000	169,830	65,897

As shown in Table 5, in 2014 there were 8,329,000 SUTs registered, which traveled a total of 109.3 billion miles, with an average of 13,123 miles per SUT. In the same year, there were 2,577,000 CUTs registered that traveled 169.8 billion miles, with an average per vehicle of 65,897 miles. Since 2010, the total VMT and the average number of miles per truck have experienced only small fluctuations, as shown in Figure 3. A closer look shows that the number of registered vehicles went down after 2009 and it wasn't until 2014 that the number reached levels similar to those in 2010.

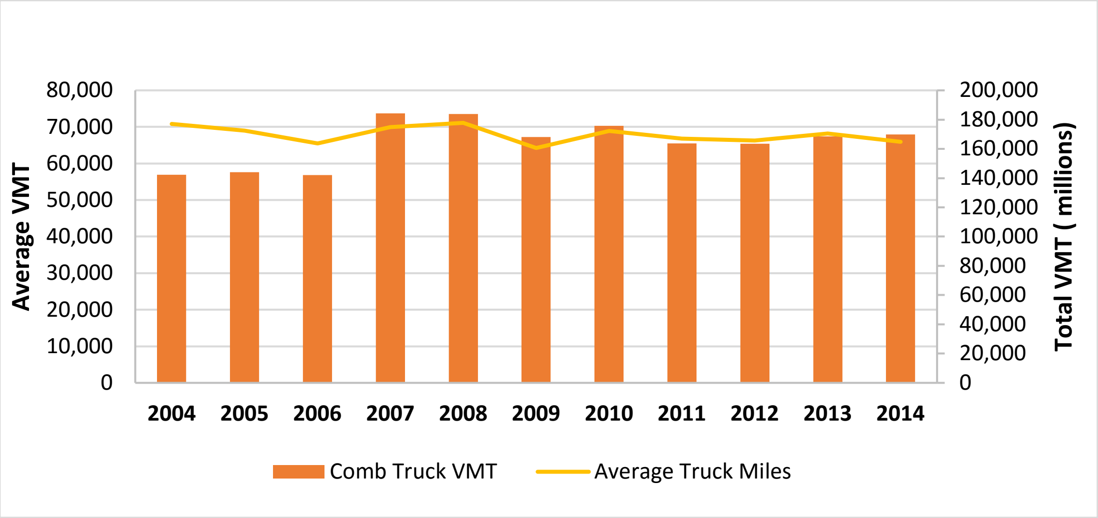

Figure 3. Total VMT (in millions) and average miles per CUT.

The number of miles traveled by each truck varies not only by the type of operation but also by the truck's age, with new trucks traveling the most. The VIUS provides the best estimate of the distribution of VMT based on the age of the vehicle. The age of the trucks also varies by truck type and operation. Figures 4, 5 and 6 show the fraction of vehicles by age and type of operations. The highest percentage of CUT age in long-haul operations was 4 to 5 years, and the highest percentage of SUT age in long-haul operations was 11 to 12 years.

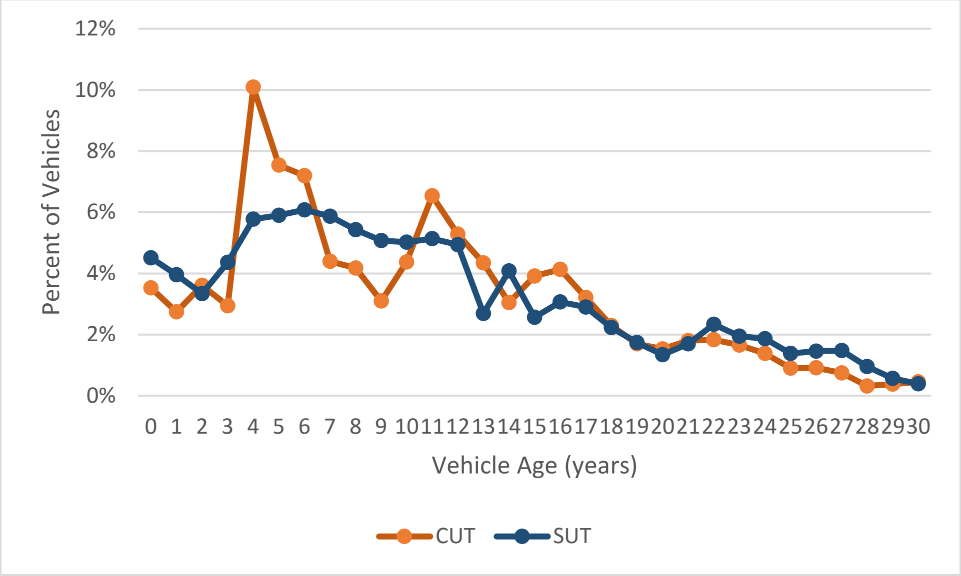

Figure 4. Percent of SUTs and CUTs by vehicle age.

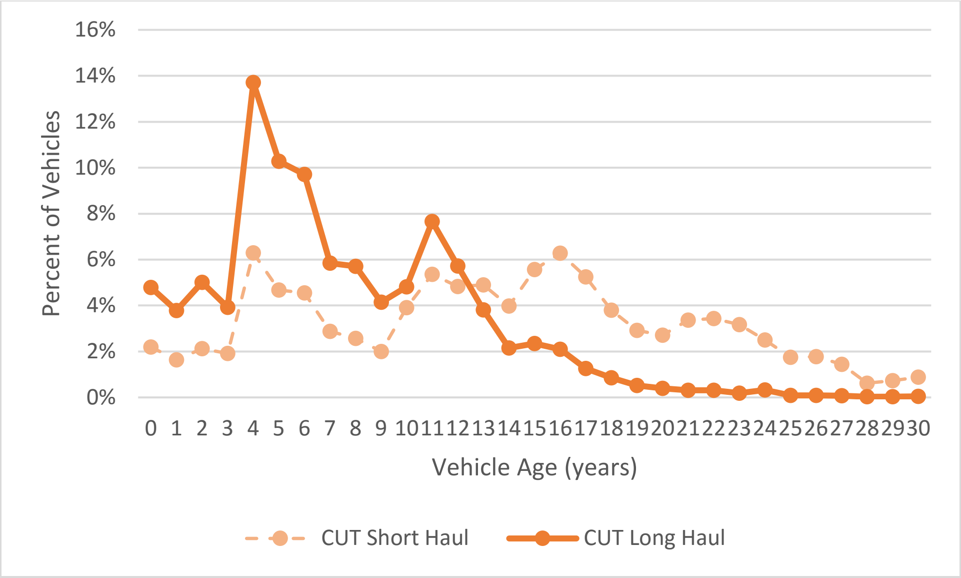

Figure 5. Percent of CUT age by operation type.

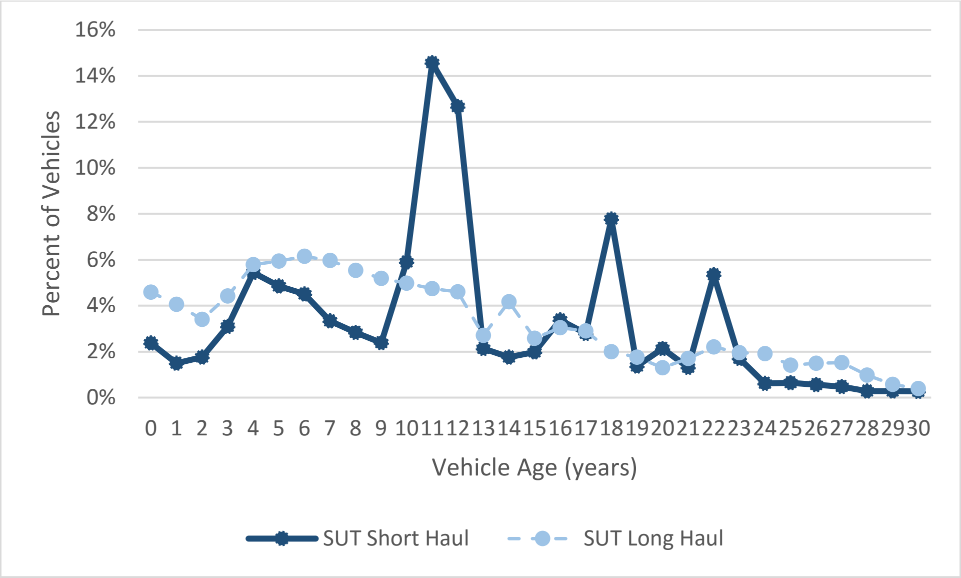

Figure 6. Percent of SUTs by operation.

Regarding future truck populations, the U.S. Energy Information Administration (2016) predicts an annual increase of 1.5% in the number of VMT between 2016 and 2040 for trucks heavier than 10,000 pounds. Similarly, the American Trucking Associations' (2016) U.S. Freight Transportation Forecast to 2027 predicted that truck load volumes will grow 2% annually between 2016 and 2020 and then 1.6% per year until 2027. In addition to the number of vehicles registered, it is important to know the number of new trucks that will enter the market for each truck category. Table 6 shows the number of new trucks by GVWR that were sold in the U.S.

Table 6. New Retail Truck Sales by GVWR (Adapted from Davis, Diegel, & Boundy, 2016)

Year	New Retail Sales (Thousands)							
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
1990	3,451	1,097	21	27	5	38	85	121
1991	3,246	876	21	24	3	22	73	99
1992	3,608	1,021	26	26	4	28	73	119
1993	4,119	1,232	27	33	4	27	81	158
1994	4,527	1,506	35	44	4	20	98	186
1995	4,422	1,631	40	53	4	23	107	201
1996	4,829	1,690	52	59	7	19	104	170
1997	5,085	1,712	53	57	9	18	114	179
1998	5,263	2,036	102	43	25	32	115	209
1999	5,707	2,366	122	49	30	48	130	262
2000	5,965	2,421	117	47	29	51	123	212
2001	6,073	2,525	102	52	24	42	92	140
2002	6,068	2,565	80	38	24	45	69	146
2003	6,267	2,671	91	40	29	51	67	142
2004	6,458	2,796	107	47	36	70	75	203
2005	6,586	2,528	167	49	46	60	89	253
2006	6,136	2,438	150	50	49	70	91	284
2007	5,682	2,623	166	51	45	54	70	151
2008	4,358	1,888	135	36	40	39	49	133
2009	3,528	1,306	112	20	24	22	39	95
2010	4,245	1,513	161	12	31	29	38	107
2011	4,714	1,735	195	10	42	41	41	171
2012	5,164	1,811	223	9	55	40	47	195
2013	5,615	2,077	254	12	60	47	48	185
2014	6,209	2,275	264	13	67	52	54	220
2015	7,161	2,417	283	24	72	55	59	249

Classes 7 and 8 correspond to trucks heavier than 26,000 pounds and the information does not differentiate between SUTs and CUTs. However, NHTSA estimates that on average, 80% of Class 8 and 10% of Class 7 trucks correspond to CUTs and the rest are SUTs. Since 2010, the number of new Class 3 to 8 vehicles increased significantly, with an average of 47,800 new Class 7 and 188,000 new Class 8 trucks for the period 2010 to 2015. Dividing by the estimated proportion of class 7 and 8 CUTs, the average number of retail sales for CUTs has been 80,000 and 155,000 vehicles per year, respectively. However, since the beginning of 2016, it was predicted that heavy-truck demand in the previous years would begin to weaken (Cullen, 2014; IHS Markit, 2016). Additionally, reductions between 29% and 39% on class 8 orders have been reported (Shedlock, 2016). Analysts point to an excessive number of new vehicles in stock, weakening pressure to replace older trucks, and a generally weak freight environment as potential reasons for this decline in sales.

Identify Safety Benefits as a Reduction in the Number of Crashes/Injuries/Fatalities

One of the main objectives in the study was to quantitatively evaluate the safety impact of ASTs. (This report evaluates ADB specifically.) As described above, two options were formulated to assess the potential cost of ADB: no ADB deployment and ADB deployment. Circular A-4 requires a BCA and a CEA to evaluate the benefits and costs of the alternatives proposed. The BCA assigns a monetary value to the benefits and costs of the alternatives and uses economic indicators to evaluate the feasibility of implementing the specific alternative. The CEA, on the other hand, is expressed as a ratio where the denominator is a quantitative measure of the benefits and the numerator is the expected cost to be able to reach those benefits. For the BCA, the criterion is that the present and future value of the benefits must be greater than the present and future value of the costs. This can be expressed as the Net Value (benefit/costs greater than zero) or as a Benefit Cost Ratio (BCR; benefit/cost greater than 1).

The CEA for vehicle safety is measured as equivalent fatalities or equivalent lives saved. The final goal is not only to justify the proposed alternative but to be able to select among different alternatives or proposed regulations to guarantee society the best allocation of the limited resources.

In the BCA, the safety benefits of ADB were computed as the difference in number of crashes/number of injury severity types (fatality equivalent) for both options (without mandatory ADB deployment and with mandatory ADB deployment) for each year over the period of the analysis:

$$AACC = \sum_{i,j}(N_{jio} - N_{ji1}) * CC_{ji}$$

where *AACC* was the average annual cost; *j* was the type of crash/injury ADB was expected to prevent; *i* was the severity of the crash or type of the injury; N_{ji0} was the number of crashes/injuries by severity *i* without mandatory ADB deployment; $\mathrm{N}_{\mathrm{jiN}}$ was the number of crashes/injuries by severity *i* with mandatory ADB deployment; and CC_{ji} was the crash cost for type *j* and severity *i* crash. To identify the number of crashes that can be prevented by the deployment of ADB, the research team identified the types of crashes that were preventable by ADB and selected the efficacy rate of ADB.

Types of Crash/Crash Scenarios Preventable by Air Disc Brakes

Air disc brakes have the capability of preventing only some types of crashes/crash scenarios. Specifically, the installation of ADB is expected to reduce large-truck rear-end, and, to a much lesser extent, head-on collisions. In general, the crashes preventable by ADB exclude crashes when the driver is incapacitated or crashes due to vehicle malfunctions (e.g., faulty brakes). To identify the type and number of preventable crashes, the research team identified the different variables and pre-crash scenarios in different crash databases.

For this study, the advisory panel recommended that ADB only be considered effective at preventing large-truck striking rear-end crashes. Any future descriptions of crashes prevented by ADB refer back to these crash types only. Thus, when indicating reduction in crashes for ADB, we are only referring to reduction in large-truck striking rear-end crashes.

Crash Databases

When societal impacts are considered, the target population refers to the total number of reported crashes (i.e., by crash type, by crash severity, by injury severity) by vehicle type that can be affected by the deployment of ADB. To this end, national crash databases are used as a tool to identify the target population and its subgroups. These crash databases include the FARS, GES, and the Motor Carrier Management Information System (MCMIS). The FARS database is usually recommended to identify the total number of fatal crashes and fatalities. The GES database has the limitation that it is an estimation of nonfatal injury crashes and property damage only (PDO) crashes. The MCMIS database includes truck crashes that are reported to FMCSA by the states. It has the limitation that, to be reported, the crash at a minimum needs to be a tow-away crash, involve a fatality, or cause an injury that results in transportation to a hospital.

The research team decided to use the FARS database to determine the number of fatal crashes and their associated fatalities and injuries, and the GES database as an estimation for injury and PDO crashes. The GES database was also used to estimate the number of injuries as a result of injury crashes. Queries were developed for ADB and information was extracted for different vehicle types for a period of six years (2010 to 2015; see Appendix B for the list of crash filtering criteria).

When filtering the GES and FARS crashes, the research team carefully considered the scenarios where ADB may have prevented the crash. Additionally, the research team used the following GES/FARS variables to further limit crashes that may have been prevented by ADB: pre-event movement, critical event, and first harmful event. Finally, all crashes that involved the use of alcohol or drugs by the large-truck driver were eliminated.

The research team generated the two matrixes shown in Table 7 and Table 8. The GES and FARS used a five-point KABCO severity scale to define the severity of injuries for all persons involved in a crash. Since many crashes have more than one injury, the worst one was used to characterize the severity of the crash. Values for the KABCO scale are as follows: K = fatal; A = incapacitating injury; B = non-incapacitating injury; C = possible injury; O = no injury.

Table 7. Total Number of Crashes by Crash Type and Maximum Injury Severity (Example)

Body Type	Fatal Crashes	Injury Crashes	PDO Crashes
	X	X	X
	X	X	X
	X	X	X

Table 8. Number of Injured Persons for Each Crash Type and Injury Severity (Example)

Crash Type	Crashes	Police Reported Number of Persons Injured						
		K	A	B	C	O	U	PDO

The number of crashes and injuries shown in Table 7 and Table 8 corresponds to crashes that may be prevented by ADB if the efficacy rate is 100%. In order to realistically estimate the number of crashes that may be prevented by ADB deployment, the ADB efficacy rate must be considered.

Efficacy of Air Disc Brakes

The efficacy rate of air disc brakes corresponds to their capability to reduce the collision probability and/or severity of the crash types prevented with the technology. Efficacy is usually expressed as a percentage or reduction in number of crashes/fatalities/injuries, or as an expected crash rate (crashes per VMT). Independent of the method of measuring effectiveness, the efficacy rate is usually expressed as a range and not as a specific value. For the present study, the advisory panel selected an efficacy range. Thus, economic indicators will be presented for the lower and higher efficacy rates. It is important to note that most of the studies in the literature review did not differentiate the efficacy rate by the severity of the crash (fatal, different type of injuries, or property damage). To this end, the research team applied the same efficacy rate to fatal crashes, injury crashes, type of injuries, and PDO crashes. The authors note that real-world effectiveness against different severities of injuries may differ, but data limitations excluded development of separate efficacy estimates for ADB at the time of this study.

Expected Number of Crashes/Injuries/Fatalities Preventable by Air Disc Brakes

The number of preventable crashes by crash type and injury severity for the base year was computed as:

$$N_{jibase(No\ ADB-ADB)} = \sum_{y} (N_{jiy}) * \frac{1}{y} * ADB_{effji} * (GR)_{bas}$$

where, N_{jibase} was the number of type *j,* category *i* crashes preventable by an ADB for the base year; crash type *j* corresponds to the specific type of crash avoided by the technology; *y* was the number of years of crash data; N_{jiy} was the total number of type *j*, category *i* crashes preventable for year *y* by an ADB; ADB_{effj} was the efficacy of an ADB for crash *j,* category *i;* and GR_{bas} was a growth factor (if any) that was applied due to the lead time.

Change of Crash Frequency over Time

It is generally accepted that there is a direct relationship between the exposure to traffic and the number of crashes. If all conditions remain equal, the number of crashes in a fleet population will increase if the number of vehicles or the mileage increases. However, it is also important to recognize that advancements in vehicle and road safety will reduce the number of crashes. Unfortunately, the latest statistics have shown an increase in the number of crashes despite those improvements and without an increase of the VMT. From

2004 to 2009, there were significant reductions in the number of crashes (likely due to the recession). During that period, large-truck fatal and injury crashes declined 33% and 37%, respectively. However, the situation reversed during the period 2010 to 2014 (when the economy improved), as shown in Table 9.

Table 9. Fatal, Injury, and PDO Crash Rates from 2010 to 2015 (Data from 2010-2015 GES)

	Fatal	Injury	PDO	VMT	Fatal rate	Injury rate	PDO rate
2010	3,271	56,000	207,000	286,527	1.14	19.54	72.24
2011	3,365	60,000	210,000	267,594	1.26	22.42	78.48
2012	3,486	73,000	241,000	269,207	1.29	27.12	89.52
2013	3,554	69,000	254,000	275,017	1.29	25.09	92.36
2014	3,424	82,000	326,000	279,132	1.23	29.38	116.79
2015	3,598	83,000	328,000	279,844	1.29	29.65	117.21

As a result of discussions with the advisory panel, a conservative approach (fewer crashes resulting in fewer benefits) was chosen. This approach, which assumed the number of crashes or the rate of crashes would remain constant at the 2004–2009 baseline average, would likely produce a conservative estimate of benefits. In other words, this approach provided lower cost-effectiveness estimates to reflect the ADB possibilities with lower crash rates.

Crash Costs

Components of the societal or public cost of truck crashes included costs associated with property damage, increases or changes in emissions, and personal costs related to fatalities or injuries, medical costs, lost productivity due to injuries, and emergency services. The Value of Statistical Life (VSL) attempts to measure the value that consumers place on their lives as computed by the price they are willing to pay to avoid death. Although VSL is a good indicator of the cost of a fatality, the reality is that most of the crashes involved only injury victims or no injuries at all. To estimate the cost of injuries and the different type of injuries, the same willing-to-pay studies can be used to estimate the quality adjusted life years (QALYs). This indicator uses a value of 1 for perfect health in a good year and a value of 0 when death occurs. These costs do not cover the unexpected costs that arise from the injury related to medical costs, legal costs, emergency services, congestion costs, emissions, and/or property damage. The deterioration of good health when someone suffers an injury is measured by estimating the QALYs. QALYs is a function of the VSL and has been used in previous studies, using an updated VSL value and the Employment Cost Index.

Regarding the VSL monetary value, the U.S. DOT annually publishes the *Guidance on Treatment of the Economic Value of a Statistical Life in U.S. Department of Transportation Analyses* (USDOT, 2015). This document provides guidance on the revised VSL and indicates how the VSL needs adjustment and determines how to account for uncertainties. Because it is expected that safety regulations affect a broad cross section of people, the U.S. DOT considers only a single nationwide VSL regardless of age, income, mode of travel, or nature of risk. The latest Guidance, issued in 2015, establishes a VSL economic value of $9.4 million (base year 2014).

For this study, FMCSA provided the research team with new cost estimates (soon to be released) of crashes per victim and cost per crash per truck. These costs are in 2014 dollars with a VLS value of $9.4 million. To update the cost, NHTSA recommended using the consumer price index (CPI). This index represents changes of all goods and services purchased for consumption by urban households. To this effect, the Bureau of Labor Statistics provides the CPI inflation calculator that uses the average CPI for a given calendar year. The CPI ratio for 2015 to 2014 was 1. Thus, the values provided by FMCSA were considered the values to use in the BCA.

As shown in Table 10, the average cost of a fatal CUT crash was estimated as $11,313,000 (in 2014 dollars), $11,175,000 of which was the monetized QALY component. The remaining $138,000 comprised medical costs, emergency services, property damages, lost productivity from roadway congestion, environmental costs, and fuel consumption. Similarly, a CUT injury crash had an average cost of $540,000. This included a monetized QALY of $476,000, plus $64,000 for medical costs, emergency services, and property damage. These values correspond to an average number of 1.192 fatalities per fatal crash and an average number of 1.38 injuries per injury crash.

Table 10. Average Crash Cost by Crash Severity for CUTs

Severity	Average Cost
All	$383,000
Fatal	$11,313,000
Injury	$540,000
Unknown and No Injury	$117,000

In this study, the authors used the disaggregation of crash costs by severity, as the number of fatalities and injuries differed among the total crashes and the specific crash types (see Table 11). For example, the cost of an incapacitating or serious injury resulted in $52,100 in medical costs, $400 in emergency services, and $853,600 in QALY. Similar to the Maximum Abbreviated Injury Severity (MAIS) scale described below, the VSL fraction provided a coefficient to estimate (when multiplied by the VSL) the cost of an injury as a fraction of a fatality.

Table 11. Average CUT Cost Per Victim Per Severity Type

Severity	Medical Costs	Emergency Services	VSL Fraction	Monetized QALY
Fatality	$41,600	$1,300	1	$9,400,000
Incapacitating Injury	$52,100	$400	0.0908	$853,600
Non-incapacitating Injury	$18,000	$200	0.0298	$279,800
Possible Injury	$11,500	$200	0.0196	$184,400
Unknown and No Injury	$800	$100	0.0047	$43,800
Injury, Severity Unknown	$6,600	$200	0.0124	$117,000

Similarly, an injury crash results, on average, in $20,000 in property damage, $43,000 in lost productivity and roadway congestion, and $3,000 in environmental costs and fuel as shown in Table 12.

Table 12. Average Cost by Crash Severity for Property Damage, Lost Productivity and Roadway Congestion, and Environmental Costs and Fuel

Type of Crash	Property Damages	Lost Productivity Roadway Congestion	Environmental Cost and Fuel
All	$11,000	$14,000	$1,000
Fatal	$20,000	$43,000	$3,000
Injury	$20,000	$16,000	$1,000
Unknown and No Injury	$8,000	$13,000	$1,000

Expected Number of Equivalent Lives Saved

Circular A-4 (2003) states that when conducting a regulatory analysis, agencies should use both BCA and CEA. The computation of the number of lives saved by each AST constitutes an excellent tool to compare each AST's efficacy. The circular describes CEA as a way "to identify options that achieve the most effective use of the resources available without requiring monetization of all of relevant benefits or costs" (pp. 11). Nonfatal injuries as a result of crashes vary widely in severity and probability, but still result in losses of the quality of life and reduction of income. Thus, capturing the "value" of these injuries is essential to conducting a CEA. As mentioned before, the VSL attempts to capture the additional cost that individuals are willing to pay for improvements in safety (reduction of risks), that in aggregate reduce the number of fatalities by one.

To translate the different nonfatal injuries to "equivalent fatalities," the U.S. DOT rated each type of accidental injury on a scale of QALYs in comparison with the alternative of perfect health. Scores were then aggregated using the Abbreviated Injury Scale (AIS), and as a result, each MAIS is associated with a coefficient that can be applied to the VSL as a corresponding fraction of a fatality, as shown in Table 13 (Spicer & Miller, 2010). These values, expressed as a fraction of VSL, can be used to convert the number of injuries to equivalent fatalities.

Table 13. MAIS Scales/Fatality Fraction

MAIS Scale	Severity	Fraction of VSL
1	Minor	0.03
2	Moderate	0.047
3	Serious	0.105
4	Severe	0.266
5	Critical	0.593
6	Unsurvivable	1

KABCO and AIS Scales are not directly related (i.e., an injury observed and a reported crash could be more or less severe than originally reported). Thus, it was necessary to apply a KABCO/AIS Data Conversion Matrix to convert the number of injuries under the KABCO system to the MAIS number (Table 14).

Table 14. KABCO/MAIS Data Conversion Matrix

KABCO MAIS	O	C	B	A	K	U	Unknown if Injured
	No Injury	Possible Injury	Non-incapacitating	Incapacitating	Killed	Injury Severity Unknown	
0	0.9254	0.23437	0.08347	0.03437	0.000	0.21538	0.43676
1	0.07257	0.68946	0.76843	0.55449	0.000	0.62728	0.41739
2	0.0198	0.06391	0.10898	0.20908	0.000	0.10400	0.08872
3	0.00008	0.01071	0.03191	0.14437	0.000	0.03858	0.04817
4	0.0000	0.00142	0.0620	0.03986	0.000	0,00442	0.00617
5	0.00003	0.00013	0.00101	0.01783	0.000	0.01034	0.00279
Fatality	0.0000	0.000	0.000	0.000	1.000	0.000	0.000
Probability	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The usefulness of this matrix can be seen with crashes classified as non-incapacitating (i.e., KABCO scale “B”). Using the MAIS matrix reveals that only 8.3% of these crashes would be classified as MAIS 0 (i.e., no injury), and 76.8% of crashes would be classified as MAIS 1 (i.e., minor injury), 10.8% would be classified as MAIS 2, etc. Additionally, the total of MAIS 1 injuries was the sum of 7.257%, 68.946%, 76.843%, 55.449%, 62.728% and 41.739% of the total number of the O, C, B, A, and U categories, respectively. This study obtained the number of equivalent fatalities that may be prevented by the installation of ADB by multiplying the crashes by the relative fatality ratios shown in Table 13. This matrix also can be used to compute the crash costs by multiplying the relative fatality ratios per the VSL, and adding the cost of property damage, lost productivity from roadway congestion, and environmental cost and fuel. Although the authors calculated both of these values as a verification measure, the crash costs reported are those obtained from FMCSA, as previously noted (soon to be released).

Annual Incremental Cost Analysis

The standard practice described above assumes a constant rate of crashes over the analysis period reflecting the useful life of the ADB/vehicle. The costs of crashes for each year are discounted to reflect the net present value (NPV) of those yearly benefits on the base year. Similarly, the costs of the installation, maintenance, and training are also discounted by the same factors. This discount factor is discussed in more detail below.

The period between when an ADB system is installed and when the crash may be prevented follows an empirical distribution that indicates the safety benefits can occur at any point during the vehicle’s lifetime. If it can be assumed a constant number of vehicles experience a constant number of crashes, the previous methodology may be refined. To capture this lag on time, it can be assumed that the distribution of the VMT can be used as a proxy for the distribution of crashes (see Table 15). A survival probability may be used to represent a large number of vehicles across the population in question. As a result, the probability of the crash occurring will depend on the percent of miles traveled per each year of life multiplied by the survival probability. Furthermore, the cumulative percentage of VMT should be used when analyzing the number of vehicle life years. A more detailed description of this procedure can be found in Kirk (2009).

Table 15. Survival Probability and Annual VMT

Year	Total Annual Miles Traveled	Survivability	Weighted Miles Traveled	% Total Weighted Miles	Raw Discount Rate		Discount Rate	
					3%	7%	3%	7%
1	240,737	1	240,737	0.10	0.985329	0.966736	0.097713	0.09587
2	226,110	0.993	224,527.2	0.09	0.95663	0.903492	0.08848	0.083565
3	212,378	0.981	208,342.8	0.09	0.928767	0.844385	0.07971	0.072468
4	199,486	0.9642	192,344.4	0.08	0.901716	0.789145	0.071446	0.062527
5	187,381	0.9432	176,737.8	0.07	0.875452	0.737519	0.063737	0.053695
6	176,017	0.9181	161,601.2	0.07	0.849954	0.68927	0.056581	0.045884
7	165,346	0.8894	147,058.7	0.06	0.825198	0.644177	0.049989	0.039023
8	155,327	0.8575	133,192.9	0.05	0.801163	0.602035	0.043957	0.033032
9	145,919	0.823	120,091.3	0.05	0.777828	0.562649	0.038479	0.027834
10	137,085	0.786	107,748.8	0.04	0.755173	0.525841	0.033519	0.02334
11	128,789	0.7473	96,244.02	0.04	0.733178	0.49144	0.029068	0.019484
12	120,999	0.7071	85,558.39	0.04	0.711823	0.45929	0.025088	0.016187
13	113,683	0.666	75,712.88	0.03	0.69109	0.429243	0.021554	0.013388
14	106,813	0.6244	66,694.04	0.03	0.670961	0.401161	0.018434	0.011021
15	100,360	0.5826	58,469.74	0.02	0.651419	0.374917	0.01569	0.00903
16	94,300	0.5411	51,025.73	0.02	0.632445	0.35039	0.013294	0.007365
17	88,609	0.5003	44,331.08	0.02	0.614025	0.327467	0.011213	0.00598
18	83,263	0.4604	38,334.29	0.02	0.59614	0.306044	0.009414	0.004833
19	78,242	0.4217	32,994.65	0.01	0.578777	0.286022	0.007867	0.003888
20	73,526	0.3845	28,270.75	0.01	0.56192	0.267311	0.006544	0.003113
21	69,096	0.349	24,114.5	0.01	0.545553	0.249823	0.005419	0.002482
22	64,935	0.3152	20,467.51	0.01	0.529663	0.23348	0.004466	0.001969
23	61,026	0.2835	17,300.87	0.01	0.514236	0.218205	0.003665	0.001555
24	57,354	0.2537	14,550.71	0.01	0.499258	0.20393	0.002993	0.001222
25	53,905	0.226	12,182.53	0.01	0.484717	0.190589	0.002433	0.000956
26	50,664	0.2004	10,153.07	0.00	0.470599	0.17812	0.001968	0.000745
27	47,620	0.1769	8,423.978	0.00	0.456892	0.166468	0.001585	0.000578
28	44,759	0.1554	6,955.549	0.00	0.443584	0.155577	0.001271	0.000446
29	42,072	0.1359	5,717.585	0.00	0.430665	0.145399	0.001014	0.000342
30	39,547	0.1183	4,678.41	0.00	0.418121	0.135887	0.000806	0.000262
31	37,175	0.1025	3,810.438	0.00	0.405943	0.126997	0.000637	0.000199
32	34,945	0.0884	3,089.138	0.00	0.394119	0.118689	0.000502	0.000151
33	32,851	0.0759	2,493.391	0.00	0.38264	0.110924	0.000393	0.000114
34	30,883	0.0649	2,004.307	0.00	0.371495	0.103668	0.000307	8.56E-05
35	29,033	0.0552	1,602.622	0.00	0.360675	0.096886	0.000238	6.4E-05
Total	3,530,235		2,427,562		0.35017		0.809473	0.642697

To determine the weighted discount factors, the authors multiplied the fraction of the weighted VMT that occurred in each year by the discount factors in that year. For example, the weighted discount factor for a vehicle 10 years old and a 3% discount rate was 0.0310. This was obtained by multiplying the fraction of total weighted VMT (0.04) by the proportion discount factor associated with a 3% discount rate at year 10 (0.7552). Figure 7 shows the plotted undiscounted and discounted distribution of the weighted VMT versus the vehicle age.

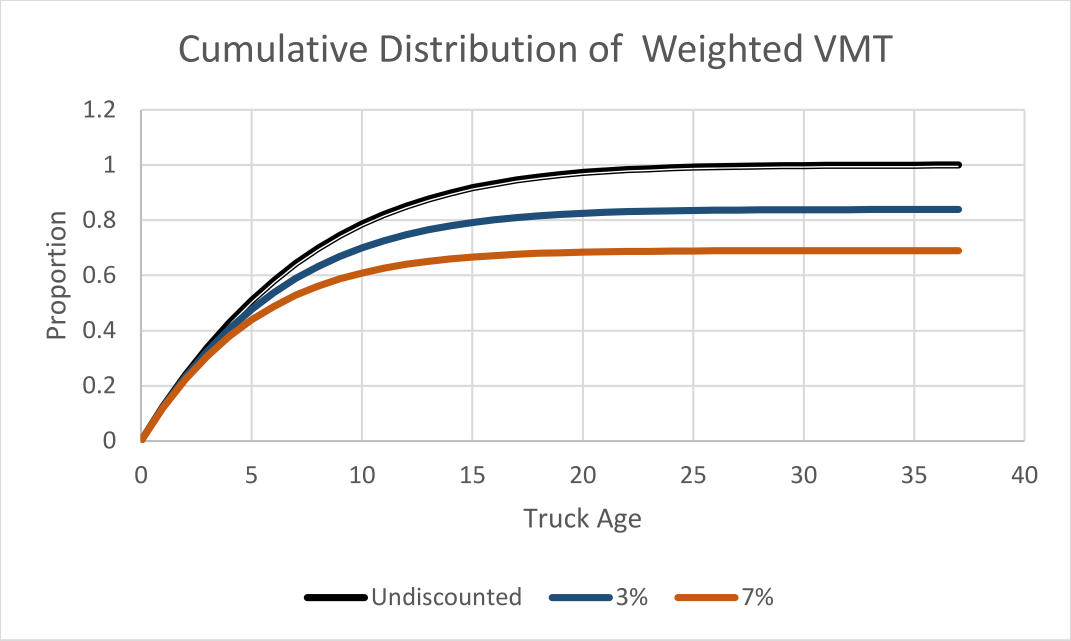

Figure 7. Distribution of weighted VMT by survival rate as a surrogate of probability of crash occurrence.

Figure 7 shows that the undiscounted distribution has a top value of 1 and the discounted distribution maximum value, or lifetime discount factor, was 0.809 for a 3% discount rate and 0.642 for a 7% discount rate. These discounts represent the lag between the investment and the return. Figure 7 also shows that all the undiscounted and discounted distributions flatten around 20 years. If a constant number of vehicles and crashes is assumed, this equals the linearized distribution for an analysis period of 20 years.

Benefit Cost Analysis Measures

This section describes the BCA measures developed to compare the benefits and costs in implementing ADB, including NPV, BCR, and sensitivity analysis.

Discount Rate

The discount rate is the rate of discounts, in the present value (PV), of the cost and benefits in any future year. The discount rate is used to compute the PV of future costs and benefits using the following formula (OMB, 2003):

$$PV = \frac{P_y}{(1+r)^n}$$

where PV is the present value of the amount invested; P_y is the dollar value of the future amount in time y; r is the discount rate; and y is the year in which P_y is computed (0, 1, … n). The higher the discount rate, the lower the PV in future costs and benefits. A real discount rate of 7% will be used per OMB (2003) recommendations. The OMB (2003) also recommends conducting a sensitivity analysis to show the impact of discount rate variation (using 0%, 3%, and 7%).

Net Present Value

The NPV is the current value of all projected PV benefits minus the sum of all projected PV costs. If the NPV is greater than zero ("0"), it can be assumed that equipping the truck with an ADB system is a good alternative. The NPV was calculated as follows (OMB, 1992; Pearce et al. 2006):

$$NPV = \sum_{y=1}^{Y} \frac{(Benefits_y - Cost_y)}{(1+r)^y}$$

where $Benefits_y$ are the expected benefits for the year y and were computed as:

$$Benefits_y = Crash\ Costs_{y0} - Crash\ Costs_{y1}$$

$Crash\ Costs_{y0}$ were the expected crash costs for the year y without mandatory deployment of ADB, and $Crash\ Costs_{y1}$ were the expected crash costs for the year y with mandatory deployment of ADB. The crash costs will be divided by VSL. $Cost_y$ was the expected cost for the year y and was computed as:

$$Costy = Cost_{y1} - Cost_{yo}$$

where $Cost_{y1}$ is the expected total cost of installing and operating the ADB for the year y with mandatory deployment; $Cost_{y0}$ is the expected total cost of installing and operating the ADB for the year y without mandatory deployment; r is the discount rate; and y is the year in which C_y is computed (0, 1, …n).

Benefit–Cost Ratio

The BCR was calculated as the NPV of benefits divided by the NPV of costs. If the BCR exceeds 1, the benefits of installing the ADB are higher than the costs incurred in buying, installing, and maintaining the ADB. The BCR was calculated as follows (OMB, 2003):

$$BCR = \frac{\sum_{y=1}^{n} \frac{B_y}{(1+r)^n}}{\sum_{y=1}^{n} \frac{C_y}{(1+r)^n}}$$

where BCR is the BCR in implementing ADB over a period of analysis n assuming a rate of return r; B_y is the benefit associated with implementing ADB in year y; Cy is the cost associated with implementing ADB in year y; r is the discount rate; and n is the number of years for the analysis period.

Cost-Effectiveness Analysis

The cost-effectiveness (CE) was calculated as the total number of equivalent fatalities that would be avoided by the installation and deployment of ADB divided by the NPV of costs. The CE was calculated as follows (OMB, 2003):

$$CE = \frac{\sum_{y=1}^{n} \frac{NC_y *}{(1+r)^n}}{\sum_{y=1}^{n} \frac{EF_y}{(1+r)^n}}$$

where *CE* was the cost of each fatality prevented by implementing ADB over a period of analysis *n* and a rate or return *r*; *NCy* was the net cost associated with implementing ADB in year *y*; EF_y was the benefit associated with implementing ADB (in this case equivalent saved lives) in year *y; r* was the discount rate; and *n* was the number of years for the analysis period.

$NCost_y$ is the expected net cost for the year *y* and was computed as:

$$NCosty = Cost_{y1} - Cost_{yo} - Crash\ Cost_{-VSLy0} + Crash\ Cost_{-VSL1}$$

Crash Cost $_{-\mathrm{VSLy}}$ was the crash cost minus the monetized VLS component.

Sensitivity Analysis

A sensitivity analysis was performed to examine how changes in the assumptions affected the outputs of the BCA or robustness of the results. The sensitivity analysis was conducted using \$5,304,000 and \$13,260,000 for low and high estimates of VSL values, and discount rates from 3% to 7% were applied.

Results

This section details the benefits and costs of ADB and the results of the BCA.

Technology and Deployment Costs per Truck

According to NHTSA, 82% of truck tractors have three axles. Typically, each three-axle tractor is equipped with one steer axle and two drive axles. Two-axle tractors, which include one steer axle and one drive axle, constitute 10% of the tractor population. The other 8% are considered service tractors. These tractors typically have more than three axles and a higher GVWR than the standard three-axle tractor. As discussed in the Methods section, the advisory panel chose to use an average price of $1,300 for ADB on three axles ($536 for steer axle only). In addition to this average cost, a high cost of $2,020 and a low cost of $700 was used.

For this study's societal BCA, the research team assumed the cost of the technology was incurred when the technology was installed or repaired, independently of the financial mechanism used by the carriers to acquire the technology. The service life of the technology was assumed to be 10 years with replacement costs equaling the cost of new technology.

According to ADB manufacturers, the maintenance required for ADB is very limited. The pad in the disc can last up to 600,000 miles and the rotor can last up to 1 million miles. Furthermore, ADB manufacturers suggest that ADB eliminate: a) the need of periodic lubrication of brake adjusters, b) drum inspection for cracking, expansion of the lining, and contamination, and c) checking of proper brake stroke length. Additionally, changing a pad takes only 20 minutes, while routine service of a traditional drum brake can take an hour or more per wheel (Park, 2015). Despite these advantages, adoption has been slow. Carriers continue to see a high upfront cost and companies continue to like the simplicity and the lower cost of drum brakes (Galligan, 2015).

An average training time of one hour per driver was used in the BCAs. Based on previous studies (e.g., Hickman et al., 2013), this analysis assumed there was one driver per truck. The cost of the driver's time was computed using the 50th percentile driver salary from the BLS ($19.36 per hour for 2015; 2016) plus fringe and overhead costs. The fringe benefits were obtained from the Employee Cost for Employee Compensation (57%; 2016). The overhead cost was based on industry data gathered by Berwick and Farooq (2003). As a result, the final driver salary per hour corresponds to $34.91 per hour.

Figure 8 shows a sensitivity analysis reflecting the impact on the total cost of ADB with an increase in the number of training hours from one hour per driver per year to one and a half and two hours per driver per year, driver retention rates of 200% and 50%, and different discount rates. The variability in these costs was not significant and was always less than the variability in equipment costs of ADB (i.e., low, average, and high). For example, a sensitivity analysis including an ADB cost of $1,300, a discount rate of 0%, a service life of 10 years with an average replacement at 10 years, and the cost for one, one and a half, or two hours of training per driver resulted in a total undiscounted cost per truck of $3,543, $3,307 and $3,508, respectively. Similar costs were obtained with different discount rates and retention rates.

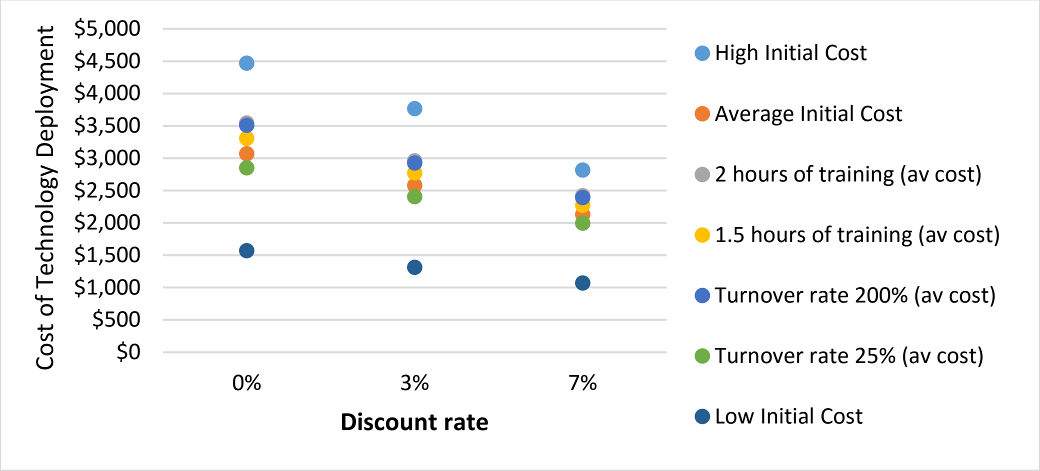

Figure 8. Impact of number of training hours and retention rates for different costs and ADB discount rates.

Crash Target Population

The initial target population was the estimated number of large-truck striking rear-end crashes, and the associated fatalities and injuries that would be prevented if all large trucks were equipped with ADB. The research team used the 2010 to 2015 GES and the FARS databases to determine these numbers of rear-end crashes and injuries, which were computed as a six-year average from 2010 to 2015.

The six-year selection period was expected to capture some of the variations in crashes due to external factors, such as recession or market changes in the number of new trucks. However, as shown in Figure 9, there was a considerable variation in the number of crashes over the years. Data from 2015 showed a relative trend of returning to values achieved prior to 2013, but the 2015 values continued to be higher than those from 2010 and 2011. Thus, a six-year average represented a more conservative approach for the BCA.

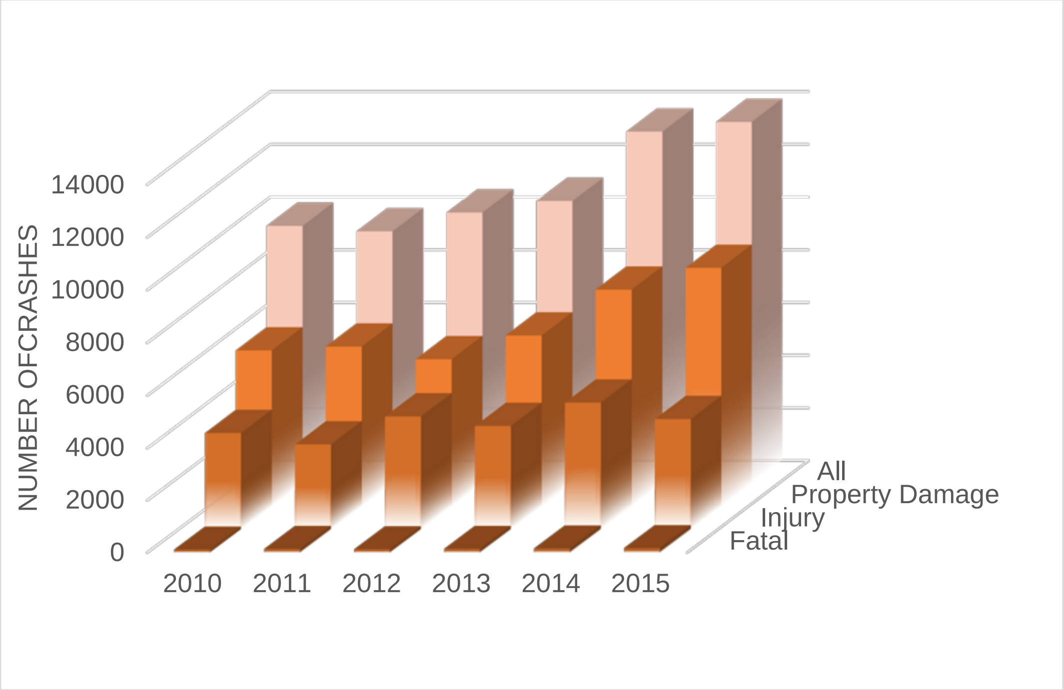

Figure 9. Number of large-truck crashes that may be prevented by ADB (data from 2010 to 2015 GES and FARS).

As shown in Table 16 below, the installation of the large truck ADB has the potential to reduce an annual maximum of 9,842 crashes. Of those crashes, 1.3% correspond to fatal crashes, 36.1% to injury crashes, and 62.6% to PDO crashes. As a result of these crashes, air disc brakes were associated with a maximum reduction of 152 fatalities and 5,906 injuries.

Table 16. Maximum Number of Crashes That May Be Preventable by Large Truck ADB, by Severity (Data from 2010 to 2015 GES and FARS)

	Number of Crashes	Percent of Total Crashes
Fatal	128	1.3%
Injury	3,549	36.1%
PDO	6,165	62.6%
Total Crashes	9,842	100%

Effectiveness of Air Disc Brakes

The efficacy rate of ADB corresponds to the capability to reduce the collision probability and/or severity of the crash types prevented with the technology. As discussed in the previous section, the advisory panel recommended lower- and upper-bound efficacy rates of 10% and 15%, respectively. Real-world efficacy may differ based on crash severity, but data limitations excluded separate efficacy estimates for ADB at this time. These efficacy rates were applied to 86.6% of crashes estimated to be prevented by ADB. This was done to account for vehicles with brakes that may be out of adjustment. This percentage was estimated based on the results of the Commercial Motor Vehicle Safety Alliance 2016 Operation Airbrake program inspections that found 12.4% of vehicles had brake violations (Transport Topics, 2016). These crashes were eliminated because poorly maintained brakes would decrease the effectiveness of ADB.

Table 17 and Table 18 below show the low, high, and maximum number of crashes and injuries that may be prevented by large-truck ADB. On average, large-truck ADB may prevent 18 to 31 fatal crashes, 497 to 869 injury crashes, and 863 to 1,510 property damage crashes each year. These crashes were associated with 21 to 37 fatalities, 75 to 131 suspected serious injuries, 236 to 414 suspected minor injuries, and 478 to 836 possible injuries.

Table 17. Average Number of Crashes by Efficacy Rate That May Be Prevented Each Year with a Large-Truck ADB (Data from 2010 to 2015 GES and FARS)

Crash Severity	Number of Crashes		
	Low Efficacy (10%)	High Efficacy (15%)	Maximum Efficacy
Fatal	18	31	128
Injury	497	869	3,549
Property Damage	863	1,510	6,165
Total	1,378	2,411	9,842

Table 18. Average Number of Injuries by Efficacy Rate That May Be Prevented Each Year with a Large Truck ADB (Data from 2010 to 2015 GES and FARS)

Injury Severity	Number of Injuries		
	Low Efficacy (30%)	High Efficacy (47%)	Maximum Efficacy
Fatal Injury (K)	21	37	152
Suspected Serious Injuries (A)	75	131	535
Suspected Minor injury (B)	236	414	1,689
Possibly Injury (C)	478	836	3,413
Injury Severity Unknown	38	66	269

Equivalent Lives Saved

To estimate the number of fatal equivalents over six years for each of the efficacy rates, the average number of fatalities and injuries was converted from KABCO to MAIS as shown in Table 14 and multiplied by the MAIS matrix (see Table 13). As a result, the installation of air disc brakes in a large truck may prevent 39 to 69 MAIS 1–5 fatal equivalents in addition to the 21 to 37 fatalities, for a total of 60 to 106 fatality equivalents prevented each year (Table 19).

Table 19. Number of Fatal Equivalents Per Year by Efficacy Rate for ADB (Data from 2010 to 2015 GES and FARS)

	Low Efficacy (10%)		High Efficacy (15%)	
	MAIS	**Fatal Equivalent**	**MAIS**	**Fatal Equivalent**
Minor (MAIS 1)	799	24	1398	42
Moderate (MAIS 2)	137	6	240	11
Serious (MAIS 3)	25	3	44	5
Severe (MAIS 4)	18	5	32	9
Critical (MAIS 5)	2	1	4	2
Unsurvivable (MAIS 6)	21	21	37	37
Total Fatal Equivalents		**60**		**106**

Cost of Crashes

Table 20 shows the annual costs of the crashes that may be prevented with ADB for each of the efficacy rates. The societal costs of crashes include medical and emergency costs, environmental and fuel costs, the cost of property damage, costs associated with lost productivity due to roadway congestion, and monetized QALY. In this study, the non-injury (i.e., lost productivity, congestion, and environmental) and injury (i.e., monetized QALY, medical, and emergency) costs were aggregated. To compute these costs, the research team used a procedure established by FMCSA and used in Hickman et al. (2013). This involved multiplying the costs provided by FMCSA (as described in the Methods chapter) by the number of crashes and number of injuries found in Table 17 and Table 18, respectively.

Table 20. Average Annual Cost of Crashes and Their Associated Injuries

	Low Efficacy (10%)	High Efficacy (15%)	100% Efficacy
Number of fatalities	21	37	152
Societal economic cost of crashworthiness	$17,788,332	$31,129,581	$127,059,515
Congestion, property damage and environmental savings	$38,794,056	$67,889,598	$277,100,399
Societal economic costs	$56,582,388	$99,019,179	$404,159,914
Monetized QALY	$558,965,884	$978,190,298	$3,992,613,460
Total monetized value per year	$615,548,272	$1,077,209,477	$4,396,773,374

Analysis Options

When implementing a new technology, several options can be analyzed. The first option includes retrofitting the entire U.S. fleet of large trucks. This approach assumes all new vehicles added to the fleet are equipped with the technology and that old vehicles are retrofitted. For ADB, the advisory panel recommended performing BCA for only CUTs (i.e., not for all large trucks or SUTs). The second approach is what is known as an annual incremental costs analysis. This approach assumes that all new vehicles will be equipped with the technology in 2018 and does not include retrofitting old vehicles. Similar to the first set of analyses, the second set of analyses was only performed for the U.S. fleet of CUTs. Societal benefits are assessed over the life of the vehicle. One of the major drawbacks of this scheme is the fact that it assumes a constant number of vehicles and a constant number of crashes.

New and Old Combination Unit Trucks are Equipped with Air Disc Brakes

This section describes the BCA, which assumed all CUTs (new and old) would be equipped with ADB. A BCA was conducted for two efficacy levels (low and high), three cost levels (low, average, and high), and three discount rates (0%, 3%, and 7%).

The assumptions used in this BCA include:

- Annual increase of 1.5% in the number of trucks,
- Annual increase of 1.5% in the number of drivers,
- One driver per truck,
- One hour of training per driver for the first 10 years followed by a 10% decrease per year, and
- A technology service life of 10 years with a replacement after year 10.

This BCA was conducted for an analysis period of 20 years. Typically, a lead time of two years is provided when regulating new technology on all large trucks. For the present study, the first year in the analysis period was the year 2018.

BCA Results for Retrofitting Entire U.S. Fleet of Combination Unit Trucks

Table 21 shows the BCA using the low efficacy rate (10%) for all CUTs equipped with ADB. For the lower efficiency rate, the low-cost option was the only combination that resulted in a BCR greater than 1 (1.67, 1.60, and 1.51 for 0%, 3%, and 7 % respectively). Furthermore, the results for the low efficacy rate showed that between 665 and 1,211 equivalent lives could be saved over six years, with a net cost per fatality equivalent ranging from $5.16 to $5.78 when all CUTs are equipped with ADB.

Table 21. Results for Retrofitting the Entire U.S. Fleet of CUTs with ADB: Low Efficacy (10%), by Cost and Discount Rate

Fleet CUT	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Equivalent Lives Saved	1,211	915	665	1,211	915	665	1,211	915	665
Vehicle Costs	$5,964	$4,661	$3,560	$14,098	$11,016	$8,415	$21,689	$16,948	$12,946
Training Costs	$1,424	$1,156	$905	$1,424	$1,156	$905	$1,424	$1,156	$905
Total AST Cost	$7,389	$5,817	$4,465	$15,522	$12,172	$9,320	$23,113	$18,104	$13,851
Soc. Savings from Crashworthiness	$356	$269	$195	$356	$269	$195	$356	$269	$195
Congestion, PD and E S	$776	$586	$425	$776	$586	$425	$776	$586	$425
Total Societal Economic Savings	$1,132	$854	$620	$1,132	$854	$620	$1,132	$854	$620
VSL	$11,179	$8,440	$6,125	$11,179	$8,440	$6,125	$11,179	$8,440	$6,125
Total Monetized Savings	$12,311	$9,294	$6,746	$12,311	$9,294	$6,746	$12,311	$9,294	$6,746
Net Cost	$6,257	$4,963	$3,845	$14,390	$11,318	$8,700	$21,982	$17,250	$13,231
Net Cost per Fatal Equivalent	$5.16	$5.43	$5.78	$11.88	$12.37	$13.08	$18.14	$18.86	$19.90
Net Benefit	$4,922	$3,477	$2,280	-$3,211	-$2,878	-$2,574	-$10,802	-$8,810	-$7,105
Benefit-Cost Ratio	**1.67**	**1.60**	**1.51**	**0.79**	**0.76**	**0.72**	**0.53**	**0.51**	**0.49**

Table 22 shows the BCA using a higher efficacy rate (15%) for all CUTs equipped with ADB. As shown in Table 22, the BCA results show the low and average-cost estimates were cost-effective at the high efficacy rate. The high-cost option continued to be non-cost-effective, with BCRs ranging from 0.85 to 0.93. The low-cost option became more attractive with a BCR of 2.92 (0% discount), 2.80 (3% discount), and 2.64 (7% discount) and a net cost per fatality equivalent ranging from $2.55 million to $2.90 million. The average-cost option had BCRs of 1.39 (0% discount), 1.34 (3% discount), and 1.27 (7% discount) and a net cost per fatality equivalent ranging from $6.39 million to $7.08 million. These results showed that high efficacy ADB may save between 1,164 to 2,120 equivalent lives over six years.

Table 22. Results for Retrofitting the Entire U.S. Fleet of CUTs with ADB: High Efficacy (15%), by Cost and Discount Rate

Fleet CUT	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Equivalent Lives Saved	2,120	1,601	1,164	2,120	1,601	1,164	2,120	1,601	1,164
Vehicle Costs	$5,964	$4,661	$3,560	$14,098	$11,016	$8,415	$21,689	$16,948	$12,946
Training Costs	$1,424	$1,156	$905	$1,424	$1,156	$905	$1,424	$1,156	$905
Total AST Cost	$7,389	$5,817	$4,465	$15,522	$12,172	$9,320	$23,113	$18,104	$13,851
Soc. Savings from Crashworthiness	$623	$470	$341	$623	$470	$341	$623	$470	$341
Congestion, PD and E S	$1,358	$1,025	$744	$1,358	$1,025	$744	$1,358	$1,025	$744
Total Societal Economic Savings	$1,980	$1,495	$1,085	$1,980	$1,495	$1,085	$1,980	$1,495	$1,085
VSL	$19,564	$14,770	$10,720	$19,564	$14,770	$10,720	$19,564	$14,770	$10,720
Total Monetized Savings	$21,544	$16,265	$11,805	$21,544	$16,265	$11,805	$21,544	$16,265	$11,805
Net Cost	$5,408	$4,322	$3,380	$13,542	$10,677	$8,235	$21,133	$16,609	$12,766
Net Cost per Fatal Equivalent	$2.55	$2.70	$2.90	$6.39	$6.67	$7.08	$9.97	$10.38	$10.97
Net Benefit	$14,155	$10,448	$7,340	$6,022	$4,092	$2,485	-$1,569	-$1,840	-$2,046
Benefit-Cost Ratio	**2.92**	**2.80**	**2.64**	**1.39**	**1.34**	**1.27**	**0.93**	**0.90**	**0.85**

Sensitivity Analysis for Retrofitting the Entire U.S. Fleet of Combination Unit Trucks with Air Disc Brakes

Sensitivity analyses were performed for a $13,260,000 VSL and $5,304,000 VSL. Since many of the analyses were not cost-effective, lowering the VSL would only make these systems less cost-effective. Thus, only the results with the higher VSL are shown below. The results with the lower VSL are shown in Appendix C. Table 23 shows the results using the low efficacy. The analyses with a BCR greater than 1.00 are highlighted. Using the low efficacy rate with a $13,260,000 VSL resulted in a CBR greater than 1.00 for the low- and average-cost estimates (except for the average-cost ADB with a 7% discount rate).

Table 23. Sensitivity Analysis for Retrofitting the Entire U.S. Fleet of CUTs with ADB with a $13,260,000 VSL: Low Efficacy (10%), by Cost and Discount Rate

Fleet	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs	2.29	2.19	2.07	1.09	1.05	0.99	0.73	0.70	1.09

Table 24 shows the results using the high efficacy rate. The high efficacy rate with a $13,260,000 VSL resulted in a BCR greater than 1.00 for each of the cost estimates.

Table 24. Sensitivity Analysis for Retrofitting the Entire U.S. Fleet of CUTs with ADB with a $13,260,000 VSL: High Efficacy (15%), by Cost and Discount Rate

Fleet	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs	4.00	3.84	3.63	1.91	1.83	1.74	1.28	1.23	1.91

Only New Combination Unit Trucks are Equipped with Air Disc Brakes

For the incremental BCA, a constant number of vehicles per year was assumed (in this case 170,000 CUTs). These numbers were obtained by computing the average number of Class 7 and 8 trucks sold in the U.S. Davis et al. (2016) found that 80% of class 8 and 10% of class 7 trucks are CUTs and the remaining trucks are SUTs (see Table 25). The average number of new SUTs and CUTs that entered the market for the same analysis period as for the crash analysis was 81,000 and 15,500, respectively.

Table 25. Total Number of Large-Truck SUTs and CUTs Sold (thousands), 2010–2015

Year	GVWR Class 7	GVWR Class 8	SUT	CUT
2010	38	107	55.6	89.4
2011	41	171	71.1	140.9
2012	47	195	81.3	160.7
2013	48	185	80.2	152.8
2014	54	220	92.6	181.4
2015	59	249	102.9	205.1
Average			81	155

The total number of crashes that each of these vehicles will experience during their lifetime will equal the annual number of crashes computed for the previous analysis. However, the crashes may occur any time during the vehicle's lifetime, and it was assumed they followed the same distribution of the weighted average of VMT and survival rate. Thus, the crashes were discounted by applying a multiplicative factor of 0.8389 for a 3% discount rate and 0.6899 for a 7% rate. Since this analysis applied only to the new trucks entering the market, system replacement was assumed to occur when the truck reached the 50% weighted average lifetime VMT. This represented an increase in the vehicle cost of the technology of 7.4% (0% discount rate), 12% (3% discount rate), and 15% (7% discount rate). Results presented were for the calendar year replacement. In this study, the research team used the same CUT survival rates as the FMCSA electronic logging device mandate (Federal Motor Vehicle Safety Standards; Electronic Logging Devices).

The number of drivers receiving training will be proportional to the number of vehicles surviving. The number of drivers receiving training followed the same scenario as described above, where each surviving truck had a driver, but the percentage of drivers receiving training was reduced by 10% after year 10. The hourly cost per driver and the cost of the technology continued to be the same as described above. The major difference was that the crashes were reduced using the new accelerated discount factors.

BCA Results for Equipping Only New Combination Unit Trucks with Air Disc Brakes

Table 26 shows the results for the low efficacy rate for all new CUTs (10%). Similar to the results for deploying ADB across the entire U.S. fleet of CUTs, both the low- and average-cost estimates were cost-effective with the low efficacy rate. The low-cost estimate had BCRs ranging from 2.26 to 2.62 (net cost per fatality equivalent ranged from $2.94 million to $3.56 million), and the average-cost estimate had BCRs ranging from 1.13 to 1.33 (net cost per fatality equivalent ranged from $6.70 million to $8.08 million). Additionally, low-efficacy air disc brakes were shown to save 39 to 61 equivalent lives over six years when all new CUTs were equipped with ADB.

Table 26. Results for Equipping all New CUTs with ADB: Low Efficacy (10%), by Cost and Discount Rate

Fleet CUT	Low Cost			Average Cost			High Cost		
	0%	**3%**	**7%**	**0%**	**3%**	**7%**	**0%**	**3%**	**7%**
Equivalent Lives Saved	61	49	39	61	49	39	61	49	39
Vehicle Costs	$167	$148	$129	$395	$349	$305	$607	$537	$469
Training Costs	$68	$57	$46	$68	$57	$46	$68	$57	$46
Total AST Cost	$235	$204	$175	$463	$406	$351	$675	$593	$515
Soc. Savings from Crashworthiness	$18	$14	$11	$18	$14	$11	$18	$14	$11
Congestion, PD and E S	$39	$31	$25	$39	$31	$25	$39	$31	$25
Total Societal Economic Savings	$57	$46	$36	$57	$46	$36	$57	$46	$36
VSL	$559	$452	$359	$559	$452	$359	$559	$452	$359
Total Monetized Savings	$616	$498	$396	$616	$498	$396	$616	$498	$396
Net Cost	$178	$158	$138	$406	$360	$314	$618	$548	$479
Net Cost per Fatal Equivalent	$2.94	$3.23	$3.56	$6.70	$7.34	$8.08	$10.21	$11.17	$12.29
Net Benefit	$381	$294	$221	$153	$93	$45	-$59	-$95	-$119
Benefit-Cost Ratio	**2.62**	**2.44**	**2.26**	**1.33**	**1.23**	**1.13**	**0.91**	**0.84**	**0.77**

As shown in Table 27, all cost estimates were cost-effective at the high efficacy rate (15%) when all new CUTs (no retrofitting) were equipped with ADB. The low-cost estimate had BCRs ranging from 3.96 to 4.59 (net cost per fatality equivalent ranged from $1.28 to

$1.63), the average-cost estimate had BCRs ranging from 1.97 to 2.33 (net cost per fatality equivalent ranged from $3.43 million to $4.21 million), and the high-cost estimate had BCRs ranging from 1.34 to 1.60 (net cost per fatality equivalent ranged from $5.43 million to $6.63 million). The high-efficacy air disc brakes were shown to save 68 to 106 equivalent lives over six years when all new CUTs were equipped with ADB.

Table 27. Results for Equipping All New CUTs with ADB: High Efficacy (15%), by Cost and Discount Rate

Fleet CUT	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Equivalent Lives Saved	106	86	68	106	86	68	106	86	68
Vehicle Costs	$167	$148	$129	$395	$349	$305	$607	$537	$469
Training Costs	$68	$57	$46	$68	$57	$46	$68	$57	$46
Total AST Cost	$235	$204	$175	$463	$406	$351	$675	$593	$515
Soc. Savings from Crashworthiness	$31	$25	$20	$31	$25	$20	$31	$25	$20
Congestion, PD and E S	$68	$55	$44	$68	$55	$44	$68	$55	$44
Total Societal Economic Savings	$99	$80	$64	$99	$80	$64	$99	$80	$64
VSL	$978	$792	$629	$978	$792	$629	$978	$792	$629
Total Monetized Savings	$1,077	$872	$692	$1,077	$872	$692	$1,077	$872	$692
Net Cost	$136	$124	$111	$363	$325	$287	$576	$513	$451
Net Cost per Fatal Equivalent	$1.28	$1.45	$1.63	$3.43	$3.79	$4.21	$5.43	$5.98	$6.63
Net Benefit	$842	$668	$517	$615	$466	$342	$402	$279	$177
Benefit-Cost Ratio	**4.59**	**4.27**	**3.96**	**2.33**	**2.15**	**1.97**	**1.60**	**1.47**	**1.34**

Sensitivity Analysis for Only Equipping New Combination Unit Trucks with Air Disc Brakes

Similar to the analyses for equipping the entire U.S. fleet of CUTs, sensitivity analyses were performed for a $13,260,000 VSL and $5,304,000 VSL. Only the results with the higher VSL are shown below. The results with the lower VSL are shown in Appendix C. The results with the higher VSL are shown in Appendix C. Table 28 shows the results based on the low efficacy rate. The low efficacy rate with a $13,260,000 VSL resulted in cost-effective solutions for all of the cost estimates.

Table 28. Sensitivity Analysis for Equipping All New CUTs with ADB Using $13,260,000 VSL: Low Efficacy (10%), by Cost and Discount Rate

Fleet	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs	3.60	3.35	3.11	1.83	1.69	1.55	1.25	1.15	1.05

As shown in Table 29, a $13,260,000 VSL and high efficacy resulted in all cost estimates being cost-effective.

Table 29. Sensitivity Analysis for Equipping All New CUTs with ADB Using a $13,260,000 VSL: High Efficacy (15%), by Cost and Discount Rate

Fleet	Low Cost			Average Cost			High Cost		
	0%	**3%**	**7%**	**0%**	**3%**	**7%**	**0%**	**3%**	**7%**
Only CUTs	6.30	5.86	5.44	3.20	2.95	2.71	2.19	2.02	1.85

Discussion

This study assessed scientifically-based estimates of the societal benefits and costs of ADB installed on CUTs. This study also assessed the societal benefits and costs of automatic emergency braking systems, lane departure warning systems, and video-based onboard safety monitoring systems; the assessment results of these ASTs are presented in separate AAAFTS reports. In addition to these ASTs, other ASTs were considered; however, the advisory panel selected ASTs that were not mandated, had empirical research evaluating the efficacy of the system, had an outdated BCA, or for which a BCA was not available. Although the literature review identified efficacy rates for ADB, these estimates were before NHTSA's 2013 mandate for improved braking performance of large trucks. Thus, the advisory panel recommended using lower efficacy rates in the analysis to better reflect the efficacy ADB relative to other braking systems that also meet the current braking performance standard. Crashes were identified using 2010 to 2015 GES and FARS data sets. Additionally, 12.4% of rear-end, truck striking crashes were excluded from the analyses to account for out-of-adjustment brakes. BCAs were performed using varying efficacy rates (low and high), costs (low, average, and high), and discount rates (0%, 3%, and 7%).

Lower and upper bound efficacy rates were used to estimate the benefits and costs associated with implementing ADB across the entire U.S. fleet of CUTs. This study used a lower and upper bound efficacy rate of 10% to 15%, respectively. Additionally, 12.4% of large-truck striking rear-end crashes were excluded from the analyses to account for out-of-adjustment brakes. This study found that ADB with a 10% efficacy may prevent 1,378 total rear-end crashes, 513 injury crashes (789 total injuries), and 18 fatal crashes (21 total fatalities) each year. ADB with a 15% efficacy may prevent 2,411 total rear-end crashes, 897 injury crashes (1,381 total injuries), and 31 fatal crashes (37 total fatalities) each year. Only two studies were found in the literature review that provided estimates on the number of crashes that may be prevented with ADB. Garrott and Dunn (2007) estimated that ADB could prevent 257 fatalities and 284 serious injuries associated with rear-end, truck striking crashes. However, these estimates were based on NHTSA's old stopping-distance regulations. Following Garrott and Dunn (2007), NHTSA required all large-truck brakes to improve stopping distance by 30%, including drum brakes and ADB. Thus, the number of crashes that may be prevented with ADB today are likely much lower than the results presented in Garrott and Dunn (2007). Salaani et al. (2010) found that ADB may reduce crashes by 43.2%; however, the authors obtained this estimate with a driving simulator, and thus, that figure may not reflect real-world effectiveness. Additionally, the study may not reflect the updated NHTSA stopping-distance regulations. Despite the sparse research into ADB, the results from this study were somewhat similar to those in Garrott and Dunn (2007). Although the number of fatalities that may be prevented with ADB in this study was lower than in Garrott and Dunn (2007), the number of injury crashes was similar.

Two sets of BCAs were conducted for ADB. Each set of analyses used a lower-bound efficacy rate (10%) and upper-bound efficacy rate (15%). Unlike the other ASTs, these analyses were only performed on crashes involving CUTs. The first set of BCAs estimated the cost-effectiveness of equipping all new and old CUTs with ADB. These analyses showed BCRs ranging from 0.49 to 1.67 using the low efficacy rate and 0.85 to 2.92 using the high efficacy rate. The second set of BCAs estimated the cost-effectiveness of equipping only new CUTs with ADB. These analyses showed BCRs ranging from 0.77 to 4.59 with the high efficacy rate.

The literature review did not identify any prior BCAs for ADB. Thus, it is not possible to compare the results of these analyses. However, these analyses did show that air disc brakes were cost-effective, regardless of cost, if they can prevent 15% of rear-end, truck striking crashes. If air disc brakes were shown to prevent 10% of crashes, only the low cost ($700) estimate was found to be cost-effective. Additionally, fleets often cite less frequent maintenance as a major factor in deciding to purchase ADB. It is possible these maintenance cost savings were not adequately captured in these BCAs; thus, the cost-effectiveness of ADB may be higher.

Conclusions

This study only considered ADB for CUTs. The results showed that air disc brakes were cost-effective given a low cost of $700. An average cost of $1,300 was also found to be cost-effective given a 15% efficacy rate and regulation only of new CUTs. Even a high cost of over $2,000 was shown to be cost-effective with a 15% efficacy rate when only new CUTs were regulated to be equipped with ADB. Thus, these results provide some guidance regarding the potential for regulating ADB on CUTs. Similar to the results found for automatic emergency braking systems (located in a separate AAAFTS report), the results showed that retrofitting old vehicles would not be cost-effective unless the costs can be reduced from $1,300 (or a 15% efficacy can be achieved). However, these analyses do suggest that installing ADB on all new CUTs would likely be cost-effective if it could be accomplished at or lower than the average cost used in the analyses reported here.

Limitations

Although the analyses used to assess the benefit-costs associated with ADB were comprehensive, there were several limitations.

- It is possible the efficacy rates used in this study may not represent the current functionality/effectiveness of the current generation of ADB relative to other braking systems that meet current braking performance standards. The research team did not find any research regarding the efficacy of ADB after NHTSA’s 2013 mandate (Federal Motor Vehicle Safety Standards; Air Brake Systems, 2013). However, the advisory panel consisted of experts with knowledge of current technology performance; thus, the efficacy rates recommended by the advisory panel for use in the analysis are believed to be reasonable estimates of ADB efficacy.
- The technology costs used in this study may differ from current costs (with costs typically decreasing over time).
- It is possible maintenance cost savings associated with ADB were not adequately captured in these BCAs; thus, the cost-effectiveness of ADB may be higher or lower.
- This study used estimated crash, technology, and labor costs. It is possible that actual costs may differ, and thus impact the cost-effectiveness of ADB.

- The GES only included crashes that required a police accident report. However, ADB may also prevent less severe crashes. Thus, these additional benefits are not accounted for in the BCAs.
- The real-world effectiveness against different severity crashes may differ significantly. However, data limitations excluded the use of separate efficacy estimates for this study.
- These analyses did not account for reduced litigation costs associated with reduced crashes. These may be significant cost savings that were not integrated into the analyses.
- This study assumed all vehicle systems were functioning as intended. However, this is unlikely to be seen in the real world. Specifically, anti-lock brakes and foundation brakes have a direct impact on a vehicle's ability to avoid a crash. If they are poorly maintained, their efficacy rates would likely be lower than those assumed in the current study.

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Appendix A: Literature Review Summary Table

Citation	**Title**	**AST**	**Effectiveness and/or cost**
Air Disc Brakes (ADB)			
Garrott & Dunn (2007)	NHTSA research efforts to significantly improve braking performance of medium and heavy trucks	ADB	• Reduction of 20–30% in stopping distance • A 20% improvement in stopping distance would prevent 104 fatalities, 120 serious injuries (AIS3-5), and save between $27M (7% discount rate) and $32M (3% discount rate). • A 30% improvement in stopping distance would prevent 257 fatalities, 284 serious injuries (AIS3-5), and save between $136M (7% discount rate) and $166M (3% discount rate). • Costs associated with technology to achieve 30% improvements = $1,308 per vehicle for ADB on all axles. Cost for ADB on just the steer axle = $536 per vehicle.
Salaani et al. (2010)	Study of heavy truck S-cam, enhanced S-cam, and air disc brake models using NADS	ADB	• Right roadside incursion: slight decrease in collisions. Statistically significant reduction in stopping distance. • Left roadside incursion: reduction in collisions. • Stopping vehicle: fewer collisions. • Stopped vehicle: fewer collisions. Only brake system effective. • Air disc brakes achieved the highest deceleration g-forces compared to the other braking systems.

Citation	**Title**	**AST**	**Effectiveness and/or cost**
Battelle (2007)	Final report: Evaluation of the Volvo intelligent vehicle initiative field operational test, version 1.3	ADB with an electronically controlled braking system	• No specific crash reduction provided for ADB, only ADB coupled with automatic cruise control.
Silvani et al. (2009)	Independent evaluation of electronically controlled braking systems	ADB coupled with electronic stability control and adaptive cruise control	• No specific crash reduction provided for ADB, only ADB coupled with electronic stability control and adaptive cruise control.

Appendix B: GES/FARS Crash Filtering Inclusion Variables

1. Vehicle Body Type
    a. 63: Single-Unit Straight Truck or Cab-Chassis(GVWR > 26,000 lbs)
    b. 64: Single-Unit Straight Truck or Cab-Chassis(GVWR unknown)
    c. 66: Truck-Tractor
    d. 68: Single-Unit Straight Truck (GVWR unknown)
    e. 72: Unknown if Single-Unit or Combination-Unit Heavy Truck (GVWR > 26,000 lbs)
    f. 78: Unknown Medium/Heavy Truck Type

2. Accident Type
    a. 11: Single Driver, Forward Impact, Parked Vehicle
    b. 20: Same Trafficway, Same Direction, Rear End, Stopped
    c. 24: Same Trafficway, Same Direction, Rear End, Slower
    d. 28: Same Trafficway, Same Direction, Rear End, Decelerating
    e. 34: Same Trafficway, Same Direction, Forward Impact, This Vehicle's Fontal Area Impacts Another Vehicle
    f. 36: Same Trafficway, Same Direction, Forward Impact, This Vehicle's Fontal Area Impacts Another Vehicle
    g. 38: Same Trafficway, Same Direction, Forward Impact, This Vehicle's Fontal Area Impacts Another Vehicle
    h. 40: Same Trafficway, Same Direction, Forward Impact, This Vehicle's Fontal Area Impacts Another Vehicle

3. Pre-event Movement
    a. 1: Going Straight
    b. 2: Decelerating in Road
    c. 3: Accelerating in Road

4. Critical Event – Pre-crash
    a. 50: Other Motor Vehicle in Lane, Other Vehicle Stopped
    b. 51: Other Motor Vehicle in Lane, Traveling in Same Direction with Lower Steady Speed
    c. 52: Other Motor Vehicle in Lane, Traveling in Same Direction while Decelerating
    d. 53: Other Motor Vehicle in Lane, Traveling in Same Direction with Higher Speed

5. Police-Reported Alcohol Involvement
    a. 0: No (Alcohol Not Involved)

6. Police-Reported Drug Involvement
    a. 0: No (Drugs Not Involved)

7. Impairment at Time of Crash – Driver
    a. Removed 1: Ill/Blackout

8. First Harmful Event
    a. 12: Collision with Motor Vehicle in Transport, Motor Vehicle in Transport
    b. 55: Collision with Motor Vehicle in Transport, Motor Vehicle in Motion Outside the Trafficway

Appendix C: Additional Analyses

Table 30. Sensitivity Analysis for Retrofitting the Entire U.S. Fleet of CUTs with ADB using a $5,304,000 VSL by Low Efficacy (10%), Cost, and Discount Rate

Fleet	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs	1.01	0.97	0.91	0.48	0.46	0.44	0.32	0.31	0.29

Table 31. Sensitivity Analysis for Retrofitting the Entire U.S. Fleet of CUTs with ADB using a $5,304,000 VSL by High Efficacy (15%), Cost, and Discount Rate

Fleet	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs	1.76	1.69	1.60	0.84	0.81	0.77	0.56	0.54	0.52

Table 32. Sensitivity Analysis for Equipping Only New CUTs with ADB using a $5,304,000 VSL by Low Efficacy (10%), Cost, and Discount Rate

Fleet	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs	1.58	1.47	1.37	0.80	0.74	0.68	0.55	0.51	0.46

Table 33. Sensitivity Analysis for Equipping Only New CUTs with ADB using a $5,304,000 VSL by High Efficacy (15%), Cost, and Discount Rate

Fleet	Low Cost			Average Cost			High Cost		
	0%	3%	7%	0%	3%	7%	0%	3%	7%
Only CUTs	2.77	2.58	2.39	1.41	1.30	1.19	0.96	0.89	0.81