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Under the Intelligent Vehicle Initiative (IVI), this study was funded to increase the understanding of the performance benefits of leading-edge foundation brake technologies and advanced brake control systems for tractor-trailers. It has been documented in previous U.S. Department of Transportation studies that brake failures are the leading cause of failed roadside inspections. For a variety of reasons, brake systems in the North American commercial truck market have not adopted new technology as rapidly as the European market. The reliability, durability, and maintenance impacts of the new brake technologies have not been clearly documented. This study analyzes the impacts of brake technologies, as well as presents other technology that is enabled though the introduction of this new technology.

North American commercial trucks rely predominantly on pneumatically controlled drum brakes. This study establishes four configurations to test the available brake technologies. The templates are anti-lock braking system (ABS) tractors with pneumatic drum brakes, ABS tractors with pneumatic disc brakes, advanced ABS tractors with pneumatic disc brakes, and electronically controlled brake system tractors with disc brakes. Three tractor configurations employed some form of stability control. In addition, tractors were equipped with adaptive cruise control (ACC).

The study focuses on documenting the operating characteristics over a period of one year. The study profiles brake technologies and gathers performance measures. The study also analyzes driver behavioral changes. Maintenance data for all brake technologies was gathered over a period of 16 months. The study discusses cost, reliability, and durability of each system, as well as compatibility of each technology with each other. In addition, driver and mechanic responses to survey questions are shown. ACC and stability control, both of which are enabled through the use of advanced control technologies, are evaluated. Driver reaction as well as safety benefits of ACC are also calculated. This study will be helpful to fleet owners considering adoption of advanced brake technologies and interested in learning the possible cost, safety, maintenance, and training implications.

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EXECUTIVE SUMMARY

Background and Rationale

The Intelligent Vehicle Initiative (IVI) was authorized under the 1998 Transportation Equity Act for the 21st Century (TEA-21). IVI was established with the goal of reducing motor vehicle crashes and incidents through research, development, testing, evaluation, and deployment of safety devices and systems. The IVI program supports the development of performance guidelines, architectures, and standards for intelligent transportation systems (ITS) and will test and evaluate promising safety technologies in cooperation with the automotive, truck, and bus industries and other industry stakeholders. The targeted safety technologies must be commercially viable, implementable in the near term, and accepted through driver demonstration. One promising technology meeting these criteria is electronically controlled braking systems (ECBS). ECBS promotes safety benefits indirectly by enabling advanced technologies to be electronically (rather than pneumatically) integrated with braking systems on heavy truck platforms. Key safety systems enabled by ECBS may include stability control and adaptive cruise control with collision mitigation. ECBS may directly improve safety by reducing brake signal actuation time (particularly to the rear axle(s) of the trailer) and by providing improved control over the ABS control valves.

ECBS has become standard technology on many tractors and trucks sold and operated in Europe. The market switchover from anti-lock braking systems (ABS) to ECBS began in the mid 1990s and generally was accompanied by a switch from drum to disc brake systems. For a variety of technological and market-based circumstances, ECBS for heavy-duty trucks has not gained commercial acceptance in the North American market. Key factors include:

- ECBS is more expensive than ABS;
- The performance benefits of ECBS alone (i.e., not in combination with disc brakes) have not been clearly documented in terms of stopping distance and safety improvements;
- The durability, reliability, and maintainability of ECBS has not been verified for North American applications and operating environments;
- ECBS is generally understood to be an “enabler” of braking control technologies (such as stability control) can offer major improvements in brake performance. However, as a stand-alone system, benefits may be moderate and not perceived as a “good value” by some fleet operators;
- Lack of a standard high-speed network connection between tractor and trailer limits development of an “optimal” ECBS control strategy for the combination vehicle, which therefore limits the relative benefits of ECBS compared to standard ABS; and
- More so than in the European market, North American tractors and trailers are of varying age, design, and even ownership, and must be compatible with one another.

With regard to the above commercialization challenges, the U.S. Department of Transportation (DOT) sponsored the field operational test of ECBS under the IVI.

Program Goals and Objectives

The main goals of the ECBS field operational test (FOT) were to achieve an improved understanding of the overall performance, reliability, maintainability, and safety of ECBS in over-the-road, revenue-generating environments and to evaluate advanced safety systems that were integrated into both ECBS and non-ECBS platforms.

Objectives of the ECBS FOT included:

- Evaluate the reliability and durability of ECBS in various real-world environments;
- Evaluate ECBS-enabled technologies. These included Stability Control and Adaptive Cruise Control with Collision Mitigation;
- Evaluate Advanced ABS (pneumatically controlled) systems with enabled technologies. This included roll stability systems;
- Evaluate air disc brake system performance relative to s-cam drum brake technology;
- Compare overall performance of ECBS systems (and enabled technologies) with that of advanced pneumatically controlled ABS systems (and enabled technologies);
- Assess overall maintainability of ECBS relative to scheduled and unscheduled maintenance requirements;
- Evaluate the compatibility of tractor and trailer ECBS from different vendors and with conventional ABS;
- Evaluate impacts on safety in terms of reducing crash or near-crash situations;
- Assess driver perceptions regarding performance, safety, and handling impacts of ECBS-equipped vehicles; and
- Determine any changes in driver behavior associated with ECBS over the course of the FOT period.

Description of Field Operational Test

The U.S. DOT selected the Freightliner LLC (Freightliner) team to participate in demonstrating ECBS technology and enabled technologies in revenue-generating service. Freightliner’s team was comprised of six members—Freightliner, Wal-Mart, MeritorWabco, Bendix, Battelle, and Aberdeen Test Center.

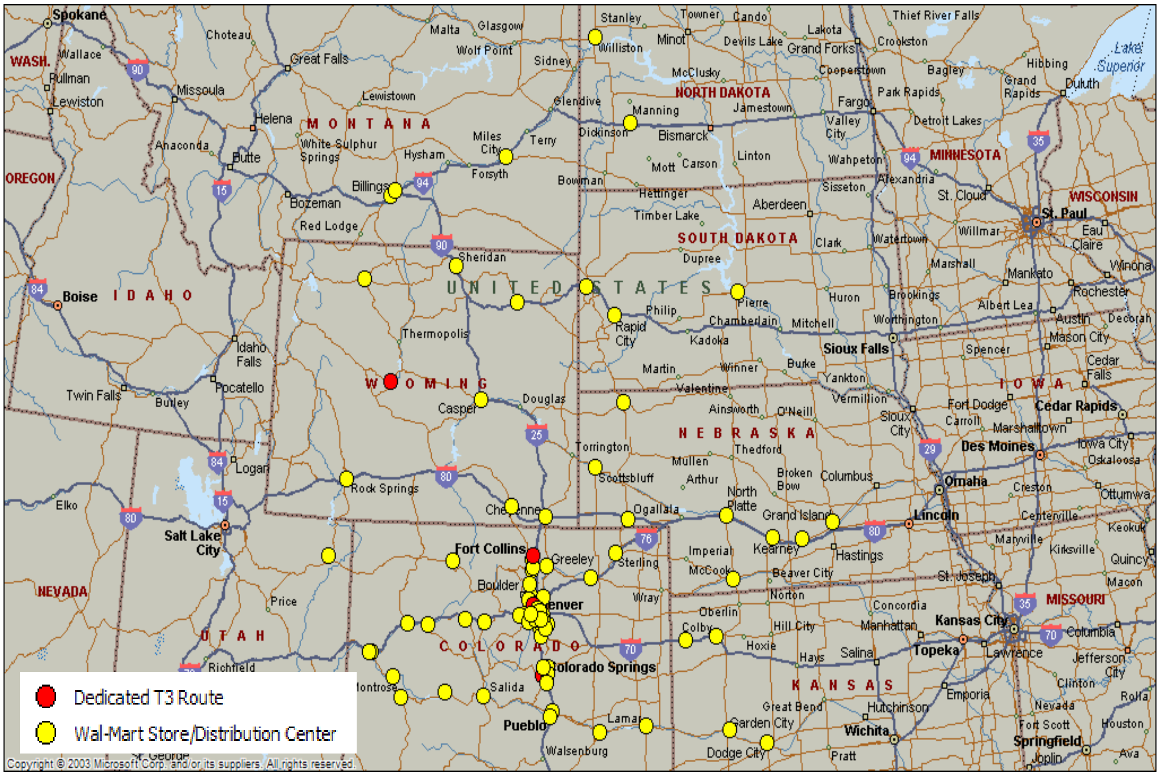
Forty-eight tractors and 100 trailers were fielded under the program. The tractors and trailers were divided into two templates. The first template, called Template 2 from the original research proposal, was designed to simulate the introduction of advanced braking technologies into the trucking market. Advanced braking technologies from different manufacturers were intended to intermix with one another and with tractors and trailers with conventional braking technologies. The second template, Template 3, was designed to demonstrate ECBS on tractor-trailer combination units and to determine the safety benefits of an optimized braking system where both the tractor and trailer were equipped with ECBS and capable of exchanging information over a high-speed data connection.

The duration of the field test was 12 months starting in May 2005 and ending in April and July 2006, with data being collected until the final vehicle was decommissioned in July 2006. During the first six months (Phase 1), the enabled technologies were off, and during the second six months (Phase 2), the enabled technologies (i.e., stability control and adaptive cruise control) were turned on. Template 3 drivers were profiled in existing tractors to establish a driving baseline for approximately two months prior to receiving their new FOT tractors. It is important to note that the adaptive cruise control (ACC) forward radar sensor was on the entire 12 months and used to monitor driver's behavior during all modes of operation.

All 48 tractors and Template 2 trailers were equipped with an on-board data acquisition system (DAS). Template 3 trailer data were transmitted and stored on the tractor's DAS when attached to a Template 3 tractor. Electronic data were stored on a PCMCIA memory card internal to the DAS, routinely removed and replaced by Wal-Mart, and forwarded to the Freightliner team. The Freightliner team was responsible for downloading the data, performing integrity checks to make sure the data were within the proper ranges, and flagging erroneous data. Empty memory cards were returned to Wal-Mart for reuse. The data were recorded on DVDs and forwarded to Booz Allen for analysis.

Wal-Mart hosted the FOT out of its Loveland, Colorado, distribution facility. Wal-Mart operates 38 distribution facilities that serve over 2,700 stores. On average, there are 135 tractors and 1,100 trailers per distribution center. The Loveland distribution facility was chosen as the FOT host site for its center-to-store operation, geographical location, and size. Exhibit ES-1 shows the stores supported by the Loveland facility.

Exhibit ES-1: Wal-Mart Store Locations Supported Loveland, CO Distribution Facility



Technologies Under Evaluation

Freightliner proposed evaluating ECBS technology along with several advanced braking and safety technologies. The technologies evaluated under this FOT include:

1. ECBS featuring roll and yaw stability control
2. Advanced ABS with roll control
3. Air disc brakes
4. ACC and collision mitigation systems integrated with other truck subsystems.

Electronically Controlled Brake Systems. ECBS is an advanced brake control system technology that controls the brakes electronically rather than pneumatically. In practice, these electronic control systems are laid over the existing pneumatic controls of a braking system. The common control layout in the U.S. and European markets is a “1E/2P” system featuring a primary electronic control system (1E) and dual pneumatic backup systems (2P). The conventional pneumatic control remains as a backup in the event of an electronic control failure and to ensure compliance with current pneumatic brake regulations (FMVSS No. 121). MeritorWabco is the manufacturer of the tractor-based ECBS evaluated under this program. The system featured a roll and yaw stability control system (ESC). Bendix supplied an ECBS system designed specifically for trailers featuring a roll stability program. The TEBS4 system overlays a single electronic circuit over the pneumatic control circuit, which serves as a backup circuit per FMVSS No. 121. The system uses conventional pneumatic supply and service line connections to the trailer.

Advanced ABS. Advanced ABS is based on a traditional ABS control system that modulates the air pressure in the brake chambers to prevent wheel lock-up and provide braking control during over-braking maneuvers. ABS monitors wheel speeds at all times and controls braking during wheel-lock situations. The ability to limit wheel-lock situations enhances vehicle stability, reduces the possibility of jackknifing, and enables steering under extreme braking conditions. MeritorWabco and Bendix supplied advanced ABS systems for evaluation under this program. MeritorWabco's system featured roll stability control (RSC), which improves vehicle stability during high lateral acceleration maneuvers such as evasive lane changes and tight radius curves.

Air Disc Brake (ADB). Bendix supplied its ADB 22X air disc brake. The brake is manufactured in partnership with Knorr-Bremese Group and Dana Corporation. The brake is designed for installation with 22.5-inch rims, via two slide pins. The ADB 22X uses a dual-piston configuration on the inboard side of the caliper. The dual-piston design provides precise brake adjustment, better force distribution, and even pad wear. The Bendix ADB 22X is assembled with a mono-block caliper to provide an overall weight of 78 pounds. The assembly provides a brake torque of up to 15,000 foot-pounds.

Adaptive Cruise Control (ACC) with Collision Mitigation System (CMS). MeritorWabco's ACC is designed to maintain a safe following interval (in seconds) to the preceding vehicle. The system uses a radar sensor to track the forward vehicle's speed, range, and bearing and uses sophisticated software to determine whether the target vehicle is in the same lane. To maintain a safe following interval, the ACC is integrated with, and can control, the throttle, engine brake, and foundation brakes. When ACC is disabled, the engine brake depowers the truck engine to decelerate as designed prior to the introduction of ACC.

Data Sources

Four sources of data were used to perform an assessment of the advanced braking and enabled technologies under evaluation:

- On-board electronic data
- Maintenance records
- Driver and technician surveys
- Brake system inspections

On-board electronic data were received from the tractor's communication networks (J1708, J1939, and CAN ISO 11992), analog sensors, and digital sensors and stored in an on-board DAS. Data was sampled at 10 Hz (i.e., 10 samples per second) from engine key on to key off for a period of 12 months generating two terabytes of electronic data. Maintenance records for brakes, wheel ends, and tires from all FOT tractors were collected at 6 and 12 months, totaling 582 repair orders. Driver and maintenance technicians were surveyed on their experiences operating and maintaining the equipment under evaluation. Surveys were administered at the beginning of the FOT regarding their knowledge to determine past experiences with the equipment, and after 6 and 12 months of operation. Physical brake inspections were performed on 15 tractors and 4 trailers. The brakes were inspected for pad, rotor, shoe, drum wear, and overall condition per established methods.

Metadata

A total of 3,558,187 "data miles" were collected during the ECBS FOT between May 1, 2005, and July 2006. "Data miles" represent the total miles accumulated based on the start and stop mileage of each data file. The official FOT end date occurred on April 30, 2006. However, data continued to be collected up until the time the tractors and trailers were decommissioned. The vehicles were decommissioned during June and July 2006. Out of the total data miles collected, Phase 1 generated 2,381,936 data miles, and Phase 2 generated 1,176,251 data miles.

The tractors traveled more miles than are reported above; however, these are the total number of miles that generated data (i.e., functioning DAS). In addition to the miles traveled by the FOT tractors, the eight Template 3 drivers were profiled in their existing Wal-Mart tractors for a minimum of 2 months prior to the FOT start. These eight drivers generated 138,258 miles during this period (Phase 0). Seventy-one percent of the miles were generated at average speeds of between 60 and 70 miles per hour. Eighty-six percent of the tractor data miles occurred at speeds above 50 miles per hour, whereas 64 percent of the hours (engine run time) occurred at 10 miles per hour or less. Out of the 57,629 hours logged at less than 10 miles per hour, 20 percent of them occurred while idling. The average hours driven per tractor configuration per day varied from 6 to 14 hours per day depending on the tractor configuration and operating routes.

There were 1.19 million total brake applications for the 47 tractors participating in the FOT. Thirty-one percent of the brake applications occurred with an initiation speed of 10 miles per hour or less. One tractor was damaged beyond repair in transit from the Freightliner manufacturing facility to Loveland, Colorado. No crashes occurred during the FOT.

Data Quality

On-board electronic data were received from the tractor's communication networks (J1708, J1939, and CAN ISO 11992), analog sensors, and digital sensors. A majority of the data were suitable for use in evaluating the performance of the systems. Unfortunately, critical sensors produced noisy, unusable, or low-resolution data, and others were incorrectly recorded. The absence of these data limited the breadth of the analysis and prevented the safety benefits analysis from being performed on ECBS. The faulty sensors include steering angle sensor on non-ECBS Template 2 tractors (unusable), Template 3 steering angle sensor (low resolution), ABS signal on all but the tractors with ABS6/Disc brakes (recorded incorrectly), wheel-speed sensors on drive axle (unusable), RSC activation signal (not broadcast or not recorded), longitudinal accelerometer (excessive noise), and the lateral accelerometer (excessive noise). Lateral acceleration is a key input for assessing the ECBS stability control system. For this reason, a significant effort was made to make these data usable. However, even with the use of sophisticated data smoothing algorithms, the data were not usable for analysis. Future programs should seek to identify commercial data acquisition systems design for the rigors of the trucking industry.

Safety

The benefits observed from the different brake technologies occurred as a result of improved braking performance and changes in drivers' behavior when the technology was present.

Although maximum braking performance was not measured during this FOT, braking events were analyzed and compared for each brake technology. Improved performance of the brakes was most clearly reflected in improved stability during braking. In addition, drivers' comments and their driving behavior were used to gauge the effectiveness of the systems. Behavioral change was evaluated in terms of the speed of trucks through curves, the following interval to the forward vehicle, and the deceleration rate during braking events.

Stability

Vehicles operating with advanced braking systems exhibited improved stability during braking. Analyzing the differential yaw rate between the tractor and the trailer during braking clearly showed improved stability for ADB-equipped trucks. ADBs had superior stability without regard to the control system used. Substantial stability improvement was also observed for trucks equipped with disc brakes on the trailer and drum brakes on the tractor.

Deceleration Rate

The average deceleration rate during each brake application was found to vary slightly between brake technologies. ECBS-equipped trucks showed a slight decrease in deceleration rate of the brake event, suggesting that braking for these trucks was accomplished by a succession of short decelerations as opposed to one long, smooth brake application. Further evidence of this was found by looking at the speed reduction and duration of each braking event. Trucks equipped with ECBS showed approximately 25-percent smaller speed reduction per brake event, and a nearly 50-percent shorter duration compared to drum brake-equipped tractors. From the drivers' comments received, the differences found in brake application style were attributed to the increased sensitivity of ECBS. Drivers commented that it was difficult to modulate the braking force of ECBS, and the brake pedal provided poor feedback. This unexpected result of reduced brake pedal feedback was noted by several drivers. The main complaint was the difficulty in modulating braking effort. For this reason, some drivers reported that braking with ECBS felt too aggressive and more difficult to control in low-speed situations.

Following Interval

To obtain a true sense of driver behavior impacts using advance braking systems, the following interval was measured while trucks were operated at highway speed. The average following interval varied from 2.5 to 3.0 seconds depending on technology. It is interesting to note that the drivers of the ABS / drum tractors had the smallest average following intervals. Conversely, the most advanced tractors (ECBS / disc) had the longest following intervals. This is the opposite trend expected when providing drivers with improved braking technologies. The data were further analyzed to determine whether this was a temporary effect due to the lack of familiarization with the system. However, the following interval was not found to vary as the test progressed.

Electronic Stability Control

The ECBS also provided the driver with electronic stability control (ESC) as an option. The system was activated only during Phase 2 of testing (January to April 2006), and the system activated 51 times in that period. Although both yaw and roll may trigger the system, over 80 percent of activations were determined to be yaw-only or yaw-dominant events. In addition, out of the 18 tractors with the system installed, three tractors accounted for 82 percent of all activations. This suggests that in addition to providing a safety benefit to the driver, analyzing these data could be a useful tool to assist in determining whether drivers require additional training. The full safety benefits of the ESC technology could not be established with the data gathered during the FOT. A key requirement to determining safety benefits is a reliable measurement of the lateral acceleration of the tractor. Although data were collected, it was found to be inaccurate and unusable for quantifying the true safety benefits.

Cornering Speed

The cornering speed of trucks was measured to determine whether the presence of a particular brake technology, or the availability of ESC, might cause drivers to alter their driving style. The ESC activation data clearly showed a section of I-70 east of Grand Junction, Colorado, where several ESC activations occurred. Two curves were analyzed, and vehicle speed was calculated for all vehicles that passed through those two curves. The data showed no significant difference in cornering speed through those curves. Overall, no difference in driver behavior with respect to cornering speed could be attributed to the presence of advanced brake technologies. This may be expected because the system is transparent to the driver and only alerts the driver when it is actively intervening.

Driver Responses

While 60 percent of drivers surveyed had a high level of acceptance and confidence of ECBS, all but one driver surveyed (90%) felt that ECBS improved braking performance. Drivers favoring the system felt the system was more responsive and quicker, and exhibited greater performance. Drivers rating the system lower felt that the system needed to “work better” when connected to trailers with differing brake control systems (e.g., ABS, non-ABS).

Most of the drivers adjusted to the feel of the brake pedal within two weeks of operation. However, a majority of them felt that ECBS reduced the amount of feedback in the brake pedal. Sixty percent of the drivers noticed the ECBS ESC system activating during the second half of the test period. All drivers surveyed felt the ESC assisted them in maintaining vehicle control. The responses were split 50/50 regarding whether the drivers drove an ECBS tractor with ESC differently.

Disc brakes were rated highly overall. Seventy-five percent of the drivers surveyed had a high level of acceptance of and confidence in ADBs at the end of the FOT, while 90 percent felt that ADBs improved braking performance. Drivers rating the system highly responded that the brakes felt great, required less air pressure to stop, and were responsive. Drivers rating the disc brakes lower felt either no difference in performance or did not experience any hard braking maneuvers to determine the difference. When asked whether they drove disc brakes differently, a majority of the drivers said yes. Most of the drivers responded that the pedal is more responsive and a lighter touch is required, and one driver noted that the performance is noticeable particularly on a long descending grade with a heavy load. The pedal feel and performance differences when compared to drums was significant enough that a few drivers noted that they had to make a mental note of which foundation brake technologies were on the tractor.

Seventy-five percent of the drivers had a high level of acceptance of and confidence in advanced ABS. Fifty percent of the drivers responded that the RSC system activated during the test period. Drivers noticed activation while negotiating curves and in the mountains with heavy loads. Of the seven drivers that noticed the RSC operating, all said that the RSC did not activate often. Four drivers felt that the RSC assisted them in maintaining control of the vehicle, two drivers felt that the RSC had no effect on their control of the vehicle, and one driver felt that the RSC contributed to loss of vehicle control. When asked whether they drove a tractor equipped with advanced ABS differently, 23 percent of the drivers responded yes. One driver responded that, without RSC, one would have to pay attention while negotiating curves.

ACC Safety Benefits

In addition to advanced brake technologies, the tractors in the FOT had ACC installed. This system is an advanced form of cruise control that engages the brakes or throttle to maintain a previously determined following interval.

While ACC following interval was calibrated to maintain a 3-second following interval, drivers were observed to follow at an average of 2.8 seconds when the system was off. With conventional cruise control systems (CCC) on, the average following interval was further reduced to less than 2.7 second. ACC clearly showed that it would increase the following interval and, therefore, the margin of safety. Although limited data were available to quantify the long-term usage patterns of ACC, significant safety benefits were observed.

Safety benefits of ACC usage on ECBS-equipped trucks was calculated based on General Estimate System (GES) historic crash and fatality rates. Exposures to “driving conflicts” were tabulated and analyzed. A driving conflict was defined as a braking event that exposed the tractor to a time-to-collision of less than 2 seconds. Usage of the ACC system resulted in a 40-percent reduction of exposure to rear-end conflicts. Based on GES rear-end collision and fatalities, nationwide use of ACC systems fully deployed could prevent over 30,373 rear-end collisions and 320 fatalities annually.

Driver Acceptance of ACC

The ACC system was well accepted by drivers. In fact, while at highway speed, the ACC was activated almost 60 percent of the time. ACC was well accepted and even relied on by the drivers. Fifteen drivers rated their confidence in the ACC system as “high” or “moderate,” while only two drivers rated the system “low” or “very low.” This confidence may be explained by the fact that the system is observed to react in a similar, yet slightly more cautious manner, than the drivers do. When looking at brake activations, the ACC system decelerates at an average of 1.5 feet per second per second. Drivers were observed to brake at a slightly more aggressive rate of 2.2 feet per second per second. There was no data to suggest that a driver deactivated the ACC system to prevent an imminent collision.

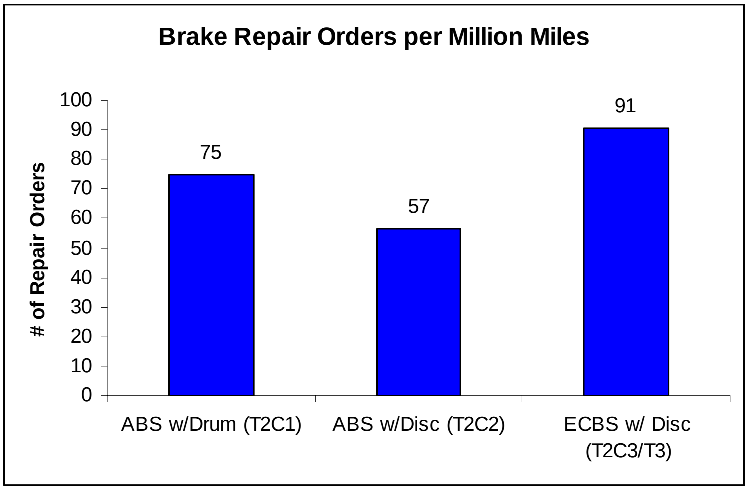
In slow-speed or heavy-traffic situations, conventional cruise control is impractical and rarely used. In contrast, ACC was used approximately 15 percent of the time, even at speeds below 30 miles per hour. Drivers can effectively use this system as an “autopilot” during heavy traffic.

Reliability

The reliability of advanced braking systems was identified by reviewing the maintenance brake repair orders that were generated during the FOT. A total of 582 repair orders were generated, with 265 brake-related repair orders. The two largest generators of repair orders were “ABS with

Drum" tractors and "ECBS with Disc" tractors. The distribution of the repair orders is shown in Exhibit ES-2.

Exhibit ES-2: Brake Repair Orders per Million Miles



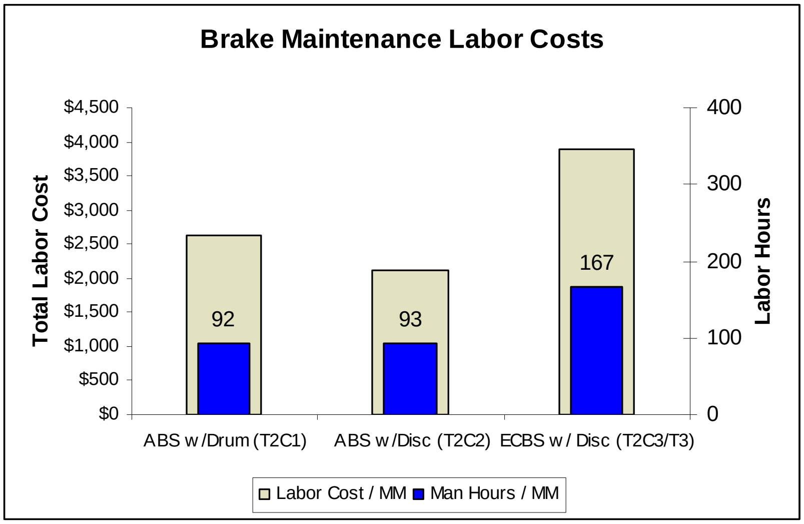
When compared to "ABS with Disc" tractors, the "ABS with Drum" tractors generated 18 percent more repair orders. According to the fleet technicians, the ADBs were more reliable due to the elimination of external adjustments. "ECBS with Disc" tractors generated 91 repair orders per million miles, which is an additional 17 percent of repair orders over "ABS with Drum" tractors. The cause for the "ECBS with Disc" repair orders could be separated into seven distinct categories—Warning Light Activated (40%), Relocation of Air Hoses (22%), System Air Leak (12%), Other (12%), Brake Transmitter Failure (7%), ECBS Wiring Failures (5%), and Foundation Brake Adjustments (2%). The ECBS warning light was illuminated due to wheel speed sensor failure, out-of-adjustment wheel speed sensors, and dirty wire harness contacts at the trailer.

The ECBS system failed (having to revert to pneumatic control) 6 times on 3 of the 18 tractors during the yearlong FOT. Two of the tractors had a single failure, and the remaining tractor had four failures. The first failure occurred in Month 4 (August 2005) of the test. Failures 2 through 5 occurred on a single tractor in February 2006. The four failures were treated as separate instances because the tractor was serviced and operated for a period of time (as much as seven days) before the dashboard lights re-illuminated indicating a problem. The final failure occurred at the end of the FOT in April 2006. After a failure, drivers reported that the feel of the brake pedal had changed and that it was necessary to push the pedal further to activate the brakes.

Durability

The effects of advanced braking systems on unscheduled maintenance were determined by reviewing the brake repair costs accumulated during the FOT. The costs include part costs and labor costs. ECBS tractors had the largest increase in unscheduled maintenance over the other technologies reviewed. ECBS tractors required an additional 75 man-hours per million miles as compared to "ABS with Drum" tractors (see Exhibit ES-3). The extra man-hours resulted in a 33-percent increase in labor costs accumulated by "ABS with Drum" tractors. The new technology and lack of familiarity of the ECBS system contributed to the mechanics requiring additional troubleshooting time as compared to ABS.

Exhibit ES-3: Brake Maintenance Labor Costs

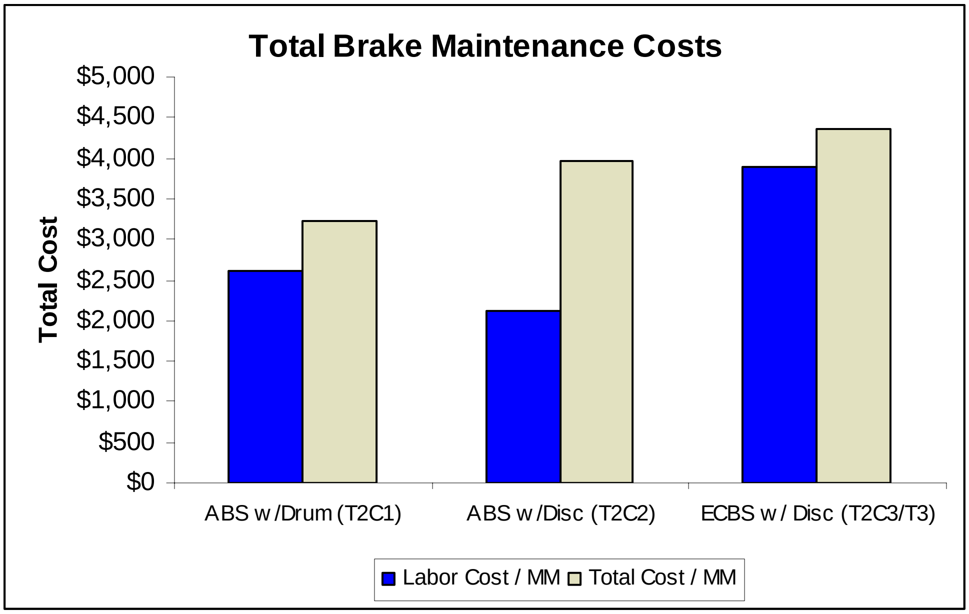


From the analysis, it was shown that ADBs are more durable (i.e., longer life) than drum brakes. Durability data for brake shoe and brake pad life was acquired from the brake inspection report. The data were gathered from a single inspection of the foundation brake components after approximately 200,000 miles of use. Brake pad life estimations were performed by Bendix, based on empirical test data. It was noted in the report that the wear rates near the end of useable friction material life can accelerate, and caution must be used in discussing projected values. By combining these data with the manufacturer's brake wear databases, it can be projected that ADB pads will have double the life expectancy of drum brake shoes. The inspection estimated 100 percent of the ADB brake pads have an expected life of greater than 500,000 miles, with 63 percent of ADB brake pads exceeding 1 million miles. In comparison, 67 percent of the drum brake shoes were not expected to exceed a shoe life of 500,000 miles, with 0 percent to reach 1 million miles. The brake drums and the brake rotors experienced comparable wear patterns. All of the inspected brake rotors are estimated to have a life expectancy in excess of 1 million miles. Overall, 83 percent of brake drums will have a life expectancy in excess of 1 million miles, while 58 percent will be in excess of 2 million miles. The inspection showed no difference in wear between ABS and ECBS brake pads.

Maintainability

Based on observations during the physical brake inspections, ADB pad replacement is expected to have a significant time and cost savings over drum brake shoe replacement. The replacement of ADB pads only requires the removal of the tractor wheel and a single retaining bracket. The pads can then be removed from the brake caliper without removing the entire assembly. No additional adjustments are required after pad installation. In contrast, after removing the tractor wheel on a drum brake assembly, the brake drum must be removed to access the brake shoes. Further intervention is required to remove the components that retain the shoes to the drum brake assembly. After the installation of the new shoes, technicians must perform brake adjustments. As a result, drum brakes are more labor intensive than ADB. From the maintenance data, labor costs for drum brakes accounted for 85 percent of total “ABS with Drum” maintenance costs. In comparison, the labor costs for “ABS with Disc” were 50 percent of the total cost (see Exhibit ES-4).

Exhibit ES-4: Total Brake Maintenance Costs



Air compressor maintenance cost for similar-sized compressors is expected to decrease for ADB-equipped tractors compared to drum-brake-equipped tractors. The compressors on the tractors with ADBs had an average run-time of 10 seconds per mile. In comparison, tractors with drum brakes experienced an average run-time of 25 seconds per mile. During the FOT, this equates to a duty cycle of 30 percent for drum-brake-equipped tractors and 13 percent for ADB-equipped tractors. The reduced air compressor duty cycle for ADB tractors is expected to significantly reduce wear, increase component life, and reduce maintenance.

Maintenance technicians provided feedback on maintaining the advanced braking technologies. Survey results indicated that 75 percent of the technicians found that maintenance on ADBs was simpler than drum brakes. The technicians appreciated the reduced maintenance requirements for ADBs. Technicians provided examples such as ease of pad replacement, reduced pad replacement time, and elimination of drum brake replacement/adjustment. In addition, surveys indicated 85 percent of technicians found ADBs simpler to diagnose than drum brakes.

Survey results for ECBS and advanced ABS contradict the reliability findings that ECBS and advanced ABS are less reliable and more difficult to maintain. Surveys indicated only 40 percent of the technicians found advanced ABS more difficult to maintain as compared to conventional ABS. The majority of the technicians felt there was little to no difference in maintaining advanced ABS. From a technician’s comments, the largest concern was the lack of knowledge and training of advanced ABS. For ECBS, the surveys indicated 55 percent of the technicians found ECBS more difficult to maintain compared to conventional disc ABS. Technicians commented on the number of defective parts and lack of replacement parts. The technicians again commented on the lack of knowledge for troubleshooting the new technology. The surveys exposed the difficulty of introducing new technologies to technicians without providing proper training for troubleshooting.

Compatibility

ADB tractors coupled with drum brake trailers were not observed to demonstrate accelerated brake component wear as compared to ADB-equipped tractors and trailers. Inspections were performed on nine tractors equipped with disc brakes at the end of the FOT. The mileage on the tractors at the time of the inspections varied between 184,307 and 259,625 miles. The tractors were part of Template 2 and, therefore, hauled drum brake trailers a majority of the time. The inspections revealed that the brake rotors on all nine tractors inspected were estimated to have a life of over 1 million miles. Similarly, the brake pad life on six tractors was estimated at or over 1 million miles and two tractors were projected to have a pad life of 700,000 miles. Bendix performed brake pad life estimations based on empirical test data. It was noted in their report that the wear rates near the end of useable friction material life can accelerate and caution must be used in discussing projected values. Bendix's inspection report noted that the hold-off valves on the steer axles of the disc brake-equipped tractors shifted more brake work from the trailer to the tractor without problems, further demonstrating the enhanced wear capabilities of disc brakes.

The stability of tractor-trailer combinations during hard braking events was shown to improve for mixed combinations of foundation brakes over the baseline drum tractor and drum trailer combinations. Comparing the yaw rate data between the tractor and trailer showed the largest difference between drum tractors in combination with drum trailers. The most stable combination (lowest differential yaw rate) was a disc tractor coupled with a disc trailer. This being said, a drum brake tractor coupled to a disc brake trailer performed equally well.

While disc tractors and drum trailers in combination did not exhibit incompatibility in pad and shoe wear, disc tractor drivers did comment that the trailer brakes were sensitive to pedal input and "grabby," particularly with older non-ABS and empty trailers. One driver commented that he felt the tractor was doing a majority of the braking, while another rated his acceptance of ECBS lower because he felt it needed to "work better" when attached to trailers with differing brake control systems.

Summary

The U.S. DOT took the initial step to increase the understanding of ECBS. The goal of this FOT was to determine the reliability, maintainability, performance, and safety of ECBS. The study addressed the primary and secondary objectives of the FOT, and its findings are as follows:

- Tractors equipped with ECBS and disc brakes were evaluated under real-world commercial conditions, and showed increased durability and lower reliability than conventional drum brakes.
- Trucks equipped with ECBS showed increased maintenance costs. Surveys suggest that a large portion of the additional cost could be reduced with additional training.

- Mixed control systems and foundation brake technologies did not result in adverse effects. However, survey responses suggest that further refinement is needed.
- Advanced brake technologies tested showed improved stability with potential beneficial impacts on safety. Safety benefits of ECBS could not be quantified due to lack of data quality.
- Overall, drivers responded with a high level of acceptance of and confidence in ECBS vehicles. Most drivers felt that ECBS provided improved performance and increased safety.
- ACC was shown to increase the following interval, and the safety benefits equation predicts up to 320 fatalities per year could be prevented for fully deployed ACC.
- Based on driver responses, stability control systems were effective. Most activations were shown to be from a small subset of drivers.

CHAPTER 1. INTRODUCTION

This chapter provides the following:

- Background on electronically controlled braking systems (ECBS)
- Background on field operational test (FOT) request for application
- Program purpose, goals, and objectives

1.1 Background on ECBS

Numerous factors play a contributing role in heavy-duty tractor-trailer crashes. In some instances, defective, poor performing, and/or out-of-adjustment brakes are a contributing factor. In numerous other instances, while braking systems may not be a contributing factor, it is clear that enhanced braking performance could help in avoiding or mitigating crash situations. Additionally, braking systems represent the second-highest vehicle maintenance cost item for most fleet operators (next to tires). Most commercial vehicle industry stakeholders recognize that brake system enhancements remain a fertile area of research, and such research will focus on improving performance and increasing reliability, while reducing overall maintenance and operational costs.

In 1993, brake manufacturer Bosch and truck manufacturer Scania introduced the first production-like brake-by-wire system for tractors, trucks, trailers, and semi-trailers. This technology is more commonly called ECBS for commercial vehicles. Since that time, other brake and truck manufacturers have developed similar, although not identical, systems. ECBS is viewed as an enabling technology that can provide shorter stopping distances due to faster brake application times, improved dynamic brake force distribution, and improved combination vehicle brake balance. Combined with additional sensors such as lateral accelerometers and yaw rate sensing, electronic stability control (ESC) programs could be developed that leverage the precise wheel-by-wheel braking control offered by ECBS. Together, ECBS and ESC could offer improved control to commercial vehicle drivers, particularly under distressed or "panic" maneuvers. Additionally, when combined with lining wear sensors, ECBS offers the potential for improved self-diagnosis and continuous brake monitoring. These features could lead to reduced overall brake system maintenance costs. Finally, ECBS offers the potential for improved anti-lock braking system (ABS) functionality by permitting more precise control of wheel speed.

Today, ECBS has become standard technology on most tractors and trucks sold and operated in Europe. The market switchover from ABS to ECBS began in the mid 1990s and generally was accompanied by a switch from drum to disc brake systems. Also, because European manufacturers have developed a standard for high-speed network communications between tractor and trailer, many European trailers are also now equipped with ECBS. The ECBS offered by European manufacturers is configured as an additional control layer over the pneumatic braking control system. To this extent, the ECBS-equipped vehicles operating in Europe are termed "1E/2P" with the electronic system (1E) acting as the primary brake control and the pneumatic systems (2P) as "backup."

For a variety of technology and market-based circumstances, ECBS for heavy-duty trucks has not gained commercial acceptance in the North American market. Key factors include:

- ECBS is more expensive than ABS;
- The performance benefits of ECBS alone (i.e., not in combination with disc brakes) have not been clearly documented in terms of stopping distance and safety improvements;
- The durability, reliability, and maintainability of ECBS have not been verified for North American applications and operating environments;
- ECBS is generally understood to be an “enabler” of braking control strategies that can offer major improvements in brake performance. However, as a stand-alone system, benefits may be moderate and not perceived as a “good value” by some fleet operators;
- Lack of a standard high-speed network connection between tractor and trailer limits development of an “optimal” ECBS control strategy for the combination vehicle, which therefore limits the relative benefits of ECBS compared to standard ABS; and
- More so than in the European market, North American tractors and trailers of varying age, design, and even ownership must be compatible with one another. This creates a “chicken and egg” challenge since maximum benefits of ECBS cannot be realized unless both tractor and trailer are equipped with the new technology. Fleet operators are reluctant to “go first” with regard to purchasing the new technology. Additionally, it is imperative that all tractor ECBS be compatible with all trailer ECBS, as well as have backward compatibility with ABS.

With regard to the above commercialization challenges, the U.S. Department of Transportation (DOT) sponsored this field operational test of ECBS. Program funding was through the U.S. DOT’s Intelligent Vehicle Initiative (IVI).

The U.S. DOT established the IVI with the goal of reducing motor vehicle crashes and incidents through research, development, testing, evaluation, and deployment of safety devices and systems. The IVI program supports the development of performance guidelines, architectures, and standards for intelligent transportation systems (ITS) and will test and evaluate promising safety technologies in cooperation with the automotive, truck, and bus industries and other industry stakeholders. The targeted safety technologies must be commercially viable, implementable in the near term, and accepted through driver demonstration. One promising technology meeting these criteria is ECBS for heavy-duty trucks.

The U.S. DOT’s IVI program administered this ECBS FOT project as a cooperative agreement between government and industry. Such cooperative agreements are issued pursuant to the authority of Section 307(a) of Title 23, United States Code. Section 5207 of the Transportation Equity Act for the 21st Century provides specific statutory authority for conducting IVI field tests. NHTSA managed the ECBS FOT.

1.2 Background on FOT Request for Application

In the fall of 2002, the U.S. DOT released to industry a request for applications (RFA). The RFA sought partners from industry to participate in demonstrating ECBS technology and applications in revenue-generating service. To this extent, the U.S. DOT sought proposals from conductor teams interested in sharing in the costs and management of this FOT.

The U.S. DOT anticipated a conductor team would consist of (at a minimum) a manufacturer of heavy-duty (Class 7 and 8) commercial trucks and tractors, a manufacturer / supplier of braking control systems for like vehicles, and a fleet operator (or host site operator). The U.S. DOT anticipated that a truck / tractor manufacturer would lead the conductor team (i.e., the truck / tractor original equipment manufacturer will act as the *prime* contractor and will be ultimately responsible for all aspects of the program). The conductor team was responsible for finalizing an overall test plan including the type and number of vehicles to be included in the FOT; configuring ECBS technology to be tested, location(s) of the field test, responsibilities of conductor team members, field test support and data acquisition plans, and overall quality control plans; finalizing design details and installation plans for adding ECBS to the vehicles selected for the FOT; building / installing the ECBS-equipped vehicles; operating the vehicles throughout the test program; and working with an independent evaluator to collect desired FOT data.

The U.S. DOT was interested in examining a cross-section of ECBS technologies and applications. To achieve this diversity of testing, the U.S. DOT sought proposals from conductor teams in three broad operational settings, or FOT "templates." Each template represents a minimum set of guidelines (in terms of number and type of vehicles to be evaluated, operational environment, and other factors) that conductor teams must adhere to in structuring their responses to this solicitation. Conductor teams were free (and, in fact, encouraged) to propose plans for conducting an FOT that expands on these requirements in a manner that would benefit the overall goals and objectives of the program. Bidders' proposals were selected for funding based on the degree to which they met the overall research goals and objectives of the program, and on the proportion of overall project costs to be borne by the conductor team (i.e., percentage cost share). Innovative strategies for collecting safety-related data, broadening the scope and diversity of testing environments, and / or demonstrating ECBS technology that employs advanced safety features were encouraged.

The following are descriptions of these templates.

Template 1 – Evaluates an ECBS-equipped vehicle in a high-frequency brake application environment. This environment is characterized as one where a vehicle is required to routinely apply service (or foundation) brakes to accomplish its basic function. Examples of vehicle types and application include a Class 7 or 8 refuge hauler, Class 7 or 8 dump truck, or 12-year service life city transit bus operating in an urban environment. This template requires a minimum of 35 vehicles for a minimum duration of 12 months.

Template 2 – Evaluates the compatibility between a tractor-based ECBS and a trailer-based ECBS by two different manufacturers. The ECBS on the tractor and trailer are not required to communicate. The control pressure signal is forwarded to the trailer via the standard pneumatic interface. This template allows for the fact that in a transition period tractors equipped with ECBS will be paired with older trailers equipped without ABS brakes. The reverse situation may also occur; that is, ECBS trailers may be paired with tractors equipped with or without ABS brakes. This template requires 25 ECBS-equipped tractors and trailers. The field test duration must be a minimum of 12 months.

Template 3 – Evaluates the operation of a single vendor's ECBS technology equipped on both the tractor and trailer. A high-speed network interface is required between the two units. The ECBS must communicate sharing control pressure information. The standard pneumatic control interface is also required in the event of a connection failure. This template requires the tractor and trailer to be "married," that is, to operate as a single unit for the duration of the field test. This template requires 25 ECBS-equipped tractor and trailer combinations. The field test duration must be a minimum of 12 months.

1.3 Program Purpose, Goals, and Objectives

Through the IVI, the U.S. DOT hopes to reduce crashes by accelerating the deployment of new safety-related technologies. Working together with industry and other stakeholders, the U.S. DOT will support development of performance guidelines, architectures, and standards and will test and evaluate promising configurations. One of these promising configurations is ECBS.

The primary goal of the ECBS FOT was to achieve an improved understanding of the overall performance, reliability, maintainability, and safety of ECBS in over-the-road, revenue-generating environments.

Primary objectives of the ECBS FOT included:

- Evaluating the reliability and durability of ECBS in a variety of real-world environments. Documenting any problems or fault codes with the systems, as well as the frequency and circumstances of ECBS failures that would result in the braking control being reverted to the backup pneumatic system;
- Assessing overall maintainability of ECBS relative to scheduled and unscheduled maintenance requirements;
- Evaluating the compatibility of tractor and trailer ECBS from different vendors and with conventional ABS; and
- Evaluating impacts on safety in terms of reducing crash or near-crash situations.

Secondary objectives included:

- Assessing driver perceptions regarding performance, safety, and handling impacts of ECBS-equipped vehicles; and
- Determining any changes in driver behavior associated with ECBS over the course of the FOT period.

In addition to ECBS, this program evaluated advanced ABS, air disc brakes, and adaptive cruise control. Having these systems evaluated under this FOT provided a unique opportunity to meet program objectives by contrasting system performance between technologies. Operating templates designed by the U.S. DOT where used to control variables and ensure objectives were met. Chapter 2 discusses these templates in more detail.

CHAPTER 2. DESCRIPTION OF FIELD OPERATIONAL TEST

This chapter provides information on the following:

- FOT conductor team
- Host fleet
- Technologies under evaluation
- FOT experimental design
- On-board data acquisition system (DAS)
- FOT schedule

2.1 FOT Conductor Team

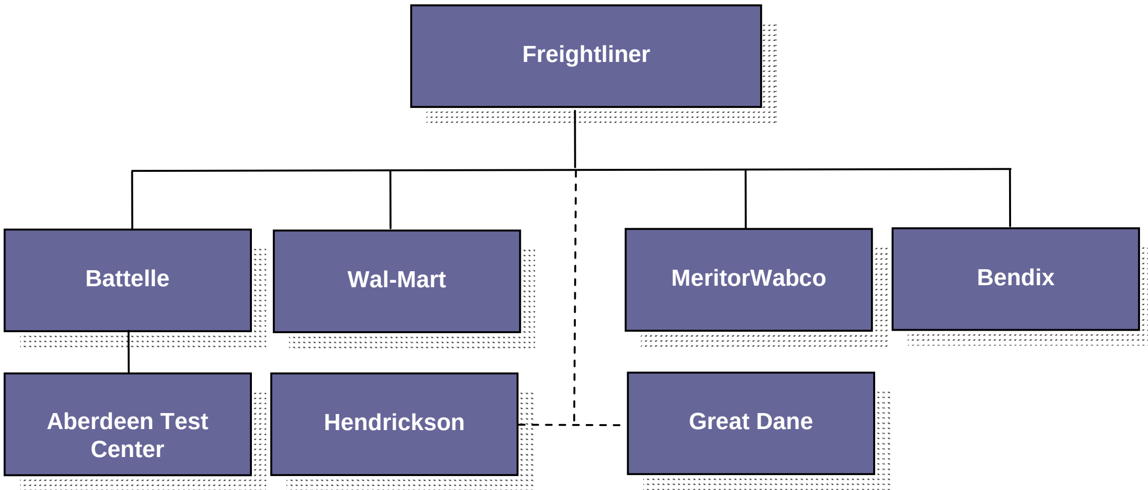
The U.S. DOT selected a single conductor team led by Freightliner LLC (Freightliner) to participate in demonstrating ECBS technology and enabled technologies in revenue-generating service. The U.S. DOT entered into a cooperative agreement with Freightliner, as the prime contractor, to conduct Templates 2 and 3 (see Section 1.2) as proposed. The U.S. DOT did not award to bidders of Template 1 due to funding constraints.

Freightliner's team was comprised of six members:

1. *Freightliner* – The prime contractor and a leading truck manufacturer in North America
2. *Wal-Mart* – The host fleet for the FOT, the largest retailer in the United States; operates a private fleet of tractors and trailers
3. *MeritorWabco* – A leading supplier of heavy-duty vehicle components, including ECBS, advanced ABS, air disc brakes, and enabled safety technologies
4. *Bendix* – A leading supplier of heavy-duty vehicle components, including ECBS, advanced ABS, air disc brakes, and enabled safety technologies
5. *Battelle* – Professionals in transportation research and development, and providing project management and coordination support to the prime contractor
6. *Aberdeen Test Center* – Field instrument provider and data collection experts

Hendrickson and Great Dane contributed to the program as suppliers of air suspension systems and trailers. Exhibit 2-1 illustrates the organizational structure of the Freightliner team.

Exhibit 2-1: Freightliner Team Organizational Structure



2.2 Host Fleet

Freightliner selected Wal-Mart as the host fleet for the ECBS FOT. Wal-Mart's fleet includes over 5,500 tractors and 32,000 trailers in regional distribution, center-to-store, and nationwide hub-to-distribution center operations. Wal-Mart operates 38 distribution centers that serve over 2,700 stores. On average, there are 135 tractors and 1,100 trailers per distribution center. Tractors operating in center-to-store operation can travel 500 miles per round trip with multiple stops and/or multiple trips per day. Tractors are assigned to drivers. Drivers typically work 6 days per week, and tractors average 125,000 miles per year. Driver average tenure with Wal-Mart is 14 years. The Wal-Mart distribution center in Loveland, Colorado, was chosen as the FOT host site for its center-to-store operation, geographical location, and size.

2.3 Technologies Under Evaluation

Freightliner proposed evaluating ECBS technology along with a host of advanced braking and safety technologies. The technologies evaluated under this FOT include:

- ECBS featuring roll and yaw stability control;
- Advanced ABS with roll control;
- Air disc brakes (ADBs); and
- Adaptive cruise control (ACC) and collision mitigation systems (CMS).

MeritorWabco ECBS. ECBS is an advanced brake control system technology that controls the brakes electronically rather than pneumatically. In practice, these electronic control systems are laid over the existing pneumatic controls of a braking system. The common control layout in the U.S. and European markets is a "1E/2P" system featuring a primary electronic control system (1E) and dual pneumatic backup systems (2P). The conventional pneumatic control remains as a backup in the event of an electronic control failure and to ensure compliance with current pneumatic brake regulations. On ECBS, an electronic circuit is integrated into the treadle valve. By depressing the treadle valve, the driver sends a deceleration command to the microprocessor-based control unit. The control unit responds by sending an electronic control signal to the pressure modulator instructing a set amount of application pressure to a specific brake chamber. The benefits of electronic control include increased control signal speeds (50% faster than pneumatic or hydraulic systems), precise regulation of application pressures, and improved brake balancing.

MeritorWabco is the manufacturer of the ECBS evaluated under this program.

MeritorWabco Advanced ABS. Advanced ABS is based on a traditional ABS control system that modulates the air pressure in the brake chamber to prevent wheel lock-up and provide braking control during over-braking maneuvers. ABS monitors wheel speeds at all times and controls braking during wheel-lock situations. The ability to limit wheel-lock situations enhances vehicle

stability, reduces the possibility of jackknifing, and enables steering under extreme braking conditions. MeritorWabco manufactured the advanced ABS evaluated under this FOT. MeritorWabco uses the identifier “advanced” to signify the addition of roll stability control (RSC). RSC is a system designed to improve vehicle stability during high lateral acceleration maneuvers such as evasive lane changes and excessive speed in curves. RSC monitors a suite of sensors including a lateral accelerometer and, upon detecting a potential rollover situation, is capable of de-throttling the engine and applying the engine brake and foundation brakes autonomously from the operator. The autonomous application of the foundation brakes is done with the use of additional ABS modulators, traction control valves, and programming. Advanced ABS also provides an integrated platform for collision mitigation systems.

Bendix ABS6. Bendix’s ABS6 is a next-generation ABS utilizing a new architecture. ABS6 can be configured with up to six wheel-speed sensors and six control modulators that include an ABS module, yaw sensor, longitudinal and lateral accelerometers, steering wheel angle sensor, control pressure sensor, application pressure sensor, and two traction control valves. The new architecture enables the system to autonomously apply the foundation brakes independent from the driver, providing a platform for roll and yaw control systems commonly referred to as stability control systems. ABS6 is available in three configurations—Advanced (yaw and roll), Premium (roll), and Standard (ABS and traction control). The Standard system was evaluated under this FOT.

Bendix Trailer Electronic Braking System (TEBS4). Bendix supplied an ECBS designed specifically for trailers featuring a trailer roll stability program. The TEBS4 system overlays a single electronic circuit over the pneumatic control circuit, which serves as a backup circuit per FMVSS No. 121. The system uses conventional pneumatic supply and service line connections to the trailer. The roll control system relies on a lateral accelerometer to determine whether the predetermined threshold has been exceeded. If the threshold has been exceeded, the system will automatically apply a low-pressure brake application. If the inside wheel decelerates, the system will automatically apply the brakes, reducing the speed of the combination unit and reducing the threat of rolling over.

Bendix ADBs. Bendix supplied its ADB 22X air disc brake. The brake is manufactured in partnership with Knorr-Bremese Group and Dana Corporation. The brake is designed for installation with 22.5-inch rims, via two slide pins. The ABD 22X uses a dual-piston configuration on the inboard side of the caliper. The dual-piston design provides precise brake adjustment, better force distribution, and even pad wear. The Bendix ADB 22X is assembled with a mono-block caliper to provide an overall weight of 78 pounds. The assembly provides a brake torque of up to 15,000 foot-pounds.

MeritorWabco ACC with CMS. MeritorWabco's ACC is designed to maintain a safe following distance to the preceding vehicle. The system uses a radar sensor to track the forward vehicle's speed, range, and bearing and uses sophisticated software to determine whether the target vehicle is in the same lane. To maintain a safe following interval, the ACC is integrated with and can control the throttle, engine brake, and foundation brakes. The sensor range is 400 feet and is available between 10 and 65 miles per hour. In addition to headway monitoring, MeritorWabco's system features a CMS. The system assists the driver in avoiding collisions by autonomously applying the foundation brakes when a time to collision threshold is reached. CMS is capable of decelerating the tractor at 0.25g.

2.4 FOT Experimental Design

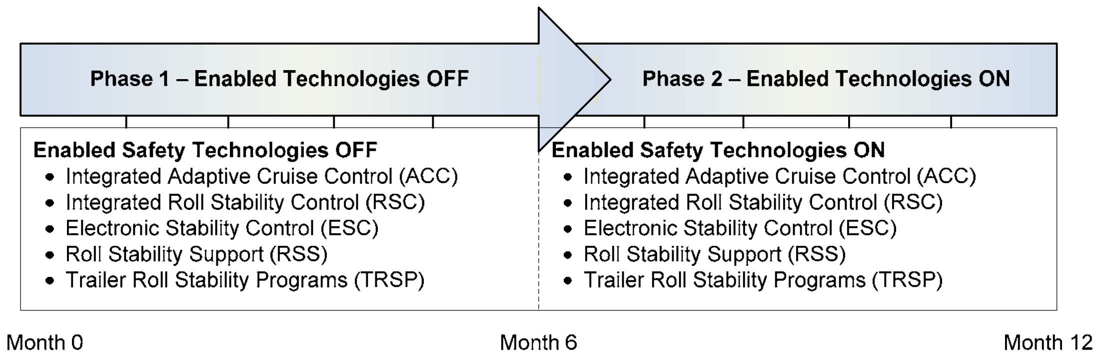
The experimental design for the ECBS FOT was a compromise of U.S. DOT research goals and objectives, host fleet operational characteristics, technology availability, integration challenges, logistics, schedule, and budgetary constraints. This section of the report provides details on the configuration of the technology and equipment to support the program, presented below by template.

2.4.1 Template 2

Template 2 was designed to simulate the introduction of advanced braking technologies into the trucking market. Advanced braking technologies from different manufacturers were intended to intermix with one another and with tractors and trailers with conventional braking technologies. The technologies were to be evaluated on their safety, maintainability, reliability, and compatibility.

Freightliner proposed to operate four different tractor and trailer configurations within this template for a total of 40 tractors and 60 trailers. Forty additional trailers were added to the original proposal to increase the chances of FOT tractors and FOT trailers operating in combination. Each tractor and trailer was equipped with a DAS. The plan was to operate the tractors and trailers for a period of 12 months. During the first six months, the safety systems were turned off, and the following six months, the safety systems were turned on. Exhibit 2-2 illustrates the Template 2 schedule.

Exhibit 2-2: Template 2 Phases



It is important to note that although the ACC system was not available to the driver during the first six months, the forward radar sensor was operational and generating information on the following interval. Exhibit 2-3 presents the four configurations of Template 2. The following paragraphs describe the configurations in more detail.

Exhibit 2-3: Template 2 Vehicle Configurations

Template 2 Configuration 1 (T2C1)		
	Tractor	Trailer
Manufacturer	Freightliner	Great Dane
Model	Columbia	Dry Van
Service/Foundation Brakes	Arvin Meritor S-cam Drum	Arvin Meritor S-cam Drum
Brake Control System	MeritorWabco Advanced ABS	MeritorWabco ABS (4S/2M)
Quantity	10	15
Safety Technology	MeritorWabco ACC MeritorWabco RSC	N/A
Data Acquisition System	Yes	Yes
Template 2 Configuration 2 (T2C2)		
	Tractor	Trailer
Manufacturer	Freightliner	Great Dane
Model	Columbia	Dry Van
Service/Foundation Brakes	Bendix ADBs	Bendix ADBs
Brake Control System	MeritorWabco Advanced ABS	MeritorWabco ABS (4S/2M)
Quantity	10	15
Safety Technology	MeritorWabco ACC	N/A

	MeritorWabco RSC	
Data Acquisition System	Yes	Yes
Template 2 Configuration 3 (T2C3)		
	Tractor	Trailer
Manufacturer	Freightliner	Great Dane
Model	Columbia	Dry Van
Service/Foundation Brakes	Bendix ADBs	Bendix ADBs
Brake Control System	MeritorWabco ECBS	MeritorWabco ECBS
Quantity	10	15
Safety Technology	MeritorWabco ACC MeritorWabco ESC	MeritorWabco RSS
Data Acquisition System	Yes	Yes
Template 2 Configuration 4 (T2C4)		
	Tractor	Trailer
Manufacturer	Freightliner	Great Dane
Model	Columbia	Dry Van
Service/Foundation Brakes	Bendix ADBs	Bendix ADBs
Brake Control System	Bendix ABS-6	Bendix ECBS (4S/2M)
Quantity	10	15
Safety Technology	N/A	Bendix RSS
Data Acquisition System	Yes	Yes

2.4.2 Template 2, Configuration 1 (T2C1)

The tractors and trailers in Template 2, Configuration 1 (T2C1) were equipped with a MeritorWabco ABS and Arvin Meritor drum brakes. The ABS control system on the tractor is an advanced system featuring MeritorWabco's RSC system. The tractors were fitted with an integrated ACC system capable of de-throttling the engine, applying the engine brake, and applying the foundation brakes autonomously from the driver. There were 10 tractors and 15 trailers in this template configuration, which were planned to operate for 12 months. During the first six months (Phase 1), the RSC and ACC were turned off, and during the second six months (Phase 2), the systems were turned on. Phase 1 data from this configuration is considered the control group as this configuration is most similar to Wal-Mart's current tractor-trailers. Data acquisition systems are equipped on both the tractors and trailers. Although the ACC system was turned off in Phase 1, the forward radar sensor was active and provided following interval data that was recorded by the data acquisition system.

2.4.3 Template 2, Configuration 2 (T2C2)

The tractors and trailers in Template 2, Configuration 2 (T2C2) were equipped with a MeritorWabco ABS and Bendix ADBs. The MeritorWabco ABS is the same system found on the T2C1 tractors featuring RSC and an integrated ACC system. There were 10 tractors and 15 trailers in this template configuration, which were planned to operate for 12 months. The RSC system was activated in Phase 2. The integrated ACC system was also activated in Phase 2 and made available to the driver.

2.4.4 Template 2, Configuration 3 (T2C3)

The tractors and trailers in Template 2, Configuration 3 (T2C3) were equipped with a MeritorWabco ECBS and Bendix ADBs. The ECBS has a single electronic control system laid over a dual redundant pneumatic setup commonly referred to as 1E/2P system. The ECBS system on the tractors featured an ESC system with both roll and yaw control programs. The trailer featured a roll stability support (RSS) system capable of assisting the tractor's roll control system and available via a high-speed communication connector. The tractors were also equipped with integrated ACC system. The ESC, RSS, and ACC systems were only active during the second phase of the program. There were 10 tractors and 15 trailers in this template configuration.

2.4.5 Template 2, Configuration 4 (T2C4)

The tractors and trailers in Template 2, Configuration 4 (T2C4) were equipped with a Bendix ABS-6 system and Bendix ADBs. The ABS-6 system is Bendix's latest ABS architecture designed to support future stability control programs. The system evaluated under this FOT was the Standard system and did not include stability control. The tractors in this template configuration were the only tractors not equipped with the MeritorWabco ACC system. However, the tractors were instrumented with a forward radar sensor for data collection purposes. The trailers featured Bendix's TEBS4. This system is designed specifically for trailers and featured a trailer roll stability program. As with all configurations under this template, the tractors and trailers operated for a period of 12 months, with the active safety systems off in the first 6 months and on in the second 6 months.

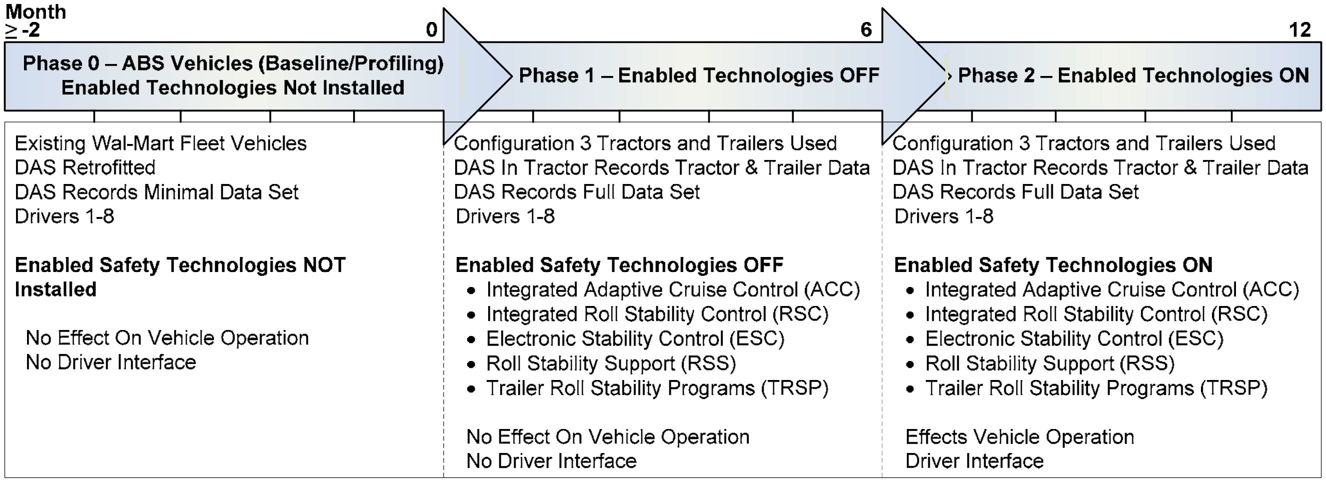
2.4.6 Template 3 (T3)

The focus of Template 3 (T3) was to demonstrate ECBS on a tractor-trailer combination unit and to determine the safety benefit of an optimized braking system where both the tractor and trailer were equipped with ECBS and capable of exchanging information over a high-speed data connection. It was also intended to evaluate other safety technologies enabled by the ECBS platform. For this template, Freightliner proposed operating eight tractor-trailer units equipped with ECBS, an ESC program, and ACC. The nature of Wal-Mart's operation prohibited the use of "married-pairs," resulting in the use of "matched-pairs," where program tractors and trailers would operate together as frequently as possible. Additional trailers were built and a General Electric Veriwise satellite trailer tracking system was employed to ease the Wal-Mart dispatcher's role and improve the frequency that FOT tractors and trailers operated in unison.

With a limited number of tractor-trailers, the use of a dedicated control group was abandoned in favor of profiling the eight drivers prior to receiving their ECBS tractors. Each driver was profiled in the current Wal-Mart ABS drum brake-equipped tractors for a minimum of two months prior to the official start of the FOT. A DAS and a forward radar sensor were installed to collect information on how drivers operate their tractors.

The duration of the Template 3 test was 14 months. During the first two months, the current tractors were instrumented and driven by the test participants to establish a baseline. After the baseline was established, the drivers operated the ECBS tractors for six months with the enabled safety technologies turned off. For the final six months of the test, the drivers operated the ECBS tractors with the enabled safety technologies turned on. Exhibit 2-4 illustrates the three phases of Template 3.

Exhibit 2-4: Template 3 Phases



Similar to Template 2, although the ACC system was not available to the driver during the first 6 months, the forward radar sensor was operational and generating data that was recorded by the DAS. It is important to note that the Template 3 trailers did not have a stand-alone system that was capable of storing data. They were equipped with an analog-to-digital converter capable of transmitting data over a serial connection between the tractor and trailer. Exhibit 2-5 presents the Template 3 tractor and trailer configuration. The following paragraphs describe the configuration in more detail.

Exhibit 2-5: Template 3 Vehicle Configuration

Template 3 (T3)		
	Tractor	Trailer
Manufacturer	Freightliner	Great Dane
Model	Columbia	Dry Van
Service/Foundation Brakes	Bendix ADBs	Bendix ADBs
Brake Control System	MeritorWabco ECBS	MeritorWabco ECBS
Quantity	8	40
Safety Technology	MeritorWabco ACC MeritorWabco ESC	MeritorWabco RSS
Data Acquisition System	Yes	No

2.4.7 Template 3 Configuration

The tractors and trailers in Template 3 are configurationally identical to the T2C3 equipment featuring a MeritorWabco ECBS and Bendix ADBs. The ECBS on the tractors featured an ESC system with both roll and yaw control programs. The trailer featured an RSS system capable of assisting the tractor's roll control system and available via a high-speed communication connector. The tractors were also equipped with an integrated ACC system that was available in the second phase of the program. There were 8 tractors and 40 trailers in this template configuration.

There were three major operational differences between Template 2 and Template 3. First, the drivers were profiled in their current tractors before obtaining an ECBS tractor. The profiling data in the report is referenced as T3 profiling tractors (T3P). Second, the FOT tractor and trailers were intended to operate in "matched pairs." Third, the tractors were placed on dedicated routes in an effort to control environmental variables.

2.5 On-Board DAS

The electronic on-board data were stored on a DAS developed and supported by the Aberdeen Test Center. DAS were mounted in each Template 2 tractor and trailer and Template 3 tractors. Template 3 trailers were fitted with an analog-to-digital converter and transmitted data to the tractor DAS via a serial communication link, where it was stored.

The tractor DAS were mounted within the cab in a compartment under the sleeper. The trailer DAS units were mounted to the underside of the trailer and protected by a sheet metal housing. The DAS were capable of storing data from analog and digital sources that included the tractor's communication bus.

Initial plans of wirelessly downloading the data were abandoned in favor of PCMCIA flash memory cards due to wireless bandwidth issues at Wal-Mart's Loveland distribution facility. Wal-Mart personnel were responsible for removing the PCMCIA cards and mailing them to the Freightliner team for processing. Exhibit 2-6 provides specifications on the DAS.

Exhibit 2-6: DAS Specifications

Data Acquisition System	
Manufacturer	Aberdeen Test Center
Architecture	PC/104
Network Interface	CAN, J1939, J1587, J1708
RAM Capacity	8 to 18 MB
Storage Memory	1 GB
RS-232 Serial Ports	2
A/D Converter	16 Channel
Memory Storage	PCMCIA

CHAPTER 3. DATA SOURCES, COLLECTION, AND PROCESS

This chapter provides information on the data sources used to evaluate the advanced braking and enabled safety technologies, the process for retrieving the data, and information on the database server used to support the program. The chapter is organized as followed:

- Data sources
- Data collection
- Data reporting

3.1 Data Sources

Four sources of data were used to perform an assessment of the safety, reliability, durability, maintainability, and compatibility of the advanced braking and enabled technologies under evaluation. The following paragraphs describe four sources in more detail:

- On-board electronic data
- Maintenance records
- Driver and technician surveys
- Brake system inspections

3.1.1 On-Board Electronic Data

On-board electronic data were received from the tractor's communication networks (J1708, J1939, and CAN ISO 11992), analog sensors, and digital sensors. Most of the data were available from sub-system electronic control units of the engine, dash, brake control system, and ACC system. Sensors that were added to the tractors include additional wheel-speed sensors and brake chamber pressure sensors. Headlight and wiper activation signal wires were tapped and monitored for a voltage signal to determine status. The DAS housed a multi-axis accelerometer, yaw sensor, and global positioning system (GPS) chipset. A majority of the data elements were recorded at a frequency of 10 Hz (i.e., 10 samples per second). Others, such as the odometer and GPS coordinates, were recorded at 1 Hz. Data elements changing infrequently (e.g., the headlight and wiper activation status) were recorded only when a system status change occurred.

Each tractor and trailer configuration had a different data set based on its braking system and safety technology. A unique data set was defined for each of the configurations below:

- Template 2, Configurations 1 and 2 (ABS / Drum and ABS / Disc)
- Template 2, Configuration 3 (ECBS / Disc)
- Template 2, Configuration 4 (ABS-6 / Disc)
- Template 2 Trailers
- Template 3 (ECBS / Disc)

Exhibit 3-1 provides summary information on the type of on-board electronic data collected on the tractors, the purpose for collecting it, and the source of the data. The appendix provides a complete listing of the data channels.

Exhibit 3-1: Tractor Data Set Summary

Data Type	Purpose	Channels
Vehicle Data	Determine and record the vehicle state and driver inputs	ID, Odometer, Accelerator Pedal Position, Steering Angle/Angle-rate, Gear, Suspension Airbag Pressure, Engine Brake Activation
Foundation Brake Data	Record how the braking system is being operated; Determine when and the effect of advanced safety technology intervention	Brake Pedal %, Control Air Pressure, Individual Chamber Pressures, Individual Wheel Speeds, Brake Activation
GPS Data	Record vehicle location and time; Correlate with geographic information system (GIS) and roadway data	Time, Longitude, Latitude
ABS/ECBS Data	Record system faults; Record when and how the system is intervening	Fault Codes, Control Information
Accelerometer Data	Determine vehicle dynamics during braking, cornering, emergency maneuvers, and accidents	Longitudinal Acceleration , Lateral Acceleration, Yaw Rate
Forward Radar/ACC Data	Determine surrounding vehicles; Study driver behavioral changes (i.e., following distance) with advanced technologies	Driver Interface Data, Target Range/Range-rate, Target Azimuth, Fault Codes, Control Information
Powertrain	Determine vehicle speed and engine load	Vehicle Speed, Engine Speed, Engine Torque
Environmental	Assess environment conditions (weather, vision)	Wiper, Headlights, Turn Signal Activation

3.1.2 Maintenance Records

Wal-Mart uses a centralized data management system to record and store maintenance actions. This system is a method of recording data based on the vehicle maintenance reporting system (VMRS). The Technology and Maintenance Council initially published the VMRS report in 1970 and established a standard coding convention for the universal tracking of equipment and maintenance costs and functions associated with heavy-duty vehicles. This standardized method of tracking costs provides the ability to track maintenance costs associated with maintaining the advanced braking systems under evaluation in this field operational test.

This data management system is used to record all maintenance activities that occur on the vehicles. The architecture of the system is “truck-based,” meaning that all maintenance actions are linked to a specific truck’s identification number. Whenever a maintenance staff person performs an action on a truck, a work order is generated. To this extent, the VMRS contains a complete history of the maintenance activity on each truck. Each work order contains a series of data fields containing codes that describe the type of work being performed; the reason for the maintenance action; and the system, component, or subsystem being worked on. The mechanic, supervisor, or other maintenance staff completing the work fills out these fields.

Work orders contain the following fields:

- **Reason for Repair Code:** This is the field for listing the reason that the maintenance action is being performed, such as accident, breakdown, scheduled maintenance, warranty, inspection, and vandalism.
- **Work Accomplished Codes:** This is the field for listing the type of action being performed such as replace, repair, inspect, or rebuild.
- **System Level Codes:** This is the field to identify codes for capturing the specific systems involved.
- **Mileage:** This field contains the mileage of the truck at the time of the maintenance action.
- **Date:** This is the date of the repair.
- **Labor Hours and Cost:** This is the total time (and computed cost based on average wage rates) required to complete the maintenance action.
- **Work Performed:** This is a text field, which allows the person filling out the work order to make any comments he or she wishes regarding what was done to the vehicle.

The VMRS can be queried in a variety of ways to summarize maintenance actions based on fleet type, nature of repair, vehicle age and mileage, distribution center where the work was completed, and other parameters.

A total of 582 brake and tire repair orders were collected from the Wal-Mart Loveland, Colorado, distribution center.

3.1.3 Driver and Mechanic Surveys

The drivers were profiled prior to the start of the FOT to obtain information on their age, commercial vehicle driving experience, and knowledge and experience with the advanced braking systems and safety technologies under evaluation. At 6 months and 12 months, the drivers were again asked to complete an interview guide on their experiences with operating the equipment. The 6-month and 12-month time intervals capture their experiences before and after the safety technologies were turned on. Exhibit 3-2 provides sample questions from the driver interview guides. The appendix of this report provides the full version of the guides.

Exhibit 3-2: Sample Questions From the Driver Interview Guide

Driver Interview – Month 12 T3 – MeritorWabco ECBS and Bendix ADBs
1. How would you rate your level of acceptance of ECBS?
2. Has the ECBS warning light come on to indicate a problem during the test period?
3. How long did it take you to adjust to the feel of the brake pedal of the ECBS?
4. Have you noticed the stability control program operating during the test period?
5. Do you operate a tractor with ECBS and a stability control system differently than you would a tractor with a conventional brake system?

Driver Interview – Month 12 T3 – MeritorWabco ECBS and Bendix ADBs
6. Do you feel that ECBS improves braking performance?
7. Have you had any difficulties connecting the communication link (wire harness) between an ECBS tractor and ECBS trailer?
8. During this test period, have you had any issues with hauling a trailer equipped with ECBS?

The maintenance technicians were also profiled and interviewed at month 6 and month 12. The technicians were interviewed to obtain information on their experiences with maintaining the advanced braking systems and enabled technologies over the course of the FOT. The profiling questions obtained information on the age of the technician, years of experience maintaining commercial vehicles, experience if any maintaining the technologies under evaluation, and a typical job description. The 6- and 12-month interview guides were developed with the understanding that the technicians may work on any of the technologies under evaluation. Exhibit 3-3 provides sample interview questions. The appendix of this report provides the full version of the form.

Exhibit 3-3: Sample Questions From the Mechanic Interview Guide

Mechanic Interview – Month 12
1. What is your level of confidence or trust in the reliability and maintainability of air disc brakes, ECBS, ABS, and ACC?
2. Have you performed any maintenance on ABS, ECBS, or disc brakes?
3. Has the ABS or ECBS generated any fault codes?
4. How would you rate the level of difficulty in diagnosing and repairing ABS, ECBS, and disc brakes?
5. How would you rate the maintenance requirements of Advanced ABS and ECBS over current ABS systems?
6. Do you feel that ECBS requires more frequent replacement of electrical components than current ABS?
7. How would you rate your level of confidence or trust in the reliability and maintainability of air disc brakes?
8. Have the air disc brake systems required maintenance since the last reporting period?

Booz Allen Hamilton developed the survey forms. The conductor team was responsible for distributing them to the appropriate personnel, collecting the completed surveys, and returning them for analysis. Personnel information was masked to protect the identity of the drivers and mechanics.

3.1.4 Foundation Brake Inspections

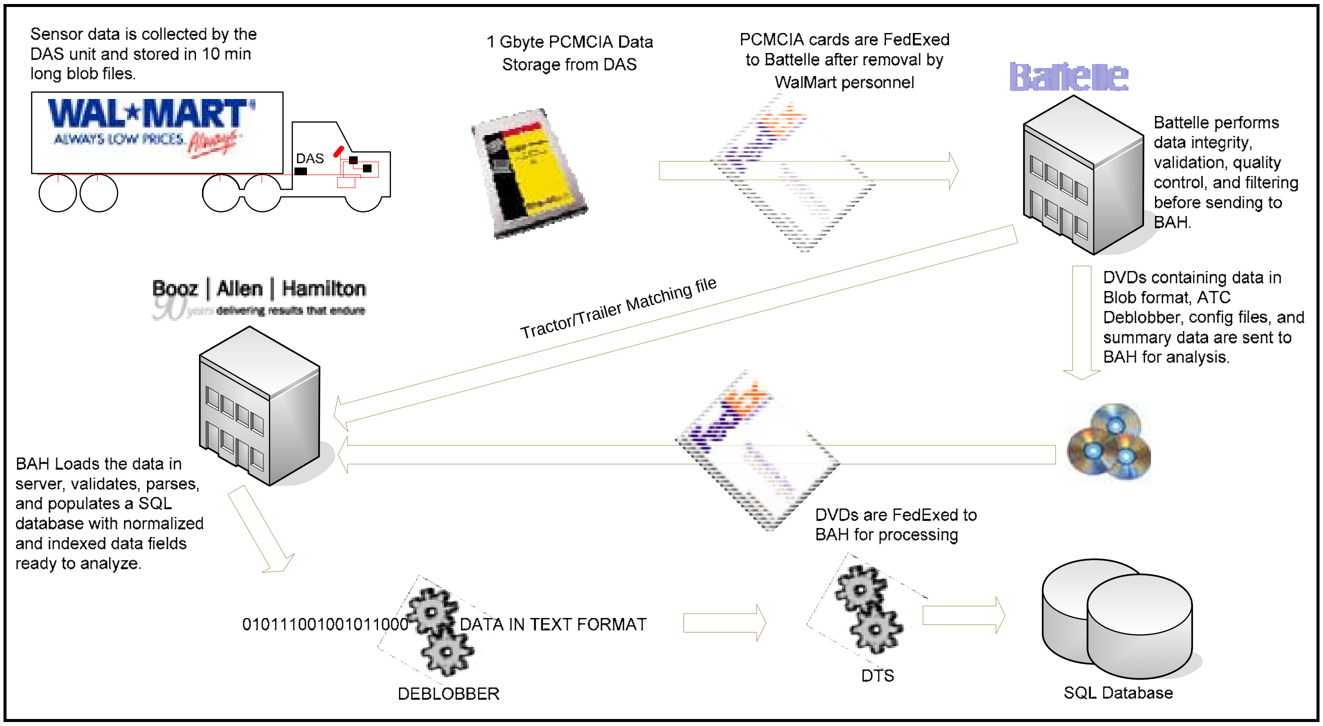
The tractors' anticipated travel throughout the 1-year FOT was 125,000 miles. This accumulation is significantly less than the life of a set of brake pads or shoe linings in this type of service. To obtain information on the wear characteristics of the brake system types, physical inspections were performed on a sample of tractors and trailers. Fifteen tractors and four trailers were inspected for pad, rotor, shoe, and drum (friction couple) wear and overall condition per established methods. All six drum brakes and six of the disc brake tractors inspected used the ABS control system. The remaining three disc brake tractors used ECBS control. Bendix engineers performed the inspections, the results of which can be found in Chapter 7.

3.2 Data Collection

On-board electronic data were stored on PCMCIA cards housed within the DAS. Wal-Mart was responsible for removing the cards from the DAS on the tractors and trailers and forwarding them to the conductor team. The conductor team was responsible for downloading the data and performing integrity checks to make sure the data were within the proper ranges, flagging erroneous data. The empty cards were returned to Wal-Mart for reuse.

The data were stored in blob file format (10 minutes worth of a continuous stream of binary bits) along with a summary database and parsing routines on DVDs and mailed to Booz Allen twice per month. Upon receiving the data, Booz Allen performed validation checks on the data, converted the blob files to ".CSV" comma delimited text files using Aberdeen Test Centers' parsing routines, and developed a data transferring services (DTS) program to export the data into a database server operating Microsoft's SQL software. Exhibit 3-4 illustrates the process for collecting, validating, and storing the data.

Exhibit 3-4: Data Collection, Validation, and Storage Process



3.3 Data Reporting

A Dell PowerEdge server, external Dell PowerVault storage unit, and SQL database engine supported the ECBS FOT. The server performed two main functions: (1) as a SQL database engine to coordinate and organize the data, which is physically stored on the separate Dell PowerVault storage unit, and (2) data analysis and reporting. The server used four 2.0 GHz Pentium processors, 4 GB of memory, 36 GB of internal hard disk space, a floppy disk, a

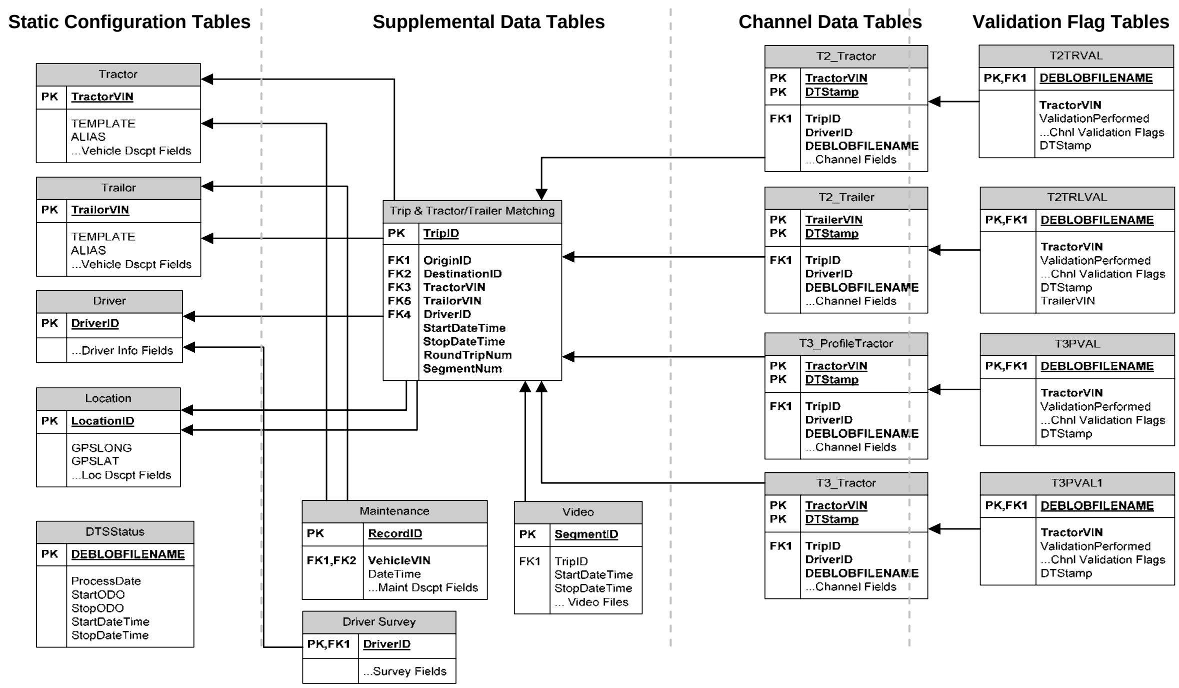
CD / DVD drive, and a preinstalled Windows 2003 Server operating system. Additionally, the server includes a fiber-channel connection to the PowerVault storage unit.

A Dell PowerVault CX300 Direct Attached Storage unit was selected to house the data; the unit is controlled by the PowerEdge sever. The PowerVault Direct Attached Storage unit uses thirty 146-GB hard-disk drives to create approximately 4.38 TB of storage space for the database and overhead associated with data backup, data parity, and a hot spare. The PowerVault storage unit directly connected via fiber-channel host bus adapters to the PowerEdge server and made all of the 30 drives appear to the user as, at most, seven logical units (seven drives). The equipment was housed in a half-height Dell rack storage unit. The rack contains a power distribution unit and a small uninterruptible power supply (UPS), sized to allow just enough time for the server and storage unit to shutdown cleanly in the event of a power failure. To improve processing time, a second server was purchased. The second server was an HP Proliant ML350 with four 2.0 GHZ processors, 16 GB of RAM, and 2.5TB total hard drive storage. Exhibit 3-5 is a photo of the HP server and Dell storage unit.

Exhibit 3-5: ECBS FOT Database Server and Storage Array

Microsoft's SQL Server 2005 was the database engine used for the analysis. SQL Server was selected as a database engine because of its ability to handle a large set of data, cost effectiveness, flexibility, ease of implementation, and familiarity to the Booz Allen team. Additionally, the Microsoft DOT NET software development environment was used to develop custom applications to perform analysis and reporting. This software environment enabled the development of a simple user interface to the database, allowing team members to perform quick and repetitive analysis of the data.

Exhibit 3-6: Database Schema



CHAPTER 4. METADATA

This chapter provides general information on the electronic on-board data collected during the FOT. It is intended to provide the reader with specifics on, for example, how the tractors were operated, average speeds traveled, and total data miles collected. Specifically, the chapter provides information on the following:

- FOT data miles
- Tractor-trailer matched data miles
- Data miles by speed
- Tractor operating hours
- FOT tractor area of operation
- Data quality

4.1 FOT Data Miles

"Data miles" represent the total miles accumulated based on the start and stop mileage of each data file. A total of 3,558,187 "data miles" were collected during the ECBS FOT between May 1, 2005, and July 2006. The official FOT end date occurred on April 30, 2006; however, data continued to be collected up until the time the tractors and trailers were decommissioned. The vehicles were decommissioned during June and July 2006. It should be noted that the support for the data acquisition system (DAS) stopped at the end of April and the frequency of the PCMCIA cards being pulled reduced as the data collection phase of the program ended. Out of the total data miles collected, Phase 1 generated 2,381,936 data miles, and Phase 2 generated 1,176,251 data miles. The tractors actually traveled more miles than is reported below; however, these are the total number of miles that generated data (i.e., functioning DAS). In addition to the miles traveled in the FOT tractors, the eight Template 3 drivers were profiled in their existing Wal-Mart tractors for a minimum of 2 months prior to the FOT start. These eight drivers generated 138,258 miles during this period (Phase 0). Exhibit 4-1 shows the total miles for Phase 1 and Phase 2 and the program total.

Exhibit 4-1: Total Data Miles Accumulated

Total Data Miles Accumulated	
Phase	Total
Phase 1	2,381,936
Phase 2	1,176,251
Program Total	3,558,187

Exhibit 4-2 illustrates the total number of data miles collected per tractor configuration. The data miles range from 618,677 for the 10 MeritorWabco ABS / drum tractors in T2C1 to 784,816 data miles for the 9 ABS-6 / drum tractors in T2C4. When comparing these data mileage figures, it should be noted that each template configuration had 10 tractors, except for the T3 and T3P (which had 8) and T2C4 (which had 9). One of the ABS-6 / drum tractors in T2C4 was damaged beyond repair in route from Freightliner's manufacturing plant in Cleveland, North Carolina, to Wal-Mart's distribution facility in Loveland, Colorado, prior to the FOT start.

Exhibit 4-2: Total Data Miles Traveled per Tractor Configuration

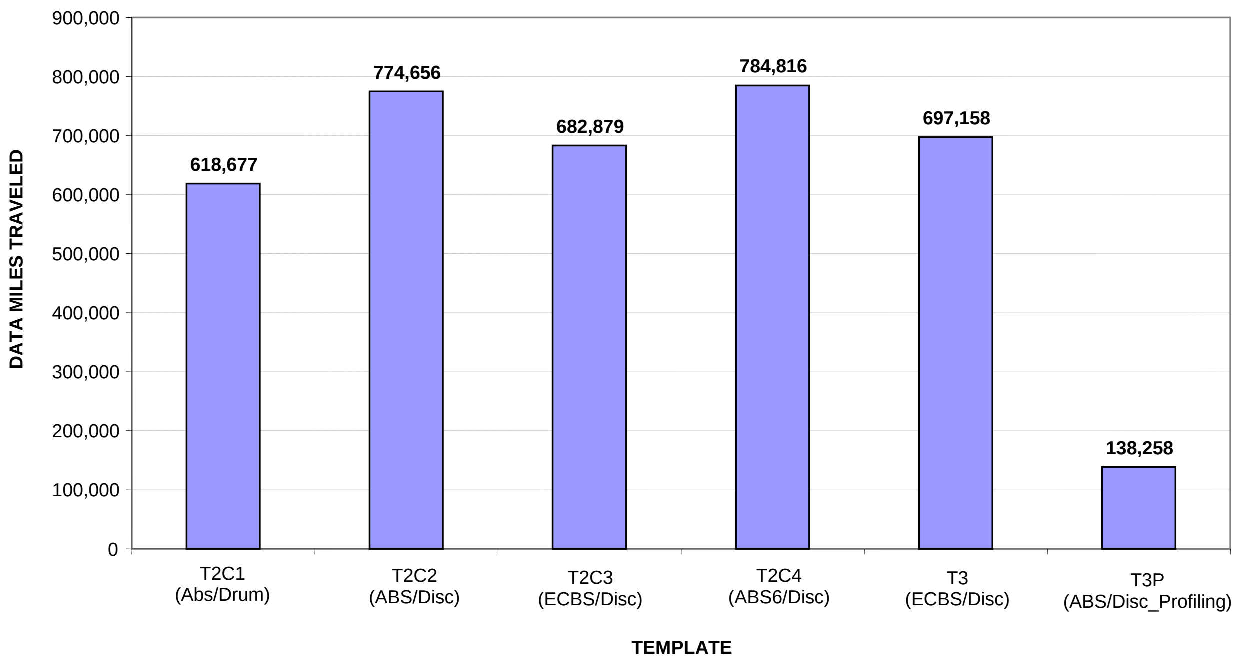


Exhibit 4-3 shows the total data miles traveled per tractor configuration and per phase. Recall that the safety technologies were off in Phase 1 and on in Phase 2. Depending on the tractor configuration, the safety technologies included roll stability control, electronic stability control, roll stability support, and adaptive cruise control. Note that the amount of data miles in Phase 1 is significantly higher than in Phase 2. This is due to issues with scheduling around Wal-Mart's busy holiday season and funding constraints that prevented the FOT from extending past the April 30, 2006, end date. The data miles variance between configurations within the same phase is due to operational differences in the route, trip numbers, and trip length.

Exhibit 4-3: Total Data Miles Traveled per Tractor Configuration per Phase

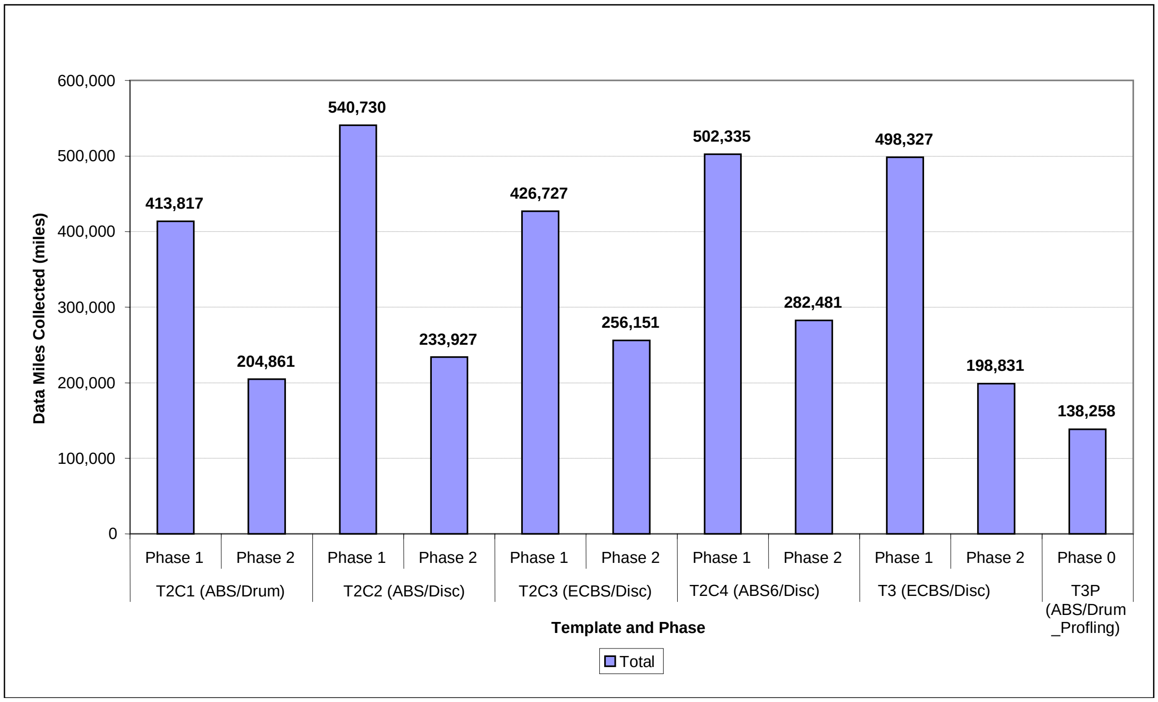


Exhibit 4-4 shows the data miles traveled by month for Template 2 tractors starting in May 2005, and ending in May 2006. The mileage ranges from 20,000 (T2C1) to over 80,000 miles (T2C2) depending on the tractor configuration. The monthly differences are due to seasonal operational differences in support. Note that both Phase 1 and Phase 2 show the months of January and February. The safety technologies were turned on during these months. This process required engineers from MeritorWabco and Bendix to travel to Loveland, Colorado, and physically change parameters within the electronic control unit of each system of each tractor. Therefore, depending on the switch date, tractors may have accumulated miles in both phases in a single month. Note that a majority of the analysis on ACC found later in this report is based on data collected on the systems post-March 23, 2006. This is the date that issues with the data acquisition were corrected, enabling data to be stored on the DAS showing when the ACC system was on.

Exhibit 4-4: Template 2 Tractor Data Miles per Month

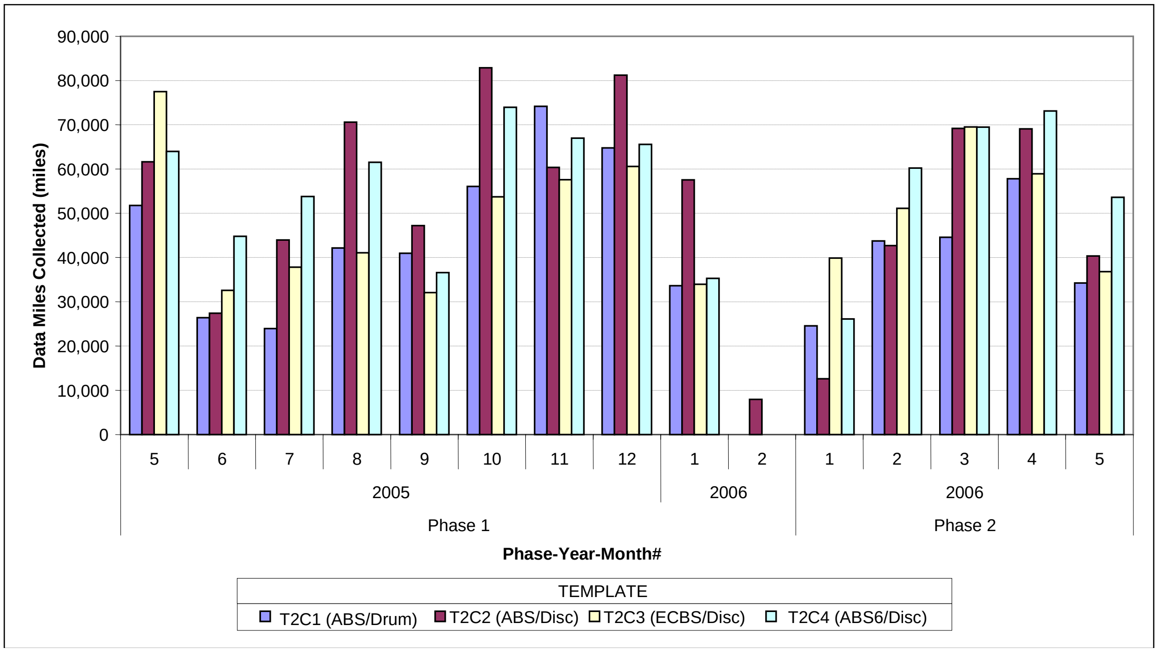
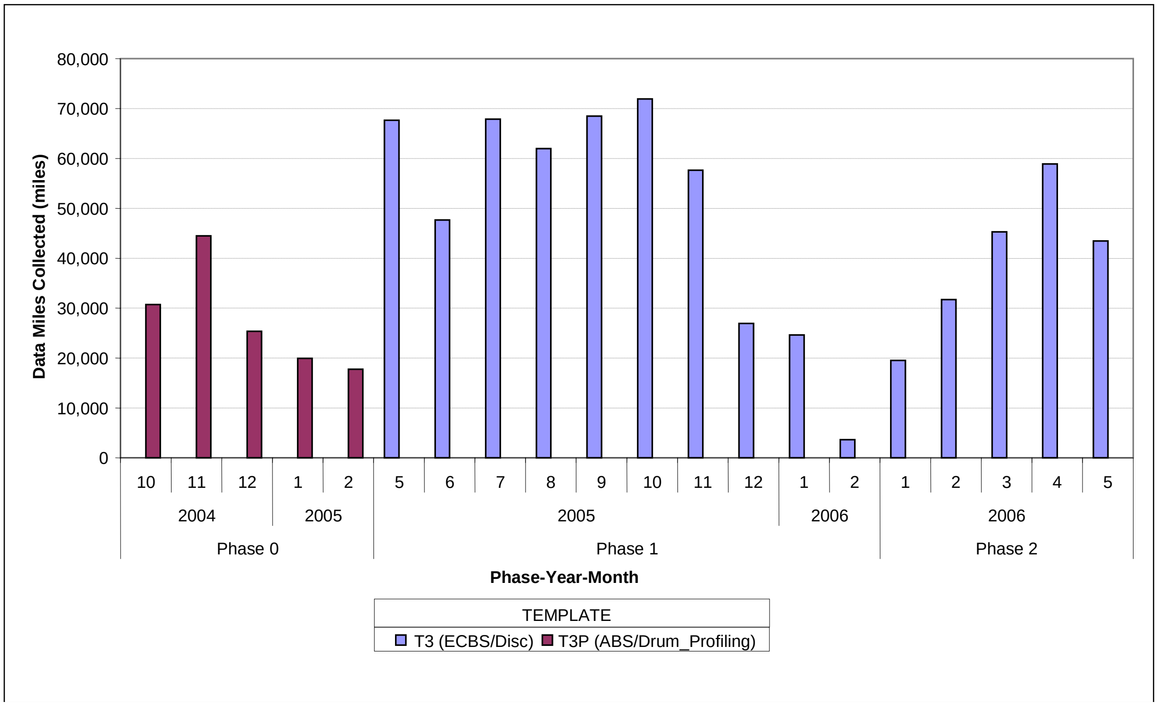


Exhibit 4-5 shows the data miles traveled for the eight Template 3 tractors by month. Similar to Template 2, total data miles range from 20,000 to over 70,000 miles depending on the month. Recall that DAS and forward radar sensors were installed on eight existing Wal-Mart tractors to profile the drivers before they received their new Freightliner Columbia tractors with ECBS and ADBs. These eight drivers were profiled between October 2004 and February 2005, shown on the exhibit as Phase 0. The safety technologies on Template 3 tractors were turned on in January and February. The exact date that the switch occurred for each tractor was recorded and entered into the FOT database, allowing this graph to be generated.

Exhibit 4-5: Template 3 Data Miles per Month



4.2 Tractor-Trailer Matched Data Miles

The ECBS FOT featured trailers with DAS providing a unique opportunity to evaluate braking technologies on tractor-trailer combinations. Exhibit 4-6 shows the total data miles collected on the various combinations of tractors and trailers in both Templates 2 and 3. Unfortunately, as shown in the table, Template 2 tractors operated a majority of the time hauling non-FOT, non-instrumented trailers. As shown, the T2C3 tractors equipped with ABS and disc brakes hauled instrumented FOT trailers for a total of 1,682 data miles out of the 682,879 data miles collected by the tractors. This equates to 168 miles per tractor. This is significantly less than the combination mileage expected based on the ratio of tractors to trailers operating out of Wal-Mart's Loveland distribution facility. This shows the challenge in conducting and controlling variables in an in-service FOT. Note that the experimental design had the Template 2 tractors and trailers intermixing randomly.

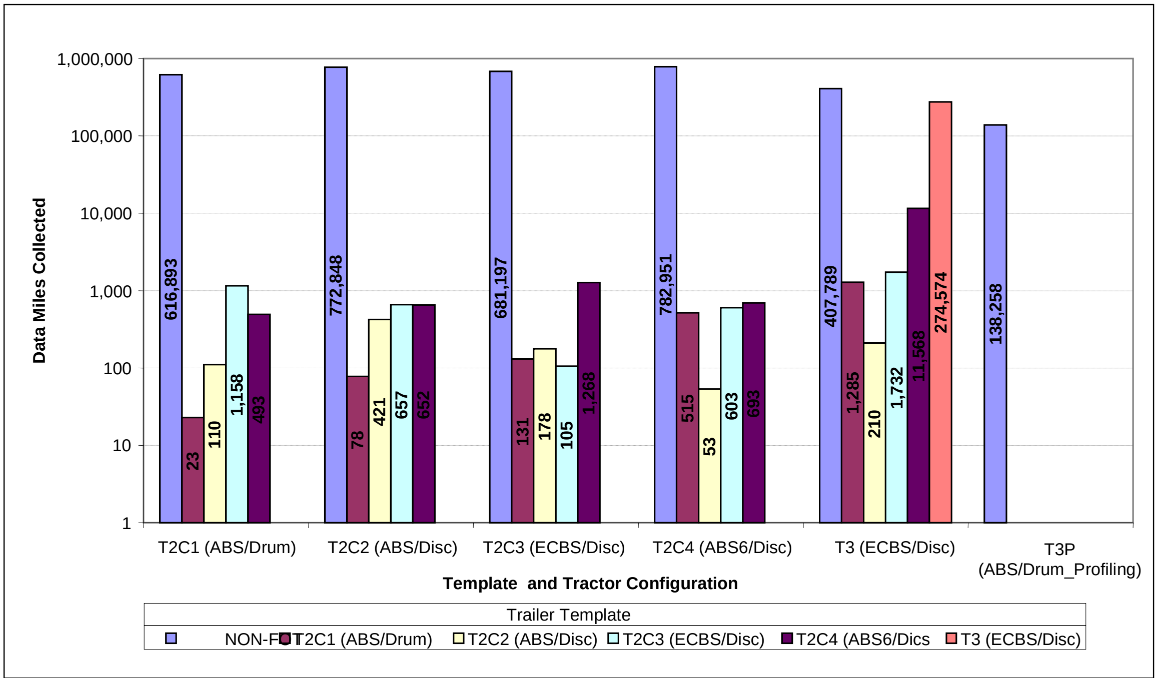
For Template 3, the tractor-trailer matching was significantly higher at 40 percent. The higher matching percentage was due to a higher ratio of Template 3 FOT trailers to tractors, a Wal-Mart dispatcher focused on matching T3 tractors and trailers when possible, and tractors placed on dedicated routes minimizing the area in which the equipment was deployed. It is interesting to note that there was a higher percentage of T3 ECBS / disc tractors matched to T2C4 Bendix TEBS4 (EBS) / disc trailers, when compared to the other instrumented trailers. In the absence of a T3 trailer, the dispatcher chose to select a T2C4 trailer over the others, resulting in 11, 569 miles where a MeritorWabco ECBS / disc tractor hauled a Bendix Trailer EBS / disc trailer.

Exhibit 4-6: Tractor-Trailer Match Data Miles (Table)

Sum of DMT	Trailer Template					
Tractor Template	Wal*Mart Non-FOT	T2C1	T2C2	T2C3	T2C4	T3
T2C1	616,893	23	110	1,158	493	-
T2C2	772,848	78	421	657	652	-
T2C3	681,197	131	178	105	1,268	-
T2C4	782,951	515	53	603	693	-
T3	407,789	1,285	210	1,732	11,568	274,574
T3P	138,258	-	-	-	-	-
Total	3,399,936	2,032	973	4,255	14,674	274,574

Exhibit 4-7 shows the same trailer matching in graphical format. When viewing the data, note that the vertical axis uses the logarithmic scale.

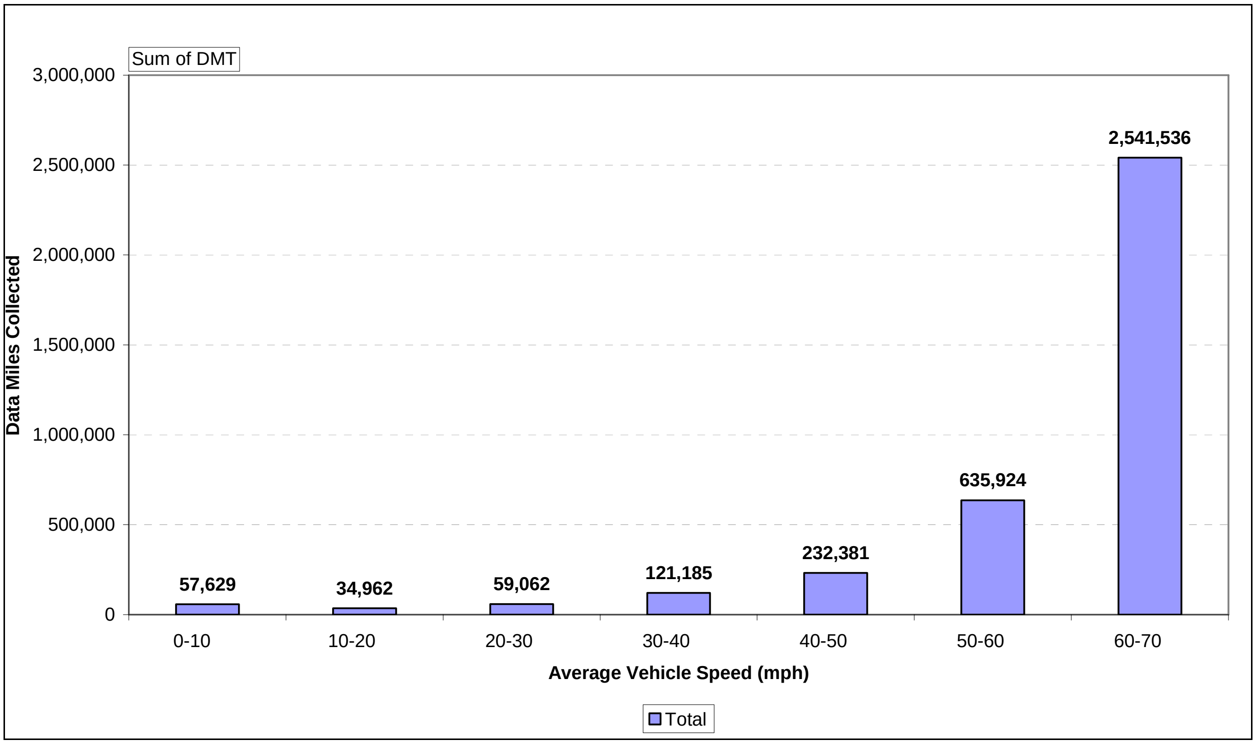
Exhibit 4-7: Tractor-Trailer Match Data Miles (Graph)



4.3 Data Miles by Speed

Exhibit 4-8 shows the total data miles for all FOT tractors binned by speed. The graph shows 2,541,536 miles or approximately 70 percent of the data miles collected occurred at vehicle speeds above 60 miles per hour. Another 635,924 data miles were collected between 50 and 60 miles per hour. The two speed bins taken together represent 86 percent of the total miles collected during the 1-year data collection phase of the FOT. This is indicative of the relatively non-congested rural highways used by the tractors operating out of Wal-Mart's Loveland, Colorado, distribution facility.

Exhibit 4-8: Total Tractor Data Miles by Speed



4.4 Tractor Operating Hours

While 86 percent of the tractor data miles occurred at speeds above 50 miles per hour, Exhibit 4-9 shows that 64 percent of the hours (engine run time) occurred at 10 miles per hour or less. A significantly smaller 28 percent of the total hours occurred at speeds above 50 miles per hour, where a majority of the data miles were generated. Out of the 115,005 hours logged at 10 miles per hour and under, 20 percent of them occurred idling. The remainder had some tractor movement.

Exhibit 4-9: Tractor Operating Hours by Speed Bin

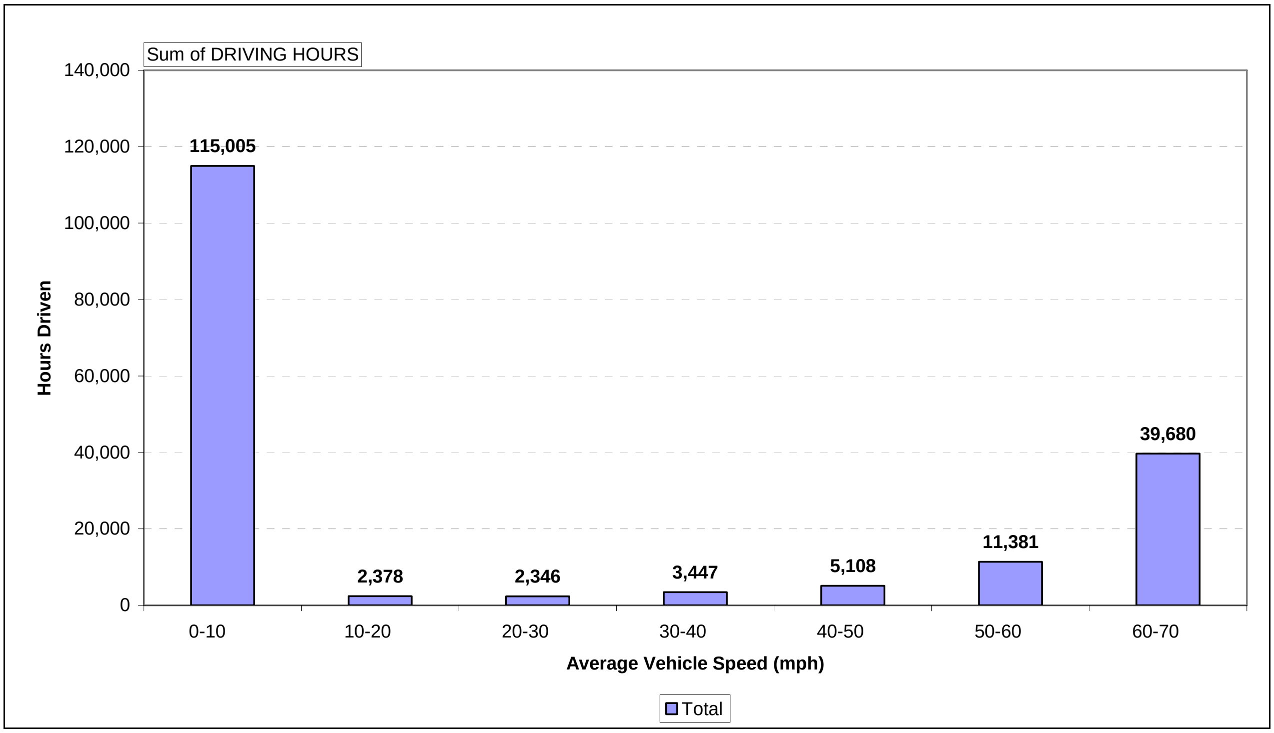


Exhibit 4-10 provides the average hours driven per tractor configuration per day. Note that Template 3 tractors average 6.31 hours per day, which is significantly less than the tractors in Template 2. FOT tractor assignments were based on seniority and their record. It may be indicative that these drivers also received first choice on store routes.

Exhibit 4-10: Average Hours Driven per Day

Average Hours Driven per Day	
Template	Hours
T2C1	11.08
T2C2	12.74
T2C3	11.72
T2C4	14.18
T3	6.31
Average	11.21

4.5 FOT Tractor Area of Operation

Exhibit 4-11 shows an aerial view of the Wal-Mart stores supported by the Loveland, Colorado, distribution facility marked with yellow circles. As shown, the Loveland distribution facility supports a heavy concentration of stores in Colorado and in six surrounding States that include Montana, North Dakota, South Dakota, Nebraska, Kansas, and Utah. Red circles indicate stores that were located on the dedicated routes supported by the Template 3 tractors. This was the planned area of operation for the ECBS FOT.

Exhibit 4-11: Wal-Mart Store Locations Supported Loveland, CO Distribution Facility

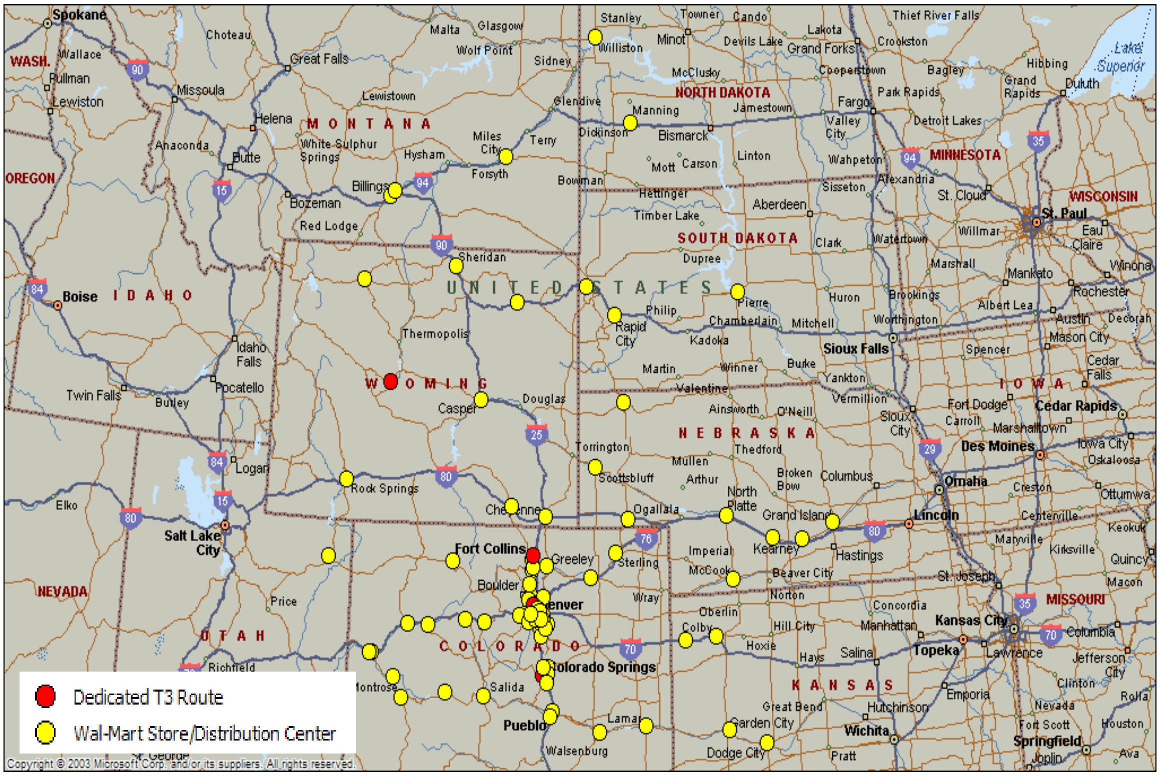


Exhibit 4-12 shows the actual area of operation of all FOT tractors. This graph was generated by taking the initial GPS coordinates of each 10-minute blob file and plotting them on a map of the United States. The yellow circles indicate at least one blob file recorded at that precise GPS location. Green circles indicate 10 or more, while blue circles indicate 100 or more blob files had the exact GPS coordinates. As shown, the highest concentration of data occurred in Colorado and the surrounding States as anticipated. However, tractors traveled as far east as Michigan, as far south as the New Mexico / Mexico border, as far west as San Francisco, and as far north as the Montana / Canada border.

Exhibit 4-12: FOT Tractor Area of Operations

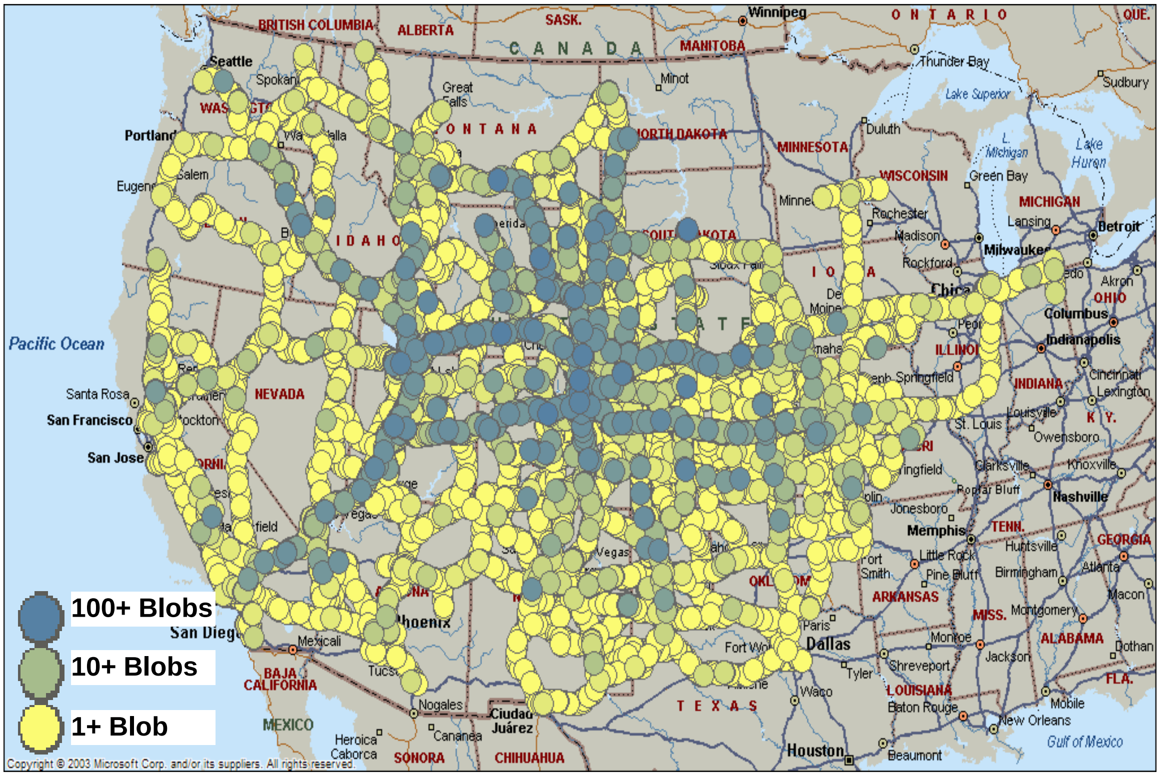
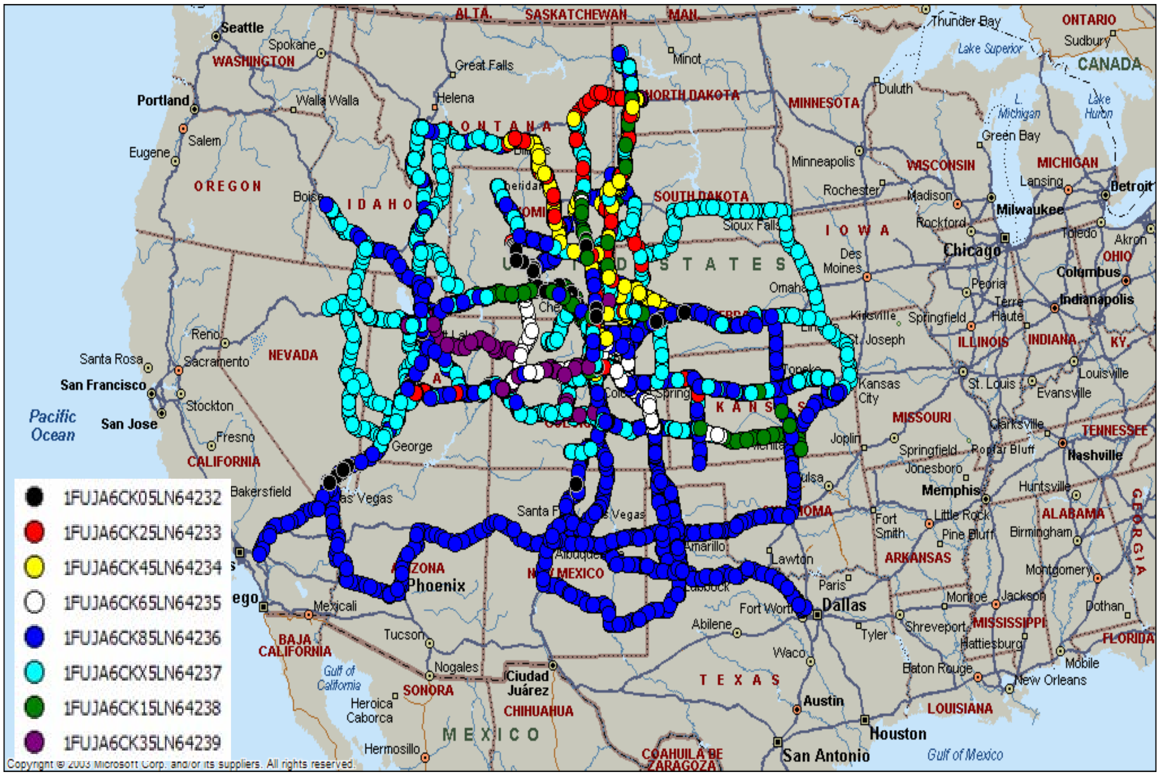


Exhibit 4-13 illustrates the area of operation of the eight Template 3 tractors. Using a similar method as above, a set of GPS coordinates for each 10-minute blob file was plotted on a map of the United States. The Template 3 tractors operated on dedicated routes, and this can be seen in the more restrictive operating pattern.

Exhibit 4-13: Template 3 Tractors Dedicated Routes



4.6 Data Quality

As discussed in Chapter 3, all data files collected from the FOT tractors and trailers were subjected to validation routines. The purpose of these routines was to identify faulty readings during the FOT in order to prevent these data from being used in the evaluation of the technologies. The validation routines employed by the conductor team were simple out-of-range checks. For example, if the vehicle speed channel recorded a speed of 200 miles per hour, the blob file and channel containing these data would be flagged as having failed the check. A table within the database was created to record all blob files containing flagged data and more specifically identify channels within the blob files that were bad. Blob files containing bad data were not discarded. Only the bad channels within the blob file were flagged as faulty and not used. The entire content of all blob files was loaded into the database. However, analysis queries were written to cross-reference the "flagged" table to ensure that only valid data were used for analysis.

Exhibit 4-14 shows a complete listing of the channels per tractor configuration with the percentage of valid data listed next to the channel. The channels discussed above as well as less critical channels with low percentages have been highlighted. A data channel glossary can be found in the appendix of this report.

Exhibit 4-14: Valid Percent of Data Miles by Channel

Valid Percentage of Data Miles Collected by Channel

T2T Channels	Template T2C1	Template T2C2	Template T2C3	Template T2C4
DTSTAMP	100%	98%	97%	100%
GPSLONG	79%	93%	90%	85%
GPSLAT	79%	93%	90%	85%
GPSALT	100%	100%	99%	100%
ODO	100%	100%	99%	100%
VS	100%	100%	98%	100%
ES	100%	100%	99%	100%
ET	100%	100%	99%	100%
SA	96%	100%	97%	99%
APP	100%	100%	99%	100%
CCS	100%	100%	99%	100%
BA	100%	100%	99%	100%
CA	100%	100%	99%	100%
BPP	100%	100%	n/a	100%
TECBSDD	100%	100%	99%	100%
TCAP	80%	92%	99%	89%
TRLCAP	73%	95%	94%	84%
EBA	95%	96%	84%	100%
EBP	99%	99%	99%	100%
CGS	100%	100%	99%	100%
WWA	100%	100%	99%	100%
HLLOW	100%	100%	99%	100%
HLHIGH	100%	100%	99%	100%
TSRIGHT	100%	100%	99%	100%
TSLEFT	100%	100%	99%	100%
HZ	48%	52%	51%	49%
AMBTEMP	99%	100%	98%	99%
SAP	77%	96%	90%	81%
LFSCP	78%	87%	89%	84%
RFSCP	78%	90%	93%	89%
LFDCP	74%	91%	83%	90%
RFDCP	77%	87%	89%	90%
LRDCP	80%	90%	87%	90%
RRDCP	75%	89%	89%	90%
LFSWSS	100%	100%	98%	100%
RFSWSS	100%	100%	98%	100%
LFDWSS	100%	100%	1%	100%
RFDWSS	100%	100%	10%	100%
LRDWSS	100%	100%	98%	100%
RRDWSS	100%	100%	98%	100%
ACCELLONG	83%	91%	95%	88%
ACCELLAT	81%	86%	89%	83%
YAW	79%	88%	90%	85%
ACCTR	97%	95%	94%	97%
ACCTRR	81%	74%	87%	82%
ACCTA	100%	100%	99%	100%
ACCTDETECT	100%	100%	99%	100%
ACCSSOW	100%	100%	99%	100%
ACCDAS	100%	100%	99%	100%
ABSA	5%	2%	0%	100%
TRLABSA	56%	57%	59%	0%
ABSF	3%	0%	0%	100%
VDCF	0%	0%	94%	0%
ECBSRCBCA	n/a	n/a	94%	n/a
ECBSRCECA	n/a	n/a	94%	n/a
ECBSYCBCA	n/a	n/a	94%	n/a
ECBSYCECA	n/a	n/a	94%	n/a
ATCBCA	85%	85%	99%	n/a
ATCECA	75%	74%	99%	n/a
RSCRCBCA	0%	0%	n/a	0%
RSCRCECA	0%	0%	n/a	0%
RSALEVEL	0%	0%	n/a	0%

T3 Channels	Template T3
DTSTAMP	98%
GPSLONG	97%
GPSLAT	97%
GPSALT	98%
ODO	98%
VS	98%
ES	98%
ET	98%
SA	97%
APP	98%
CCS	98%
BA	98%
CA	98%
BPP	n/a
TECBSDD	98%
TCAP	98%
TRLCAP	95%
EBA	81%
EBP	98%
CGS	98%
WWA	98%
HLLOW	98%
HLHIGH	98%
TSRIGHT	98%
TSLEFT	98%
HZ	55%
AMBTEMP	97%
SAP	96%
TRLSAP	92%
LFSCP	91%
RFSCP	91%
LFDCP	93%
RFDCP	84%
LRDCP	92%
RRDCP	92%
LFTCP	85%
RFTCP	85%
LRTCP	86%
RRTCP	86%
LFSWSS	98%
RFSWSS	98%
LFDWSS	3%
RFDWSS	8%
LRDWSS	98%
RRDWSS	98%
LFTWSS	98%
RFTWSS	98%
LRTWSS	98%
RRTWSS	98%
ACCELLONG	96%
ACCELLAT	97%
YAW	93%
TRLACCELLONG	75%
TRLACCELLAT	72%
TRLYAW	88%
ACCTR	94%
ACCTRR	89%
ACCTA	98%
ACCTDETECT	98%
ACCSSOW	98%
ACCDAS	98%
ABSA	0%
TRLABSA	62%
ABSF	98%
VDCF	95%
ECBSRCBCA	95%
ECBSRCECA	95%
ECBSYCBCA	95%
ECBSYCECA	95%
ATCBCA	98%
ATCECA	98%

T3P Channels	Template T3P
DTSTAMP	100%
GPSLONG	83%
GPSLAT	100%
GPSALT	80%
ODO	100%
VS	100%
ES	100%
ET	100%
APP	100%
CCS	100%
BA	100%
EBA	100%
EBP	100%
BPP	100%
AMBTEMP	95%
ACCELLONG	85%
ACCELLAT	16%
YAW	89%
ACCTR	94%
ACCTRR	99%
ACCTA	100%
ACCTDETECT	100%
ABSA	100%
ABSF	100%
ABSRC	100%
EL	100%
PBA	100%

While the verification routines proved to be an effective means to set aside out-of-range data, critical sensors produced either noisy or unusable data that passed the validation routines. These critical sensors included:

- Steering angle (Template 2 ABS tractors, T3);
- Longitudinal accelerometer;
- ABS message;
- RSC message (T2C1 and T2C2 tractors); and
- Lateral accelerometer.

The steering angle sensors used on the ABS tractors in Template 2, which were developed specifically for use on this FOT, were found to be problematic. These data from these sensors swung full range from their minimum to their maximum thresholds without any indication of the tractor's steering direction. Close examination of the channel provided no confidence in these data and ultimately led to these data being deemed unusable.

Steering angle sensor problems were also identified with one configuration of the ECBS tractors. Recall that there were two sets of ECBS tractors, a group of 10 under Template 2 and a group of 8 under Template 3. The hardware configuration for both tractors was identical even though the tractors were in separate templates, and the steering angle sensors were factory-installed as part of the MeritorWabco's ECBS. The issue lied with the resolution of the steering angle sensor on the Template 3 tractors. The resolution with these sensors was limited to 5.7 degrees, whereas the Template 2 tractors had a resolution of 0.57 degrees. Close examination of these data confirmed that these data were recorded correctly by the DAS unit and was input correctly into the database. Although not confirmed, the issue is believed to be with either the sensor itself or, more likely, the ECU's J1939 broadcast settings. The lower resolution proved to be problematic with the analysis of the stability control systems because the analysis relied on the steering angle data to calculate the steering angle rate of change, which was one of the key pieces of data used to identify events of interest, particularly with lane change maneuvers. The lower resolution overestimated the steering angle rate of change, so the analysis approach developed for Template 2 tractors could not be used for those in Template 3.

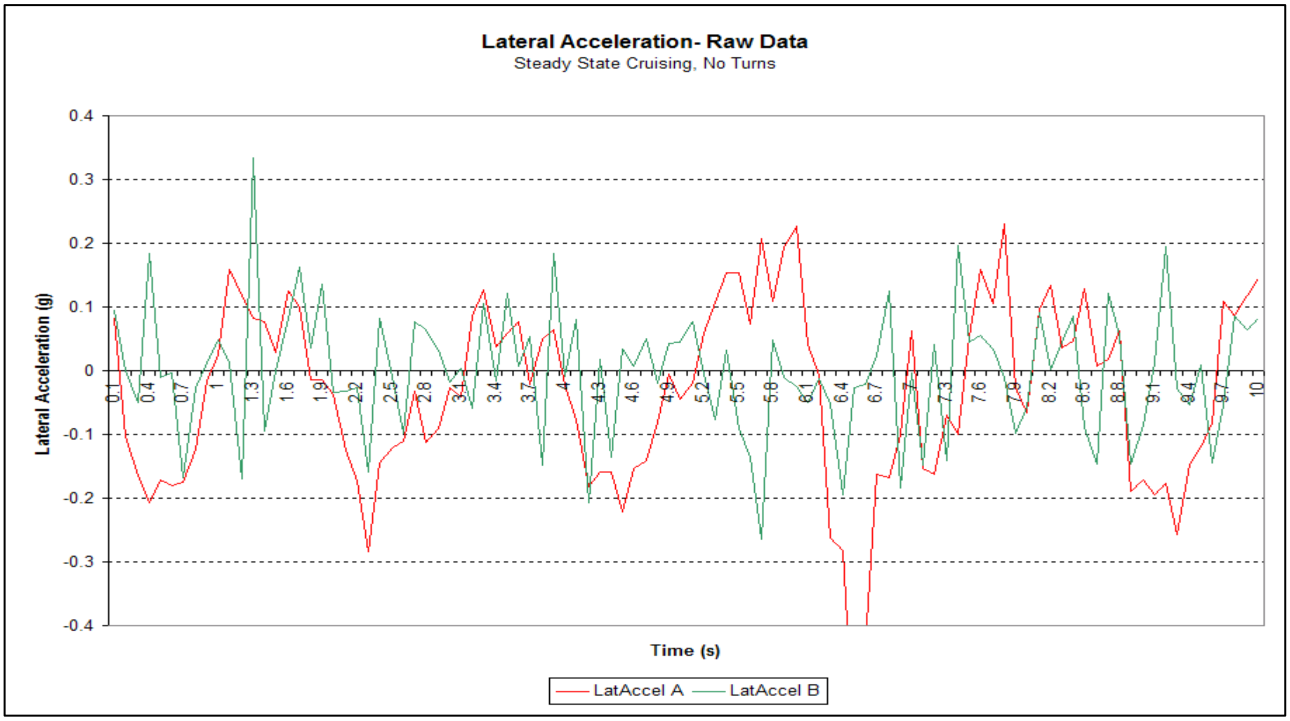
The ABS data on all MeritorWabco tractors was recorded incorrectly; two bytes of the J1939 message were truncated. The RSC message on the Advanced ABS tractors (T2C1 and T2C2) was not recorded, preventing analysis of this system.

The longitudinal accelerometer was housed within the DAS and proved too noisy to be useful. Rather than employing smoothing techniques, it was decided to use the derivative of the velocity channel (J1939 vehicle speed) or the change in speed from two consecutive time points. This proved to be an acceptable method to determine the deceleration rate of the tractors.

The lateral accelerometer sensor was also housed within the DAS. These data collected from this sensor was within the expected range, but contained a significant amount of noise. This issue was originally identified in the profiling of the Template 3 drivers in Phase 0. The conductor team made an effort to eliminate the noise by selecting an alternative, more secure location for the DAS on the FOT tractors. While this location improved the issue, a significant amount of noise remained. Sophisticated filters were employed to make use of these data. Several different smoothing algorithms were attempted, and the "differential" smoothing was deemed to provide the best balance between filtering out the noise and not overly dampening real events. Unfortunately, even the most sophisticated smoothing algorithms were insufficient to make these data useful for sophisticated analyses. Some of the smoothing techniques are detailed below.

Lateral acceleration is a key input for stability control algorithms. For this reason, a significant effort was made to make these data usable. Exhibit 4-15 shows a sample of two tractors traveling over a straight road at highway speed. During this operation, little to no lateral acceleration is expected.

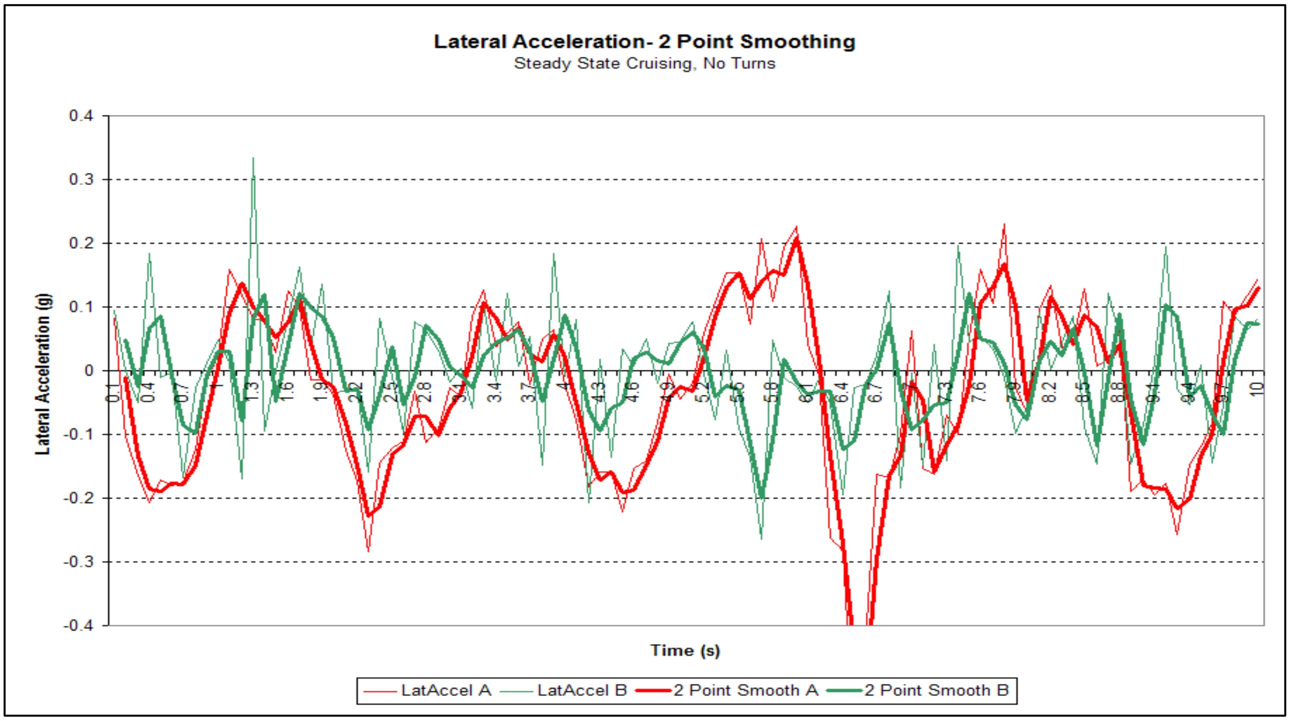
Exhibit 4-15: Lateral Acceleration Raw Data



Over the 10 seconds displayed for each tractor, lateral acceleration oscillates between +/- 0.2g, and even goes beyond -0.4g for a moment. Recall that this is straight-line (as verified by GPS location information) high-speed cruising where no lateral acceleration should be present. This representative sample shows the level of noise within the lateral acceleration channel.

The first smoothing algorithm employed was a simple 2-point average. With this technique, the lateral acceleration reading was averaged with the preceding value. Exhibit 4-16 compares the smoothed data to the raw data.

Exhibit 4-16: 2-Point Average



Different variations of this method were also tried. Moving average and weighted average are shown in the following exhibits.

Exhibit 4-17: Moving Average

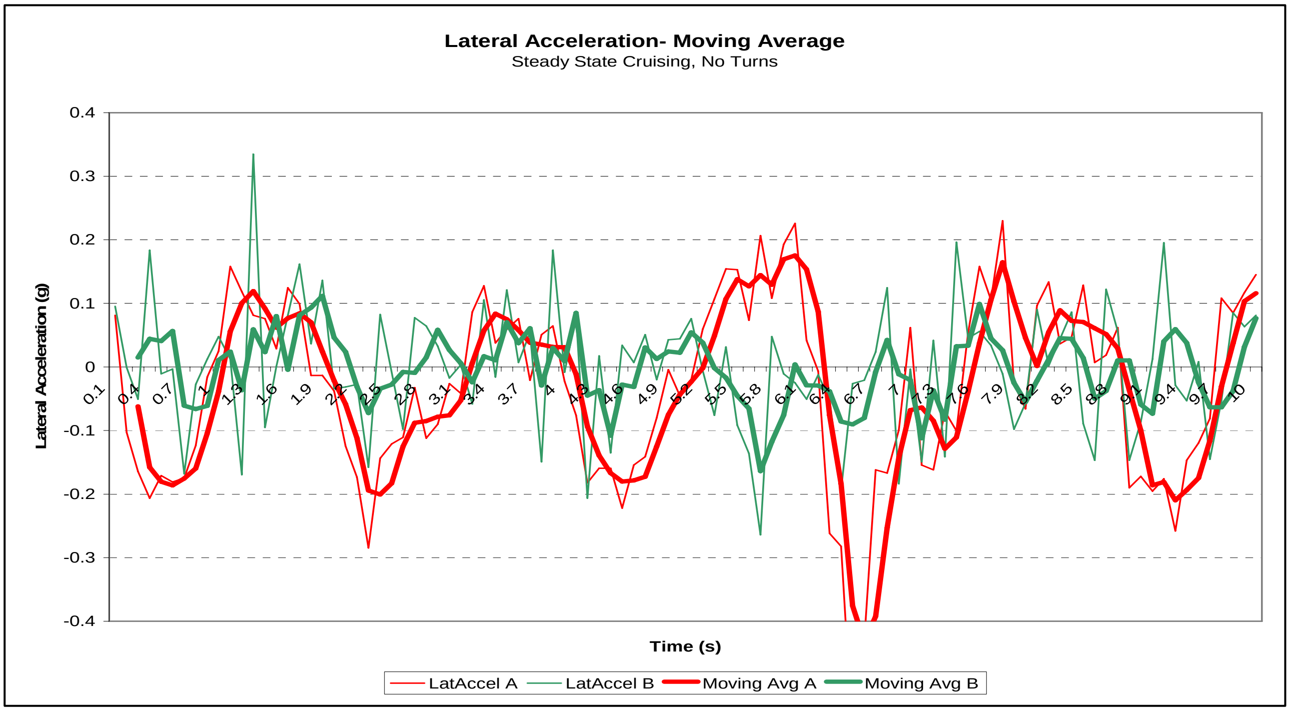
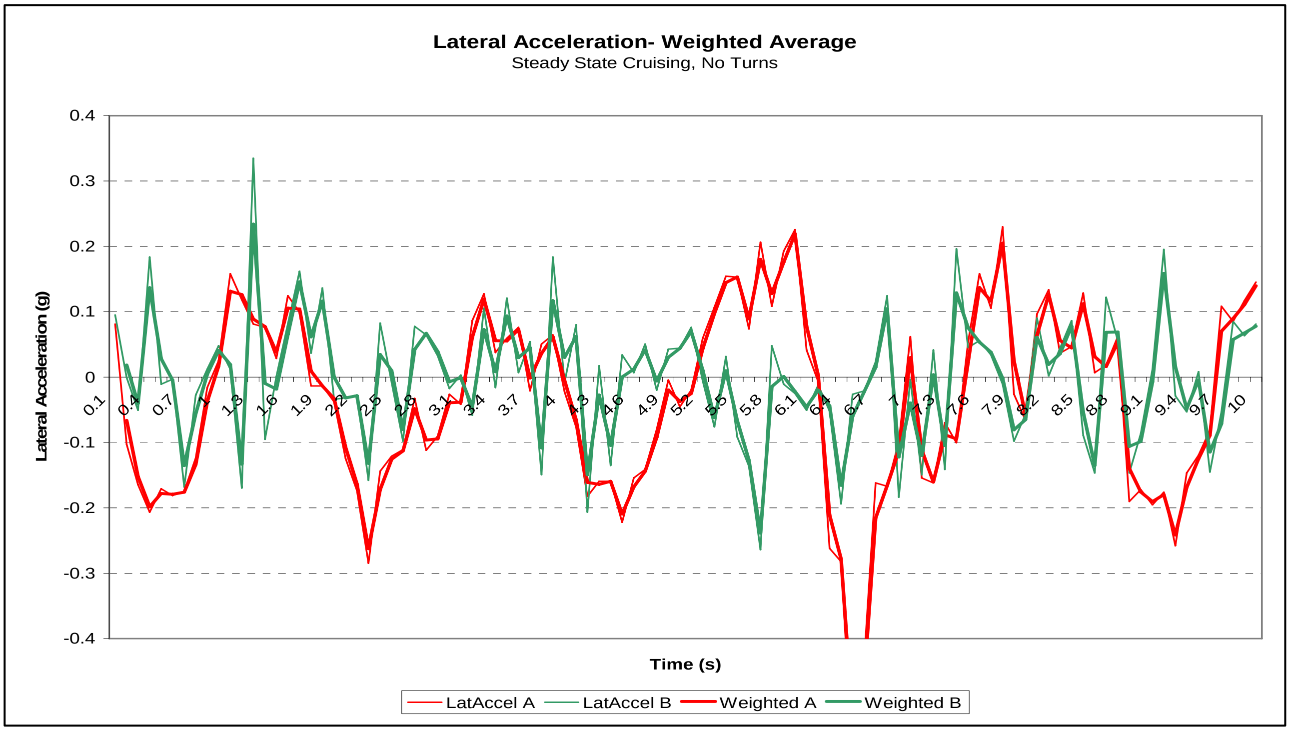


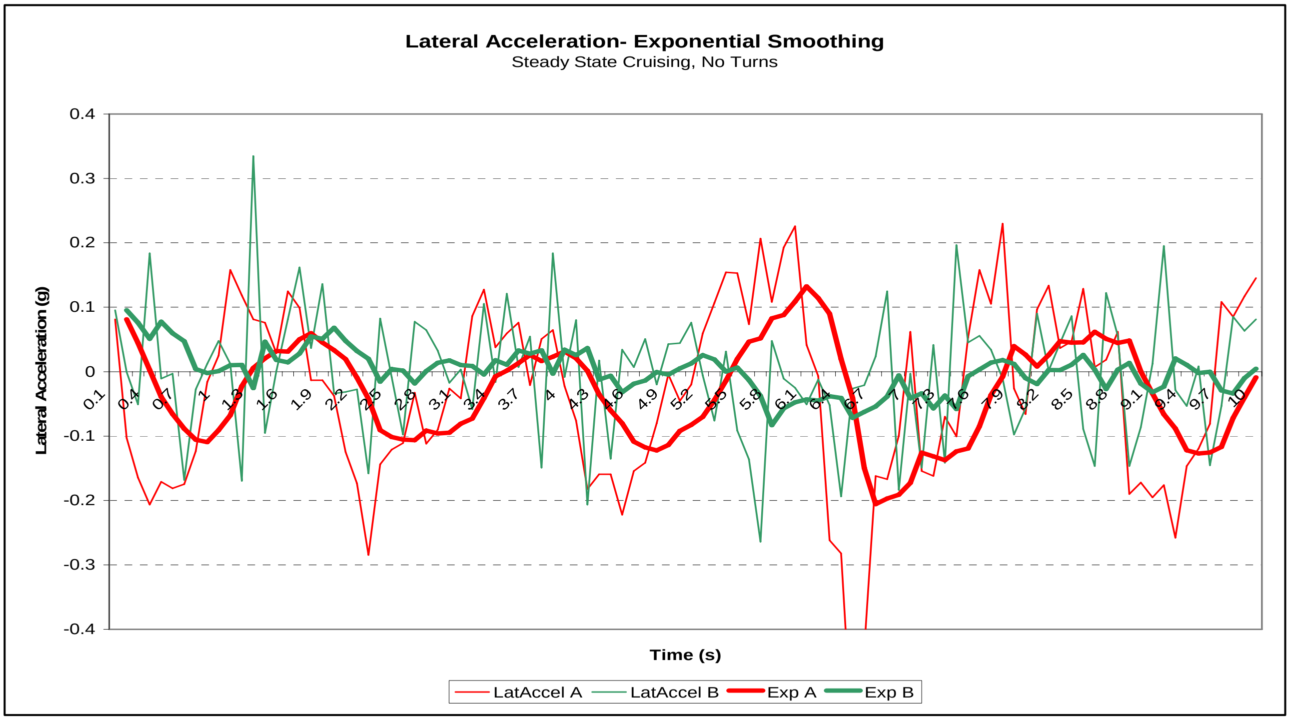
Exhibit 4-18: Weighted Average



As is shown in the graphs above, the linear smoothing approaches (2-point, moving, weighted) helped smooth out the small, rapid oscillations. However, the dataset contains larger and longer-lasting oscillations that are not appropriately dampened. More sophisticated techniques were evaluated for performance.

Exponential smoothing of these data is shown in Exhibit 4-19. This technique showed significant improvement in its ability to filter out noise in these data. Thus far, only straight-line application had been explored. Exponential smoothing's effect on these data while the tractor was negotiating a turn had not yet been explored.

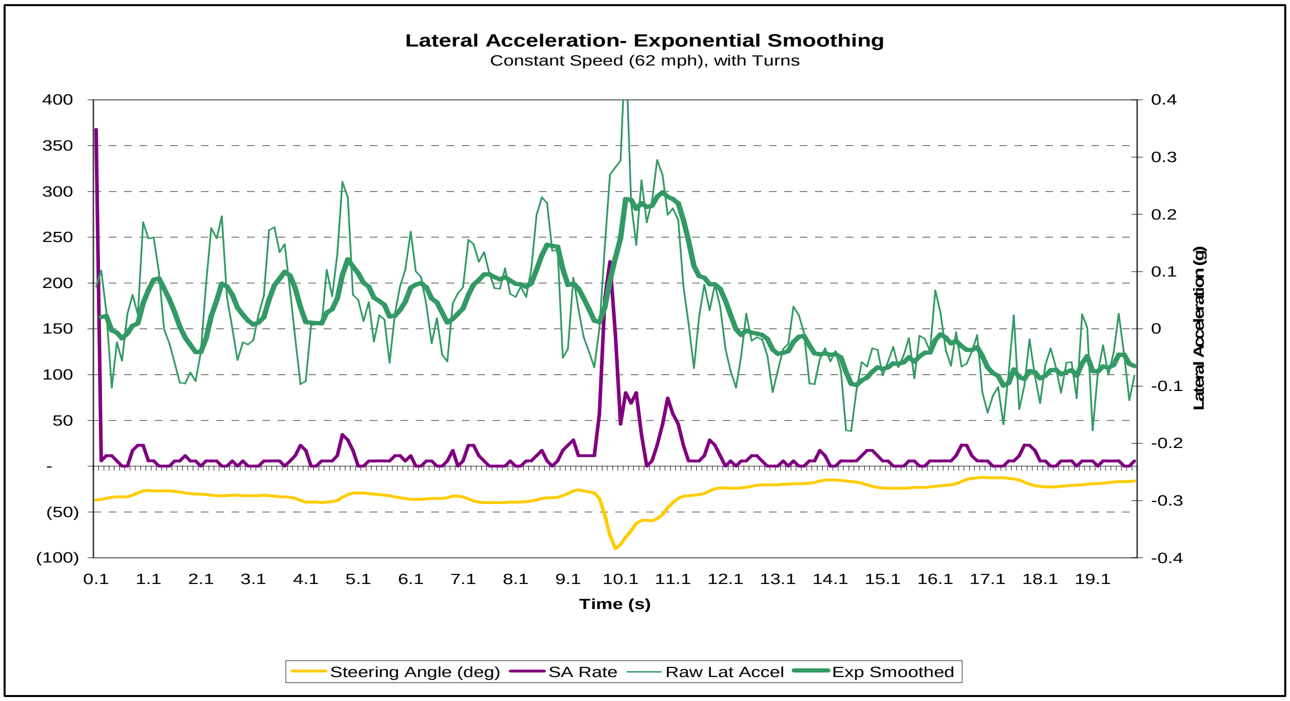
Exhibit 4-19: Exponential Smoothing



To evaluate the effectiveness of exponential smoothing on "real" lateral acceleration (i.e., when the tractor is negotiating a turn), several tractors were evaluated. Locations were identified where some lateral acceleration was expected and the analysis was performed.

Exhibit 4-20 shows the results of the exponential smoothing on a sample data set. Note that the steering event occurs in the middle of the event, and lateral acceleration is expected immediately following the steering input.

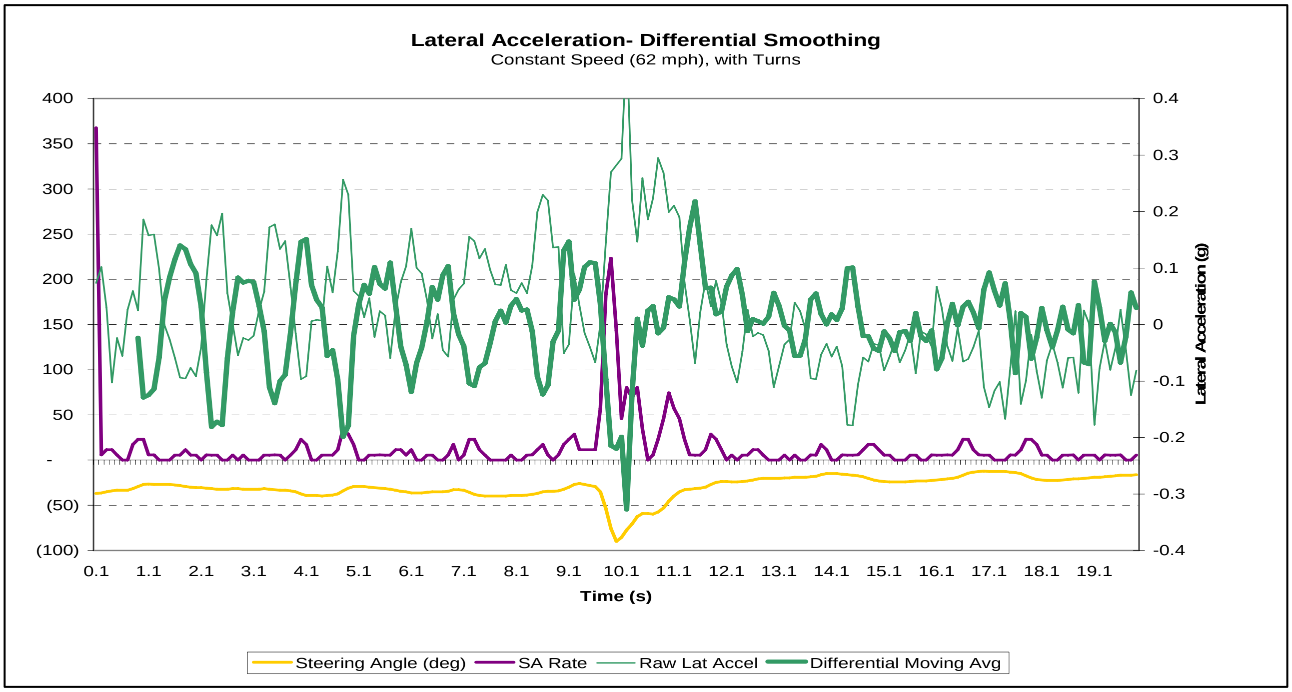
Exhibit 4-20: Exponential Smoothing in a Curve



Although exponential smoothing performed adequately during straight-line operation, it provided too much dampening of lateral acceleration during turns, effectively masking any real events. Therefore, this method was not useful in identifying events.

A modified approach to the exponential smoothing was then attempted. The difference of the current exponentially smoothed value and the previous 1-second average of the value was compared to what we named the “differential” smoothing algorithm. Exhibit 4-21 shows the differential smoothing results over the same curve.

Exhibit 4-21: Differential Smoothing



It should be noted that differential smoothing introduces two peculiarities into these data that must be accounted for during analysis. First, the polarity is reversed because a difference is being calculated. This is not a concern because during analysis no difference is made between left and right hand turns; therefore, the absolute value of the lateral acceleration is taken. Second, the 1-second moving average introduces a slight delay (generally 0.2 to 0.3 seconds) into these data. This delay must be accounted for during any queries. Although this makes for slightly more complex programming, no errors result from it.

After several iterations and modifications to each smoothing routine, the differential smoothing routine was selected as the most beneficial. Although each had its advantages, differential smoothing provided the best overall performance.

Exhibit 4-22: Smoothing Routine Effectiveness

Algorithm	Straight line Results	Curve Results		
		False Positives	False Negatives	17 Event Detection
2-Point Average	0	0	0	2
Moving Average	1	0	0	2
Weighted Average	2	1	2	2
Exponential	3	3	1	0
Differential	**N/A**	3	4	4

4 Best   3 Above Average   2 Average   1 Below Average   0 Worst

As a measure of each routine's effectiveness, 17 events (those where stability control activated) were selected. Each smoothing algorithm was measured on its ability to find the 17 events. The results are shown in Exhibit 4-22. False positives continued to be an issue with the differential smoothing algorithm. Unfortunately, the noisy lateral acceleration data coupled with the low resolution from the steering angle sensor prevented an accurate calculation of safety benefits from ECBS.

In addition to the sensors listed above, other key information that was either not broadcast or not recorded by the DAS included the RSC activation messages. The RSC system on the Template 2 ABS tractors (T2C1 and T2C2) was capable of de-throttling the engine and applying the service / foundation brakes in the event that a roll condition was detected to assist the driver in maintaining control of the tractor. These activation signals were never recorded. This information was needed to identify the activation of the roll control systems in Phase 2 so that the events could be studied and the parameters in which the systems triggered could be used to determine the exposure of the tractors to roll with the system turned off in Phase 1 in support of the safety benefits analysis. The absence of these messages prevented RSC from being evaluated.

CHAPTER 5. BRAKE TECHNOLOGIES

This chapter discusses the observations and findings for the brake technologies evaluated under this FOT. The chapter starts with a brief description of the brake technologies followed by data on the brake usage, behavioral impacts, and ECBS analysis, and a review of the electronic stability control activations. Specifically, this chapter is organized as follows:

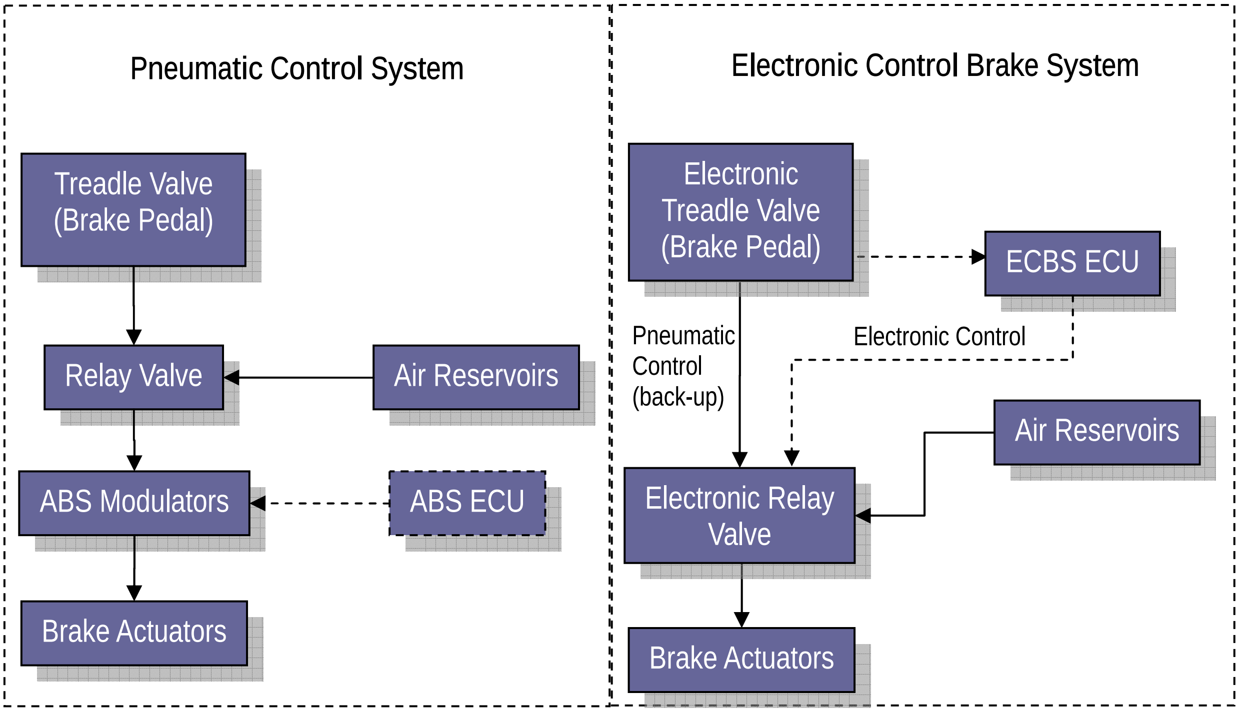
- System overview
- Brake application overview
- Driver behavioral changes
- Electronic stability control events review
- Driver reaction to electronic stability control

5.1 System Overview

5.1.1 Electronically Controlled Brake System

ECBS is an advanced brake control system technology that controls the brakes electronically rather than pneumatically. In practice, these electronic control systems are laid over the existing pneumatic controls of a braking system. The common control layout in the U.S. and European markets is a 1E/2P system featuring a primary electronic control system (1E) and dual pneumatic backup systems (2P). The conventional pneumatic control remains as a backup in the event of an electronic control failure and to ensure compliance with current pneumatic brake regulations. On ECBS, an electronic circuit is integrated into the treadle valve. By depressing the treadle valve, the driver sends a deceleration command to the microprocessor-based control unit. The control unit responds by sending an electronic control signal to the pressure modulator instructing a set amount of application pressure to a specific brake chamber. ECBS integrates into the standard foundation brakes. The friction material, slack adjusters, and brake chamber type and size are identical to those used with conventional pneumatic control system. Exhibit 5-1 shows a block diagram of both a pneumatic and an electronic control system.

Exhibit 5-1: Control System Comparison Schematic



The benefits of electronic control include increased control signal speeds, precise regulation of application pressures, and improved brake balancing (equalizing lining wear). It also enables the integration of other electronic devices or enabled technologies such as stability control programs and adaptive cruise control, two technologies evaluated under this FOT.

MeritorWabco is the manufacturer of the ECBS evaluated under this program. The system was configured with four wheel-speed sensors and four pressure control channels (4S/4M).

5.1.2 Advanced ABS

Advanced ABS is based on a traditional ABS control system that modulates the air pressure in the brake chamber to prevent wheel lock-up and provide braking control during over-braking maneuvers. ABS monitors wheel speeds at all times and controls braking during wheel-lock situations. The ability to limit wheel-lock situations enhances vehicle stability, reduces the possibility of jackknifing, and enables steering under extreme braking conditions. There were two Advanced ABS system evaluated under this FOT, MeritorWabco's Advanced ABS and Bendix's ABS-6 system.

MeritorWabco uses the identifier "advanced" to signify the addition of RSC to its anti-lock braking system. RSC is a system designed to improve vehicle stability during high lateral acceleration maneuvers such as evasive lane changes and tight radius curves. RSC monitors a suite of sensors including a lateral accelerometer and, upon detecting a potential rollover situation, applies the foundation brakes autonomously from the operator. The autonomous application of the foundation brakes is done with the use of additional ABS modulators, traction control valves, and programming. Advanced ABS provides an integrated platform for systems such as adaptive cruise control, collision warning, and lane departure.

Bendix's ABS6 is the next-generation ABS utilizing a new architecture. ABS6 can be configured with up to six wheel-speed sensors and six control modules that include an ABS module, yaw sensor, longitudinal and lateral accelerometers, steering wheel angle sensor, control pressure sensor, application pressure sensor, and two traction control valves. The new architecture enables the system to autonomously apply the foundation brakes independent from the driver, providing a platform for roll and yaw control systems commonly referred to as stability control systems. ABS6 is available in three configurations—Advanced (yaw and roll), Premium (roll), and Standard (ABS and traction control). The Standard system was evaluated under this FOT.

5.1.3 Air Disc Brakes

Bendix supplied its ADB 22X air disc brake. The brake is manufactured in partnership with Knorr-Bremese Group and Dana Corporation. The brake is designed for installation with 22.5-inch rims, via two slide pins. The ABD 22X uses a dual-piston configuration on the inboard side of the caliper. The dual-piston design provides precise brake adjustment, better force distribution, and even pad wear. The Bendix ADB 22X is assembled with a mono-block caliper to provide an overall weight of 78 pounds. The assembly provides a brake torque of up to 15,000 foot-pounds.

5.2 Brake Application Overview

There were 1.15 million brake applications for the 47 tractors participating in the FOT. As shown in Exhibit 5-2, the number of brake applications ranged from 210,377 to 277,665 depending on the tractor configuration. These data were normalized per 1 million miles for comparison purposes.

Exhibit 5-2: Total Number of Brake Applications by Tractor Configuration

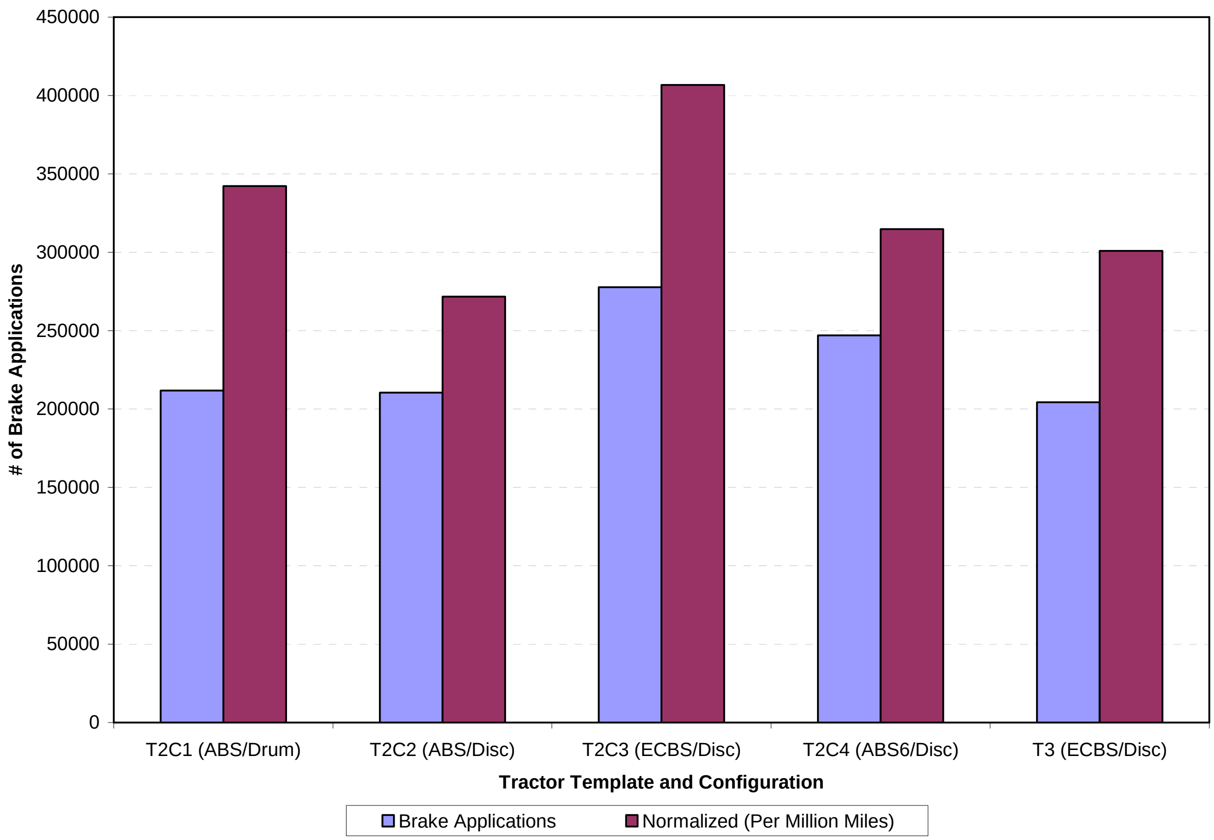
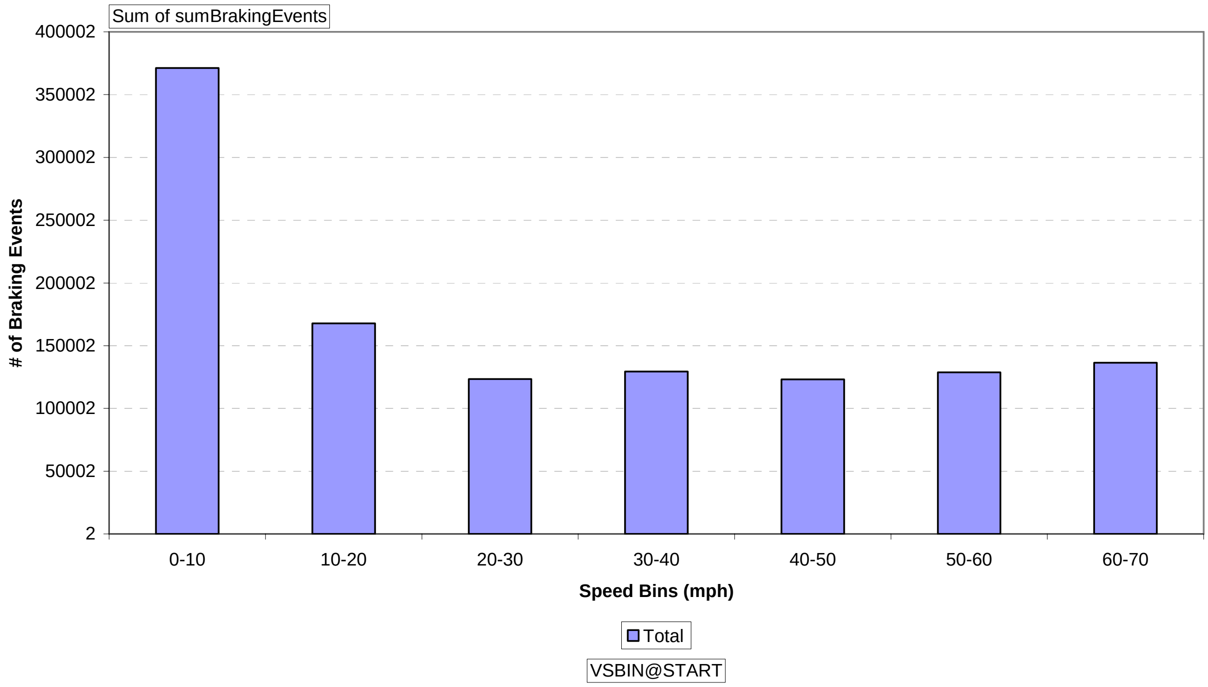


Exhibit 5-3 bins the braking events by the speed at which the brake event started. For example, if the driver applied the service brakes at 55 miles per hour and decelerated down to 40 miles per hour, that braking event would be binned in the 50 to 60 miles per hour speed bin. As shown, a large percentage of the braking events were initiated at 10 miles per hour or less. The initiation speed of the remaining braking is evenly distributed in the other speed bins.

Exhibit 5-3: Braking Application Binned by Start Speed



The average deceleration rate for the 1.15 million brake applications is 2.30 feet per second per second. Exhibit 5-4 shows that the average deceleration rate by tractor configuration is similar, ranging from 2.25 to 2.36 feet per second per second. The ABS / disc tractors recorded slightly higher average deceleration rates, and the ECBS / disc tractors recorded slightly lowered average deceleration rates per brake application.

Exhibit 5-4: Average Deceleration Rate per Brake Application by Tractor Configuration

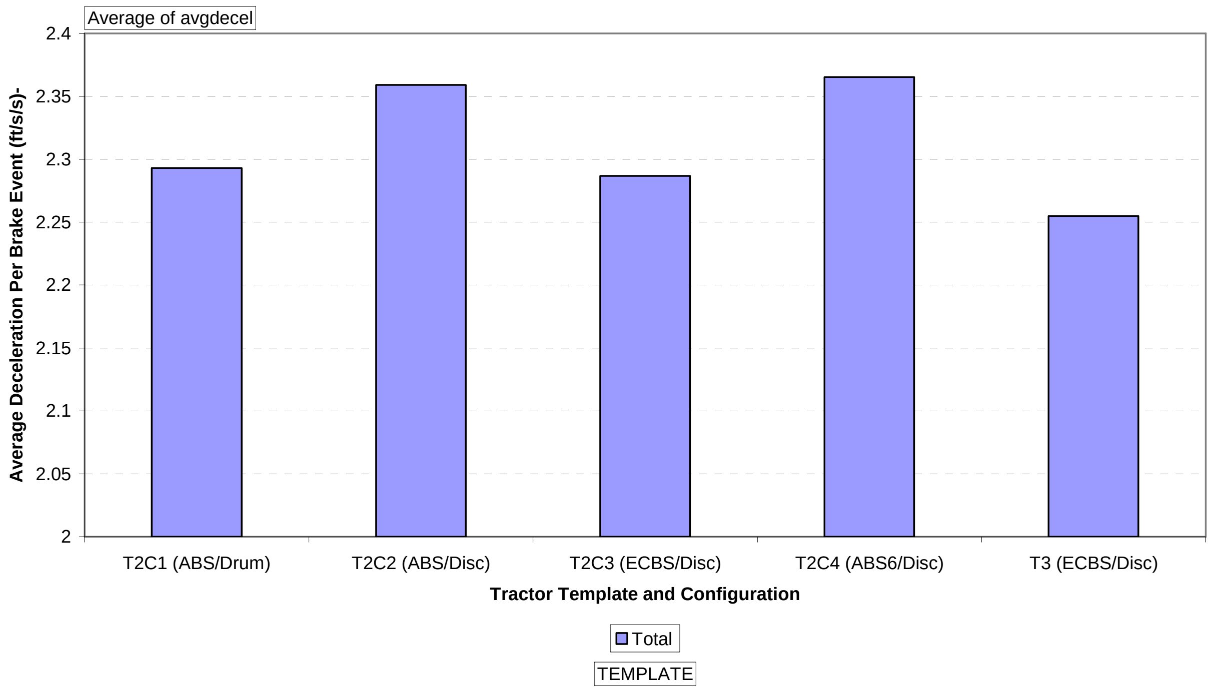


Exhibit 5-5 shows the average duration of each brake application. The average for all tractors taken together is 10 seconds, with individual tractor configurations ranging from 8.6 to 12 seconds. A similar pattern is evident between the ABS / disc and ECBS / disc equipped tractors.

Exhibit 5-5: Average Duration of Brake Application by Tractor Configuration

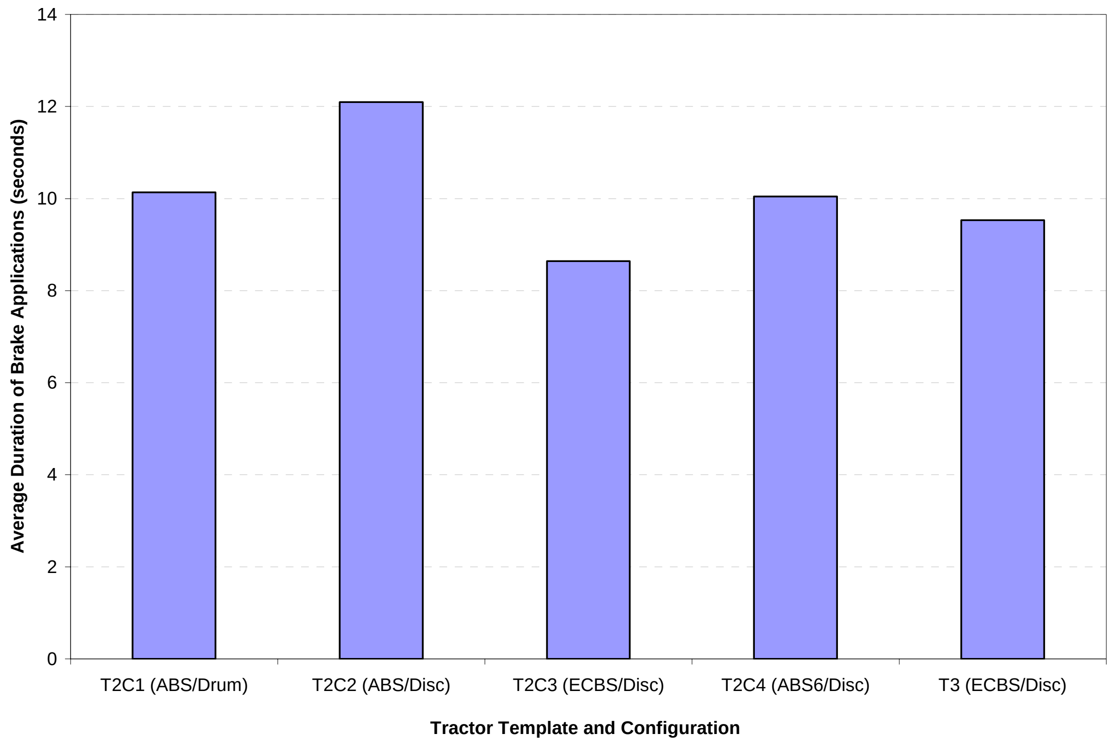
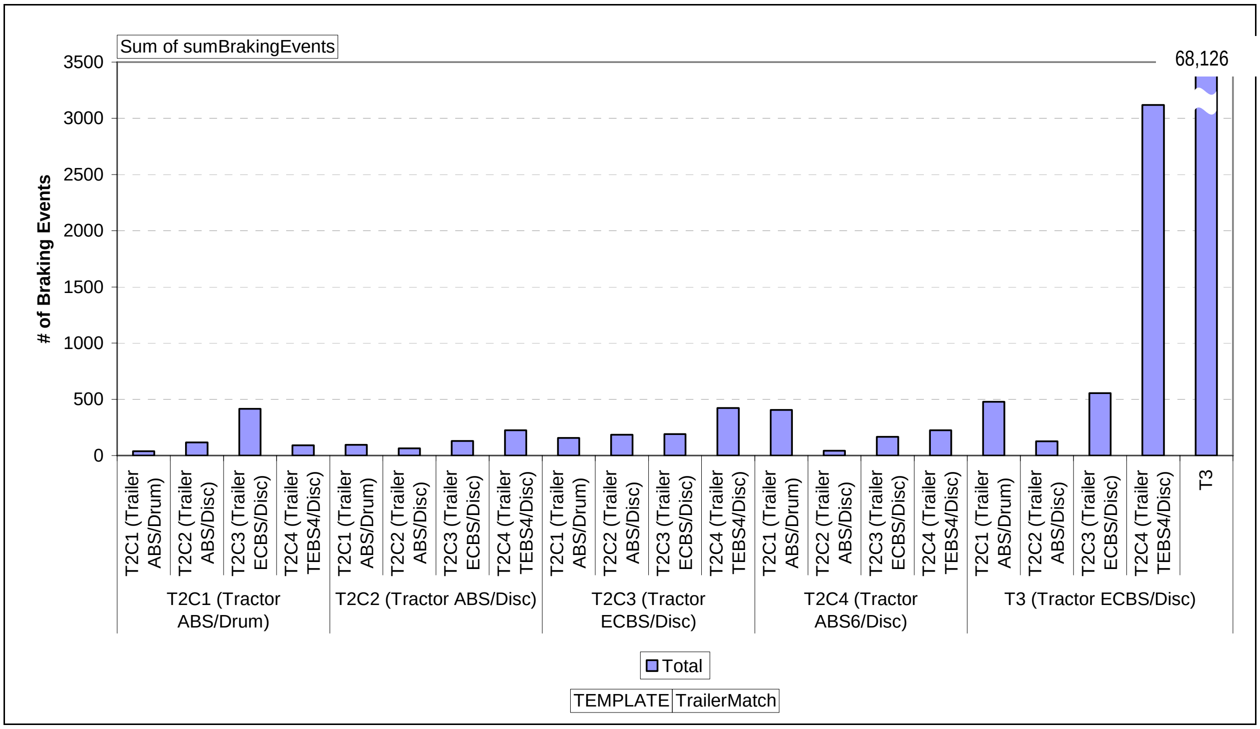


Exhibit 5-6 presents the total number of brake applications with FOT tractors and trailers operating in combination. Consistent with the limited mileage accumulation presented earlier in this report on tractor and trailer combinations, less than 500 braking applications were made with FOT tractors coupled with FOT trailers. The exception is the ECBS / disc tractors and trailers in Template 3. Template 3 tractor-trailer combinations accumulated 68,125 braking events.

Exhibit 5-6: Total Brake Applications With FOT Trailer Attached



5.3 Driver Behavioral Changes

This section discusses driver behavioral changes observed with the operation of advanced brake technologies and control systems. With a focus on evaluating brake technologies, these data presented in this section is without the use of either conventional cruise control or adaptive cruise control. A majority of the data presented is from the first six months of the FOT (Phase 1). Data from both templates is presented together to enable a comparison of the different tractor brake configurations. As a means to filter data that was not of significance, events were defined. In those cases, a description of the event is provided.

5.3.1 Following Interval

Exhibit 5-7 shows the average following interval for each tractor configuration based on following events. A following event was defined to have a vehicle speed of greater than 10 miles per hour, with a target detected in front of the tractor for a minimum of 15 consecutive seconds. The event duration was specifically chosen to determine a steady state following interval and eliminate any short duration events such as vehicles crossing in front of the tractor. To obtain a true sense of driver behavior impacts using advance braking systems, these data presented below is Phase 1 only, and only when the conventional cruise control system (CCC) system was off. As shown, the average following interval varies from 2.5 to 3.0 seconds. It is interesting to note that the drivers of the ABS / drum tractors had the shortest average following intervals and, conversely, the most advanced tractors (ECBS / disc) had the longest following intervals. This is the opposite trend expected when providing drivers with improved braking technologies.

Exhibit 5-7: Average Following Interval (CCC and ACC "Off")

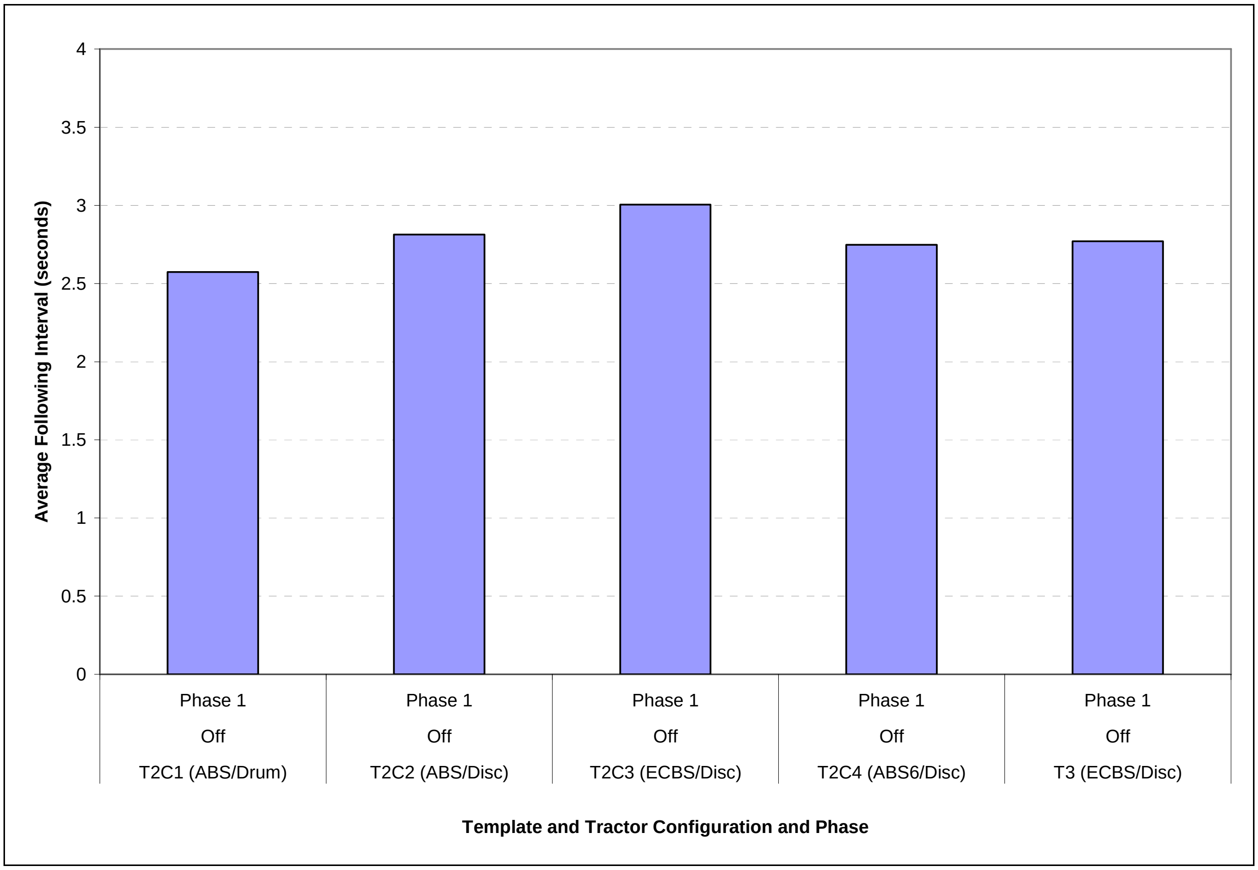


Exhibit 5-8 shows the average following interval of the same eight drivers in their original ABS / drum tractors and their new ECBS / disc tractors. Eliminating the effects of driver variance, the driver's average following interval was reduced from 2.96 to 2.77 seconds when switching from the existing ABS / drum tractors to their new ECBS / disc tractors. This trend would be expected when providing drivers with improved braking technologies.

Exhibit 5-8: Average Following Interval for Template 3 Tractors (CCC and ACC "Off")

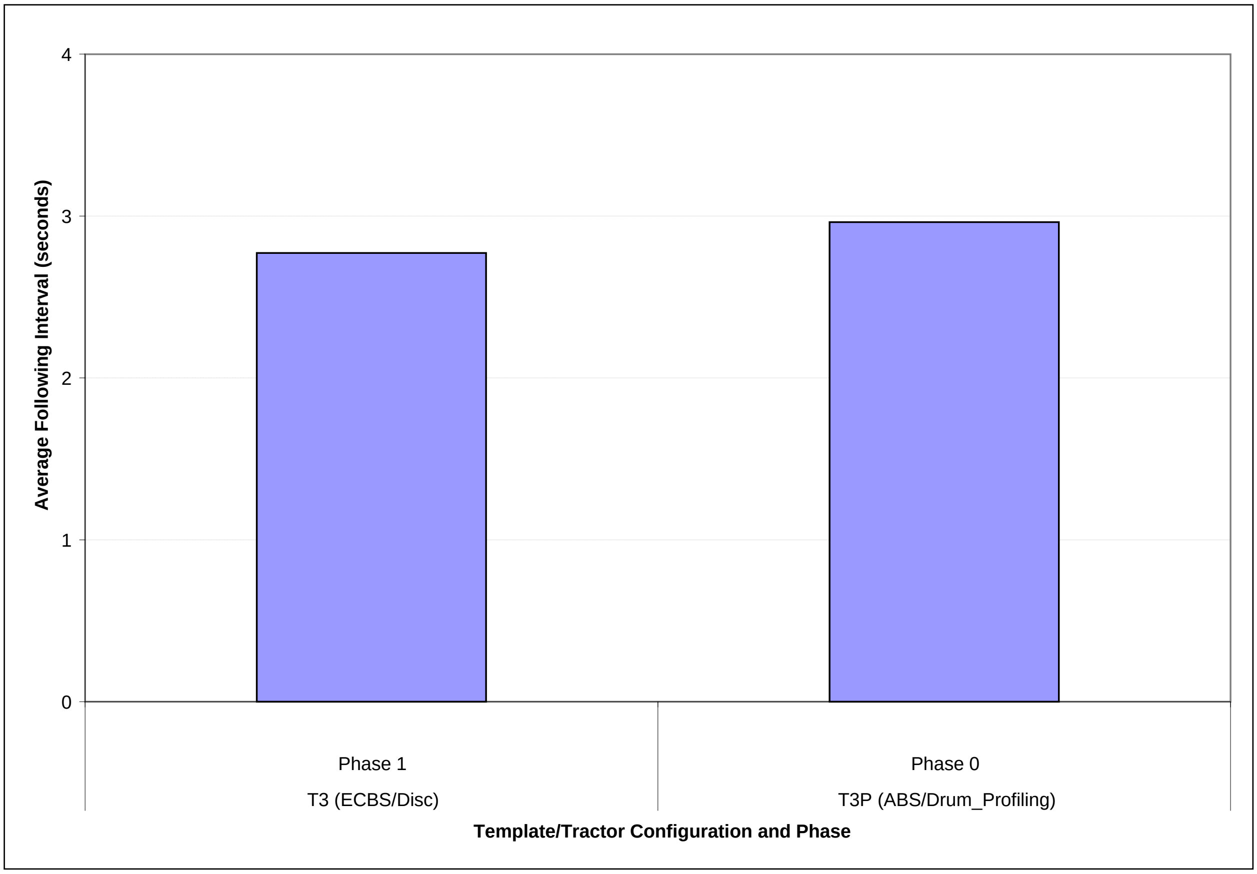


Exhibit 5-9 shows the average following interval by month for the ECBS / disc (T2C3) tractors using the same definition of a "following event" described above. As shown, the average following interval remained relatively constant, varying from 2.9 to 3.23 seconds. The purpose of the exhibit is to show that the average following interval did not vary significantly with time of operation.

Exhibit 5-9: Average Following Interval by Month for T2C3 (ECBS/Disc) Tractors

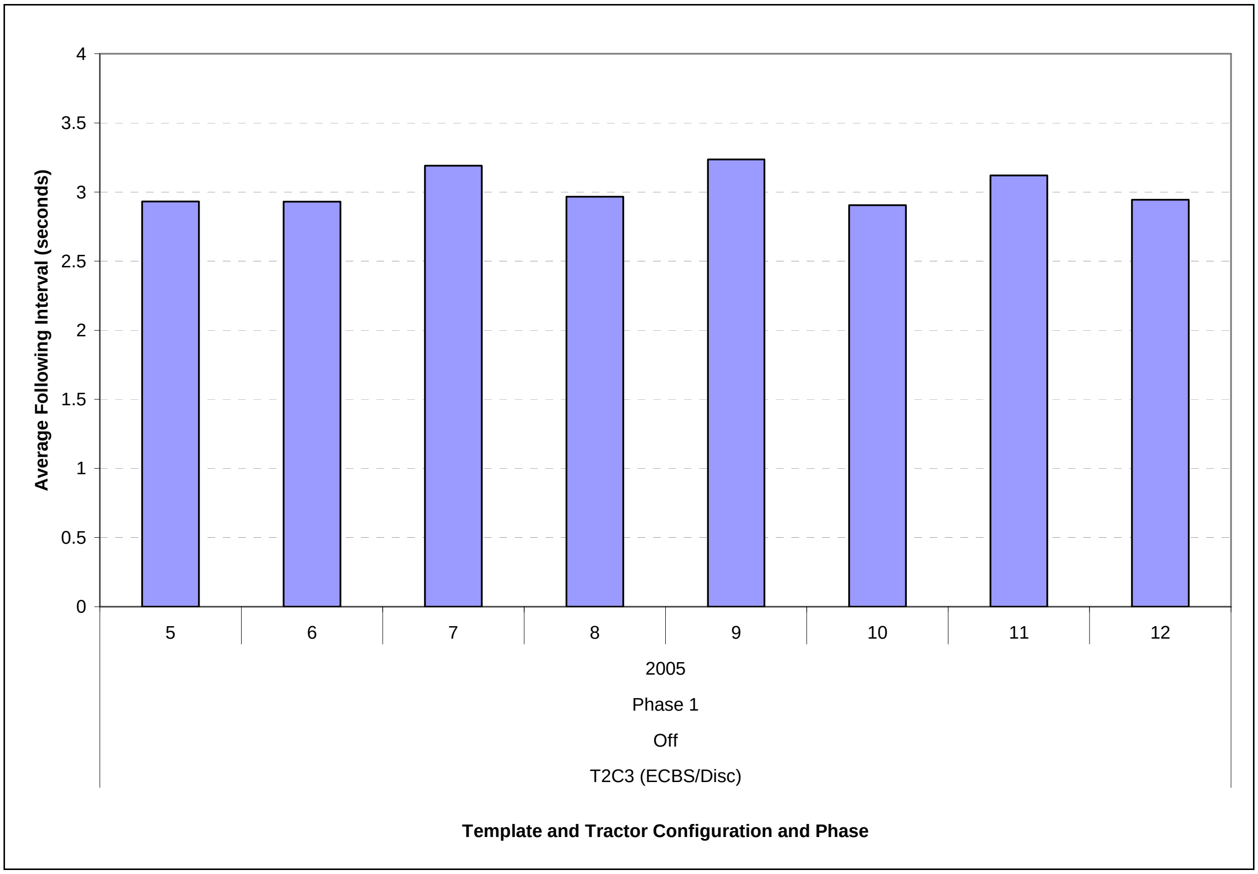
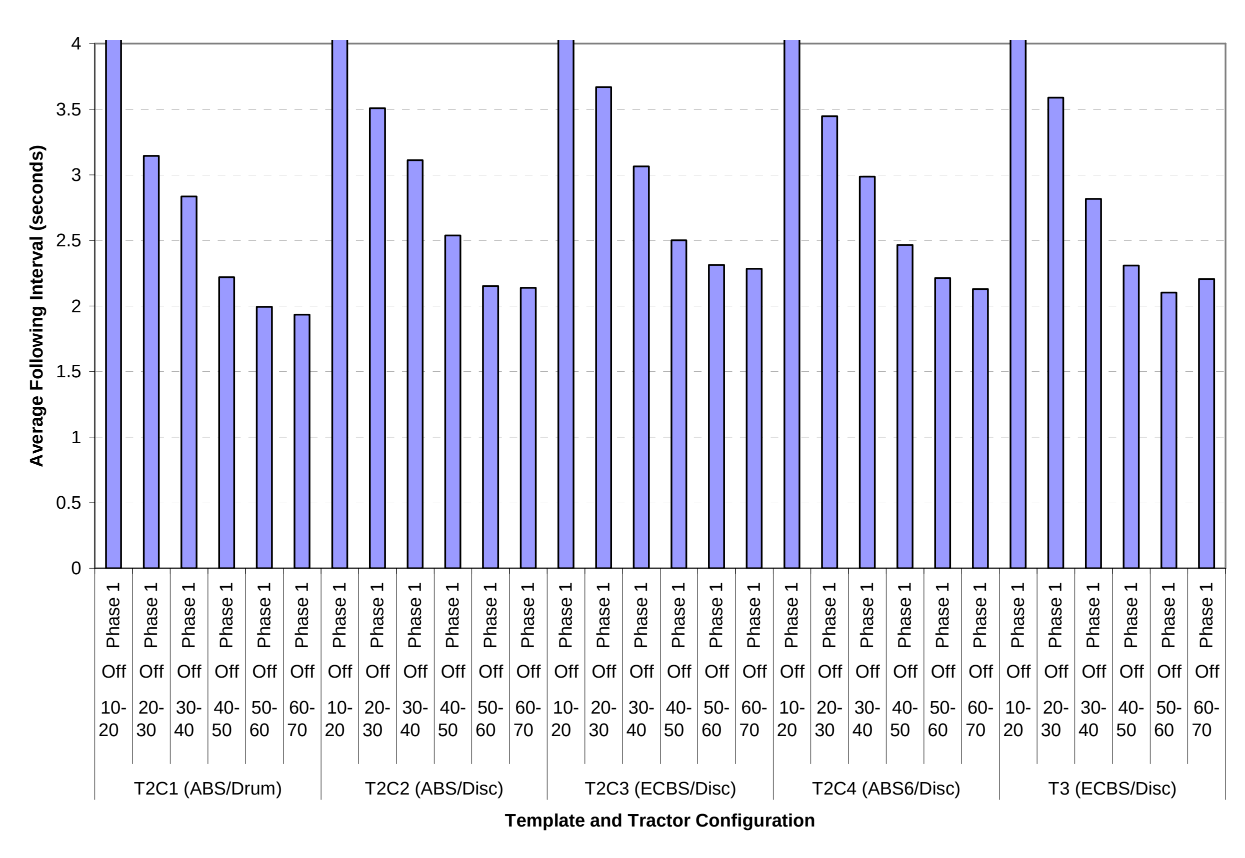


Exhibit 5-10 shows the average following interval by speed bin. The events were placed in speed bins based on the average speed of the event. The exhibit shows speed bins ranging from 10 to 70 miles per hour. It is interesting to note that as the speed increased, the following interval decreased—indicating that driver's judge distance rather than time.

Exhibit 5-10: Average Following Interval by Tractor Configuration by Speed Bin



5.3.2 Average Deceleration Rate

Exhibit 5-11 shows the average deceleration rate per braking event for each tractor configuration for speeds above 10 miles per hour. As shown, deceleration rates between the tractors are similar, averaging between 2.21 and 2.43 feet per second per second. Drivers had a significant influence on the average deceleration rates, which masked differences between braking technologies.

Exhibit 5-11: Average Deceleration Rate per Braking Event by Tractor Configuration

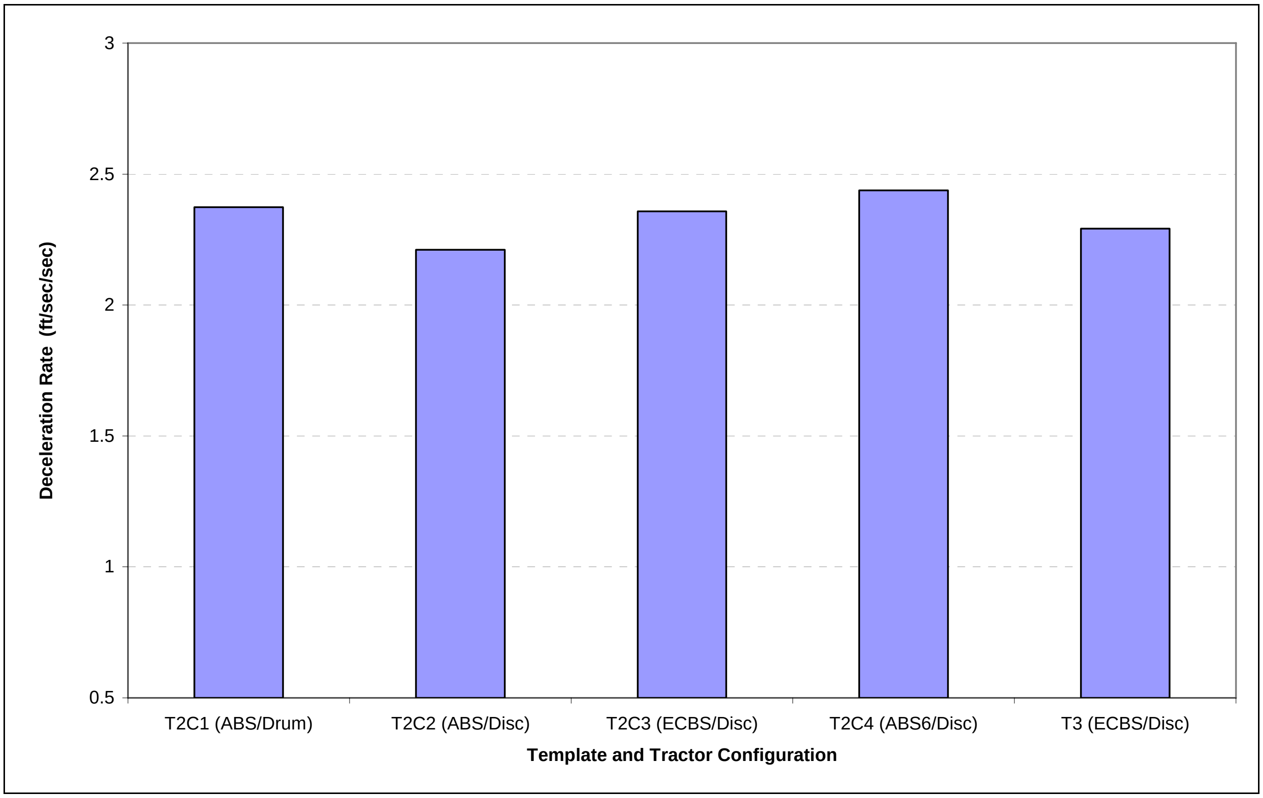


Exhibit 5-12 shows the average deceleration rates for the FOT tractors separated into speed bins. As shown, average deceleration rate increases with the starting speed of the braking event. For example, the average deceleration rate for ABS/drum tractor with a brake initiation speed of between 10 and 20 miles per hour is approximately 2.1 feet per second per second and as high as 2.7 feet per second per second for brake events with an initiation speed of between 50 and 60 miles per hour. Of interest is the higher deceleration rate of the ABS/drum tractors at a brake initiation speed of between 10 and 20 miles per hour compared with the ADB tractors.

Exhibit 5-12: Average Deceleration Rates Per Tractor Configuration per Speed Bin

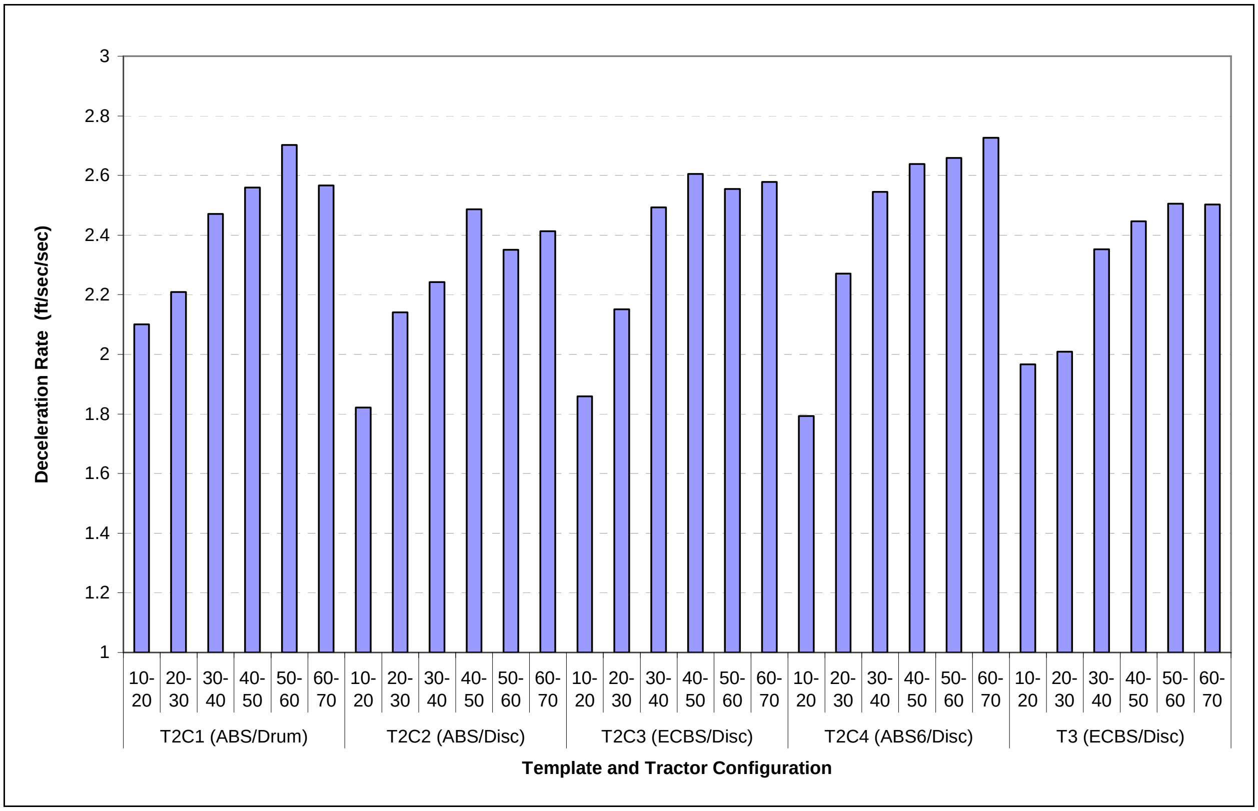
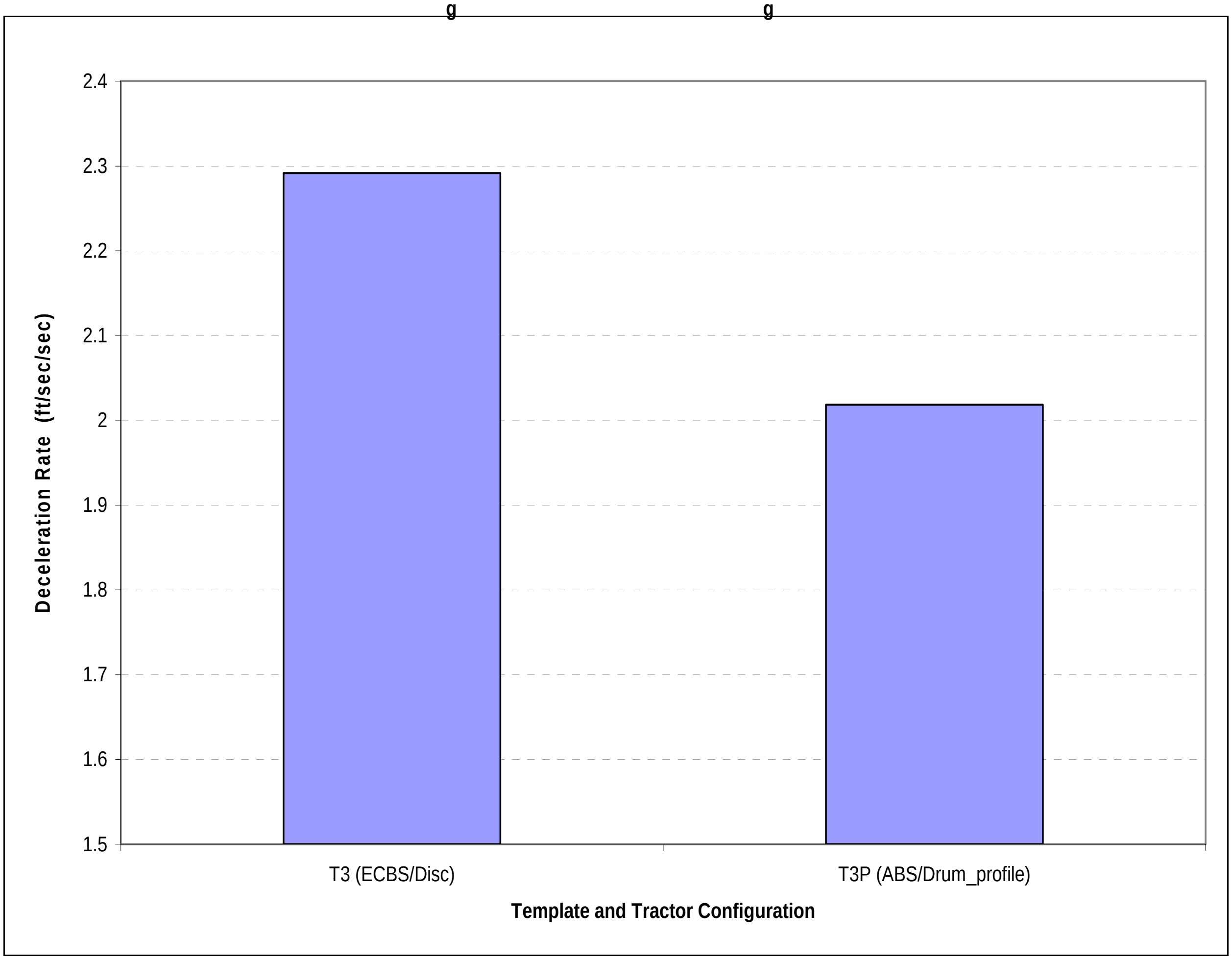


Exhibit 5-13 shows the average deceleration rates for the Template 3 drivers at a brake initiation speed of greater than 10 miles per hour. Remember that the T3 drivers were profiled in their existing Wal-Mart tractors for two to four months prior to receiving their new FOT tractors. As such, this comparison eliminates the variability in the braking style of the different drivers that heavily influenced these data above. As shown, the T3 drivers had an approximately 14-percent higher average deceleration rate operating the new ECBS / disc tractors versus their previous ABS / drum tractors. It should be noted that some of the differences might be due to the difference in the age of the equipment.

Exhibit 5-13: Average Deceleration Rate Between T3 and T3 Profiling Tractors



5.3.3 Average Speed Reduction per Braking Event

Exhibit 5-14 shows the average reduction in speed for the 1.15 million FOT braking events. As shown, the average reduction in speed per braking event varied between approximately 4.8 and 7.4 miles per hour. It is interesting to note that the two sets of ECBS / disc tractors had the lowest average reduction in speed per braking event at 4.8 and 5.5 miles per hour.

Exhibit 5-14: Reduction in Speed by Tractor Configuration per Braking Event

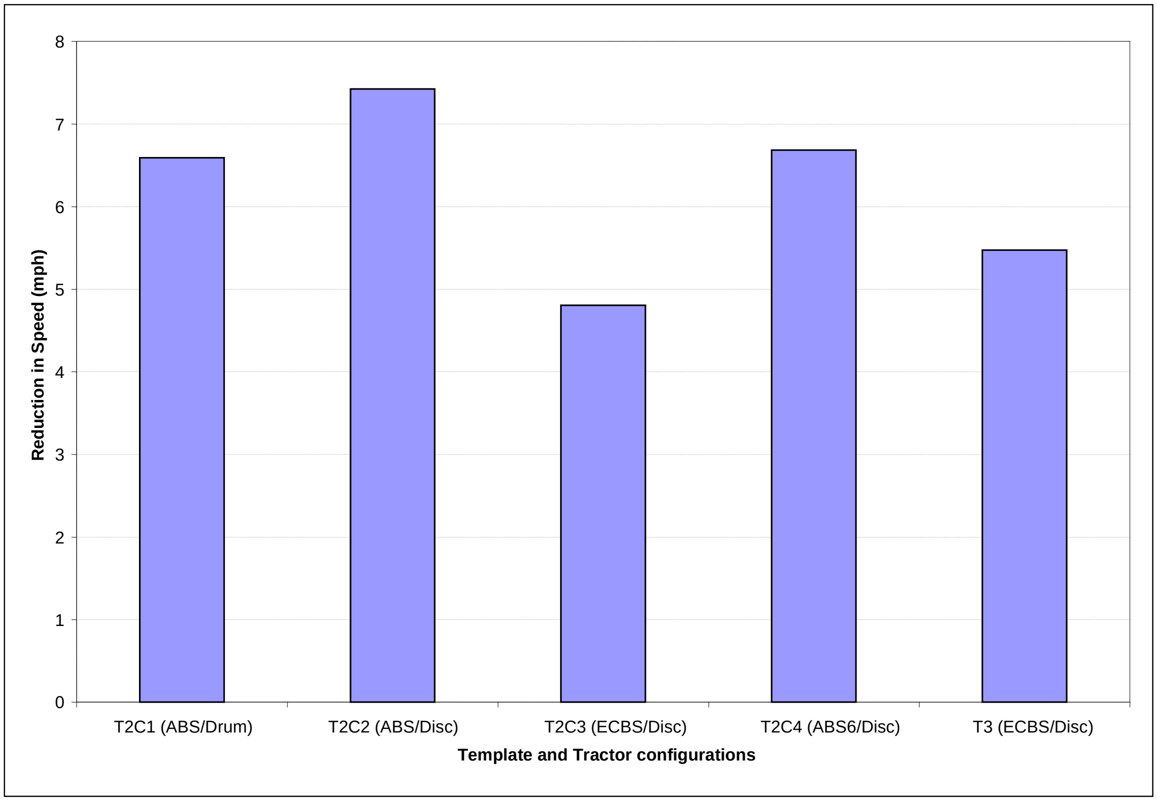


Exhibit 5-15 shows the average reduction in speed for the FOT tractors per speed bin or the speed at which the brakes were applied. As shown, a similar trend is visible for each of the tractor configurations, with the maximum speed reduction occurring in the 30 to 40 miles per hour speed bin.

Exhibit 5-15: Reduction in Speed per Brake Event per Speed Bin

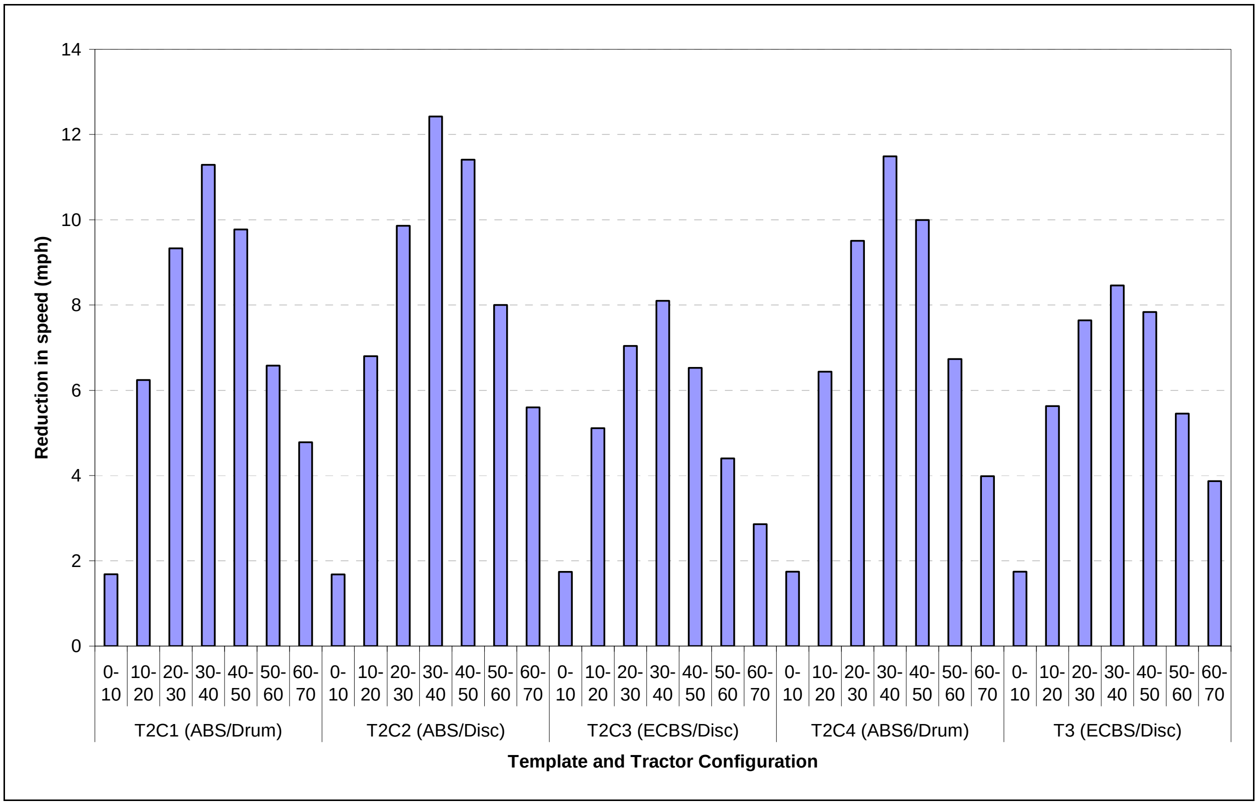
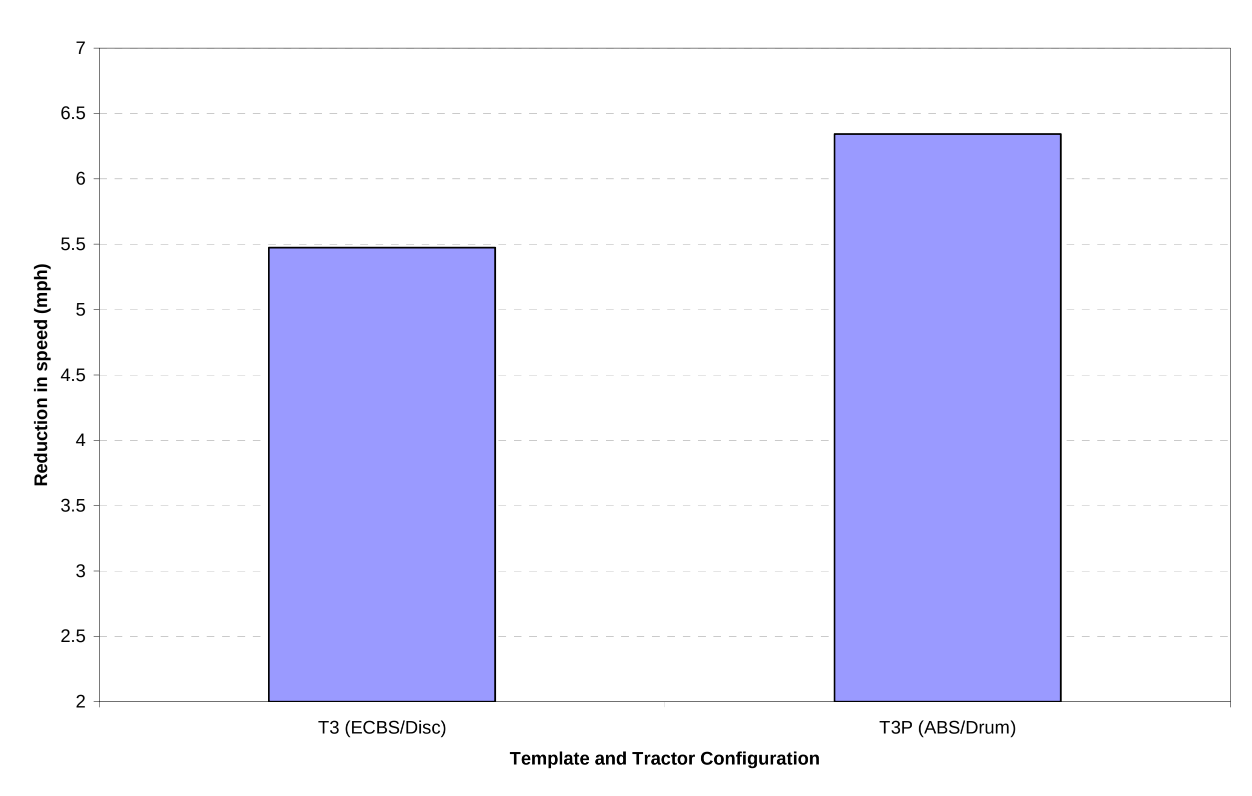


Exhibit 5-16 shows the average reduction in speed for the Template 3 (ECBS / disc) tractors and the profiling (ABS / drum) tractors. This comparison again eliminates the variation in driver performance because the same eight drivers transitioned from the existing ABS / drum tractors to the new ECBS / disc tractors. As shown, the reduction in speed per braking event is 15 percent lower for the T3 ECBS / Disc tractors than for the T3 ABS / Drum profiling tractors.

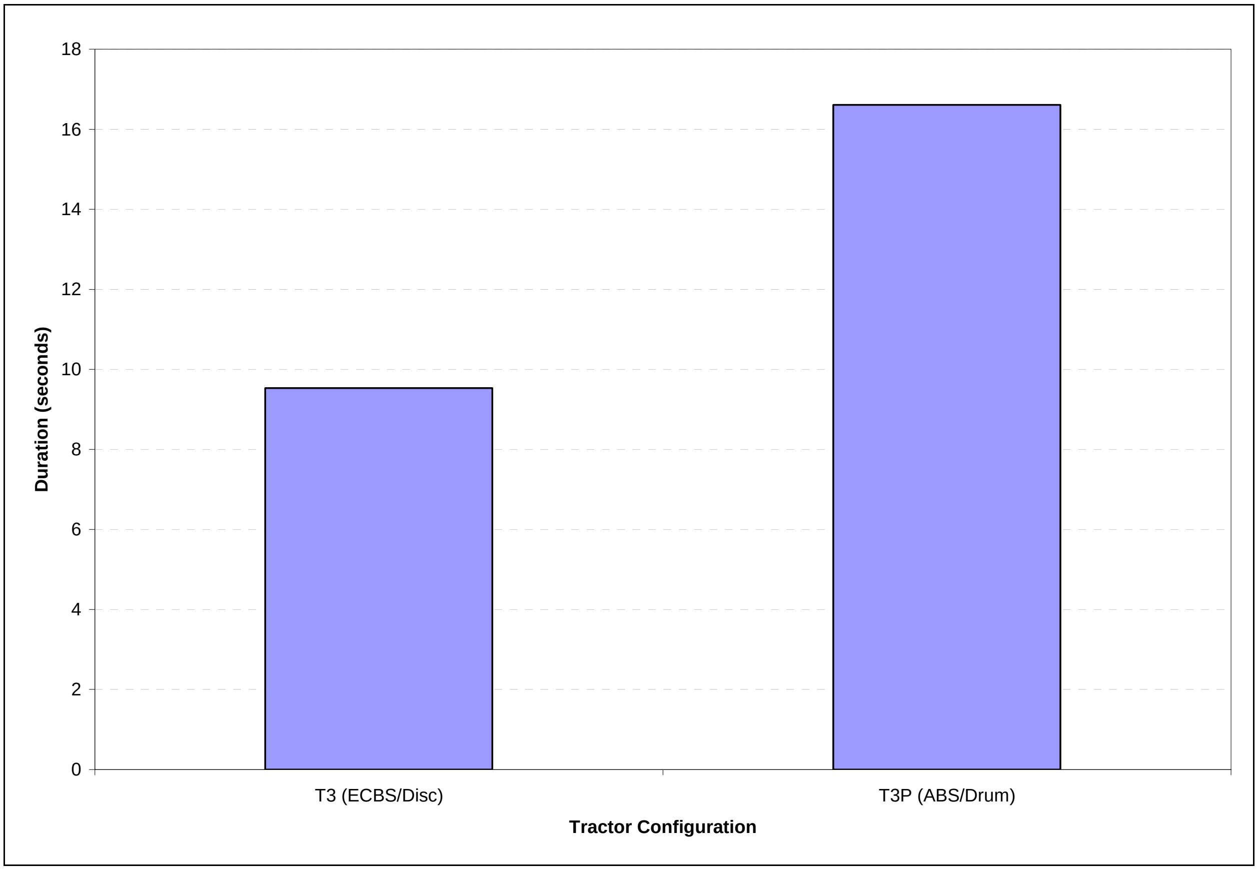
Exhibit 5-16: Average Reduction in Speed per Braking Event for T3 Tractors



5.3.4 Average Brake Event Duration

Exhibit 5-17 shows the average braking duration for the T3 ECBS / Disc and T3 ABS / Drum profiling tractors. The average duration for the two sets of tractors is 9.5 and 16.6 seconds, respectively. Note that the ECBS / disc tractors exhibited higher average deceleration rates, lower reduction in speed per braking event, and shorter brake application duration than the ABS / drum profiling tractors. This observation is consistent with the feedback from the ECBS / disc driver, who commented that the ECBS / disc tractor's brakes were challenging to modulate.

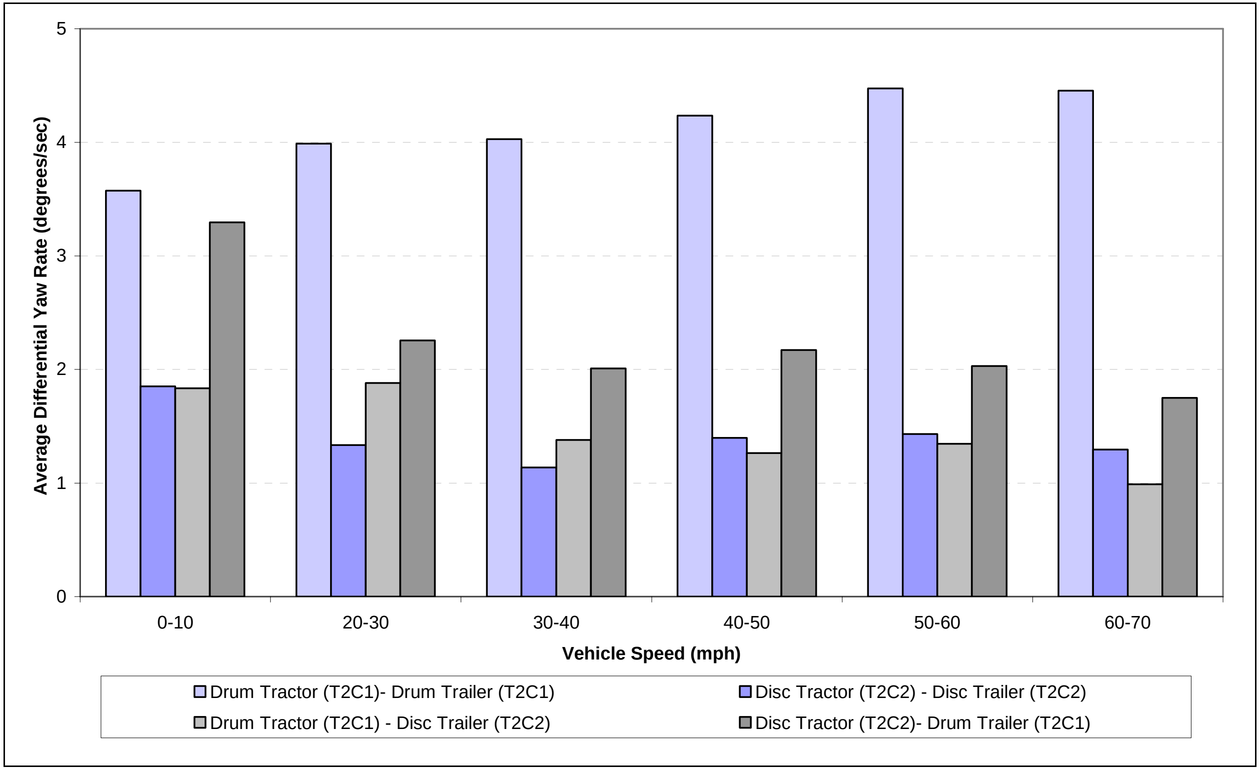
Exhibit 5-17: Average Duration per Braking Event for Template 3 Tractors



5.3.5 Tractor Trailer Stability During Braking

Exhibit 5-18 shows the difference in the yaw rate sensors between tractor and trailer combinations. As shown, there is data on four Template 2 combinations that include drum tractor / drum trailer, drum tractor / disc trailer, disc tractor / drum trailer, and disc tractor / disc trailer. Recall that the tractors and trailers in this template were equipped with yaw rate sensors. These data below presents the average difference between the yaw rate data generated by those sensors during braking events. These data are presented in speed bins based on the speed at which the braking event was initiated. The greatest difference in yaw rate was seen on the drum tractor / drum trailer combination with an average difference of 3.5 to 4.25 degrees per second varying with speed. Conversely, the disc tractor / disc trailer combination had some of the lowest differential yaw rates between the two units. Note the significance of having disc brakes on the trailer in reducing the differential yaw between the two units with the results from the drum tractor / disc trailer combination.

Exhibit 5-18: Differential Yaw Rate Between Tractor and Trailer Combinations



5.4 Electronic Stability Control Events

The ESC system activated 51 times on tractors equipped with ECBS during Phase 2 of the FOT, which ran from approximately January to May 2006. Recall that Phase 2 began in January/February of 2006 and ended in May 2006. Exhibit 5-19 shows the location of the ESC activation events that had valid GPS data. As noted in Section 4.6 Data Quality, RSC activation were either not recorded correctly by the DAS or never broadcasted to the vehicle network on the advanced ABS tractors (T2C1 and T2C2). Hence, data presented in this section addresses only the ECBS tractors.

Exhibit 5-19: ESC Activation Locations

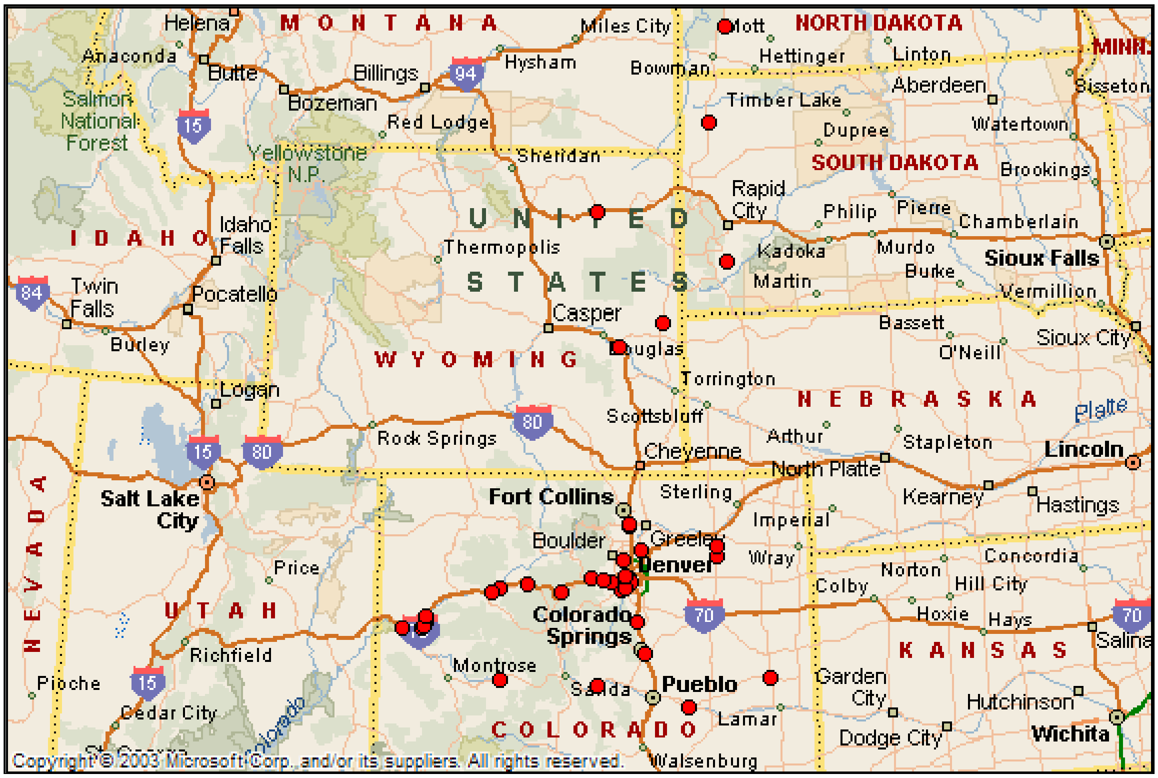


Exhibit 5-20 summarizes the ESC activations. As shown in the exhibit, ESC activations occurred in each month of Phase 2 testing with a high concentration of events in February and March (34 of 51 ESC activations). Out of the 18 ECBS tractors, nine had ESC activations. Of these nine, three tractors accounted for 42 of the 51 ESC activations. Two of the tractors had 16 unique ESC activations, and the third had 10 unique ESC activations.

The ESC activations were separated into four distinct categories—Roll-Only Events, Roll-Dominant Events, Yaw-Dominant Events, and Yaw-Only Events. A number of events were selected from each category to illustrate the functionality of ESC. The events were selected based on a number of factors. Only events with a clear data set were considered, eliminating all events with erroneous data. In addition, GPS data were preferred to ensure vehicle location and the surrounding environment could be illustrated. Finally, events were chosen based on unique situations (e.g., extreme data values, unique signal combinations). An in-depth review of the selected events is discussed in more detail in the following paragraphs. Note that there were no "Roll-Only" events.

Exhibit 5-20: ESC Activation Summary

Template and Event #	Driver ID	Date	Time	Amb Temp. (ºF)	Speed@ ESC (miles per hour)	CCC Status	ACC Status	Target Detected	Headlight Status	Turn Signal Status	Windshield Wiper Status	ECBS Trailer Attached
Roll-Only Events												
No Events												
Roll-Dominant Events												
T2C3-1	D46	4/3/2006	8:34:28 PM	55.4	66	Off	On	No	LB	Off	No	N/A
T2C3-2	D46	3/30/2006	6:20:23 PM	59	63	Off	Off	No	LB	Off	No	N/A
T2C3-3	D41	3/30/2006	10:15:35 AM	78.8	63	On	Off	No	LB	Off	No	N/A
T3-4	D39	2/8/2006	10:25:34 AM	50	60	Off	N/A	Yes	HB	Left	No	Yes
T3-5	D39	2/8/2006	11:24:48 AM	35.6	54	Off	N/A	No	HB	Off	No	Yes
T3-6	D35	3/2/2006	9:31:02 AM	33.8	63	On	N/A	Yes	LB	Off	No	No
T3-7	D35	3/2/2006	10:07:47 AM	62.6	47	Off	N/A	No	LB	Off	No	Yes
T3-8	D35	5/26/2006	6:41:35 AM	68	64	Off	N/A	No	LB	Off	No	No
T3-9	D35	2/1/2006	7:57:27 PM	62.6	56	Off	N/A	Yes	LB	Off	No	No
Yaw-Dominant Events												
T2C3-10	D40	2/19/2006	12:19:16 PM	41	64	Off	N/A	Yes	LB	Off	No	N/A
T2C3-11	D40	2/4/2006	4:04:39 PM	30.2	50	On	N/A	No	LB	Off	No	N/A
T2C3-12	D40	3/16/2006	9:01:40 PM	68.8	29	Off	Off	No	LB	Right	No	N/A
T3-13	D35	1/12/2006	3:06:02 PM	55.4	60	On	N/A	No	LB	Off	No	Yes
T3-14	D35	1/28/2006	2:40:45 PM	30.2	56	Off	N/A	No	LB	Off	No	Yes
T3-15	D35	2/2/2006	4:23:11 PM	59	63	On	N/A	Yes	LB	Off	No	Yes
T3-16	D35	3/5/2006	12:42:54 PM	33.8	65	Off	N/A	No	LB	Off	No	No
T3-17	D35	3/1/2006	9:52:22 PM	41	54	Off	N/A	Yes	LB	Off	No	No
Yaw-Only Events												
T2C3-18	D40	2/4/2006	1:41:18 PM	50.0	44	Off	N/A	No	LB	Off	No	N/A
T2C3-19	D40	3/14/2006	1:33:36 AM	68.0	12	Off	Off	No	LB	Left	No	N/A
T2C3-20	D40	3/14/2007	2:24:24 PM	66.2	19	Off	Off	No	LB	Left	No	N/A
T2C3-22	D40	3/17/2006	3:14:25 AM	59.0	5	Off	Off	Yes	LB	Left	No	N/A
T2C3-23	D40	3/17/2007	4:08:55 AM	62.6	25	Off	Off	No	LB	Right	No	N/A
T2C3-24	D40	3/21/2006	2:37:23 PM	53.6	15	Off	N/A	Yes	LB	Right	No	N/A

Template and Event #	Driver ID	Date	Time	Amb Temp. (ºF)	Speed@ ESC (miles per hour)	CCC Status	ACC Status	Target Detected	Headlight Status	Turn Signal Status	Windshield Wiper Status	ECBS Trailer Attached
T2C3-25	D40	3/22/2007	8:32:59 AM	68.0	19	Off	N/A	No	None	Left	No	N/A
T2C3-26	D40	3/22/2006	9:51:54 AM	46.4	15	Off	N/A	Yes	LB	Right	No	N/A
T2C3-27	D40	3/22/2006	6:50:16 PM	42.8	18	Off	Off	No	LB	Left	No	N/A
T2C3-28	D40	3/23/2006	12:50:50 AM	64.4	12	Off	Off	No	LB	Left	No	N/A
T2C3-29	D40	3/23/2006	6:29:39 PM	73.4	14	Off	Off	No	LB	Right	No	N/A
T2C3-30	D40	3/24/2006	6:55:41 PM	60.8	16	Off	Off	No	LB	Left	No	N/A
T2C3-31	D40	3/31/2006	3:46:05 PM	33.8	23	Off	Off	No	LB	Right	No	N/A
T2C3-32	D46	4/3/2006	6:46:23 PM	73.4	67	Off	Off	No	LB	Off	No	N/A
T3-33	D32	3/30/2006	2:45:52 PM	35.6	18	Off	N/A	No	LB	Left	No	No
T3-34	D34	2/3/2006	7:50:00 PM	46.4	65	Off	N/A	No	LB	Off	No	Yes
T3-35	D34	3/3/2006	8:24:08 PM	53.6	65	Off	N/A	No	LB	Off	No	Yes
T3-36	D35	1/28/2006	12:49:28 PM	17.6	64	On	N/A	No	LB	Off	No	Yes
T3-37	D35	2/4/2006	8:51:50 PM	35.6	53	Off	N/A	No	LB	Off	No	No
T3-38	D35	5/21/2006	10:57:20 AM	55.4	36	Off	N/A	No	LB	Off	No	No
T3-39	D35	5/22/2006	5:11:32 AM	62.6	65	Off	N/A	No	LB	Off	No	No
T3-40	D35	4/9/2006	11:27:41 AM	46.4	66	Off	N/A	No	LB	Off	No	No
T3-41	D35	3/5/2006	9:03:42 AM	6.8	64	Off	N/A	No	LB	Off	No	No
T3-42	D35	2/25/2006	1:52:04 PM	69.8	14	Off	N/A	No	LB	Left	No	No
T3-43	D37	4/23/2006	2:37:08 PM	46.4	33	Off	N/A	Yes	LB	Left	No	No
T3-44	D37	5/2/2006	1:20:37 PM	66.2	11	Off	N/A	No	LB	Left	No	No
T3-45	D37	3/21/2006	2:31:20 PM	44.6	50	Off	N/A	No	LB	Off	No	Yes
T3-46	D37	3/21/2006	2:35:25 PM	44.6	53	Off	N/A	No	LB	Off	No	Yes
T3-47	D37	4/11/2006	2:28:03 PM	68.0	26	Off	N/A	No	LB	Left	No	No
T3-48	D37	2/18/2006	7:31:08 PM	55.4	25	Off	N/A	Yes	LB	Left	No	No
T3-49	D37	2/4/2006	7:25:22 PM	64.4	11	Off	N/A	No	LB	Left	No	No
T3-50	D37	3/4/2006	2:27:52 PM	64.4	11	Off	N/A	Yes	LB	Left	No	No
T3-51	D37	3/4/2006	6:28:33 PM	55.4	12	Off	N/A	Yes	LB	Left	No	No
T3-52	D37	1/31/2006	2:13:46 PM	66.2	20	Off	N/A	No	LB	Left	No	No

5.4.1 Roll-Only Events

Roll-only events are defined as ESC activations that triggered only the roll control engine or roll control brake signals. Of the 51 identified ESC activations, no activation occurred with only these signals active.

5.4.2 Roll-Dominant Events

Roll-dominant events are defined as ESC activations that trigger both the roll control signals and the yaw control signals. An event was determined to be roll-dominant if the lateral acceleration was the principle trigger of the ESC activation. For these events, the yaw rate generally maintained a value of less than 3 degrees per second. Nine events were identified as roll-dominant events. A majority of roll-dominant events occurred at higher speeds (greater than 45 miles per hour) on curved and straight (obstacle avoidance) sections of highway.

ESC Event T2C3-1

Exhibit 5-21 shows Event T2C3-1 occurred south of Fairburn, South Dakota, along I-79, which is in the southwestern part of the State.

Exhibit 5-21: GPS Data for Roll-Dominant Event T2C3-1 (30-mile view)

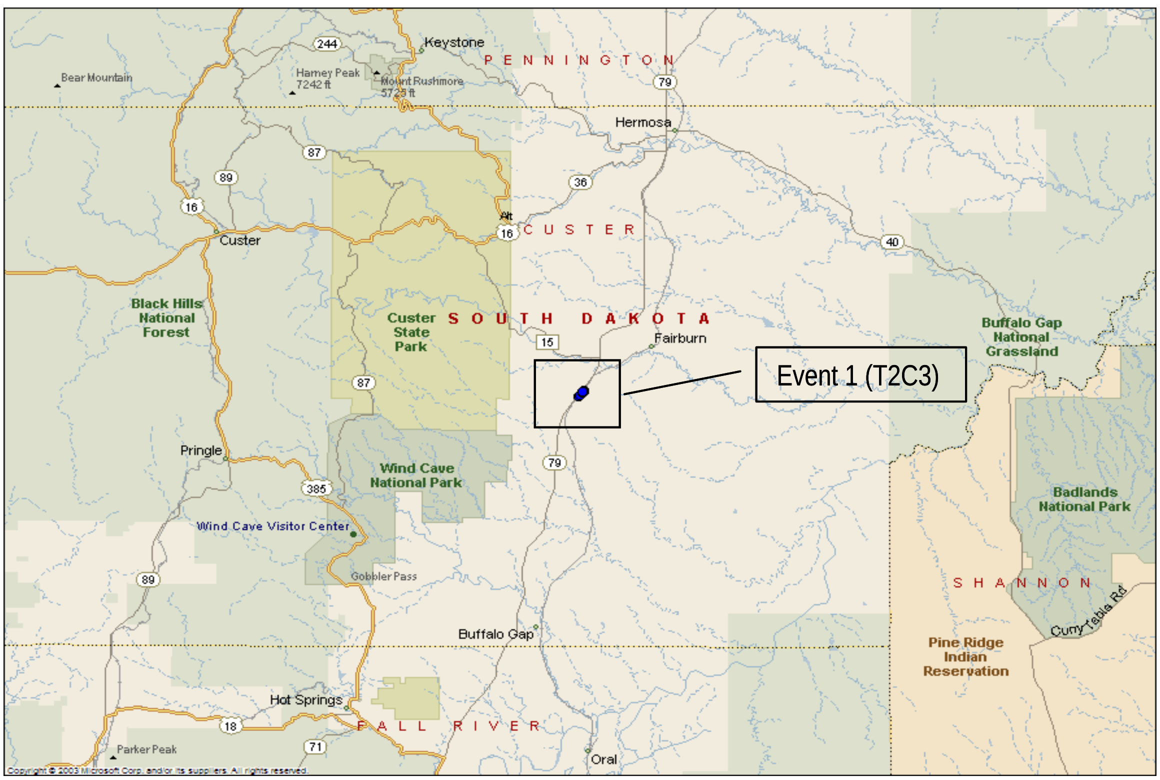


Exhibit 5-22 shows a close-up view of I-79 at the location of the ESC activation. The blue circles indicate 20 seconds of GPS data, with 10 seconds before and after the actual event. A square box has been drawn to pinpoint the location of the ESC activation. As shown, I -79 is relatively straight at the point of the event.

Exhibit 5-22: GPS Data for Roll-Dominant Event T2C3-1 (3-mile view)

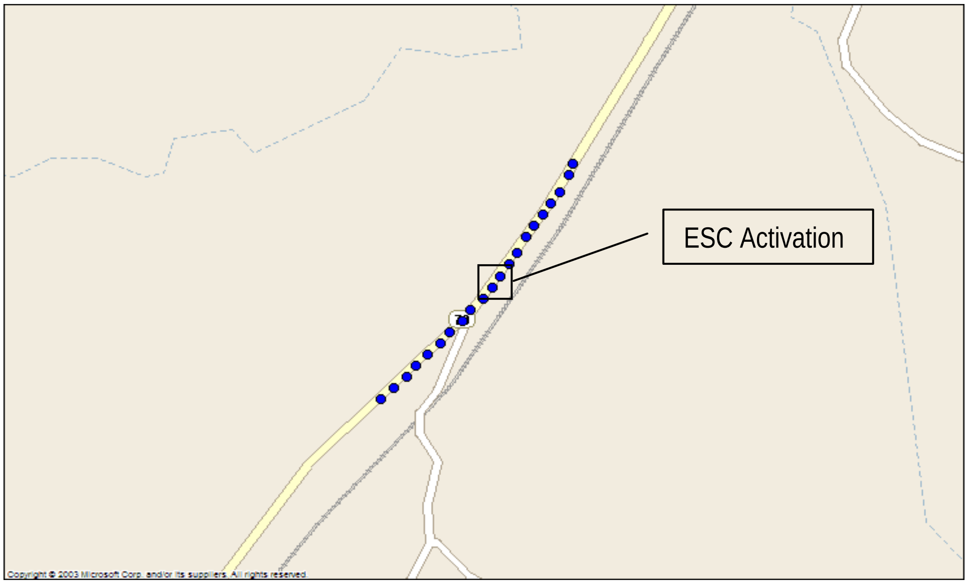
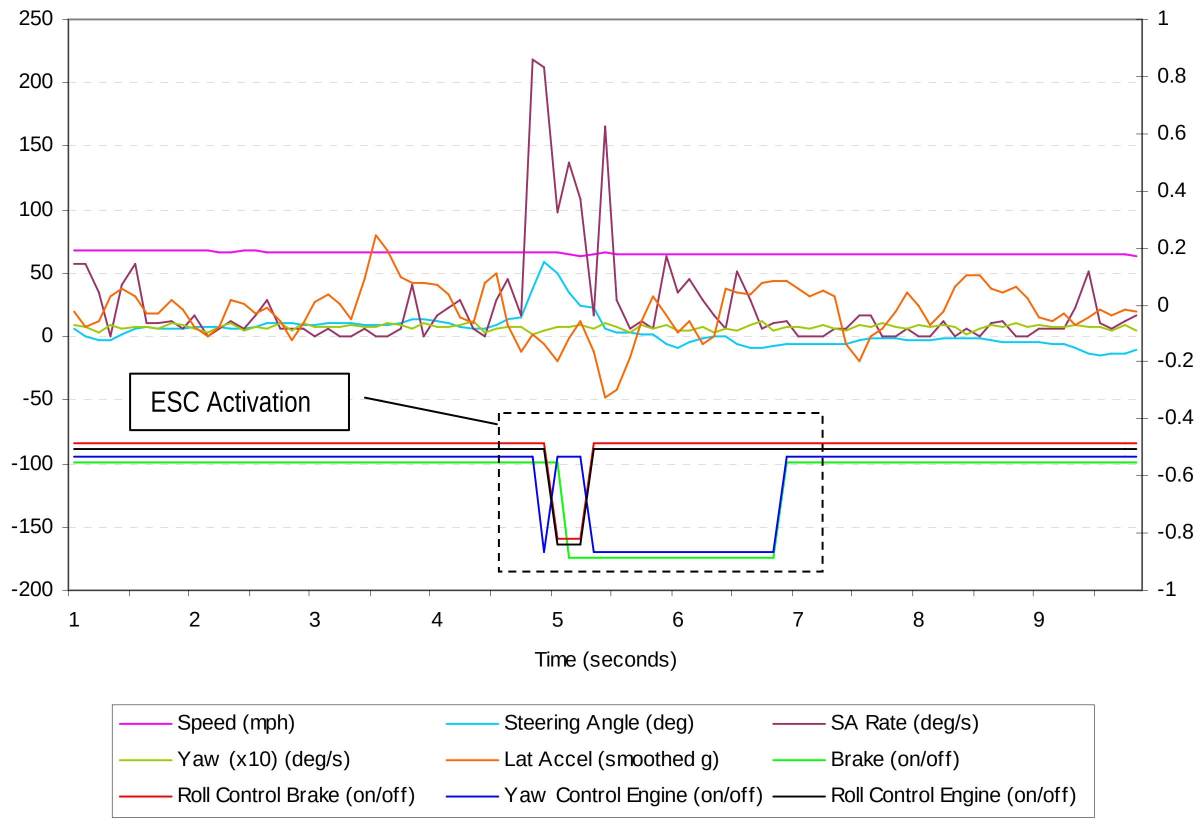


Exhibit 5-23 plots nine data channels against time for ESC activation T2C3-1. All nine channels are engineering data collected from sensors on the tractor except for the steering angle rate of change denoted as “SA Rate” in the graph’s legend. This channel was calculated using the steering wheel sensor and date-time data. It should also be noted that the lateral acceleration channel was filtered using a 2-point moving average.

The ESC system activated on April 4, 2006, at 8:34:28 pm. The ambient temperature was 55.4 degrees Fahrenheit. At the time of ESC activation, the tractor was traveling at 66 miles per hour. The ACC system was on; however, a forward target was not detected. As the steering angle (light blue line) data shows, the driver makes a sudden 50-degree steering input to the left and back again at a rate of over 200 degrees per second. Shortly thereafter, the ESC system briefly activates the engine brake (blue line), immediately follows with a 0.3-second application of the service brakes (red line), and then reapplies the engine brake for over 1 second. The light green line denotes the driver also applied the service brakes a tenth of a second after the ESC activates the service brakes. The lateral acceleration peaked at 0.32g one second after the initial steering input. At the end of the event, the tractor is traveling at 64 miles per hour or 2 miles per hour less than the speed at the start of the event. Note that the ESC activations are digital signals of ones and zeroes. To present these data clearly on the graph, the amplitude and maximum values for each of these channels were adjusted.

Exhibit 5-23: Signal Graph - Roll-Dominant Event 1 (T2C3- Driver D46)



ESC Event T2C3-2

Exhibit 5-24 shows Event 2 occurring south of Castle Rock, Colorado, on I-25, 40 miles due south of downtown Denver. The same driver triggered both Events 1 and 2.

Exhibit 5-24: GPS Data for Roll-Dominant Event T2C3-2 (30-mile view)

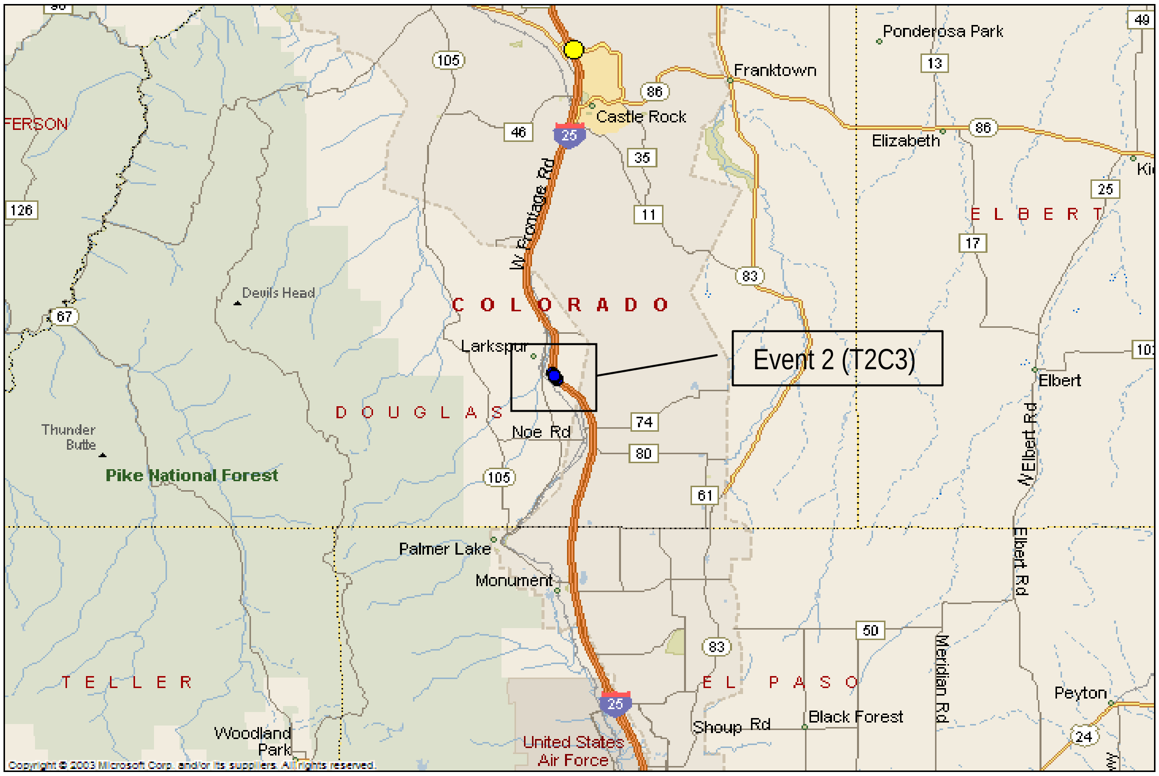


Exhibit 5-25 shows a close-up of I-25 at the point of ESC activation. As shown, the activation occurred in the southbound lane negotiating a curved section of highway.

Exhibit 5-25: GPS Data for Roll-Dominant Event T2C3-2 (3-mile view)

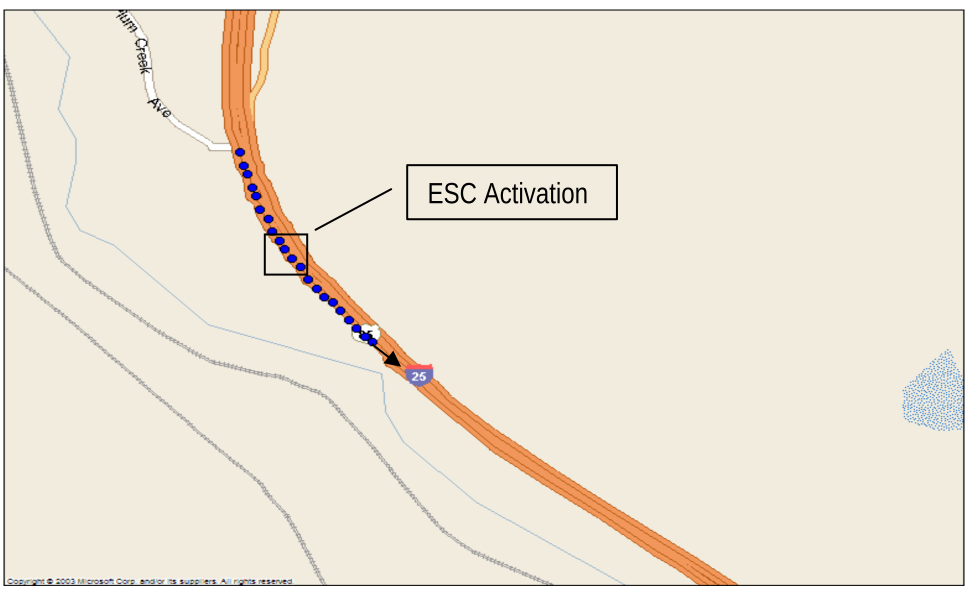
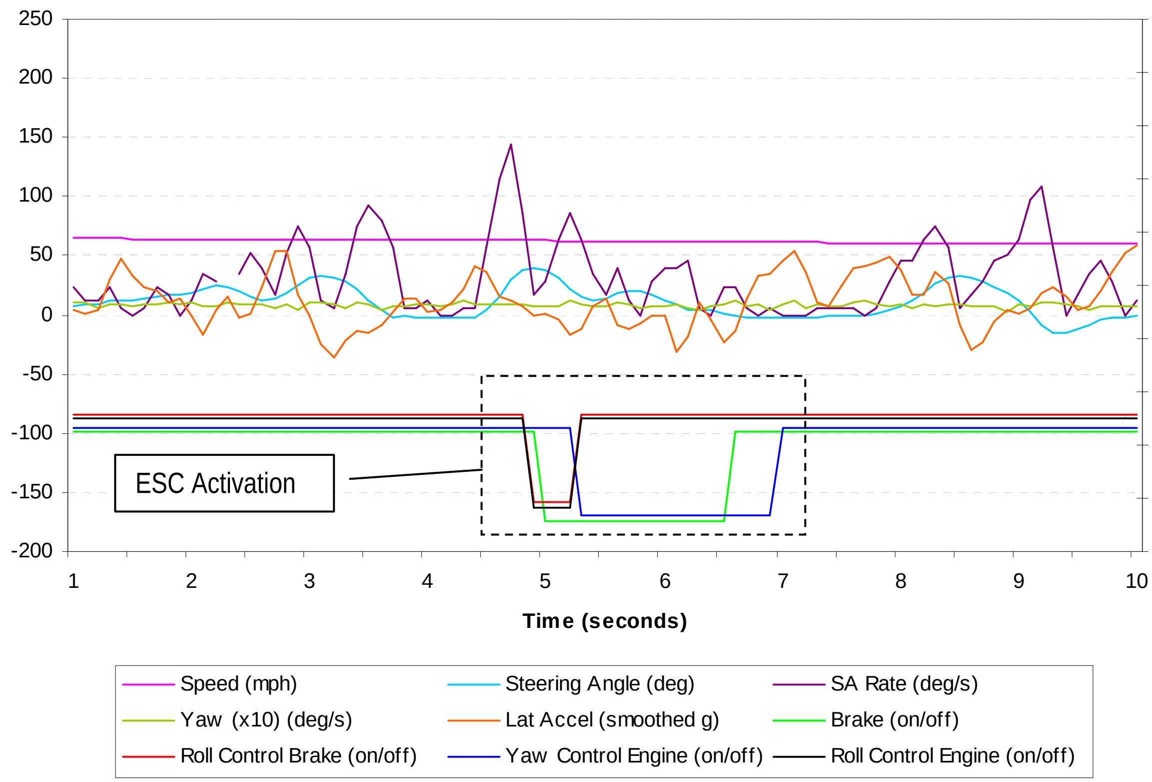


Exhibit 5-26 shows the engineering data on Event 2. The ESC activated on March 30, 2006, at 6:20:23 pm. The ambient temperature was 59 degrees Fahrenheit. The tractor was traveling at 63 miles per hour, the ACC system was off, and a forward target was not detected. Notice how the steering angle data oscillates prior to the ESC activation and the lateral acceleration reaches 0.32 g without ESC activation. Roughly a second later, the driver makes a steering input at a rate of 143 degrees per second and the system immediately triggers by applying the service brakes for three-tenths of a second followed by the engine brake for 1.5 seconds. This events shows that, for roll events, the ESC system triggers on the presence of both a high steering angle rate (greater than 110 degrees per second) of change and lateral acceleration (greater than 0.15g). On this event, the activation occurred with the steering angle rate of change of 143 degrees per second and a lateral acceleration of 0.18g. The activation reduced the tractor's speed by 2 miles per hour.

Exhibit 5-26: Signal Graph – Roll-Dominant Event 2 (T2C3- Driver D46)



ESC Event T3-4

Exhibit 5-27 shows Event 4 occurring on I-70 near Empire, Colorado, due west of Denver. The red dot indicates a Template 3 tractor.

Exhibit 5-27: GPS Data for Roll-Dominant Event T3-4 (30-mile view)

Exhibit 5-28 shows a close-up of I-70. At the point of ESC activation, the tractor was traveling westbound on a straight section of highway.

Exhibit 5-28: GPS Data for Roll-Dominant Event T3-4 (3-mile view)

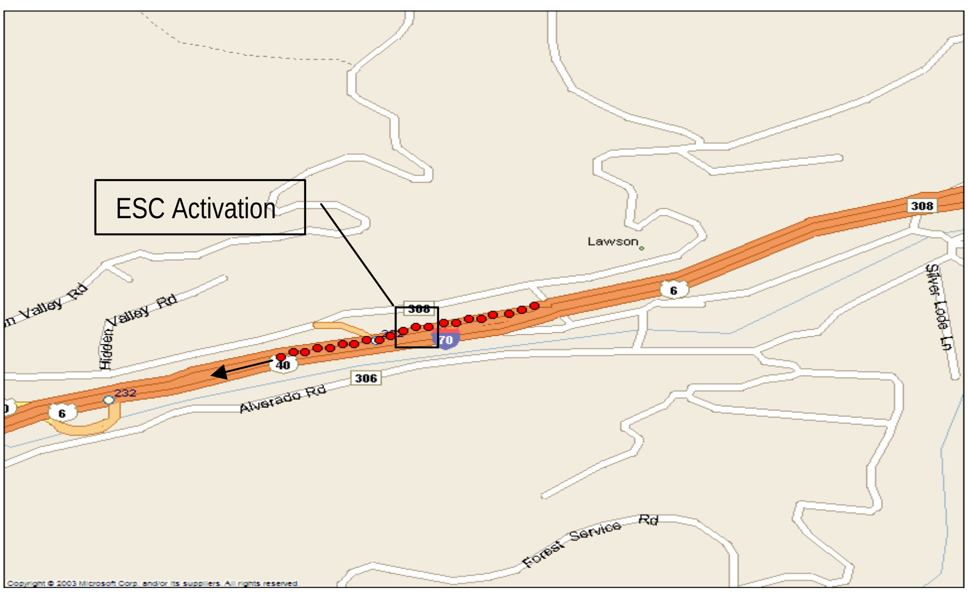
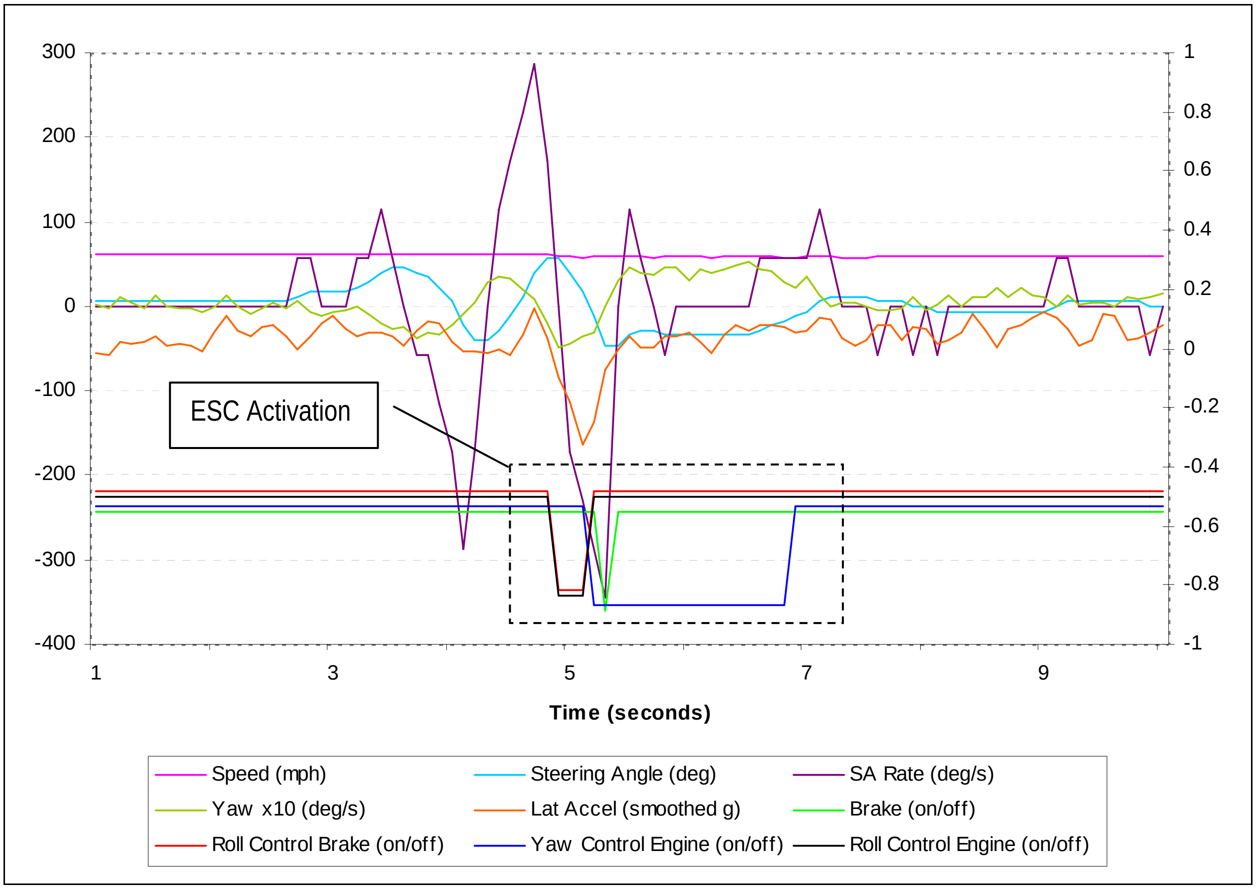


Exhibit 5-29 shows the engineering data on Event 4. The ESC activated on February 8, 2006, at 10:25:34 p.m. The ambient temperature was 50 degrees Fahrenheit. The tractor was traveling at

60 miles per hour, the CCC was off, and a forward target was detected. The headlights were set to high beams, and the left turn signal was on. Studying the target range, azimuth, range rate (not shown), and steering angle, the driver appeared to make an evasive maneuver to avoid contact with the forward vehicle. The ESC system responded by applying and releasing the service brakes followed by the engine brake. The light green line shows the driver applied and released the service brakes after the initial ESC activation. The peak steering angle rate of change and lateral acceleration were 343 degrees per second and 0.32g, respectively. Vehicle speed reduced from 60 to 57 miles per hour.

Exhibit 5-29: Signal Graph - Roll-Dominant Event 4 (T3 – Driver D39)



ESC Event T3-7

Exhibit 5-30 shows Event 7 occurring east of Idaho Springs, Colorado, on I-70, 23 miles due west of downtown Denver.

Exhibit 5-30: GPS Data for Roll-Dominant Event T3-7 (30-mile view)

Exhibit 5-31 shows a close-up of I-70 at the point of ESC activation. As shown, the activation occurred in the westbound lane beginning the negotiation of a curved section of highway.

Exhibit 5-31: GPS Data for Roll-Dominant Event T3-7 (3-mile view)

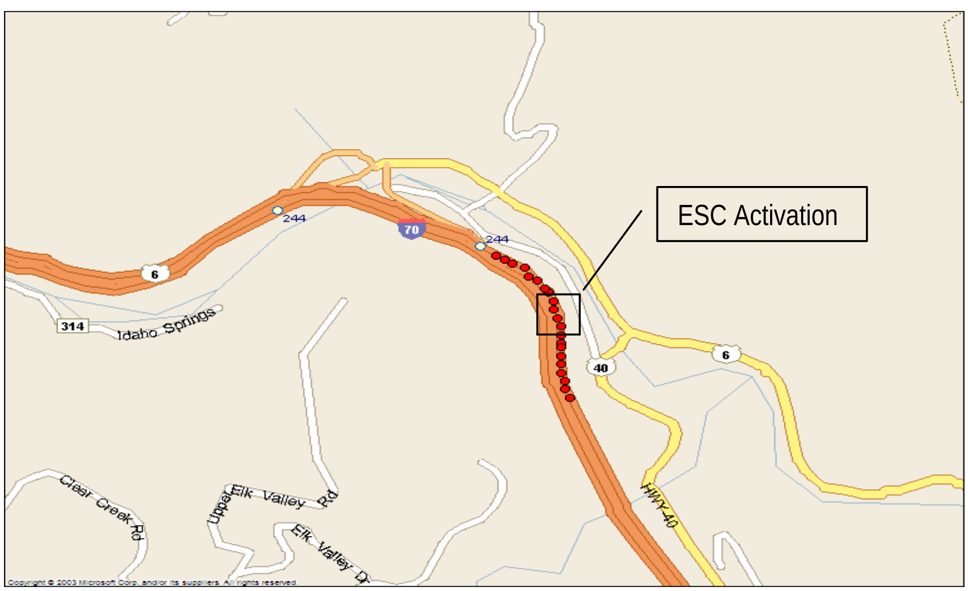
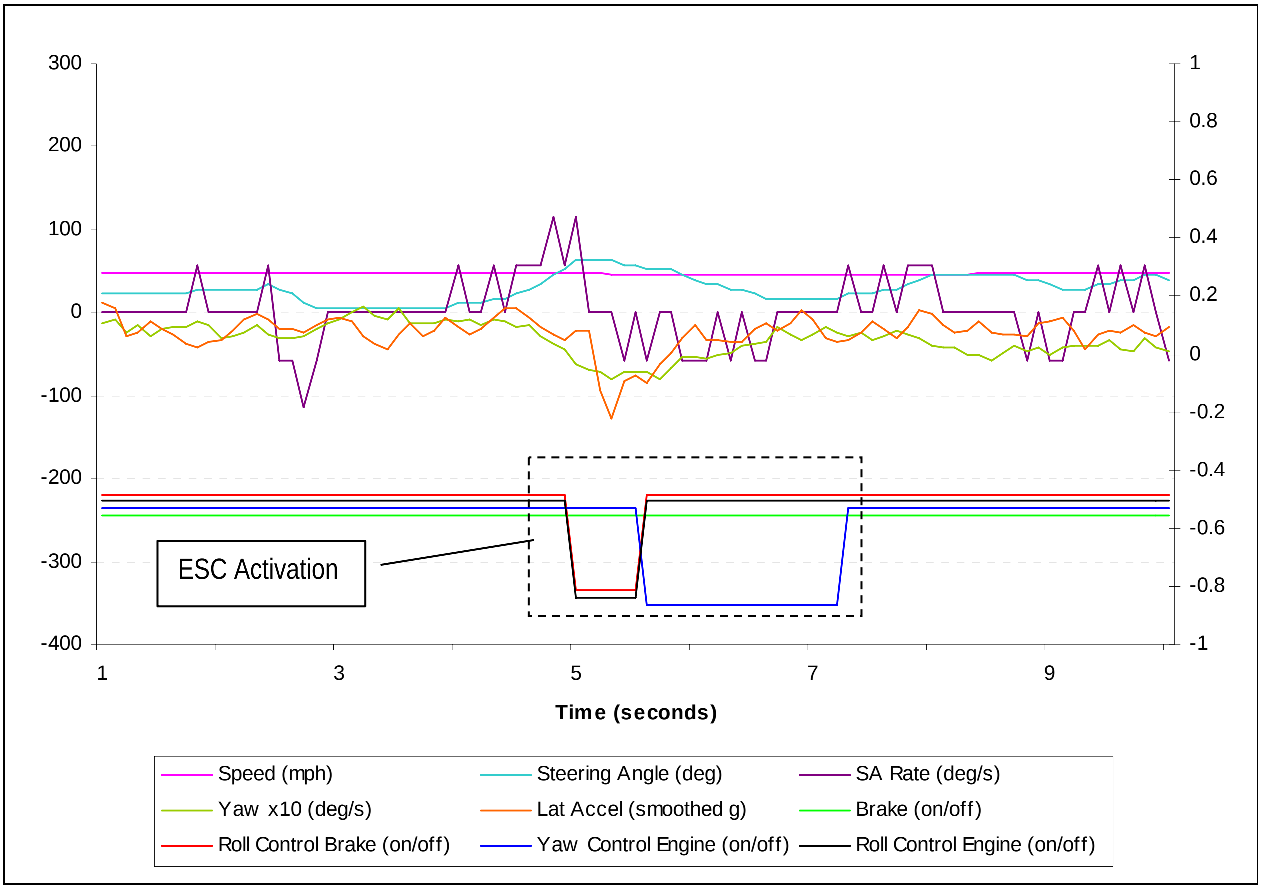


Exhibit 5-32 shows the engineering data on Event 7. The ESC activated on March 2, 2006, at 10:07:47 a.m. The event occurred 30 minutes (20 miles) after a previous event by the same driver. The ambient temperature was 62.6 degrees Fahrenheit. The tractor was traveling at 47 miles per hour, the cruise control was off, and a forward target was not detected. At 4.5 seconds, the steering wheel began moving, and the lateral acceleration reached 0.16g. The steering wheel movement remained constant until 5 seconds when the ESC activated as the rate of change reached a maximum of 110 degrees per second. The ESC applied the service brake for 0.3 seconds. The lateral acceleration reduced and the steering wheel movement stabilized. The driver did not apply the brakes during this period, and the vehicle speed remained constant.

Exhibit 5-32: Signal Graph - Roll-Dominant Event 7 (T3 – Driver D35)



ESC Event T3-9

Exhibit 5-33 shows Event 9 occurring south of downtown Denver, Colorado, on I-25 within the city limits of Denver.

Exhibit 5-33: GPS Data for Roll-Dominant Event T3-9 (30-mile view)

Exhibit 5-34 shows a close-up of I-25 at the point of ESC activation. As shown, the activation occurred in the southbound lane negotiating a curved section of highway.

Exhibit 5-34: GPS Data for Roll-Dominant Event T3-9 (3-mile view)

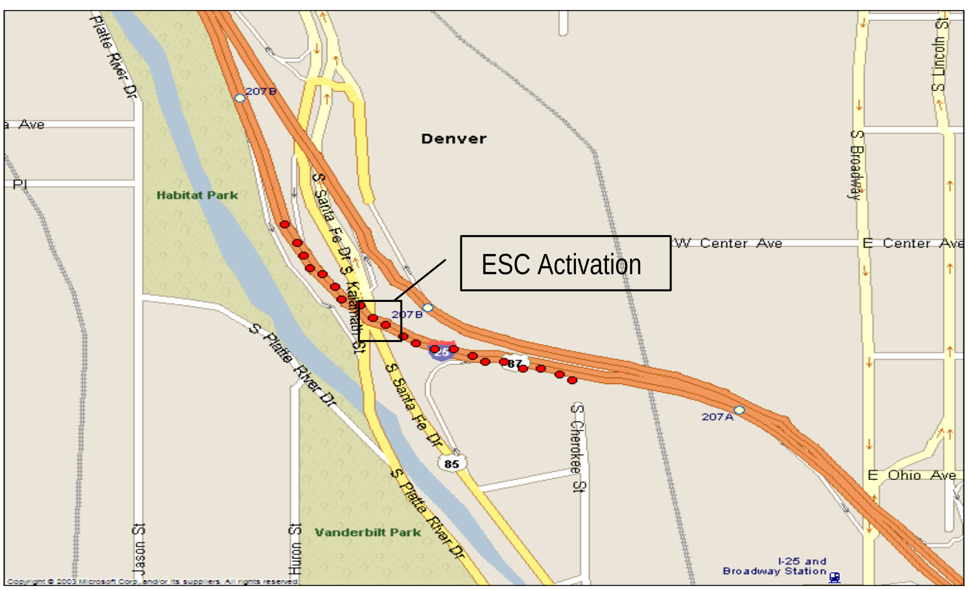
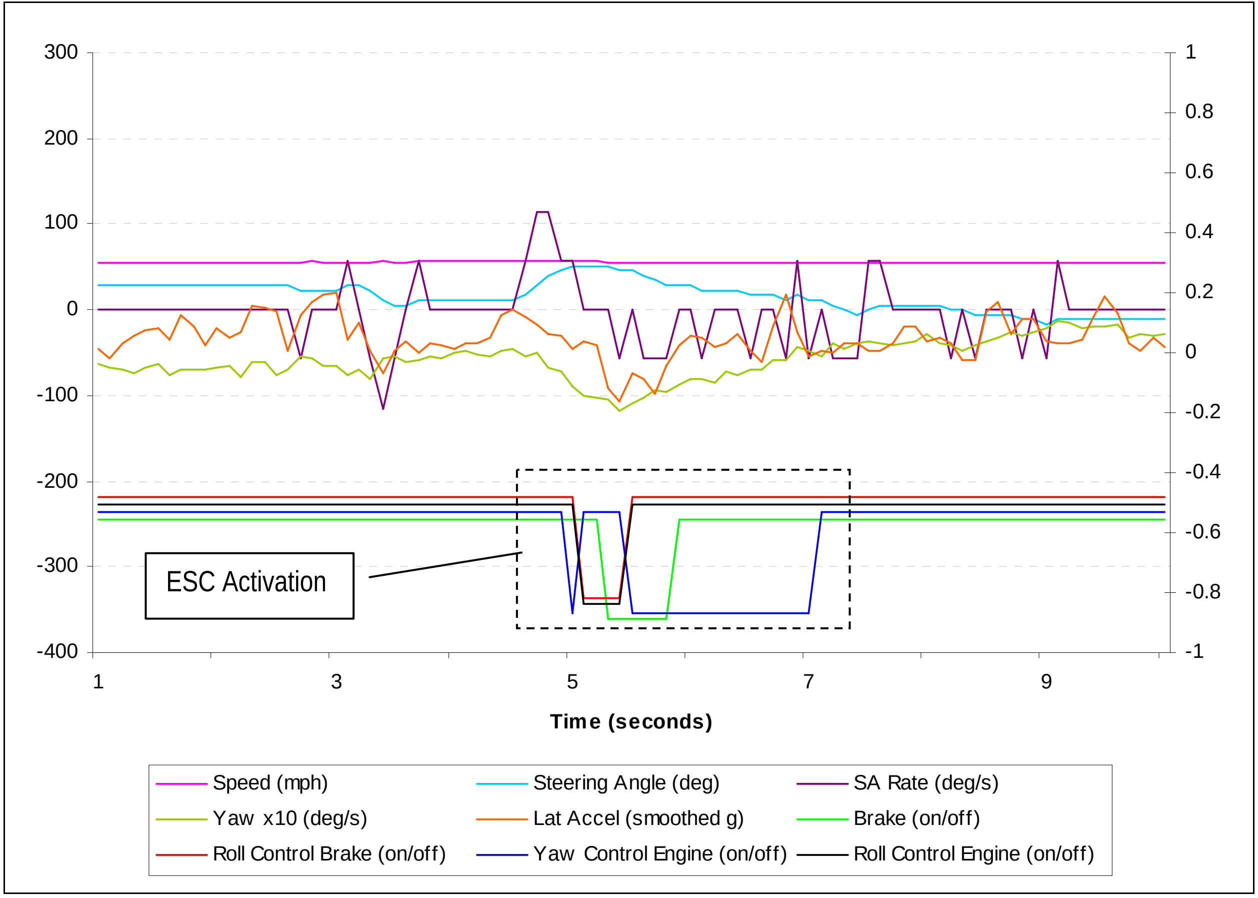


Exhibit 5-35 shows the engineering data on Event 9. The ESC activated on February 1, 2006, at 7:57:27 p.m. The ambient temperature was 62.6 degrees Fahrenheit. The tractor was traveling 56 miles per hour, the cruise control was off, and a forward target was detected. The lateral acceleration oscillated prior to the ESC activation. At 4.5 seconds, the lateral acceleration hit 0.15g. During this time, the yaw rate oscillated at 8 degrees per second. Approximately 0.5 seconds later, the steering angle rate of change reached 110 degrees per second and the system triggered by applying the brakes for 0.3 seconds. After 0.1 seconds, the lateral acceleration reached -0.15g and the yaw rate was 11 degrees per second. The driver also applied the service brake at this time, for 1 second. The vehicle speed did not reduce during this time. The yaw rate returned to zero after 5 seconds.

Exhibit 5-35: Signal Graph - Roll-Dominant Event 9 (T3 – Driver D35)



5.4.3 Yaw-Dominant Events

Yaw-dominant events are defined as ESC activations that trigger both the yaw control signals and roll control signals. An event was determined to be yaw-dominant if the yaw was the principle trigger of the ESC activation. For these events, the yaw exceeded 5 degrees per second for every event. The lateral acceleration varied between events without any discernable pattern. Eight events were identified as yaw-dominant. Seven of the eight events occur at speeds greater than 50 miles per hour and were predominately on curved sections of highway.

ESC Event T2C3-10

Exhibit 5-36 shows Event 10 occurring on I-70 east of Grand Junction, Colorado. Grand Junction is on the backside of a mountain range west of Denver. Note that there were multiple ESC activations on I-70 during the FOT denoted by the blue (Template 2 ECBS tractors) and red (Template 3 ECBS tractors) dots. Also, two Wal-Mart store locations in the city of Grand Junction are denoted by the yellow dots.

Exhibit 5-36: GPS Data for Yaw-Dominant Event T2C3-10 (30-mile view)

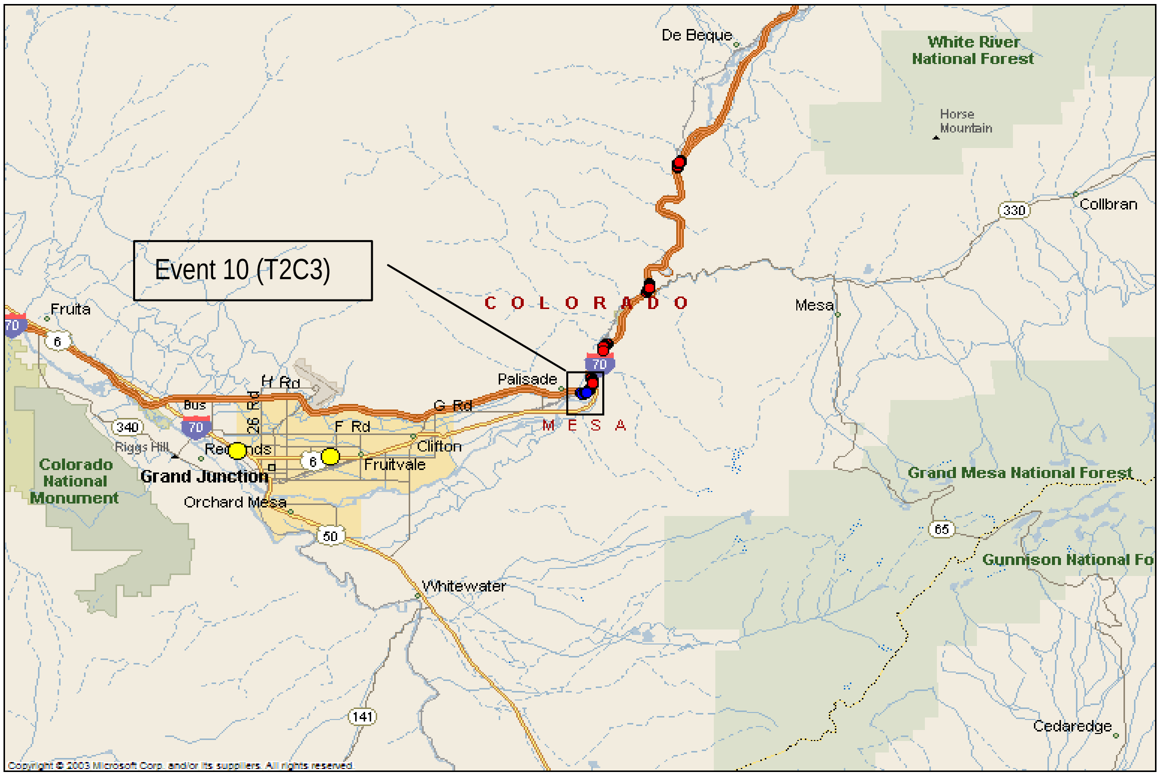


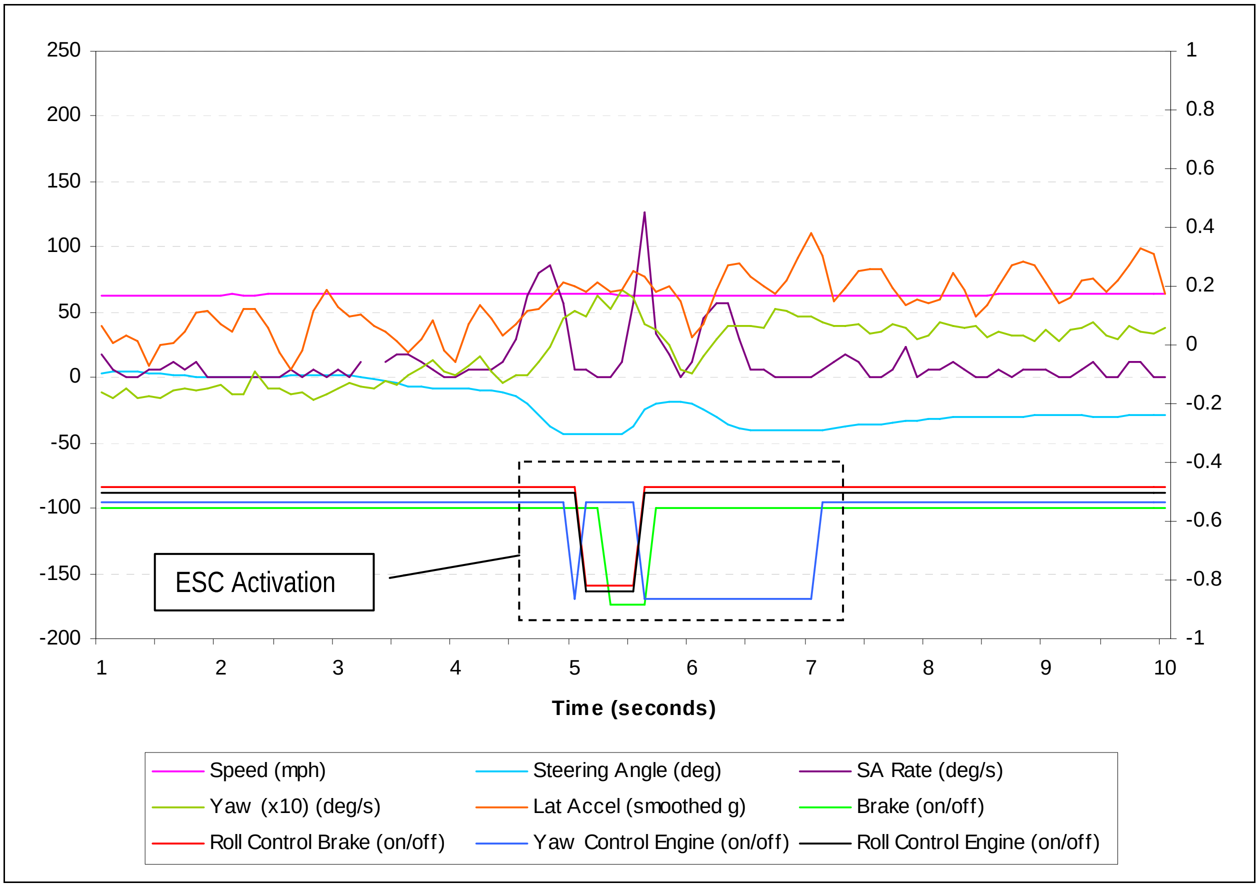
Exhibit 5-37 shows a close-up of I-70. At the point of ESC activation, the tractor was traveling westbound while negotiating a right-hand radius curve.

Exhibit 5-37: GPS Data for Yaw-Dominant Event T2C3-10 (3-mile view)

The ESC activated on February 19, 2006, at 12:19:16 p.m. The ambient temperature was 41 degrees Fahrenheit. The tractor was traveling at 64 miles per hour, the CCC was off, the status of ACC is unknown, and a forward target was detected.

Exhibit 5-38 shows the driver traveling relatively straight and then adding a steering input to negotiate the curve. The steering angle rate of change spiked to 85 degrees per second. The ESC system did not activate until the lateral acceleration and the yaw rate climbed above 0.2g and 5 degrees per second, respectively. Remember that the yaw rate data shown in the exhibit has been multiplied by 10 to scale accordingly. The lateral acceleration continued to trend upward after the event while the steering angle input remained constant. The ESC activated the service brakes for 0.3 seconds and applied the engine brake for 1.5 seconds. The light green line shows the driver briefly applied the service brakes after the initial ESC system response. Vehicle speed reduced from 64 to 63 miles per hour.

Exhibit 5-38: Signal Graph - Yaw-Dominant Event 10 (T2C3- Driver D40)



ESC Event T2C3-11

Exhibit 5-39 shows Event 11 occurring on US-50 in Sapinero State Wildlife Area, which is west of Gunnison, Colorado. Note that the yellow dot is the location of a Wal-Mart store.

Exhibit 5-39: GPS Data for Yaw-Dominant Event T2C3-11 (30-mile view)

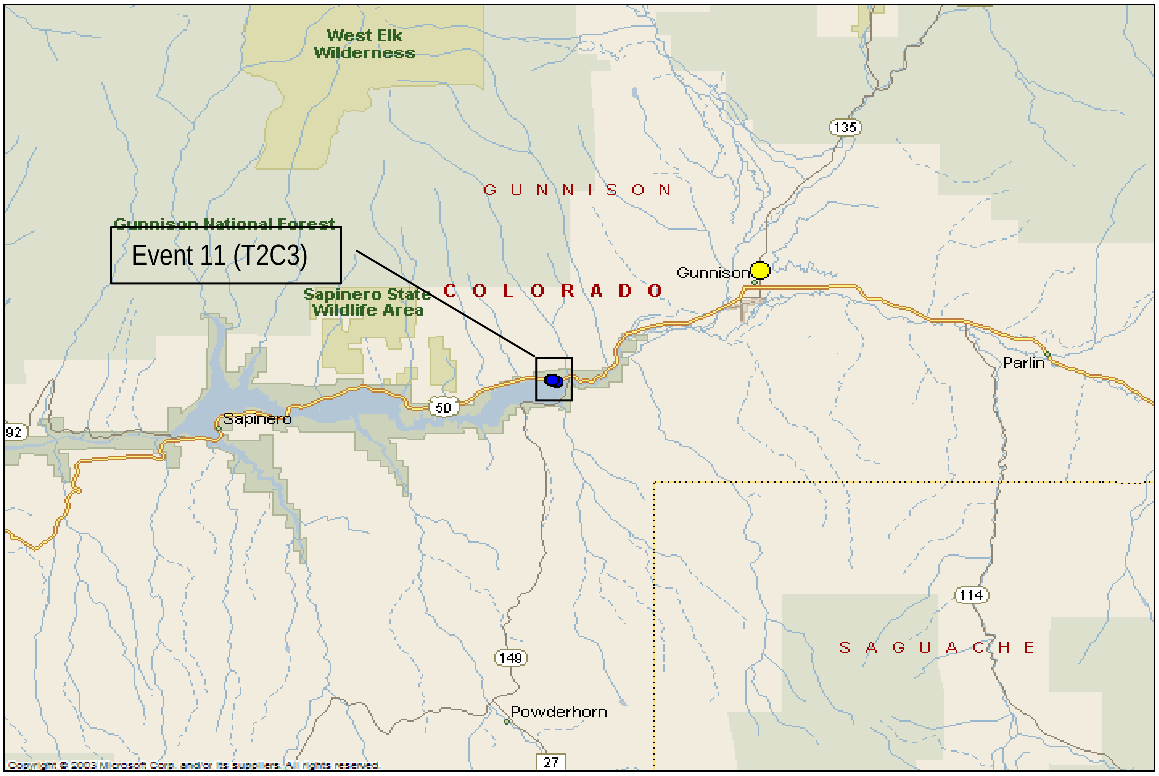
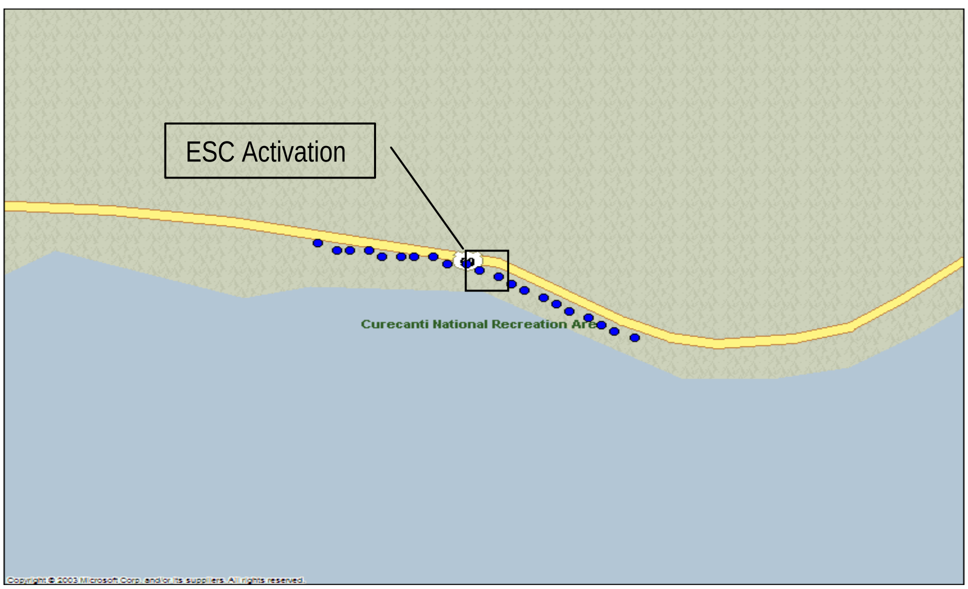


Exhibit 5-40 shows a close-up of US-50. At the point of ESC activation, the tractor was traveling westbound while negotiating a left-hand radius curve.

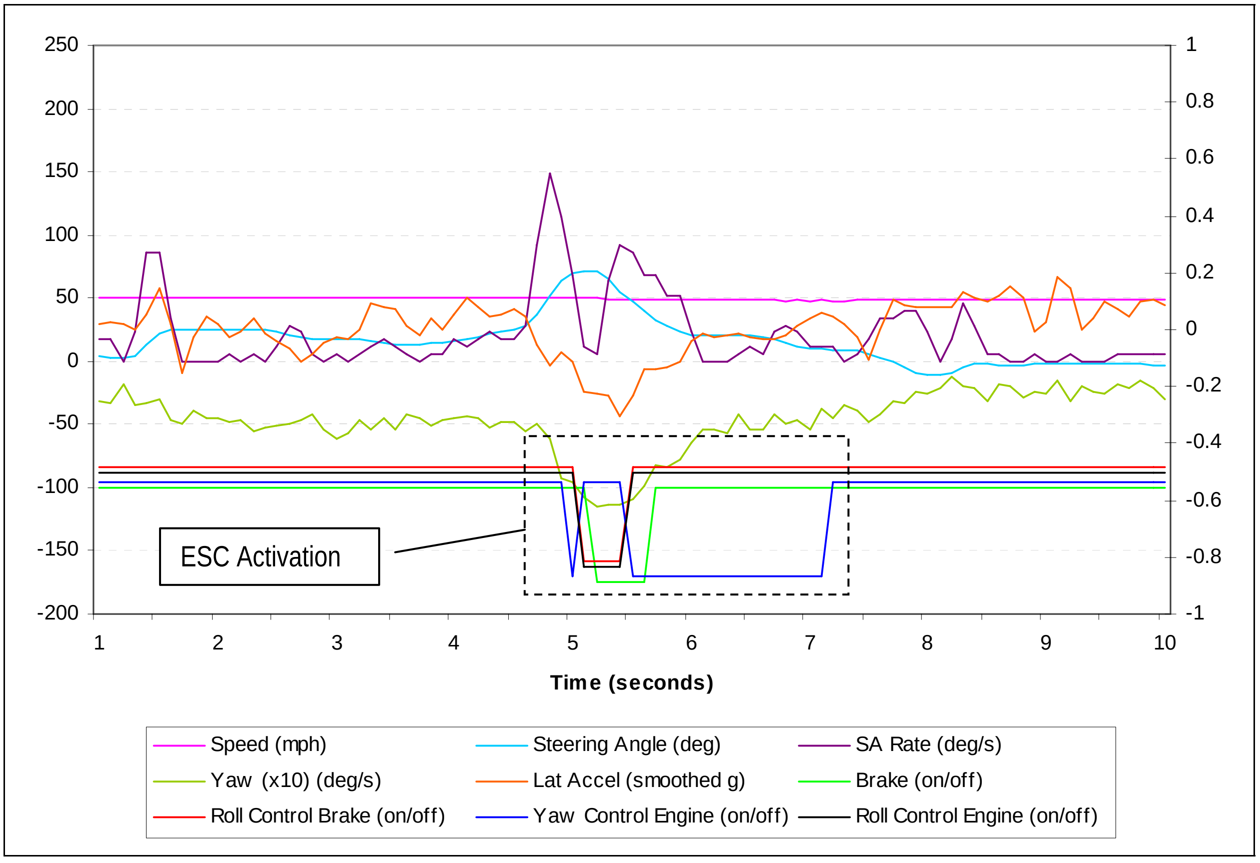
Exhibit 5-40: GPS Data for Yaw-Dominant Event T2C3-11 (3-mile view)



The ESC activated on February 4, 2006, at 4:04:39 p.m. The ambient temperature was 30.2 degrees Fahrenheit. The tractor was traveling at 50 miles per hour, the CCC was on, and a forward target was not detected.

Exhibit 5-41 shows the driver negotiating a left-hand turn at a constant rate. At 5 seconds, the steering angle suddenly moved to the left at a rate of 150 degrees per second. The ESC system triggered with the application of the service brakes followed by the application of the engine brake. The lateral acceleration peaked at 0.30g and the yaw rates peaked at 11 degrees per second. The driver returned the tractor to its original direction of travel at a steering angle rate of 91 degrees per second. The light green line shows the driver applying the service brakes for 0.4 seconds immediately following the system trigger. Vehicle speed reduced from 50 to 48 miles per hour.

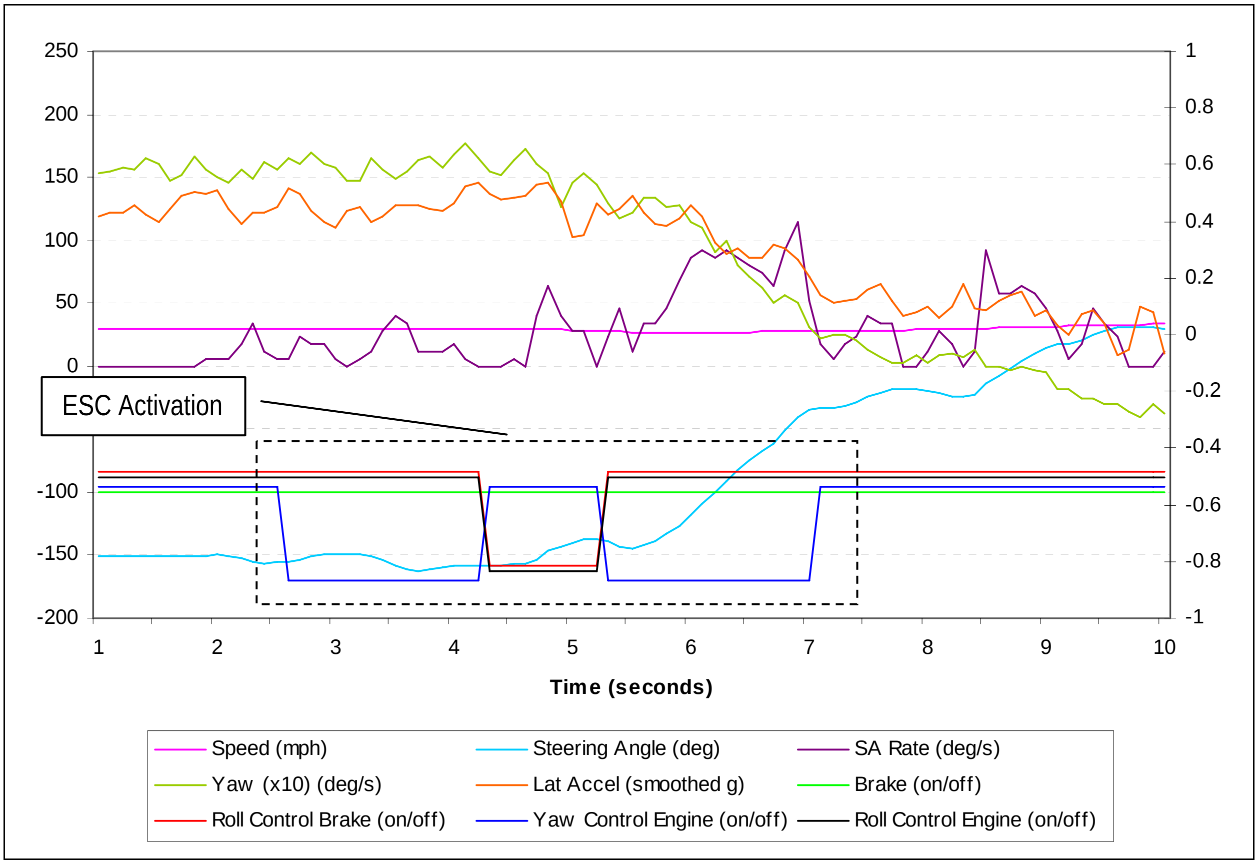
Exhibit 5-41: Signal Graph - Yaw-Dominant Event 11 (T2C3 – Driver D40)



ESC Event T2C3-12

Exhibit 5-42 shows the engineering data on Event 12. Event 12 occurred on March 17, 2006, at 9:01:40 p.m. No GPS data were available to identify the location of the event. The ambient temperature at the time of the activation was 50 degrees Fahrenheit. At the time of the ESC activation, the tractor was traveling at 29 miles per hour. The CCC was off and no forward target was detected. The right-hand turn signal was on and the steering angle was 150 degrees, possibly indicating that the tractor was negotiating an off-ramp. This ESC activation is unique in that it is one of the few events that occurred at a lower speed with roll control signals triggering in the absence of a high steering angle rate of change. The ESC activated on lateral acceleration (0.51g) and yaw rate (1.5 degrees per second). As shown, the initial response of the system was to activate the engine brake, followed by the application of the service brake, and then the reapplication of the engine brake. The light green line shows the driver never intervened. Vehicle speed was reduced from 29 to 26 miles per hour. Events 10, 11, and 12 occurred with the same driver.

Exhibit 5-42: Signal Graph - Yaw-Dominant Event 12 (T2C3- Driver D40)



ESC Event T3-17

Exhibit 5-43 shows Event 17 occurring east of Glenwood Springs, Colorado, on I-70, 114 miles west of downtown Denver.

Exhibit 5-43: GPS Data for Yaw-Dominant Event T3-17 (30-mile view)

Exhibit 5-44 shows a close-up of I-70 at the point of ESC activation. As shown, the activation occurred in the eastbound lanes while negotiating a curved section of highway.

Exhibit 5-44: GPS Data for Yaw-Dominant Event T3-17 (3-mile view)

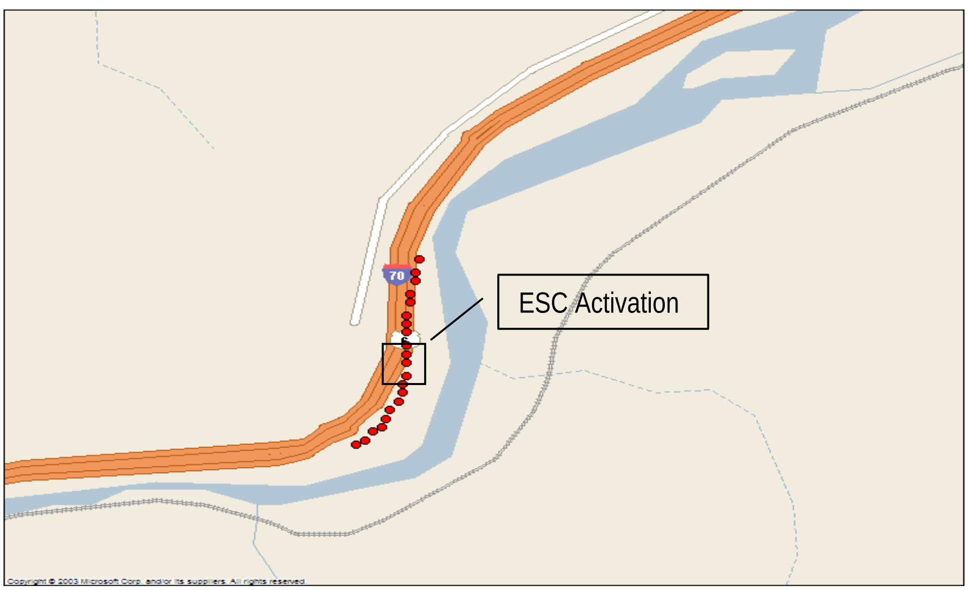
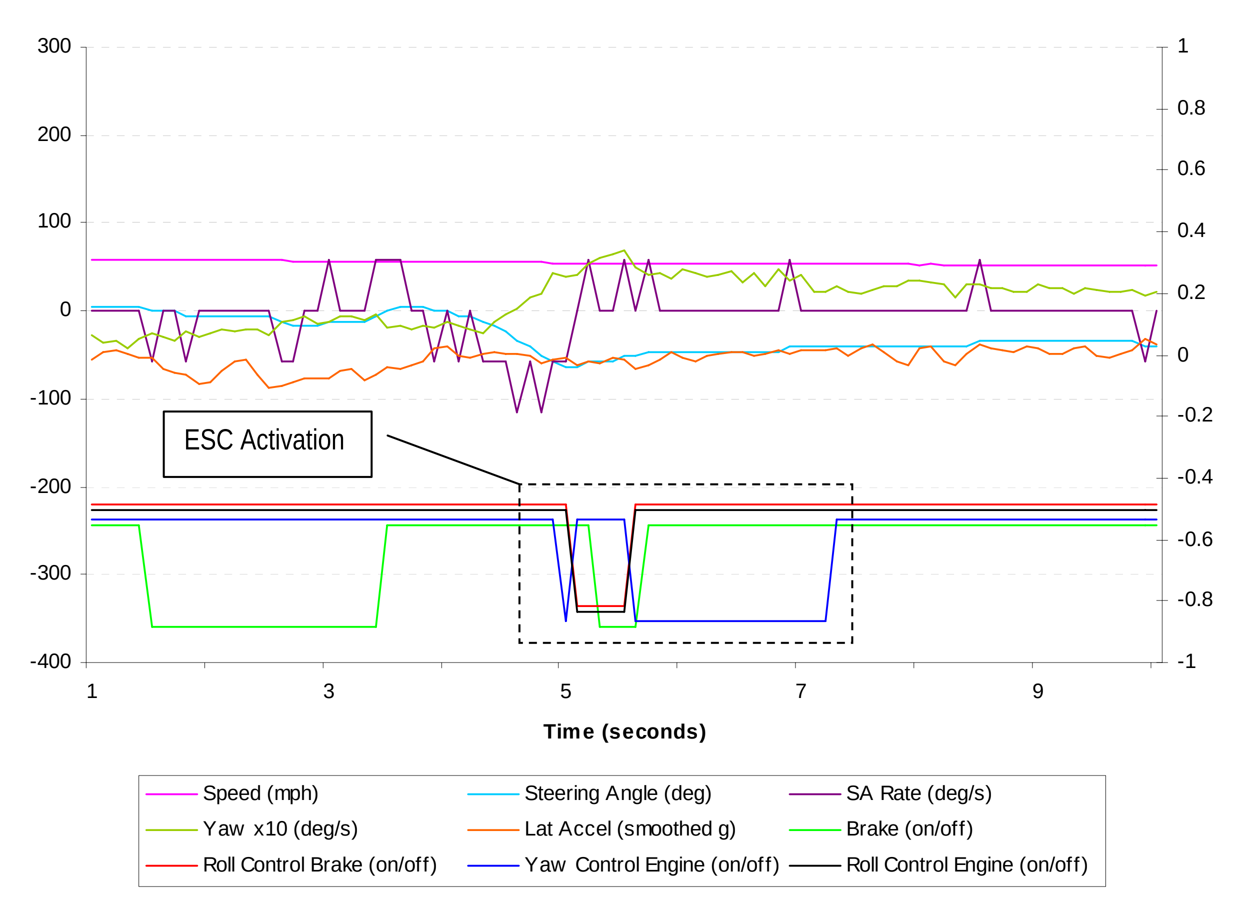


Exhibit 5-45 shows the engineering data on Event 17. The ESC activated on March 1, 2006, at 9:52:22 a.m. The ambient temperature was 41 degrees Fahrenheit. The tractor was traveling at 54 miles per hour, the cruise control was off, and a forward target was detected. The driver applied a service brake for 2 seconds at the beginning of the plot. No significant information is shown to explain this application. The yaw rate began to climb at 4.5 seconds, reaching a rate of 5 degrees per second after 0.5 seconds. At that time, the steering wheel rate of change hit 110 degrees per second. The system triggered a brake application at this time for 0.3 seconds. The driver applied the brake 0.1 seconds after the system, and maintained it for 0.3 seconds. During this time, the lateral acceleration oscillated, but had an average value of 0g. The brake applications reduced the tractor's speed by 5 miles per hour.

Exhibit 5-45: Signal Graph - Yaw-Dominant Event 17 (T3 – Driver D37)



5.4.4 Yaw-Only Events

Yaw-only events are defined as ESC activations that trigger only the yaw control brake and yaw control engine signals. A total of 34 events were identified as yaw-only events. Out of the 18 ECBS tractors, six had yaw-only ESC activations. A single tractor accounted for 13 of the 14 yaw-only T2C3 tractor yaw-only activations. The majority of these events occurred within an 11-day period in March 2006.

The yaw-only events were predominately linked to tractors maneuvering through entrance or exit ramps or performing right or left-hand turns. Sixty-five percent of the yaw events had an active turn signal at the time of ESC activation. The majority of the events recorded excessive steering angle changes denoting more than one complete revolution of the steering wheel prior to or during the event. The high steering angle value can be attributed to the vehicle performing a tight turn.

ESC Event T2C3-18

Exhibit 5-46 shows Event 18 occurred 16 miles west of Canon City, Colorado.

Exhibit 5-46: GPS Data for Yaw-Only Event T2C3-18 (30-mile view)

Exhibit 5-47 shows a close-up of event on State Route 50 at the point of ESC activation. As shown, the activation occurred along a straight stretch of highway.

Exhibit 5-47: GPS Data for Yaw-Only Event T2C3-18 (3-mile view)

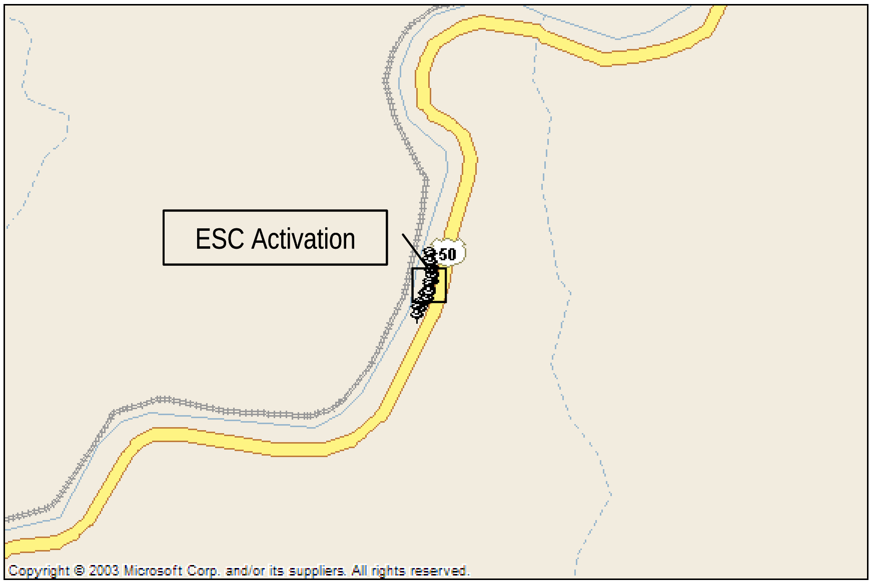
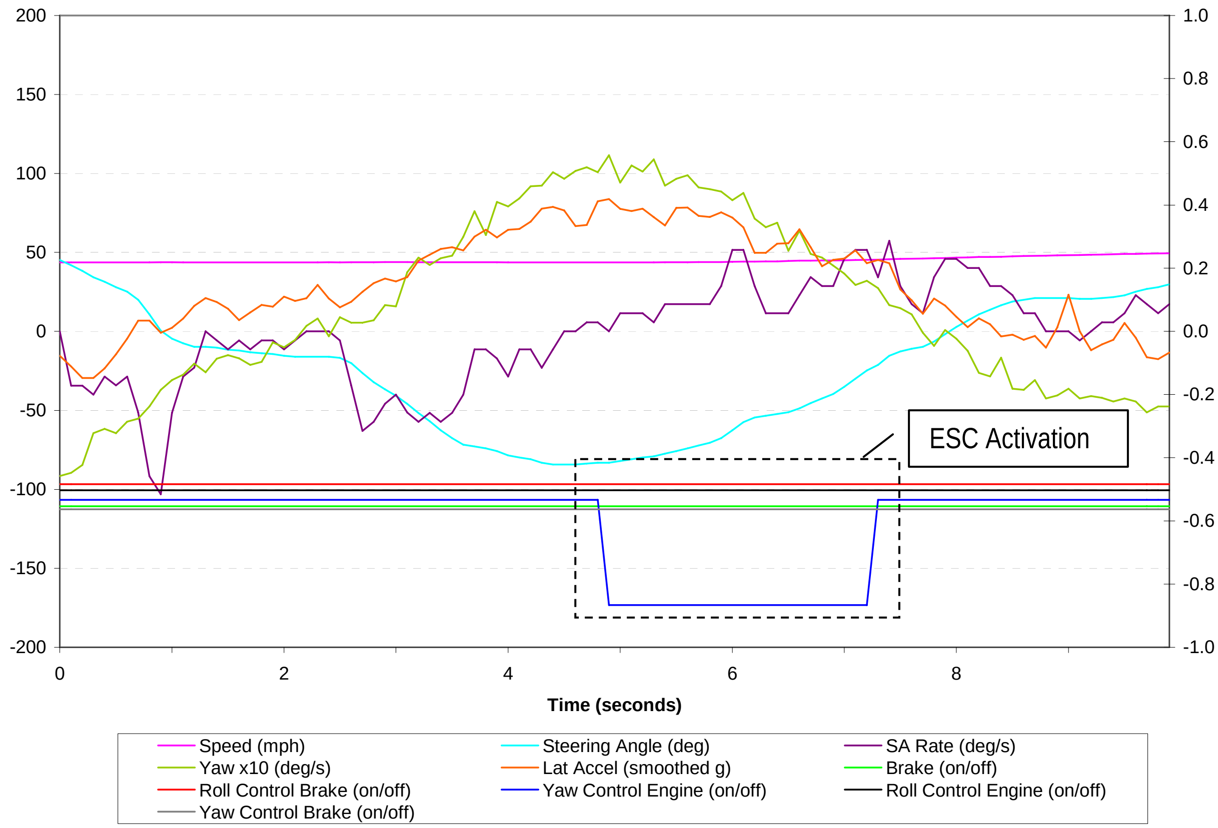


Exhibit 5-48 shows the engineering data on Event 18. The ESC activated on February 4, 2006, at 1:41:18 p.m. The ambient temperature was 50 degrees Fahrenheit. The tractor was traveling 44 miles per hour, the cruise control was off, and a forward target was not detected. At 5 seconds, the yaw sensor reached a maximum value of 11.1 degrees per second, triggering the yaw control engine signal for 2.25 seconds. The peak yaw value coincided with a peak lateral acceleration of 0.4g. The steering angle rate of change on average did not exceed 50 degrees per second. The largest steering angle rate of change occurred with a lateral acceleration of less than 0.05g. The activation did not reduce the speed of the vehicle. The roll control signal was not activated during the ESC event.

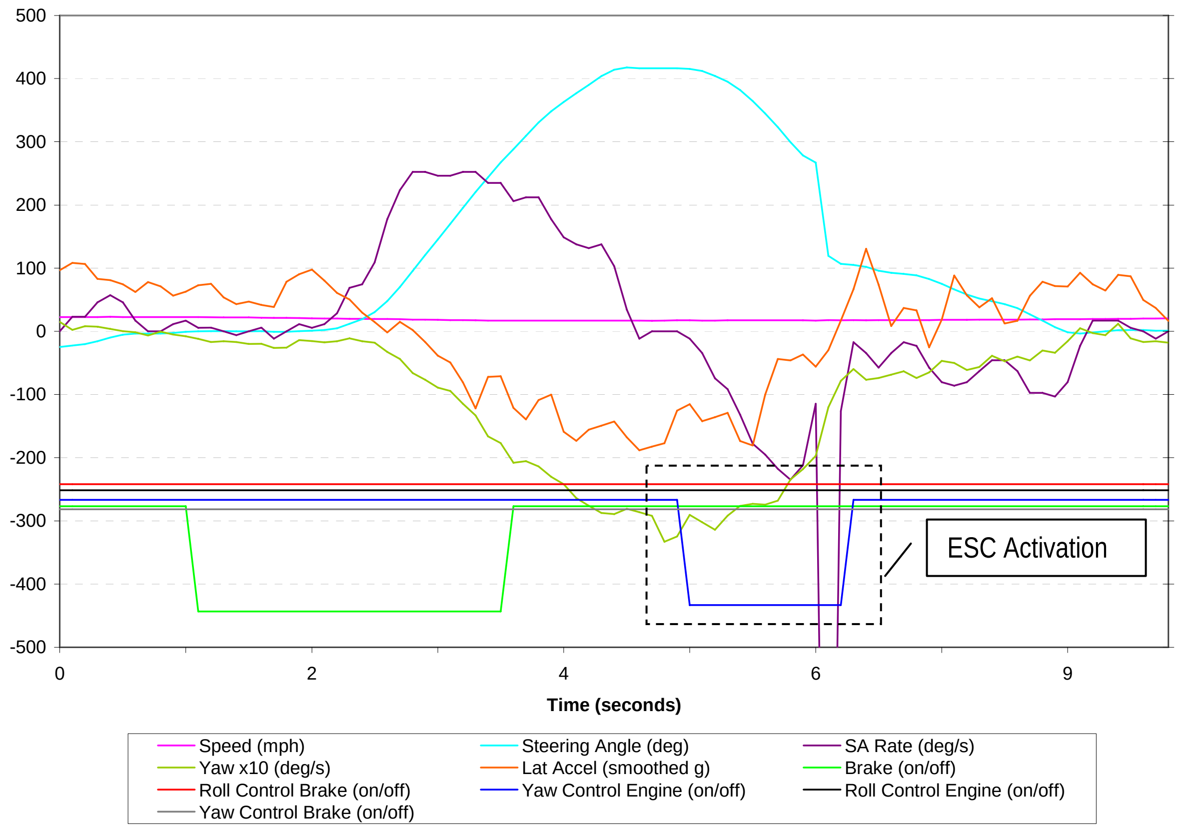
Exhibit 5-48: Signal Graph - Yaw-Only Event 18 (T2C3 – Driver D40)



ESC Event T2C3-3

The GPS coordinates for Event 20 were not available. Exhibit 5-49 shows the engineering data on ESC Event 20. The ESC activated on March 14, 2006, at 2:24:24 p.m. The ambient temperature was 66 degrees Fahrenheit. The tractor was traveling 19 miles per hour, the cruise control was off, the left turn signal was active, and a forward target was not detected. According to these data, the vehicle was negotiating more than a standard left turn. Prior to the event, the driver activated the vehicle brake for 2.5 seconds, leading to a high steering angle rate. At 3 seconds, the steering angle rate peaked at 252 degrees per second for one second before decreasing steadily. During this time, the lateral acceleration increased from 0.05g to in excess of 0.2g. The vehicle speed was below 20 miles per hour and a roll control event was not triggered. At 5 seconds, the yaw reached a peak of 33 degrees per second, the steering angle rate approached 100 degrees per second and the lateral acceleration was between 0.25g and 0.3g. In response, the yaw control engine signal activated for 1.25 seconds. During the activation, the steering angle rate reached a maximum of 1,400 degrees per second. As the yaw control signal was already active, no further action was taken by the ECBS. After the activation, the yaw, steering angle rate, and lateral acceleration returned to acceptable levels. The vehicle speed was reduced by 5 miles per hour during the event. The roll control signal was not activated during the ESC event.

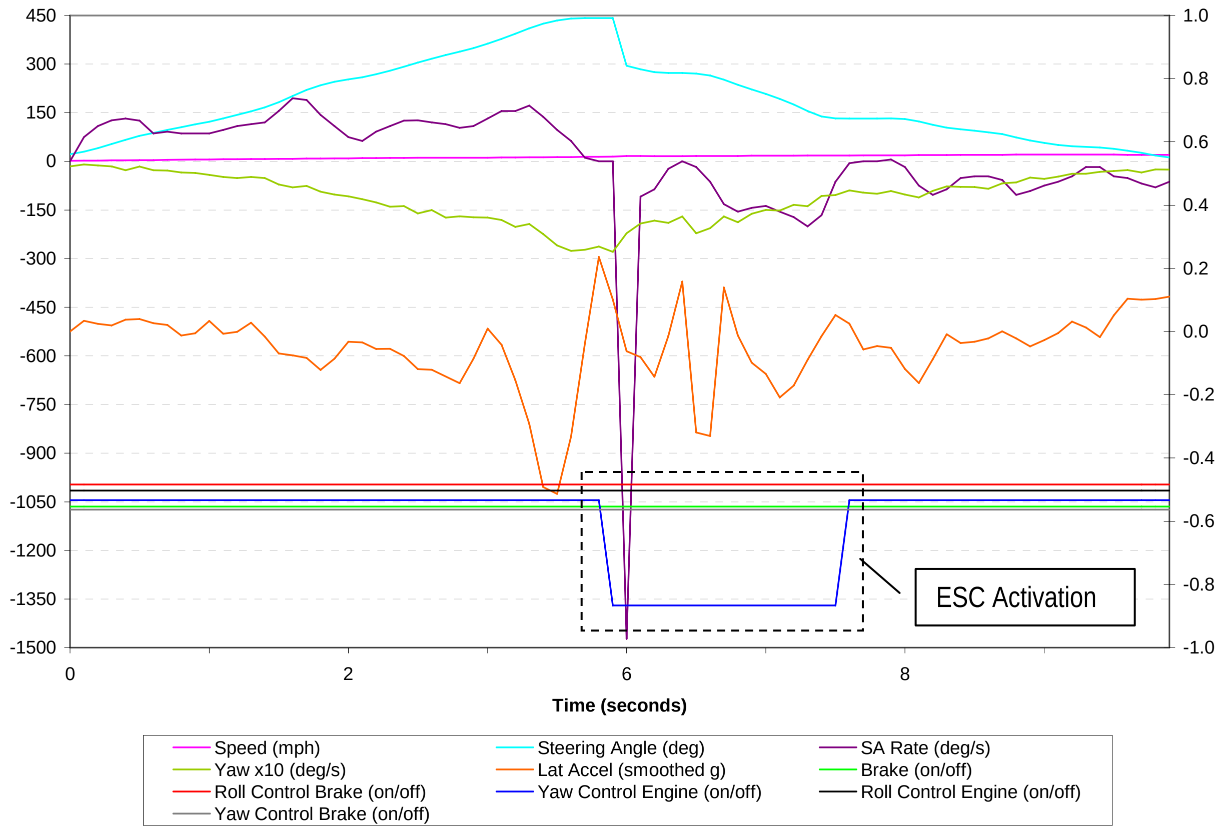
Exhibit 5-49: Signal Graph - Yaw-Only Event 20 (T2C3 – Driver D40)



ESC Event T2C3-30

The GPS coordinates for Event 30 were not available. Exhibit 5-50 shows the engineering data on ESC Event 30. The ESC activated on March 24, 2006, at 6:55:41 p.m. The ambient temperature was 61 degrees Fahrenheit. The tractor was traveling 16 miles per hour, the cruise control was off, the left turn signal was active, and a forward target was not detected. The recording has many extremes, including a steering angle rate of 1,500 degrees per second. Prior to the event, the steering angle rate was consistent at 120 degrees per second. While the vehicle was negotiating a turn to the left, the yaw steadily increased to a value of 27 degrees per second before decreasing as the steering angle returned to zero. During the 10-second recording, the lateral acceleration maintained a value of 0.1g, except for the time period between 4 and 8 seconds. During this time, large oscillations occurred with the values peaking between -0.5g and +0.2g. The yaw control engine signal activated at the 5-second mark. The event coincided with the maximum lateral acceleration, steering angle rate, and yaw. Unlike other yaw events, the lateral acceleration and steering angle rate had extreme fluctuations in values over short periods of time. It is difficult to determine whether a single event or a combination of events triggered the ESC event. The vehicle speed increased by 5 miles per hour after the triggering of the event.

Exhibit 5-50: Signal Graph - Yaw-Only Event 30 (T2C3 – Driver D40)



ESC Event T2C3-32

Exhibit 5-51 shows ESC Event 32 occurred 12 miles north of Lusk, Wyoming, in an area called Hat Creek.

Exhibit 5-51: GPS Data for Yaw-Only Event T2C3-32 (30-mile view)

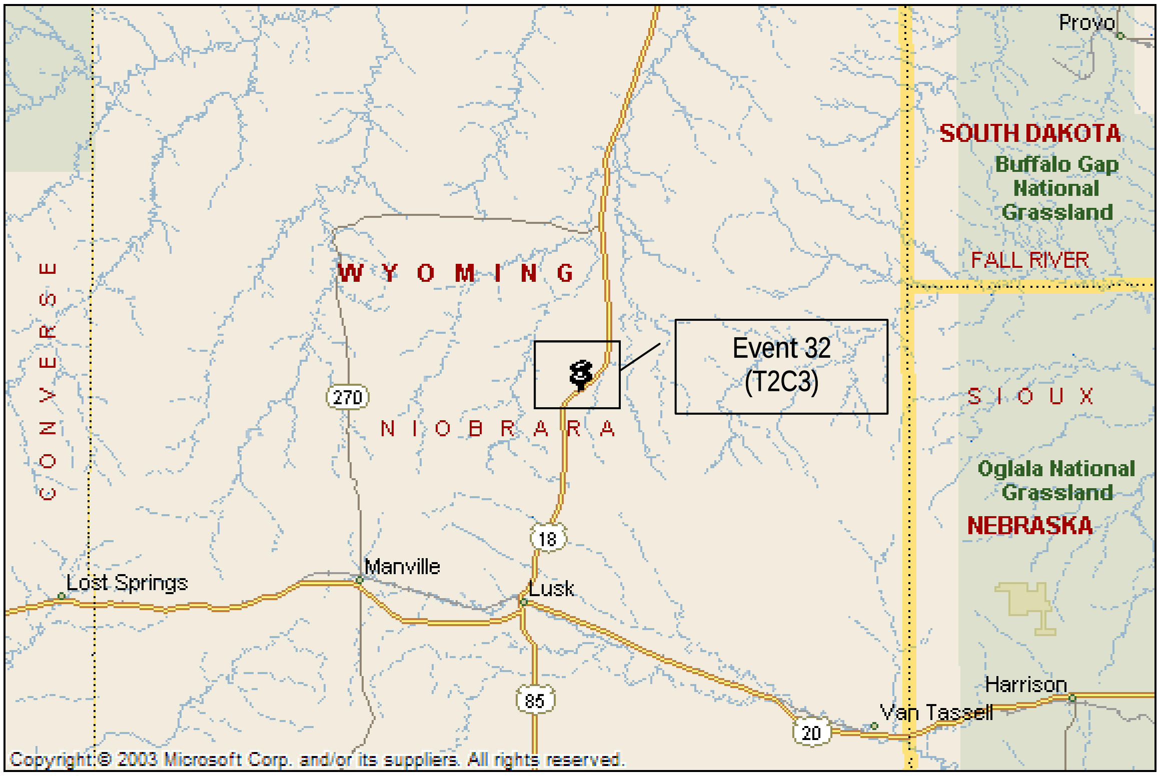
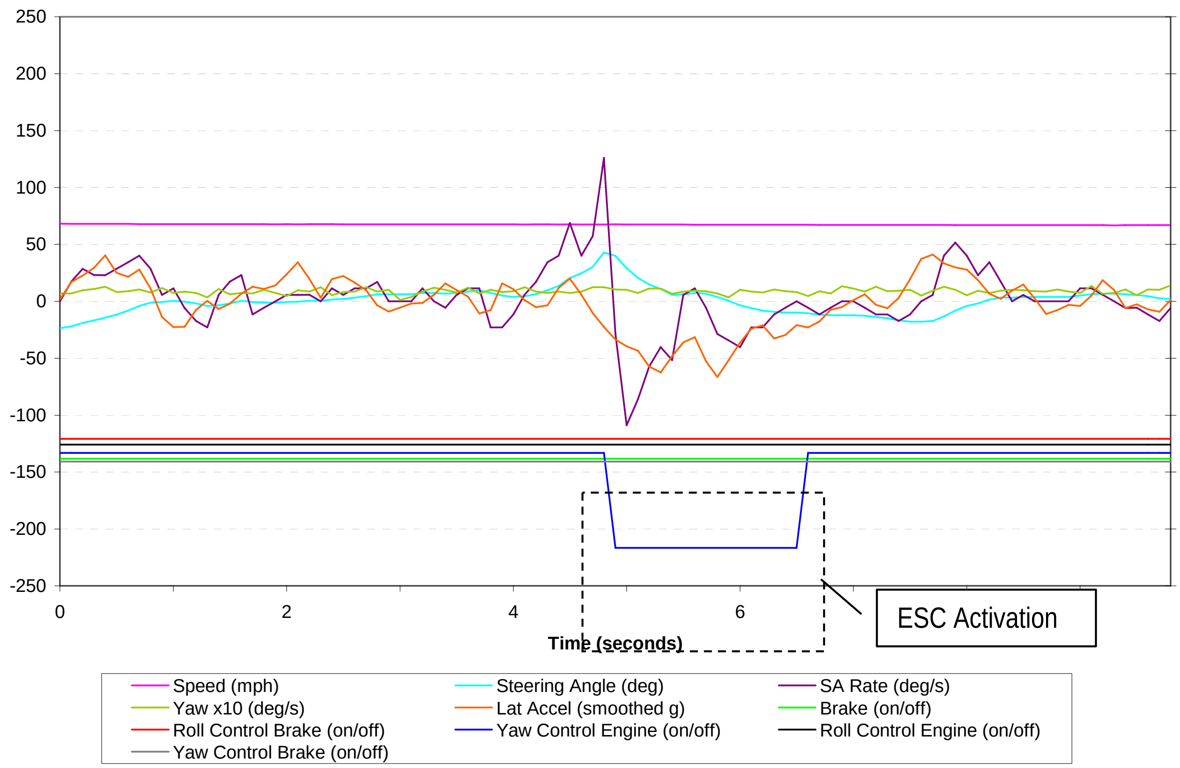


Exhibit 5-52 shows a close-up of event on State Route 85 at the point of ESC activation. As shown, the activation occurred along a straight stretch of highway.

Exhibit 5-52: GPS Data for Yaw-Only Event T2C3-32 (3-mile view)

Exhibit 5-53 shows the engineering data on Event 32. The ESC activated on April 3, 2006, at 6:46:23 p.m. The ambient temperature was 73 degrees Fahrenheit. The tractor was traveling 67 miles per hour, the cruise control was off, and a forward target was not detected. At the beginning of the event, lateral acceleration and steering angle rate were at approximately zero. Yaw had a steady value of 1.2 degrees per second throughout the 10-second recording. At 4 seconds, the steering angle rate and lateral acceleration began to increase. At 5 seconds, the steering angle rate peaked at 126 degrees per second and the lateral acceleration was 0.2g. The yaw control engine signal activated at this time for 1.5 seconds. After the activation, all signal values returned to zero. No roll control event was triggered. The vehicle speed did not change as a result of the event.

Exhibit 5-53: Signal Graph - Yaw-Only Event 32 (T2C3 – Driver D46)



ESC Event T3-37

Exhibit 5-54 shows ESC Event 37 occurred east of New Castle, Colorado, approximately 120 miles west of Denver on Interstate 70.

Exhibit 5-54: GPS Data for Yaw-Only Event T3-37 (30-mile view)

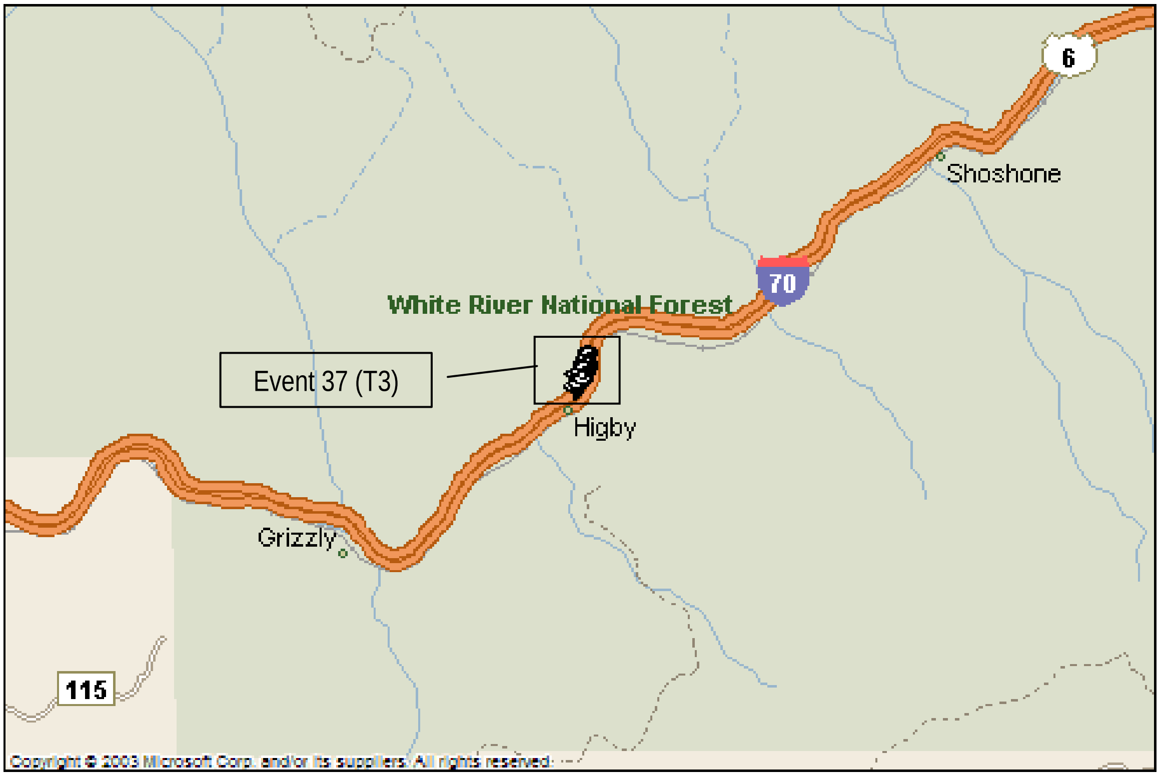


Exhibit 5-55 shows a close-up of the event on Interstate 70 at the point of ESC activation. As shown, the activation occurred while traveling south on Interstate 70 outside of Shoshone, Colorado. The vehicle was negotiating a section of highway curving towards the right.

Exhibit 5-55: GPS Data for Yaw-Only Event T3-37 (3-mile view)

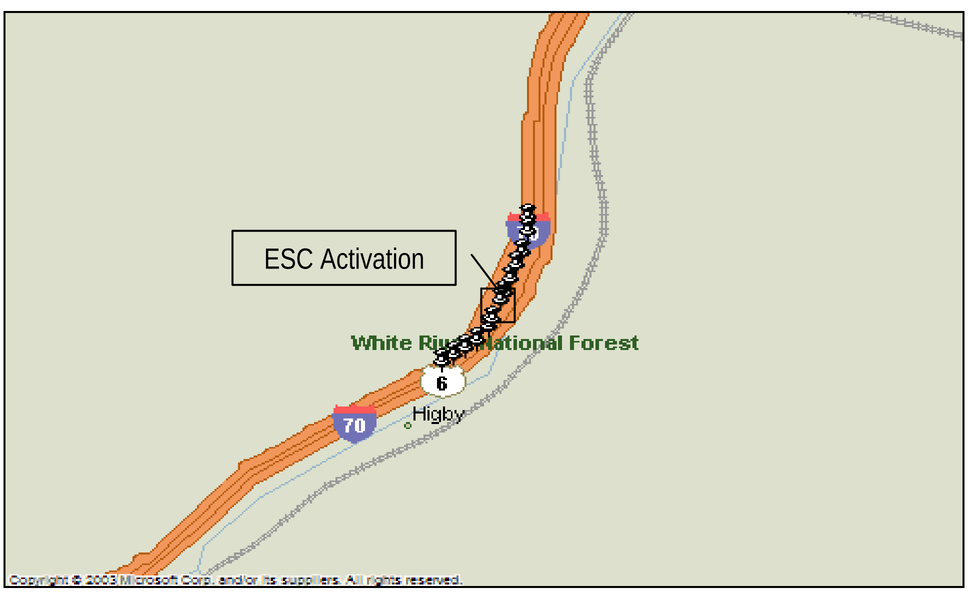
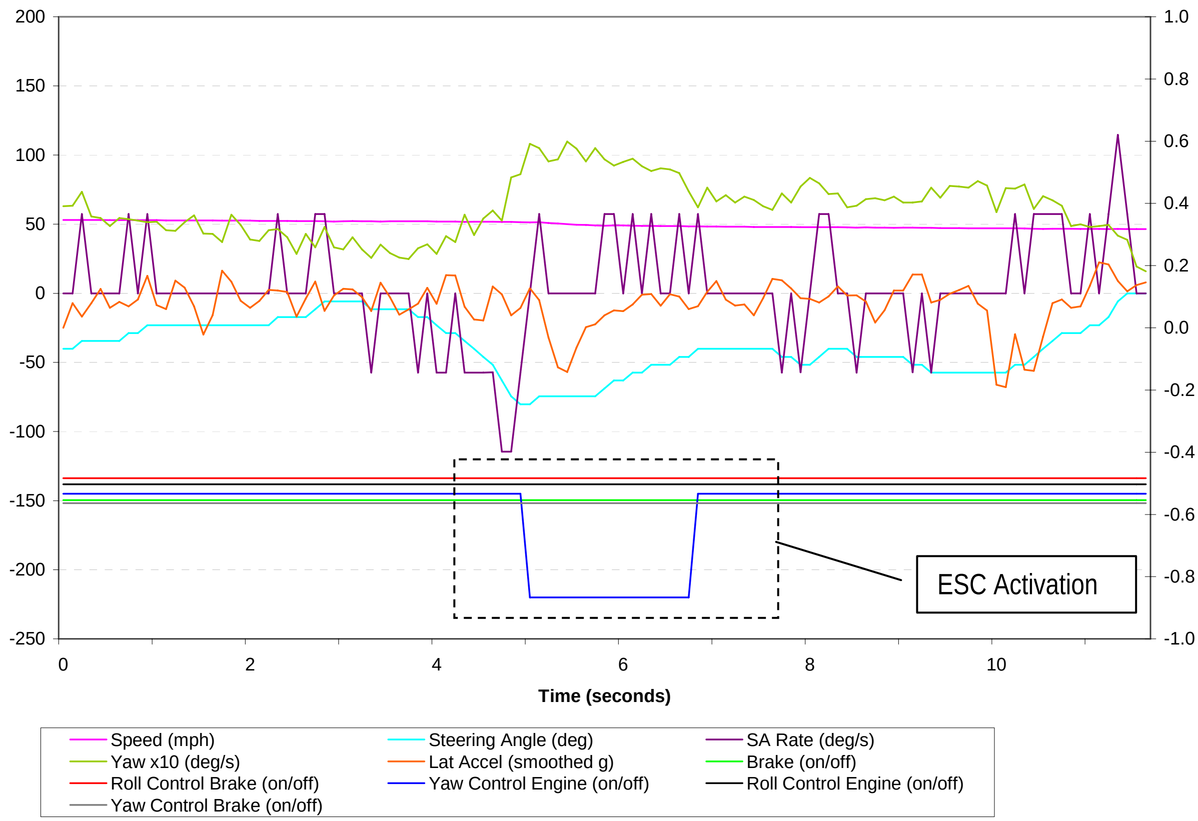


Exhibit 5-56 shows the engineering data on Event 37. The ESC activated on February 4, 2006, at 8:51:50 p.m. The ambient temperature was 35.6 degrees Fahrenheit. The tractor was traveling at 53 miles per hour, the cruise control was off, and a forward target was not detected. The trailer was not equipped with ECBS. The recording started with a yaw value of 5.6 degrees per second, but did not trigger an ESC activation. At 2 seconds, the lateral acceleration reached 0.18g. At 4.7 seconds, the steering angle rate of change peaked at 114 degrees per second, but the lateral acceleration and yaw were below 0.03g and 5 degrees per second. At the 5-second mark, the yaw control engine signal was activated for 2 seconds. The signal was activated to coincide with a maximum yaw value of 10 degrees per second. The activation did not coincide with any peak values for lateral acceleration or steering angle rate of change. Lateral acceleration reached a second peak of 0.2g at 10 seconds, but it did not coincide with a high steering angle rate of change. The activation reduced the speed of the vehicle by 6 miles per hour. The roll control signal was not activated during the ESC event.

Exhibit 5-56: Signal Graph - Yaw-Only Event 37 (T3 – Driver D35)

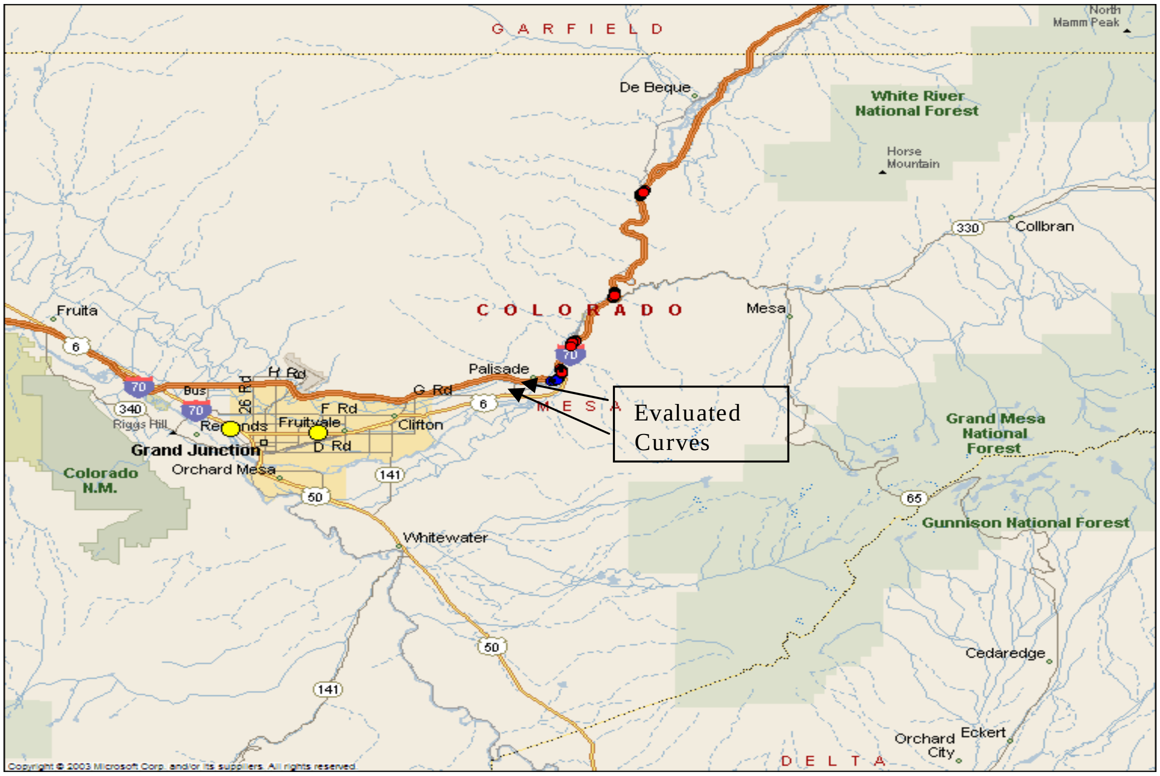


5.5 Driver Reaction to ESC

The previous section detailed some of the 51 ESC activations during the FOT. Of particular interest is to find out whether the presence (and activation) of a stability control system affected drivers' behavior. To determine the effect of the stability control system on drivers, the speed through curves was analyzed.

As shown previously, and detailed in Exhibit 5-57, a mountainous section of I-70 in Colorado saw a significant number of ESC activations. Over that stretch of highway, at least seven ESC activation events occurred in the FOT. This section of highway is clearly an area of interest that can be used to quantify any behavioral change in the drivers. The study focused on a stretch of highway less than a mile long with two curves where ESC activation occurred.

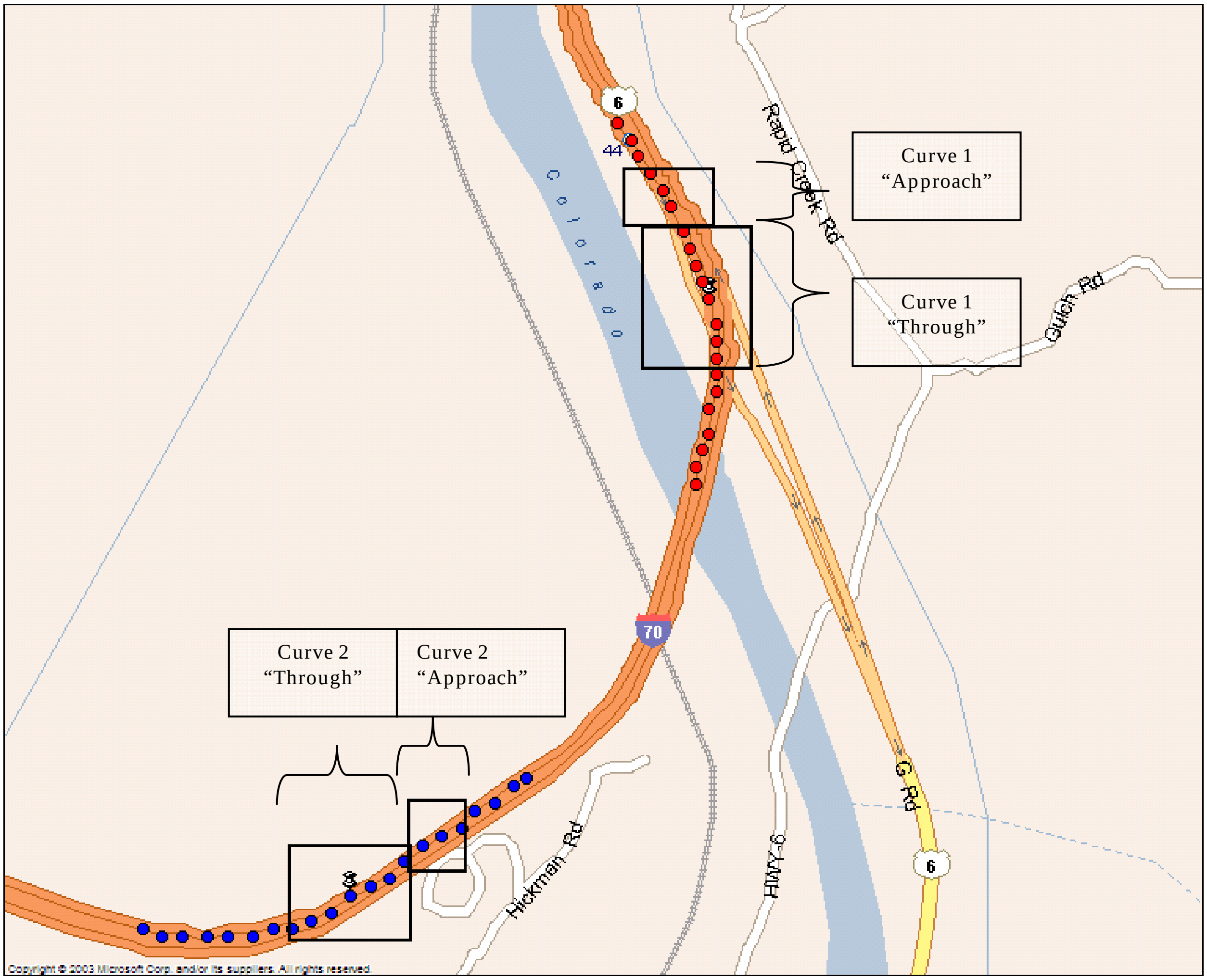
Exhibit 5-57: Location of Curve Evaluation



The two curves selected are less than one-half mile apart. Since all ESC activation events on these curves occurred while the trucks were traveling westbound, only westbound trucks were considered for the analysis. Exhibit 5-58 shows in more detail the curves selected for analysis.

Each curve was assigned a geographical box representing the approach to the curve and a box representing the actual curve. The approach to the curve was defined as having a length of approximately 250 feet, starting 500 feet before the curve. The “through” box was defined as having a length of approximately 600 feet, centered about the point of ESC activation. The end of the “approach” box was made to coincide with the beginning of the “through” box.

Exhibit 5-58: Geographic Boxes Used for Speed Analysis



The database was searched to find all instances when tractors in the T2C3 and T3 Templates (both ECBS equipped) traveled through these curves. Over 1,700 such events were identified. The average "approach" and "through" speed of all tractors was calculated within each of the four boxes.

Exhibit 5-59 Average Speed Through Curve

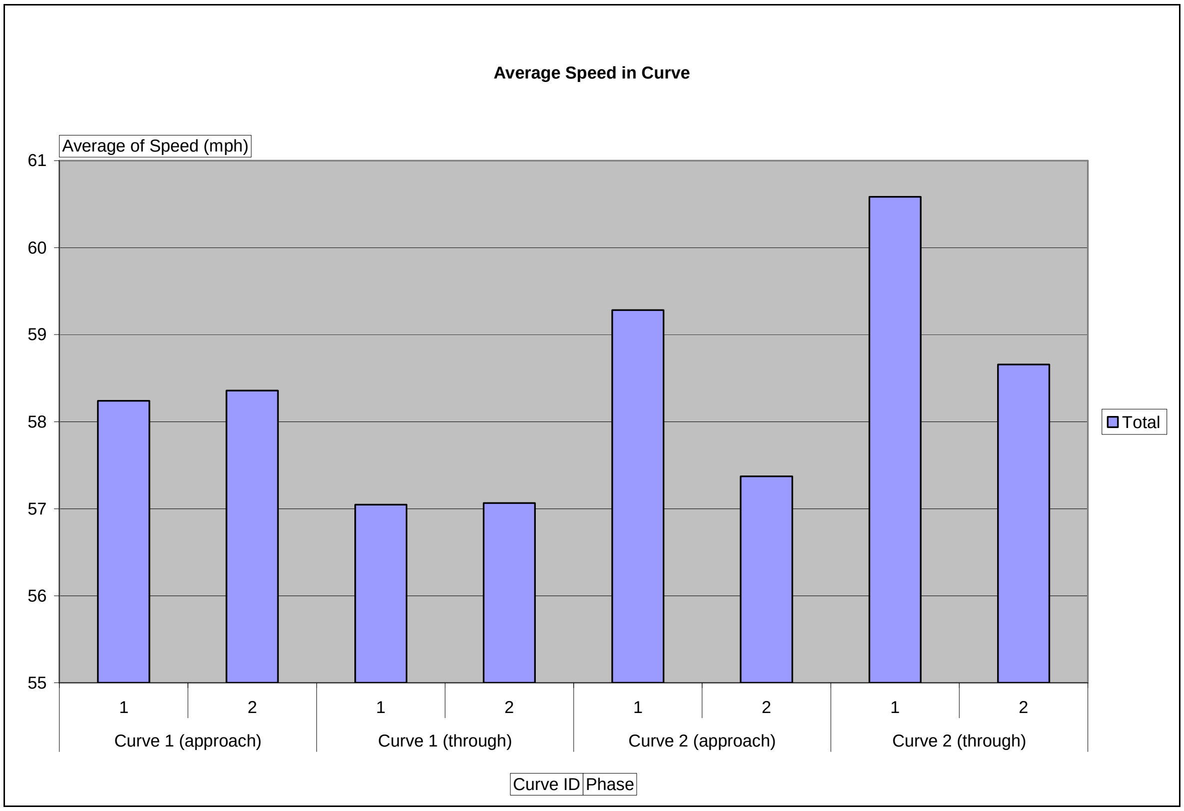
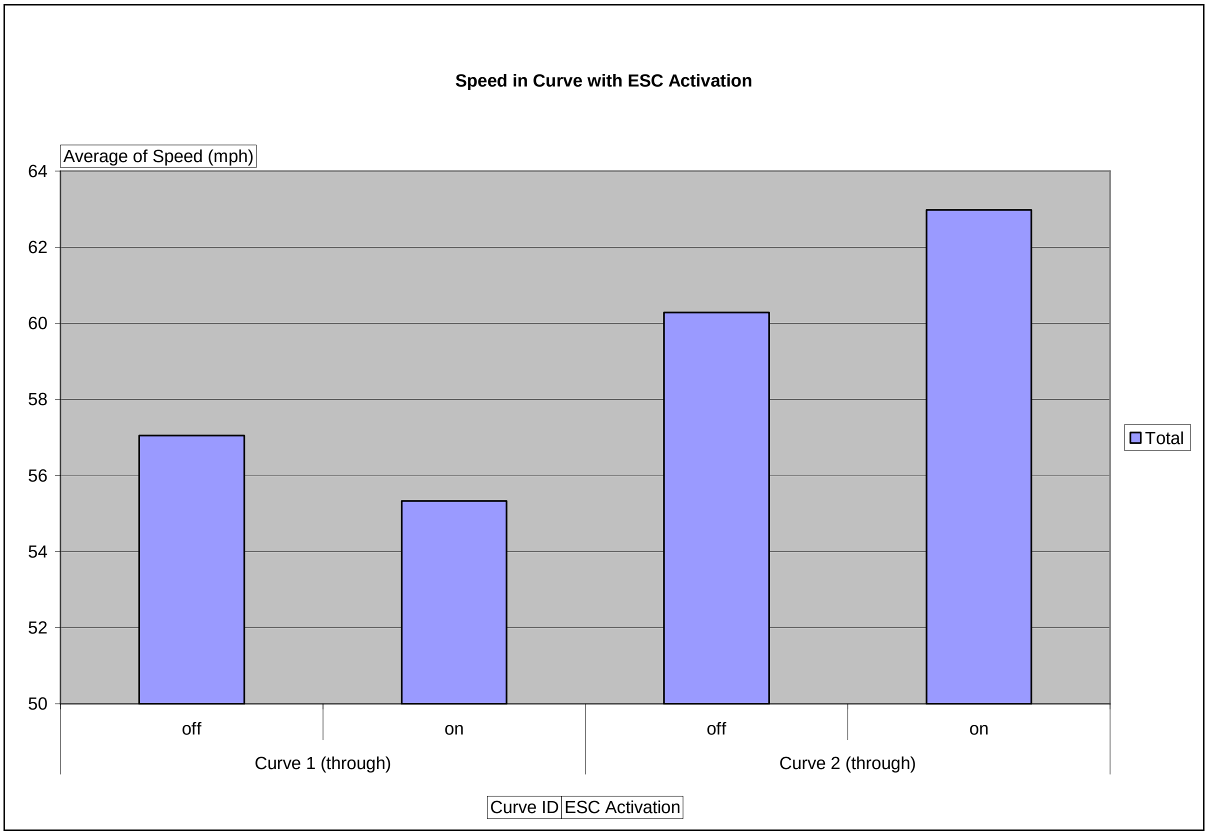


Exhibit 5-59 shows the results of the first analysis. As can be seen, there is little difference in speed between Phase 1 and Phase 2 in Curve 1. Curve 2, on the other hand, shows a slight but noticeable decrease in speed during Phase 2 of the FOT. It is difficult to attribute the decrease in speed as a result of ESC presence during Phase 2. The driver has no audio or visual signal of the presence of ESC until the system responds to an unsafe condition.

Exhibit 5-60: Speed During ESC Activation



It is interesting to note that the speed at which ESC activated during each curve is not necessarily higher than the average speed. In fact, as Exhibit 5-60 shows, the speed at which ESC activated in Curve 1 is approximately 2 miles per hour slower than the average speed through that curve. Although not known from data collected, it is reasonable to assume that other factors, particularly the trailer load, played an important role in causing the ESC to activate. In contrast, ESC activation in Curve 2 occurs while the truck is traveling approximately 3 miles per hour faster than the average speed through that curve. In this scenario, it is possible that the increased speed is the dominant factor affecting ESC activation.

From data shown above, the presence of ESC seems to have no discernable effect on driver's behavior with respect to speed in curves. Other factors, such as the actual trailer load, may play a large role in dictating a driver's speed through a given curve. Although safety benefits could not be accurately quantified with these data available, it is reasonable to assume that the benefits of operating tractors equipped with ESC will be gained from actual ESC intervention, and not from a change in driver's behavior.

CHAPTER 6. ADAPTIVE CRUISE CONTROL

6.1 System Overview

Conventional cruise control (CCC) regulates vehicle speed. The driver selects a vehicle speed and the system will maintain the selected speed by regulating engine power. This system is unable to apply brakes (foundation or engine brakes) to prevent the vehicle from accelerating past the selected speed in downhill sections of roadways. The CCC is available only at speeds greater than 20 miles per hour.

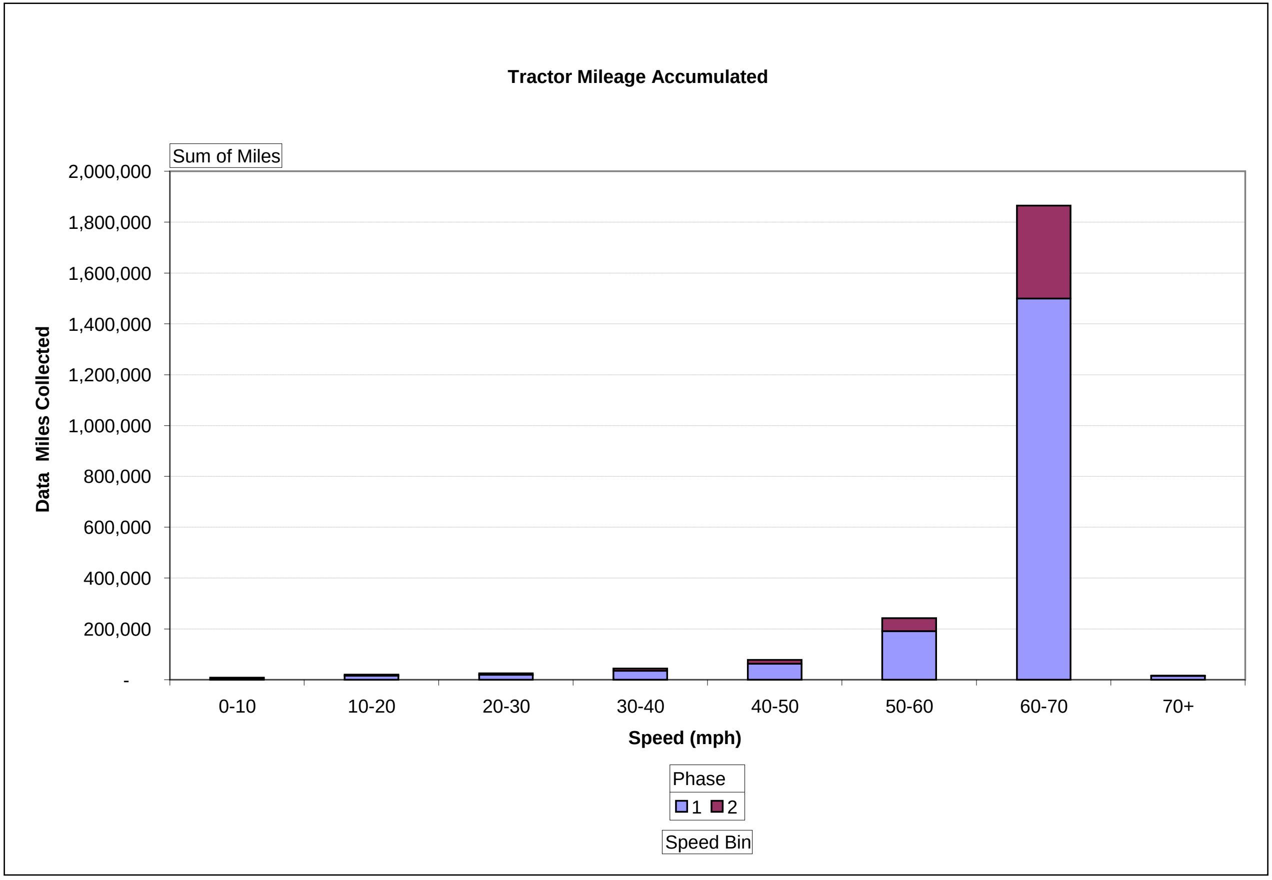
Tractors in the FOT were also equipped with MeritorWabco's adaptive cruise control (ACC) with collision mitigation system (CMS), which was not commercially available at the time of the FOT. MeritorWabco's ACC is designed to maintain a safe following interval to the preceding vehicle. ACC works like CCC when there is no vehicle within the specified following interval ahead of the host vehicle. If a vehicle is within the specified interval, the system uses a radar sensor to track the forward vehicle's speed, range, and bearing and uses sophisticated software to determine whether the target vehicle is in the same lane. To maintain a safe interval, the ACC can control the throttle, engine brake, and foundation brakes to vary the distance between the vehicles. The sensor range is 400 feet and is available between 10 and 65 miles per hour. In addition to headway monitoring, MeritorWabco's system features a CMS. The system assists the driver in avoiding collisions by autonomously applying the foundation brakes when a time to collision threshold is reached. CMS is capable of decelerating the tractor at 0.25g.

While the driver is required to select a target vehicle speed, the system is preprogrammed to maintain a minimum following interval of 3 seconds. ACC activates the engine brake or foundation brakes in order to maintain this following interval.

6.2 Summary of Driving Experience With ACC

As expected with the type of service that the FOT tractors perform, most of the mileage accumulated occurred at high speeds on rural highways (further discussion on the type of service encountered during the FOT can be found in Chapter 4: Metadata). Exhibit 6-1 shows the total mileage accumulated during each phase at different speeds. Clearly, the high mileage accumulated at high speeds suggests that cruise control use (both conventional and adaptive) could be high.

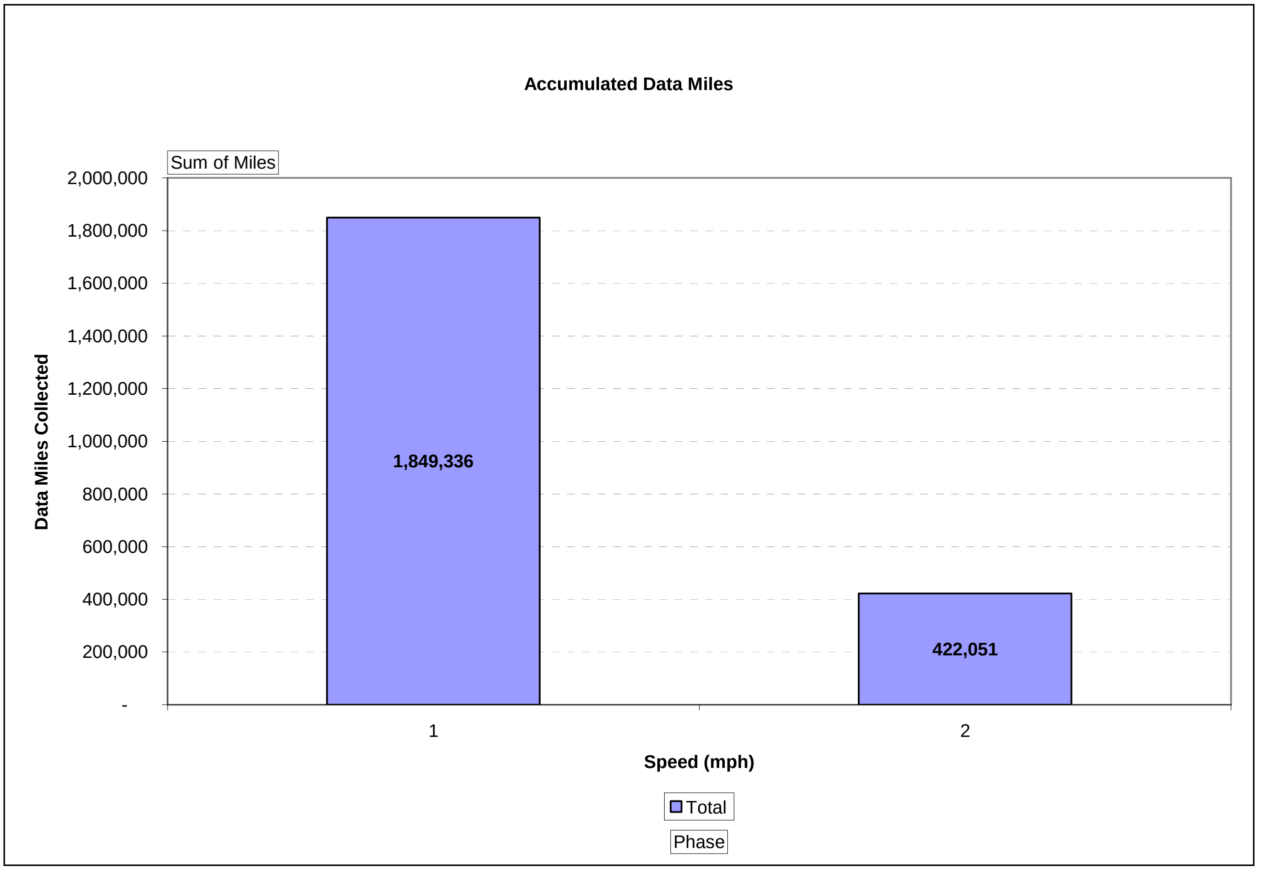
Exhibit 6-1: Data Miles Accumulated by Speed



The following sections of this report provide a detailed discussion of the usage pattern of cruise control. In addition to ACC and CCC usage patterns, changes in driving behavior are observed when ACC is available but not used. As will be demonstrated in the next section, ACC was well accepted by the drivers, and its use grew compared to that of CCC. Safety benefits from the use of ACC are discussed at the end of this chapter (Section 6.6).

Note that due to data acquisition problems, the starting date for Phase 2 was March 23, 2006. Although ACC was available to the drivers starting January 1, the DAS was not able to differentiate between CCC and ACC usage for the first three months. Because of this limitation, all cruise control usage recorded from January through March 23 was treated as Phase 1, CCC usage. Throughout this chapter, the Phase 2 starting point is defined as March 23, 2006. Exhibit 6-2 illustrates the disparity in mileage collected between Phase 1 and Phase 2. Phase 1 collected four times as many miles as Phase 2.

Exhibit 6-2: Accumulated Miles by Phase



6.3 Usage Rate

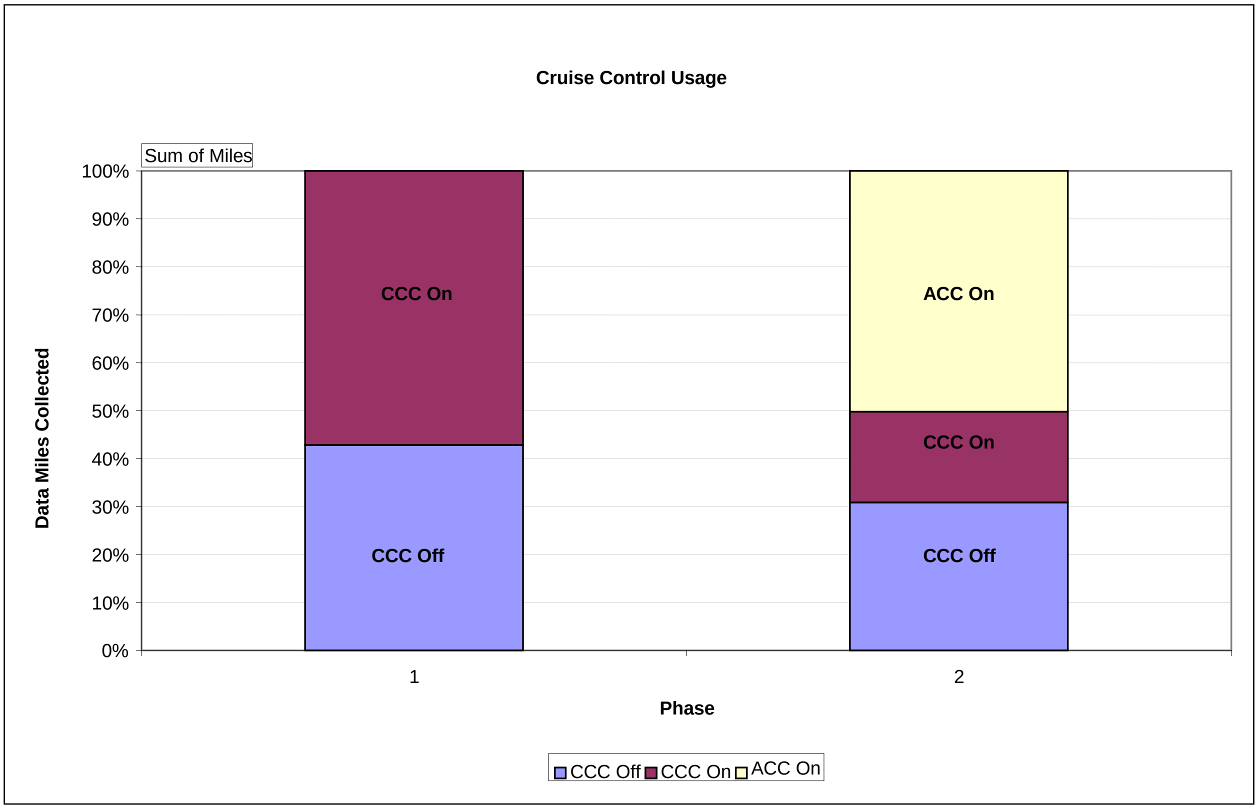
The following sections explore how often cruise control is used and whether ACC is used in a different manner than conventional cruise control. Observing how and when drivers choose to use each type of cruise control will help identify strengths and weaknesses of the new system.

6.3.1 Overall Usage

Phase 1 usage rate of conventional cruise control is expected to provide a baseline of the expected usage rate. Since tractors in the FOT were expected to operate mainly in rural highways, cruise control usage was expected to be high.

As illustrated in Exhibit 6-3, during Phase 1, almost 60 percent of data miles were accumulated with conventional cruise control (CCC) active. The proportion of overall cruise control usage grew during Phase 2. In fact, during Phase 2, total cruise control usage increased to about 70 percent (ACC approximately 50%, CCC approximately 20%) of the total miles. As will be shown later, Exhibit 6-3 under-represents the rate for ACC usage. In fact, the true usage rate for ACC may be closer to 60 percent. The shift in usage pattern when ACC is available will be explored throughout this section.

Exhibit 6-3: Cruise Control Usage Rate



Data in Exhibit 6-4 illustrates the overall rate for cruise control usage grew from 57 percent to over 69 percent in Phase 2. Assuming that CCC was used under similar conditions in Phase 2 as was used in Phase 1, the 12-percent growth observed may be attributed to new usage caused by ACC. In other words, in addition to replacing some of the CCC usage, ACC has replaced some of the manual driving. The new behavior is likely attributed to drivers fully utilizing the ACC system's capabilities to deal with traffic. Drivers may use ACC during periods of heavy or moderate traffic when CCC use is impractical.

Exhibit 6-4: Cruise Control Usage

	Phase 1	Phase 2
CCC On	1,056,979 (57.1%)	79,698 (18.9%)
CCC and ACC Off	792,356 (42.9%)	130,294 (30.9%)
ACC On	n/a	212,060 (50.2%)
Total	1,849,336	422,051

Exhibit 6-5: Cruise Control Use by Month

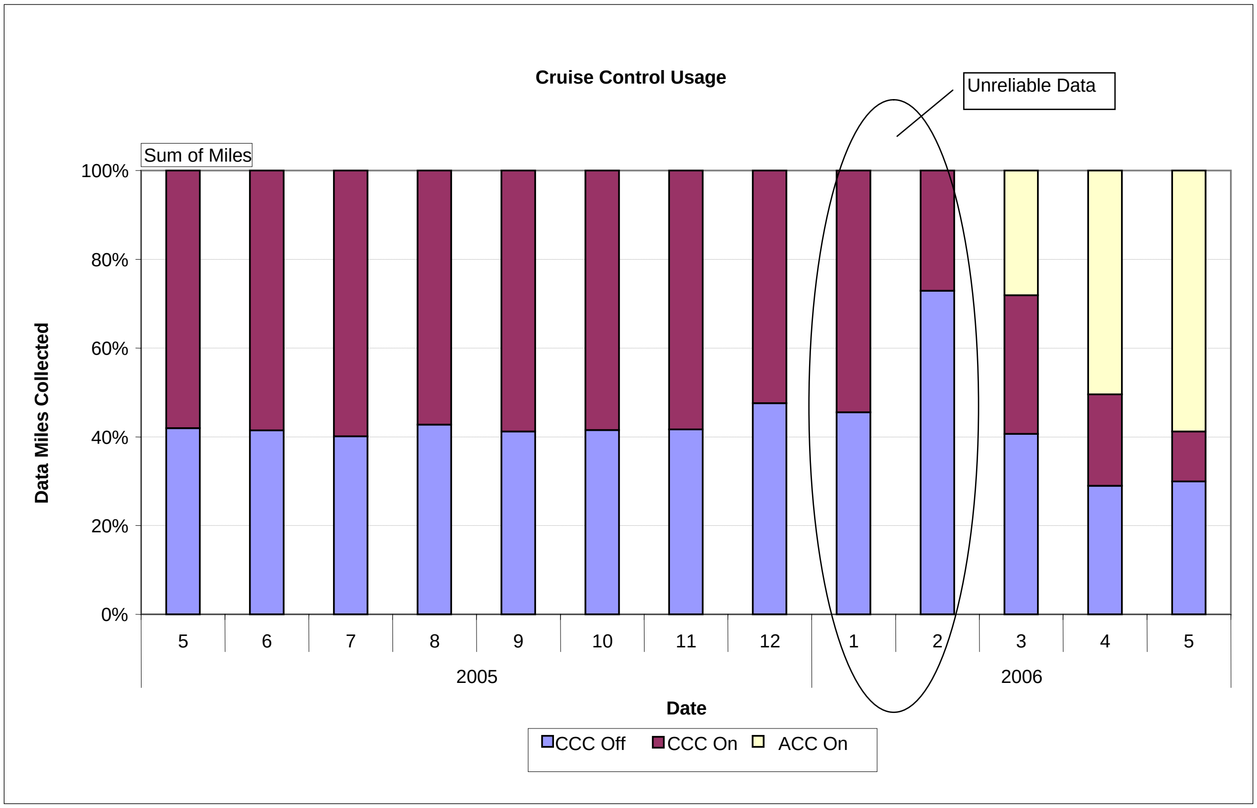
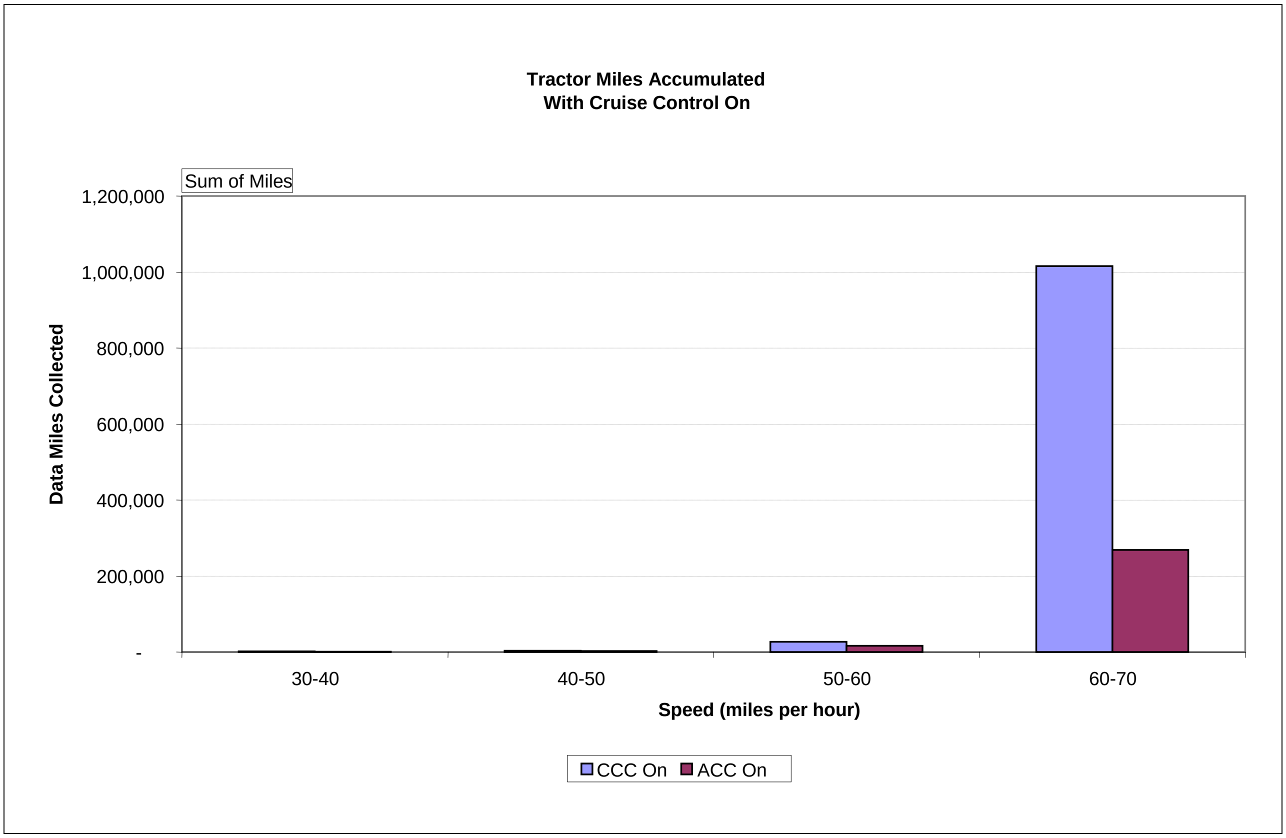


Exhibit 6-5 shows the pattern of use throughout the FOT. From data available (starting March 23, 2006), immediate adoption of ACC is clearly evident. The share of ACC usage grows to over 50 percent immediately. Note that ACC usage for March 2006 is underrepresented as only eight days of the month have accurate ACC data. Despite this limitation of data, the eight days of ACC usage account for approximately 25 percent of all mileage accumulated that month. Data for the last two months of the FOT suggest that the true rate of ACC usage may be closer to 60 percent. Due to data acquisition problems, the true proportion for earlier months cannot be accurately measured.

These data presented above are helpful in determining the level of acceptance of ACC by the drivers. Unfortunately, it does not provide us with accurate data for the January through March timeframe and, therefore, does not accurately measure how quickly the system was embraced by the drivers. Recall that ACC is available to the drivers starting January 2006; however, the first three months of usage is not recorded accurately and was not counted toward ACC usage. Knowing the usage pattern for the first three months would add valuable information to measure the acceptance of the system by the drivers. Section 6.4.2 provides further discussion on this issue. The usage of ACC continues to grow into months four and five. The proportion of CCC usage declines during Phase 2, providing further evidence that the drivers are embracing the new system and show preference of it over CCC. These data suggest that drivers prefer to use ACC over CCC once they are accustomed to it.

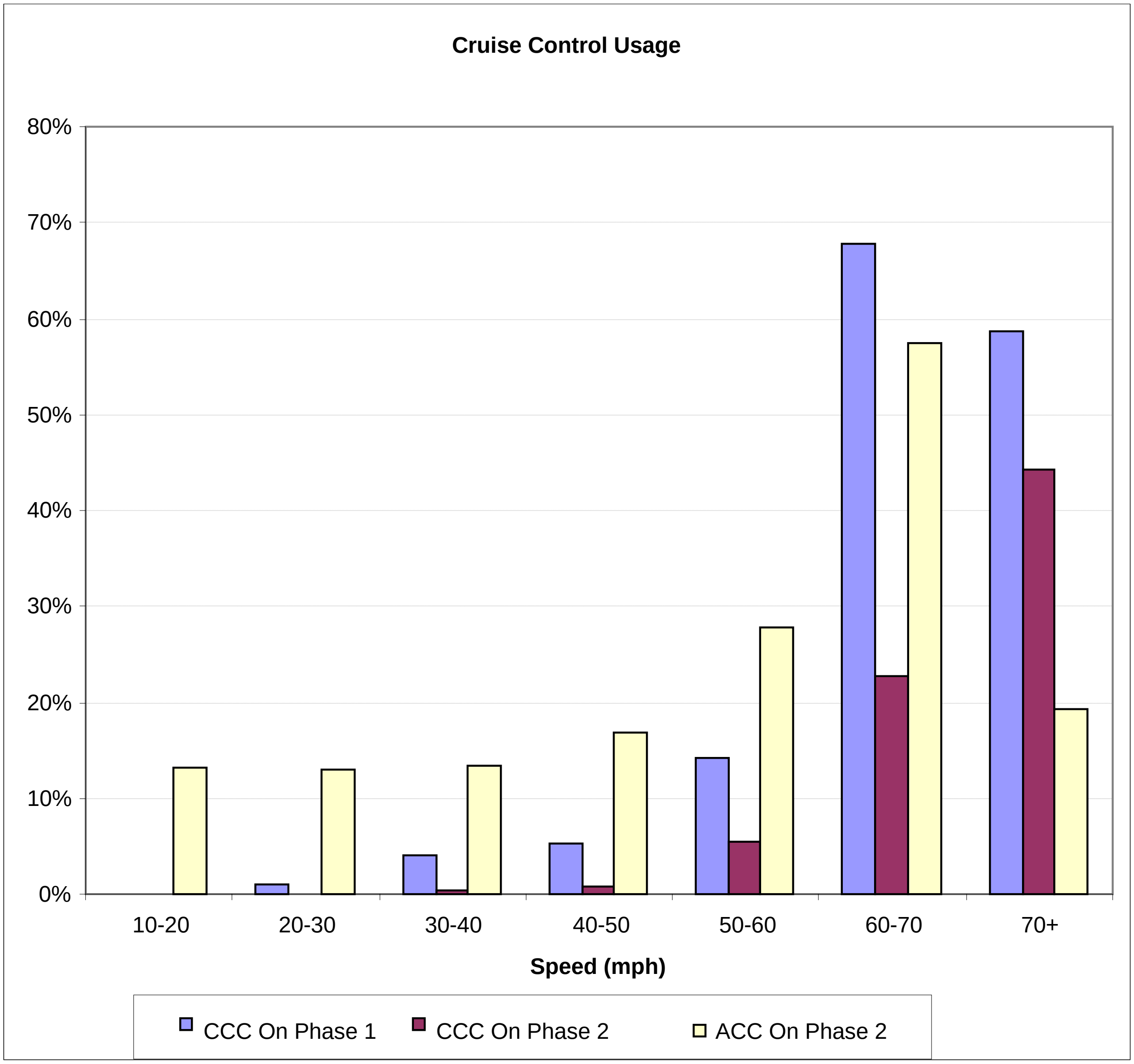
Exhibit 6-6: Cruise Control Usage by Speed



As expected, most cruise control usage occurs at higher speeds. Exhibit 6-6 shows the impact of speed on cruise control usage. Not surprisingly, Phase 1 shows much higher mileage accumulation. Recall that Phase 2 accounts for only one-fourth of the miles of Phase 1.

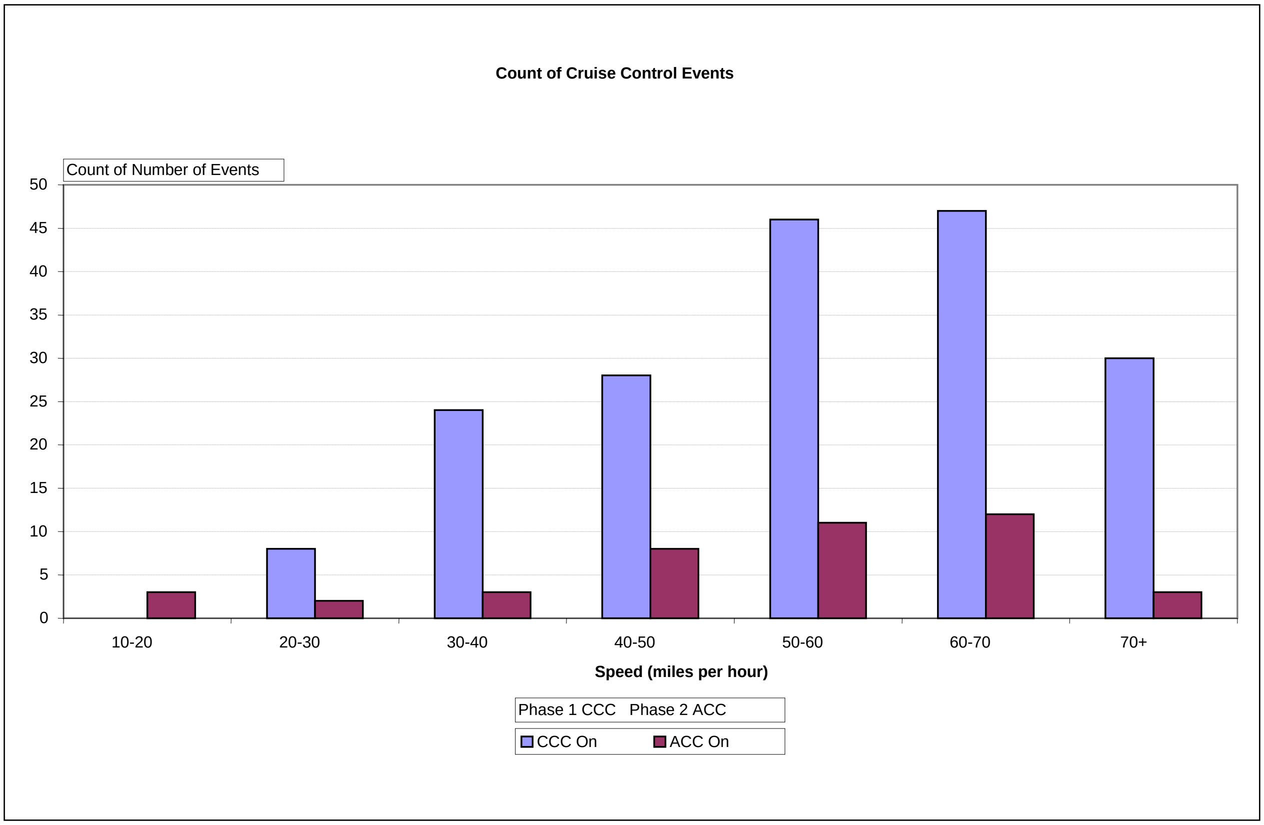
It was suggested that the FOT would show an increase in cruise control usage during Phase 2 due to the availability of ACC. ACC provides drivers with the possibility of using cruise control at lower speeds (and likely heavier traffic) compared to CCC. ACC usage at lower speeds was expected to be significantly higher than CCC usage. Exhibit 6-7 displays the usage pattern of the different cruise control systems across all recorded speeds.

Exhibit 6-7: Cruise Control Usage



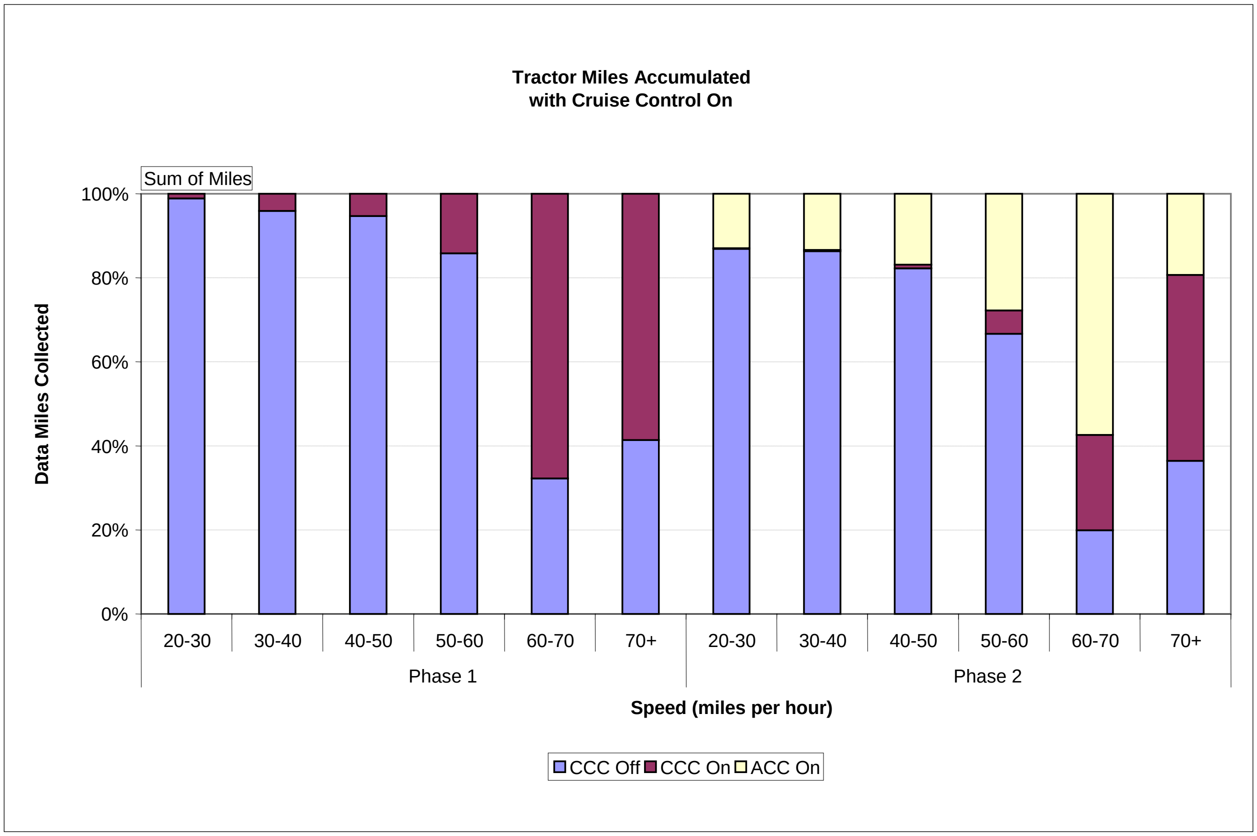
The usage pattern is strikingly different at lower speeds. This result was somewhat expected due to the additional functionality of the ACC system. At speeds below 50 miles per hour, when CCC usage is practically zero, ACC usage accounts for approximately 15 percent of all mileage accumulated. Cruise control use of either system at higher speeds follows a similar pattern. The high usage rate for any cruise control at high speeds indicates that the trucks were likely exposed to low traffic condition in rural highways. Note that the exhibit above is based on mileage traveled at each speed. It does not take into account time spent at each speed. Further examination of these observations is illustrated in Exhibit 6-8.

Exhibit 6-8: Cruise Control Activation



A count of cruise control activations reveals a similar trend from the previous observation. At low speed, cruise control usage count (each "event" is the activation of the system) is low. Recall that less than 3 months of data are available during Phase 2, and 10 months of data are available during Phase 1. All data displayed is total count and not adjusted by total mileage or time. Closer examination of these data is presented in Exhibit 6-9, where it becomes evident that ACC is preferred over CCC at lower speeds, while high-speed usage is similar. Note also that CCC can be expected to have a higher count, because each time the driver applies the brakes, the system is deactivated and must be reset, resulting in an additional instance of a cruise control "event."

Exhibit 6-9: Percent of Cruise Control Usage by Speed



Another examination of the influence of speed on cruise control usage provides further documentation that cruise control is used mostly at high speed, and that ACC is preferred over CCC at low speed. The usage of CCC during Phase 2 is intriguing. As speed increases, so does the proportion of CCC usage. This may be explained by the fact that CCC does not have a programmed maximum speed. ACC, however, has a maximum set speed limit of 65 miles per hour. The observed usage of CCC during Phase 2 at high speed may in fact be due to drivers wishing to use cruise control at higher than allowable speeds for ACC. The fraction of ACC usage displayed for over 70 miles per hour may be erroneous data.

6.4 Following Interval Behavior

6.4.1 Baseline Behavior

The baseline behavior of the drivers with respect to following distance can be determined by their Phase 1 behavior. All events in this section are mined from the database of verified data.

A following event was defined to have a vehicle speed greater than 10 miles per hour, with a target detected in front of the truck for a minimum of 15 consecutive seconds. The event duration was specifically chosen to try to determine the "steady state" following distance and eliminate any short duration events, such as vehicles crossing in front of the truck, that would otherwise shorten the average following interval.

Exhibit 6-10: Average Following Interval – Phase 1

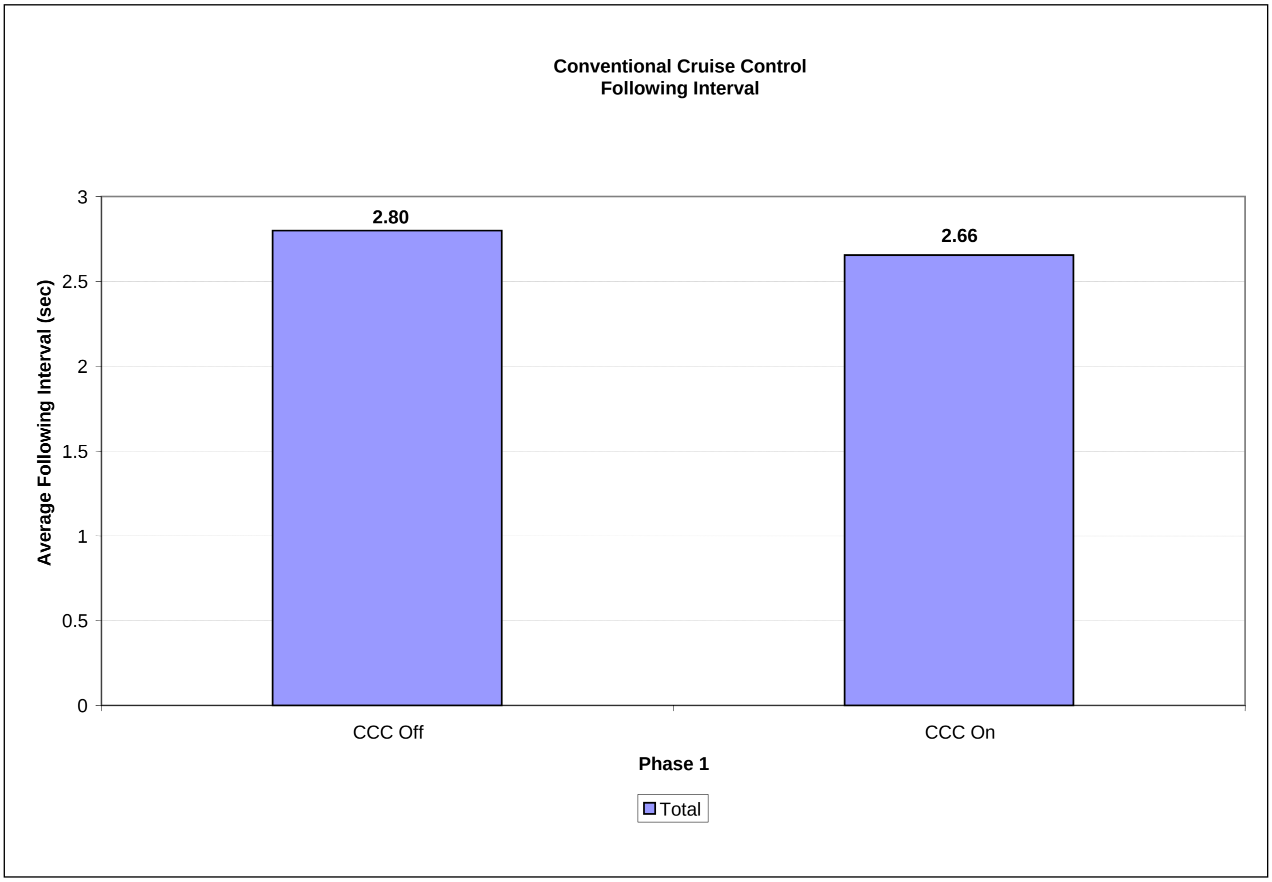
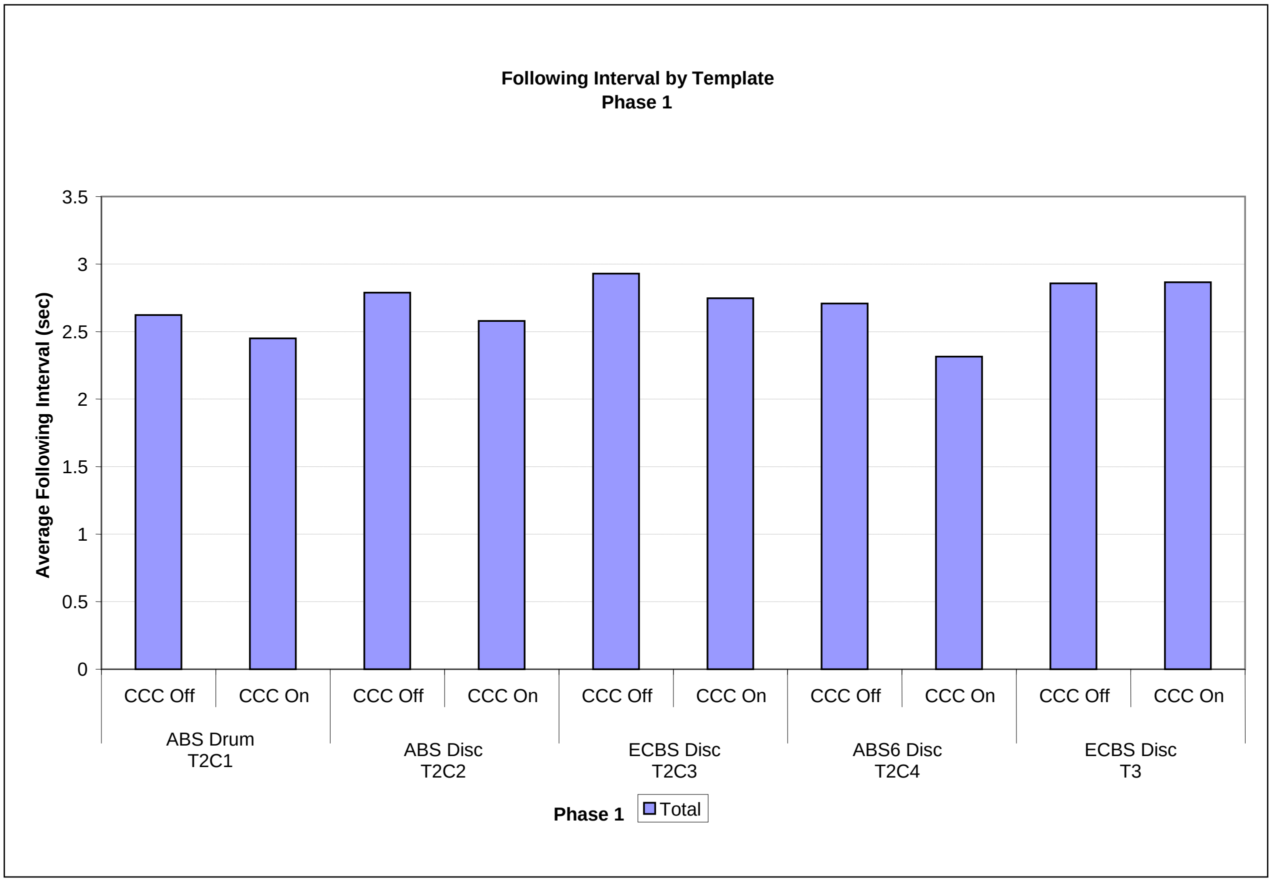


Exhibit 6-10 shows that the drivers not using any form of cruise control system follow at an average interval of 2.80 seconds. Once the CCC is activated, the average following interval decreases to 2.66 seconds. The interval shown in this exhibit represents the average across all templates to remove any possible effect generated by the various braking technologies represented in the FOT. To increase our confidence in the result, the average for each template is calculated in Exhibit 6-11.

Exhibit 6-11: Following Interval by Template – Phase 1

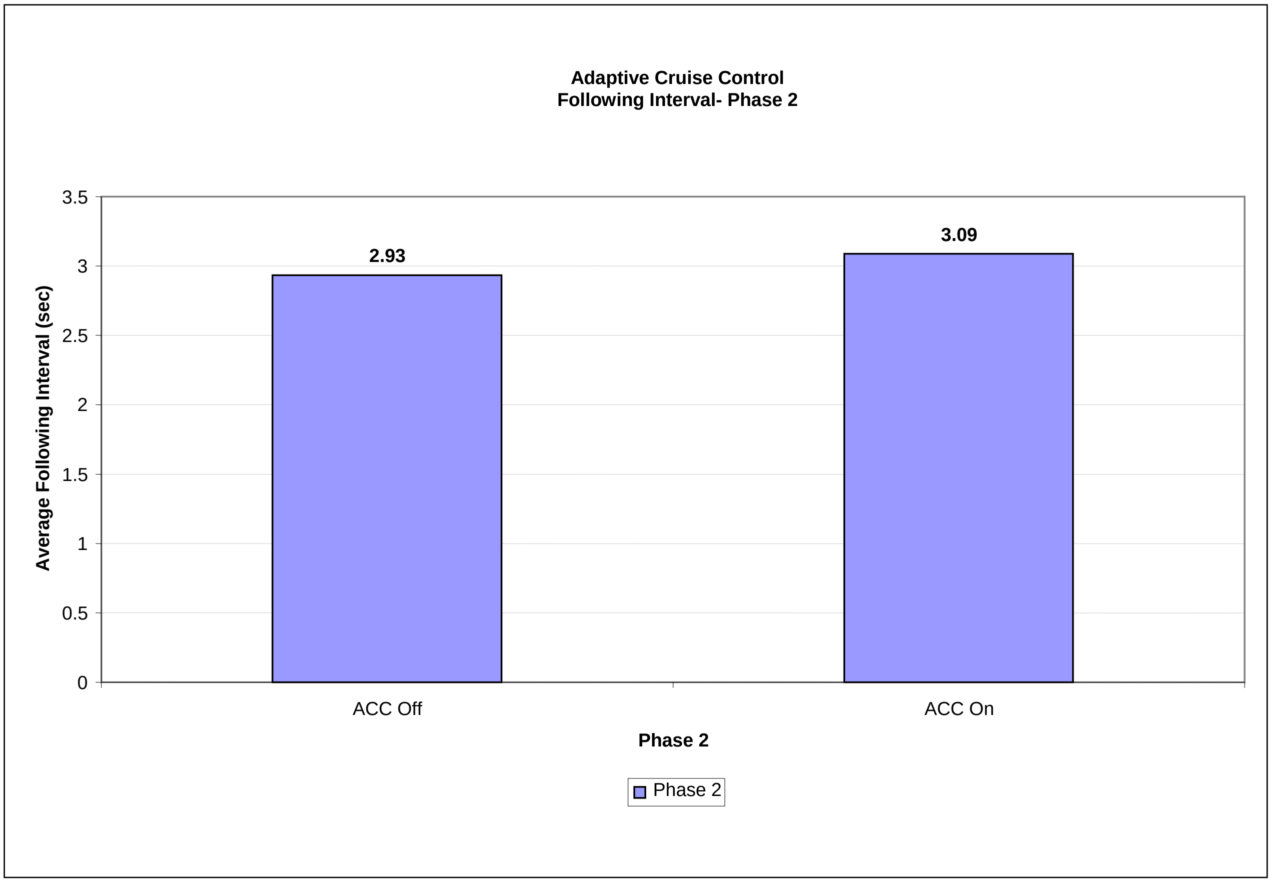


When measured by template, the same pattern is observed—in all but one case, during Phase 1 of the FOT, the following interval is reduced when CCC is used. This is a significant result, meaning that using CCC in effect leads to more hazardous driving conditions. CCC is generally used at high speed and in low-traffic situations (see Exhibit 6-6), so this result appears counter intuitive. Preliminary research to explain this phenomenon shows that the driver disengages CCC (i.e., applies the brakes) only when the following interval is significantly reduced (see appendix on the hypothesis on brake application before disengaging).

6.4.2 Following Interval With ACC

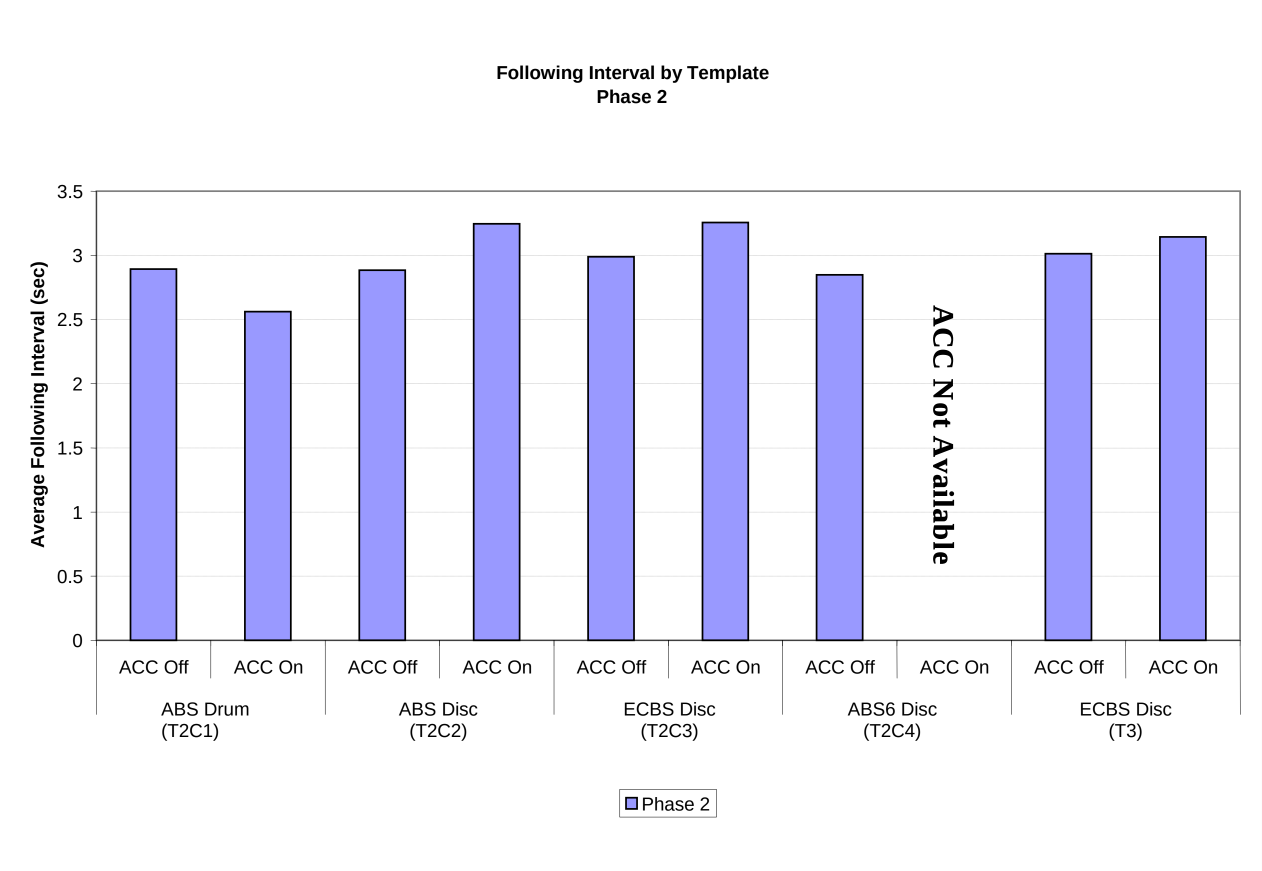
To assess the impact of ACC on following interval, Phase 2 data is used for comparison. The next exhibits discuss the effect that ACC has on following interval.

Exhibit 6-12: Average Following Interval – Phase 2



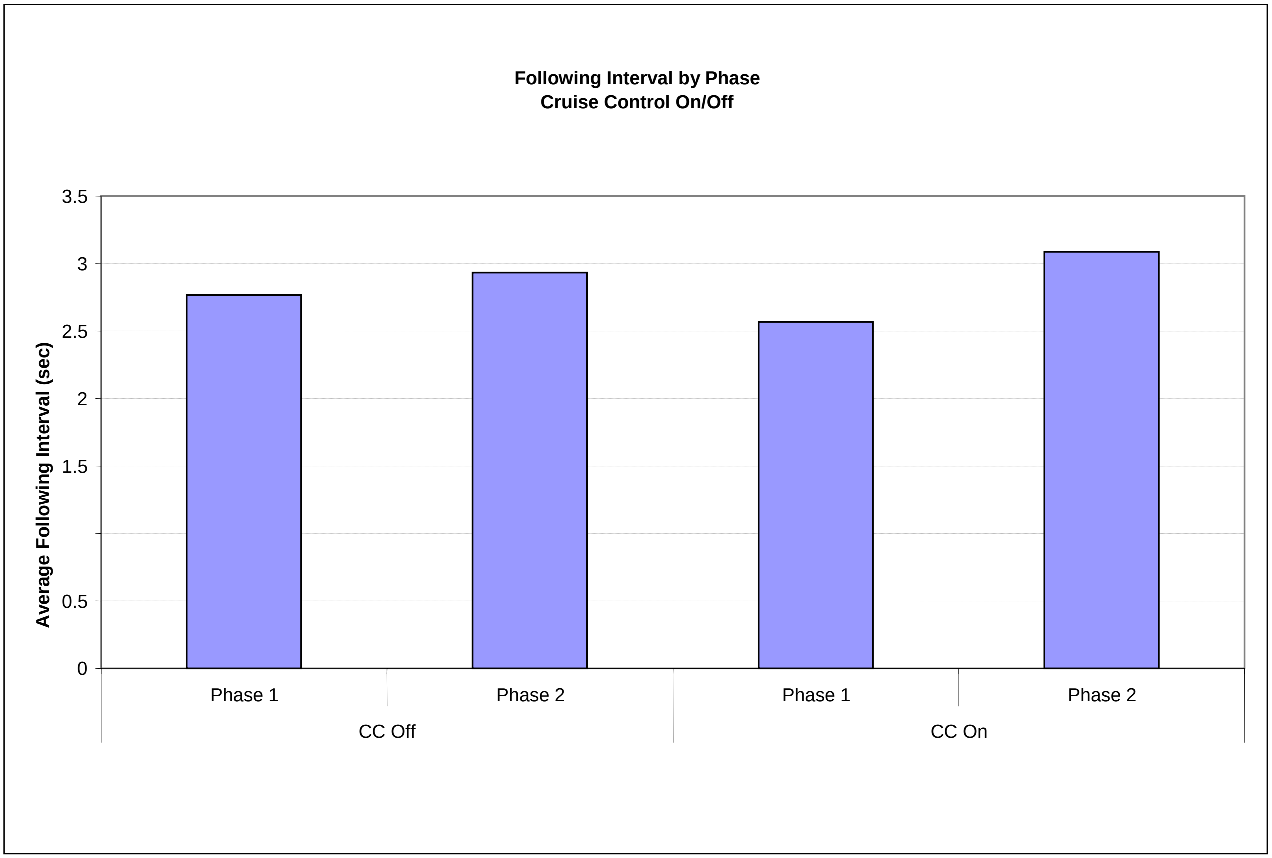
When calculating the following interval during Phase 2, two new patterns are observed. First and most obvious is the fact that, as opposed to decreasing the following interval, using ACC leads to an increase in the following interval. This is not surprising because ACC is programmed to maintain a following interval of 3 seconds, which is larger than the baseline of 2.80 seconds measured during Phase 1. Therefore, using ACC results in a safer driving condition compared to using CCC or to not using any cruise control system.

Exhibit 6-13: Following Interval by Template – Phase 2



Once again, the pattern is examined across all templates. As shown in Exhibit 6-13, the increase of following interval is consistent for all templates except ABS-Drum combination (T2C1). This observation provides further evidence of the increased safety of operating with ACC on. The reason for the T2C1 exception is explored further in this report (see Exhibit 6-17). Although it seems to contradict the overall finding, the reason for the difference is found in the operating duty cycle of these trucks.

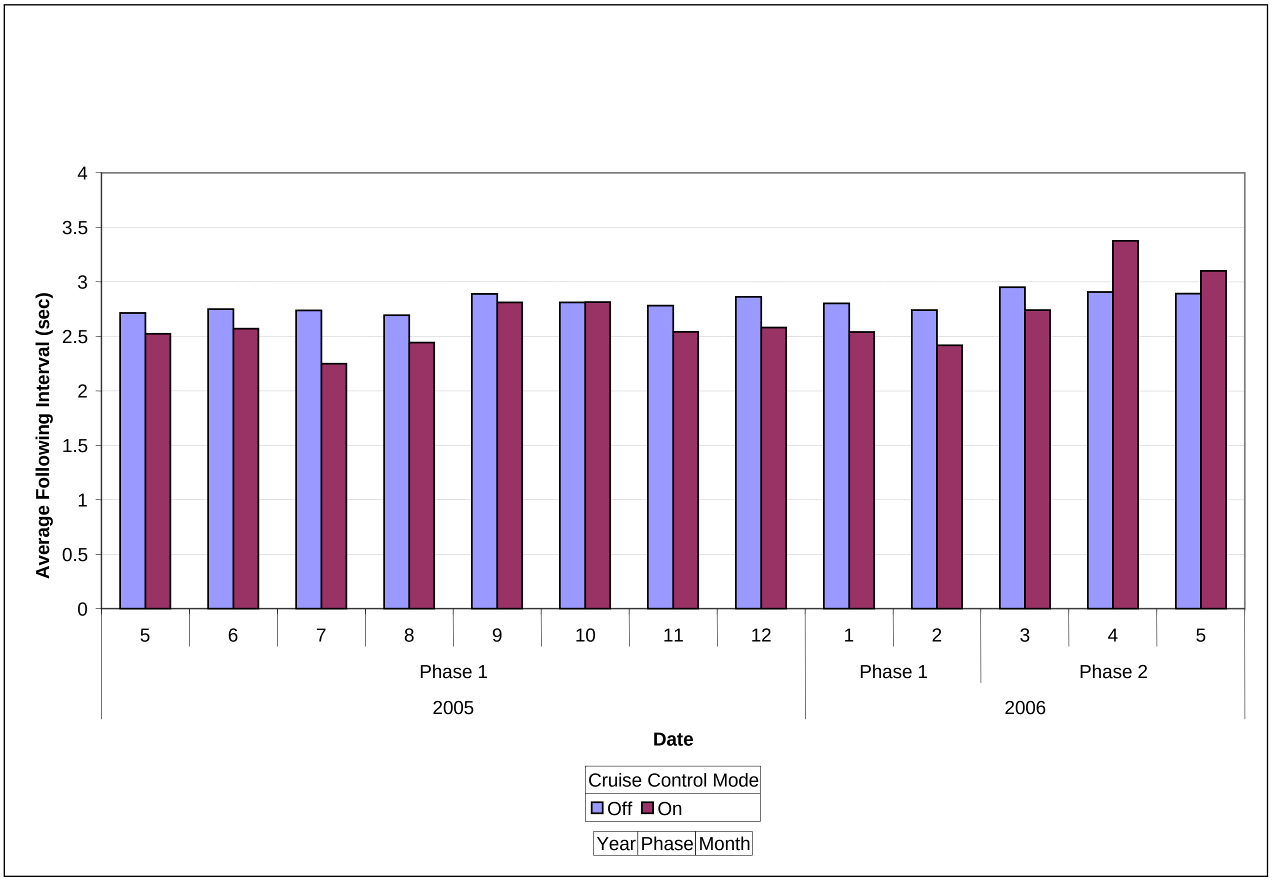
Exhibit 6-14: Following Interval Comparison: Phase 1 versus Phase 2



A second and perhaps more surprising observation is shown in Exhibit 6-14. ACC is observed to increase the following interval compared to the Phase 1 baseline even when the system is off. The following interval when the cruise control system (ACC or CCC) is off is greater in Phase 2 than Phase 1. Recall that during Phase 1 with CCC off, the interval is 2.8 seconds. In Phase 2, with ACC off, there is no reason to suspect an increase in the following interval; however, the interval is actually measured to be 2.93 seconds. This finding suggests that the presence of ACC, even if not active, modifies the driver's behavior. Therefore, in addition to increasing the following interval when ACC is active, the system has the added benefit of improving driver behavior when the system is off. Whether this phenomenon is short lived or long term is explored in the following analysis.

Measuring the change in the following interval throughout the test period is useful to determine how drivers' behavior is impacted as they become more comfortable with each system. No change in driver behavior is expected with respect to CCC usage (Phase 1). CCC is the traditional cruise control system to which they are accustomed, and therefore, it is considered the baseline behavior. Any modification to a driver's behavior due to CCC usage has occurred prior to the start of this FOT.

Exhibit 6-15: Following Interval Through Time

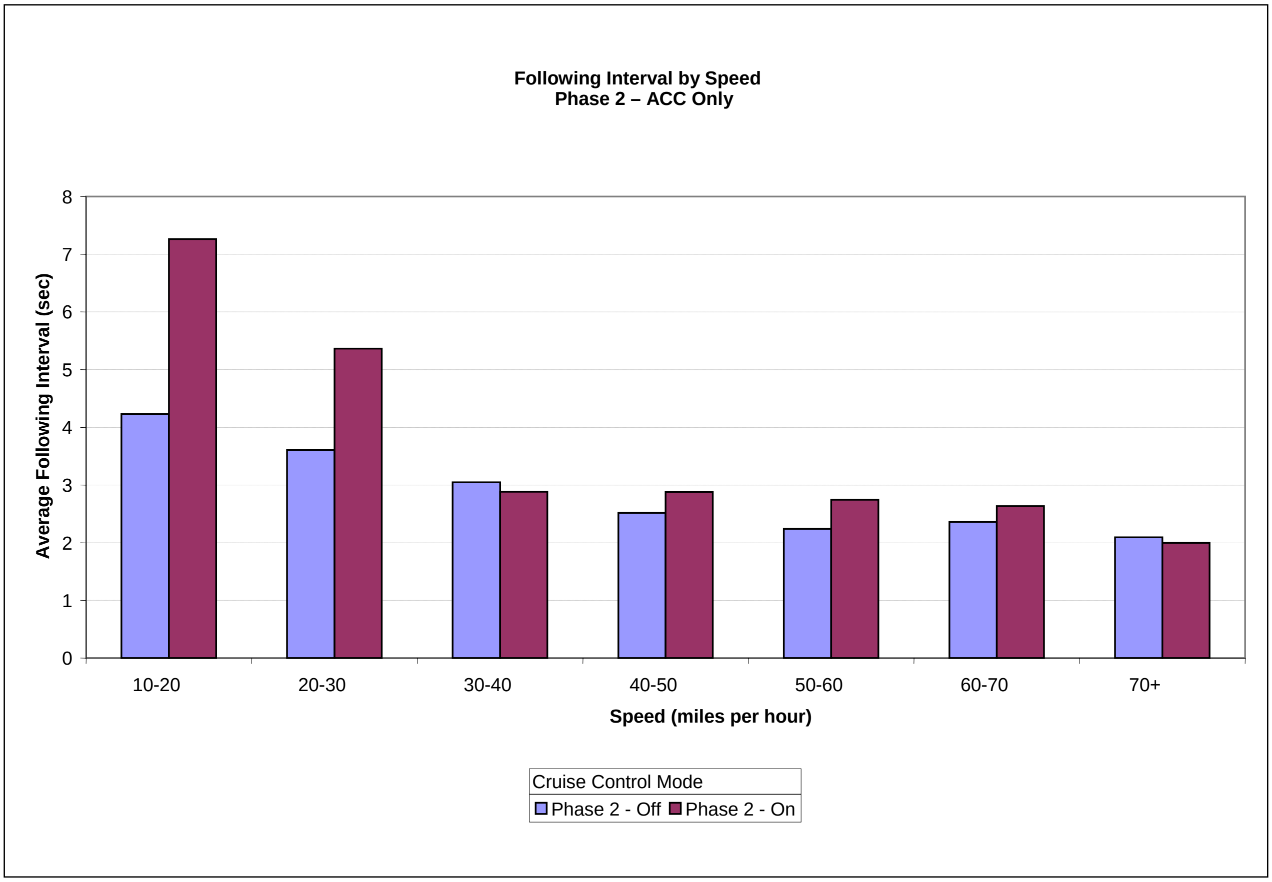


At first encounter with ACC (start of Phase 2, March 2006), an increase in following interval is observed. The increase is observed with the ACC system active or inactive, suggesting that, during this "learning" period, the drivers drive more defensively. Unfortunately, the first 2 months of ACC usage were not captured in the DAS. These initial months may have provided additional insight into the driver's behavior during the learning and familiarity period. After the learning period, once drivers have grown accustomed to the system, it can be expected that the following interval when the system is inactive may decrease to pre-ACC levels. That decrease with the ACC system off is evident in months 4 and 5. The following interval seems to level off at approximately 2.8 seconds during those months. Any subsequent months could see a continuation of the plateau or a slight decrease in following interval. The FOT terminated before a clear determination on the long-term impact of ACC on following interval could be made.

The following interval also appeared to be related to vehicle speed. Thus far, the following interval discussed represents the average overall speeds. However, two separate scenarios may be considered—high speed and low speed.

During the high-speed scenarios, say above 30 miles per hour, the following interval closely mimics the overall average (i.e., intervals between 2 and 3 seconds) with ACC usage slightly increasing the interval. Exhibit 6-16 shows the impact that vehicle speed has on following interval.

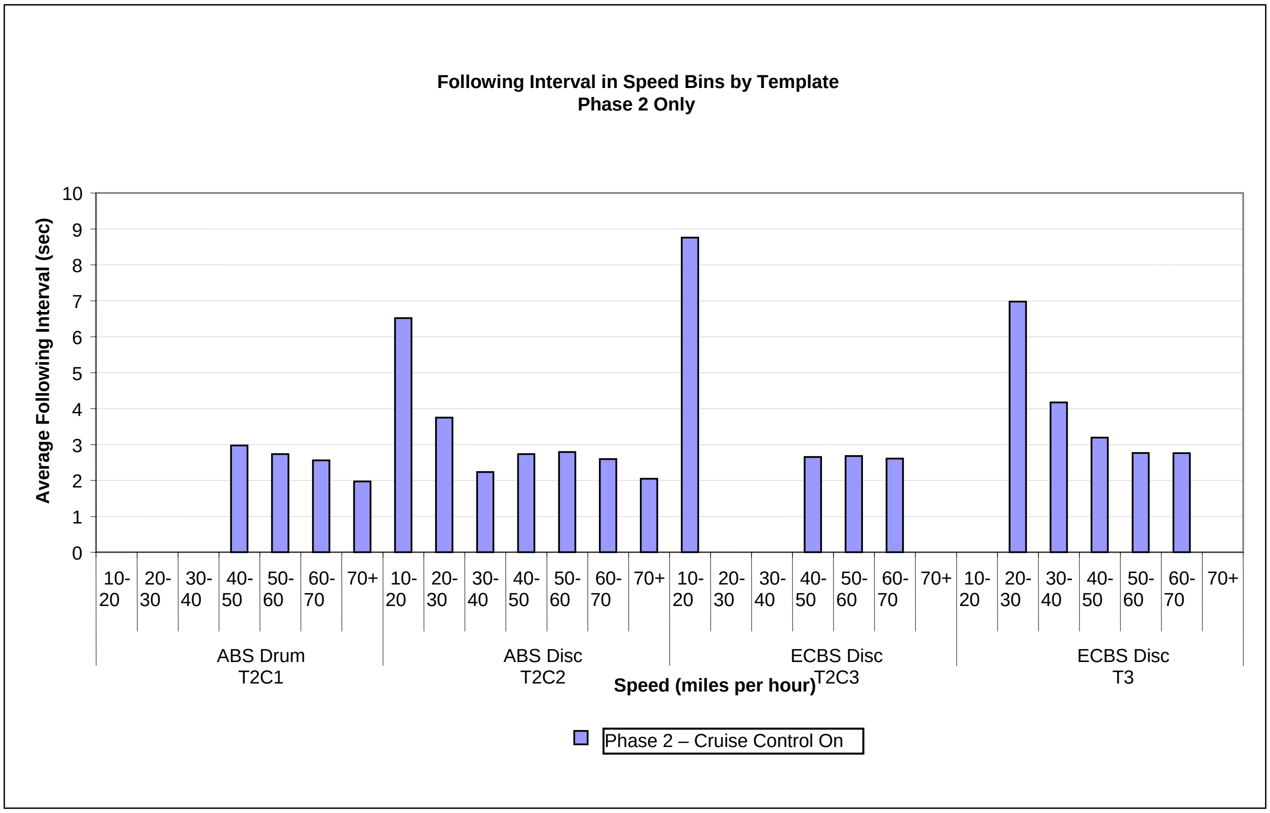
Exhibit 6-16: Following Interval by Speed – Phase 2



However, below 30 miles per hour, a different pattern emerges. Usage of ACC greatly increases the average following interval. This suggests that drivers use ACC in slow-speed, heavier traffic conditions as a type of "autopilot" to help maintain a safe following distance. This ability is unique to ACC because it can be used at speeds as low as 10 miles per hour, and of course can regulate speed based on the front vehicle speed. Although CCC can be used at speeds as low as 20 miles per hour, it is generally undesirable to use it at low speed. CCC only maintains a constant speed, and operating at continuous low speed is a rare occurrence for these trucks.

Recall that Exhibit 6-13 showed a steady increase in following intervals with the use of ACC. The sole exception to this was for tractors in Template T2C1, which saw a decrease in average following interval using ACC. This was the lone exception that otherwise showed consistent increase in following interval with ACC usage. Exhibit 6-17 examines the usage pattern for all templates.

Exhibit 6-17: Following Interval by Template – Phase 2



As shown above, the usage pattern of ACC for Template ABS-Drum (T2C1) is unique. There are no ACC events below 40 miles per hour. It is unknown whether this reflects actual duty cycle differences, or there are data acquisition issues that prevented recording ACC events below 40 miles per hour. However, there is no evidence to suggest that data acquisition problems existed. Absent the slower speed and greater interval of slower-speed events, the overall following average for ABS-Drum (T2C1) is smaller than the other templates. The unique usage pattern of T2C1 explains the anomaly found in Exhibit 6-13. Note, however, that the following interval at greater than 40 miles per hour is consistent for all templates, including T2C1. This observation allows us to reaffirm the findings shown in Exhibit 6-12—namely, that ACC usage increases the average following interval.

6.5 ACC Vehicle Control

ACC adjusts vehicle speed by controlling engine power, engine braking, and foundation brakes as necessary. If the system is responding to a potentially dangerous situation, the driver is alerted while the system begins to decelerate. It is important to know how reliable the system is at detecting impending danger and how appropriate its response is.

If the system is overly sensitive, drivers are unlikely to use it, as it will be perceived as interfering during normal driving. In addition, if the system responds too slowly, drivers may feel uneasy with its response and, therefore, will not use it. A properly calibrated system is likely to be viewed as helpful and will likely be used often. To determine the sensitivity of the system compared to normal driver's reaction, close examination of braking events with the system activated are examined and compared to the braking events during otherwise normal operation.

6.5.1 ACC Behavior

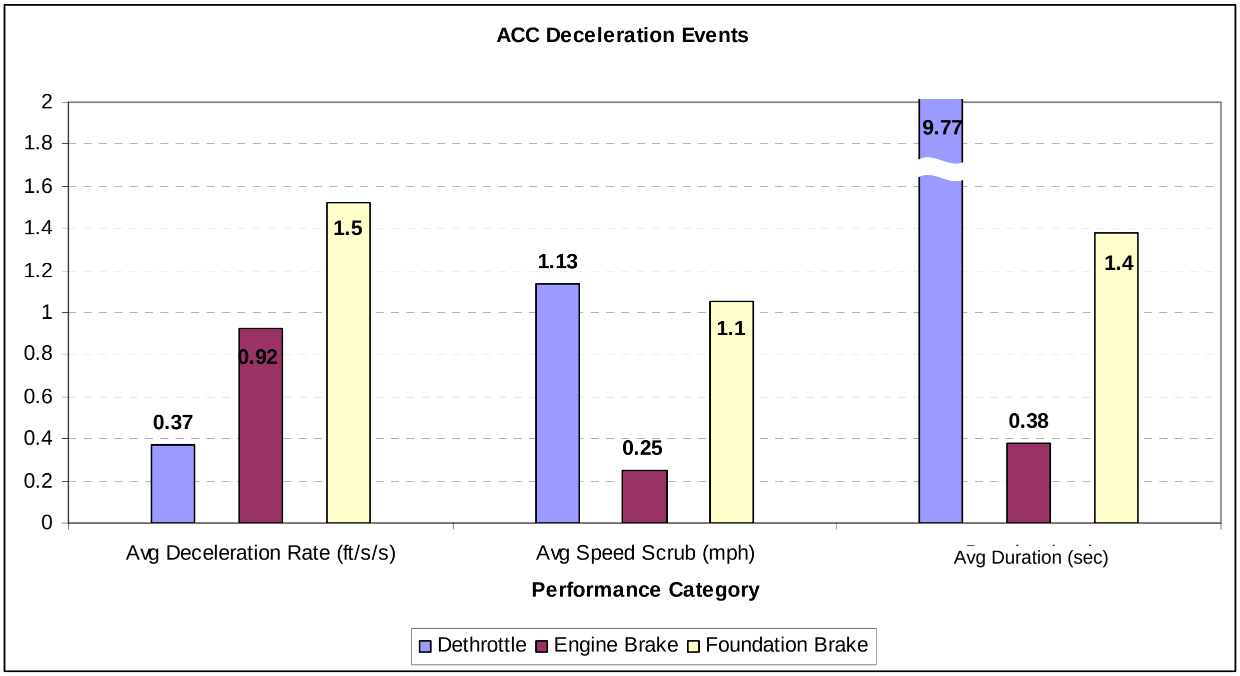
The impact of ACC on following interval has already been explored. Measuring how often and how severely the ACC system decelerates is useful to determine whether it mimics a driver's behavior or if it is overly aggressive or not sufficiently aggressive. ACC is able to reduce engine power, engage the engine brake, or activate the foundation brake. The maximum deceleration rate allowable for the system is 8 feet per second per second (0.25 g).

The system is observed to rely heavily on depowering of the engine to reduce speed. This is expected and is similar to CCC functionality. The ACC system is continuously adjusting speed to maintain the specified following interval. The difference in speed scrub for each event is minimal, and therefore, most adjustments required are small and can be accomplished by depowering the engine.

Exhibit 6-18: ACC Deceleration

	Brake Events per 1 million miles	Average Speed Scrub (miles per hour)
Depower	183,800	1.13
Engine Brake	109	0.25
Foundation Brake	5,144	1.1

Exhibit 6-19: ACC Deceleration Events



Although depowering the engine is an effective deceleration technique, it provides limited force and, thus, requires significant time to slow down the tractor. While foundation brakes were activated for only an average of 1.4 seconds, dethrottling required almost 10 seconds to produce a comparable decrease in vehicle speed.

When more immediate action is required (e.g., sudden deceleration of the lead vehicle), the system relies on foundation brakes and, to a lesser extent, engine brakes. Engine brake and foundation brakes provide, on average, 2.5 and 4 times greater deceleration than engine depower, respectively. For this reason, the ACC system uses engine brake and foundation brakes when depowering does not provide sufficient braking force.

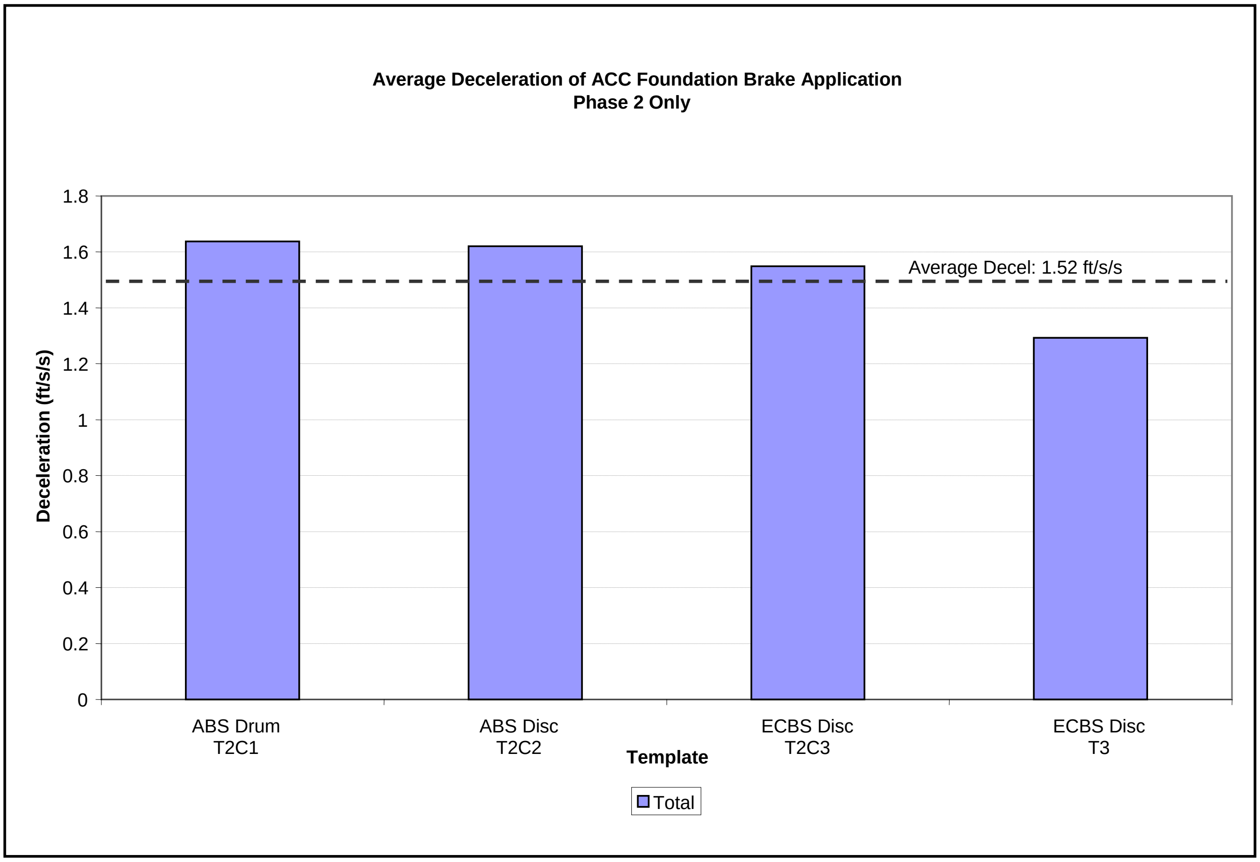
Exhibit 6-20: ACC Deceleration

	Average Deceleration Rate (feet per second per second)	Average Speed Scrub (miles per hour)	Duration (sec)
Depower	0.37	1.134	9.77
Engine Brake	0.92	0.249	0.38
Foundation Brake	1.52	1.05	1.38

As observed in the preceding exhibits, the system does not often rely on engine braking. Instead, while the approaching speed to the front vehicle is small and when a collision would not occur for several seconds, the system uses depowering as a means to reduce speed. However, if the approach speed increases (leading to a shorter time to collision), the system activates the foundation brakes. There are few “in between” cases when the engine brake provides sufficient braking force to reduce the necessary speed. Note that the average deceleration rate for foundation brake is less than one-fourth of its maximum limit of 8 feet per second per second. The system does not activate at the last possible moment to avoid collisions and maintains spare braking capacity.

The following explains the rate of deceleration obtained from different brake technologies. As Exhibit 6-21 shows, the average deceleration does not vary greatly with respect to braking technology.

Exhibit 6-21: ACC Deceleration by Template



How the rate of deceleration produced by the system compares to deceleration rates produced by driver-activated brakes is of interest. This comparison provides a useful measure of the aggressiveness of the system versus the driver. An overly aggressive system will be perceived as harsh and unrefined, while overly soft systems may be perceived as too cautious and slow.

An additional comparison is made in Exhibit 6-22 showing how speed scrub varies by template. It is interesting to note that although T2C3 and T3 tractors showed slightly smaller deceleration rates (Exhibit 6-21), they account for three to four times greater speed scrub. This result may be explained by the greater fidelity of brake control provided by ECBS. Recall that ECBS automatically reacts to provide the desired level of deceleration. Unlike conventional pneumatic systems where the driver simply regulates braking force, with ECBS, the driver regulates desired deceleration with the brake pedal, and the system automatically adjusts the braking force necessary to achieve the deceleration required. ACC seems to rely on ECBS to a greater extent, and is able to request a slow and constant deceleration. It appears that this fine level of control is not available with the conventional systems, and thus the ACC benefits from ECBS.

Exhibit 6-22: Speed Scrub From ACC Brake Activation

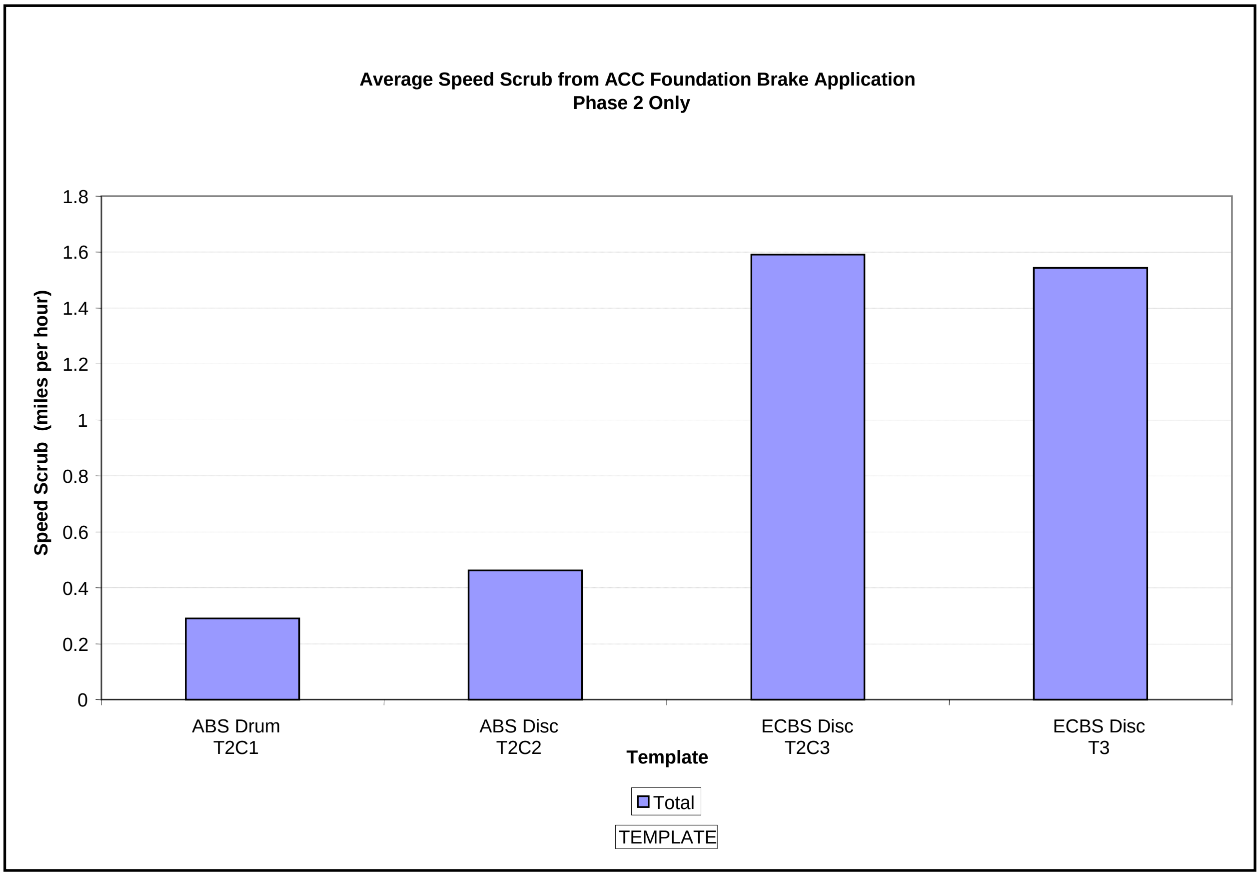


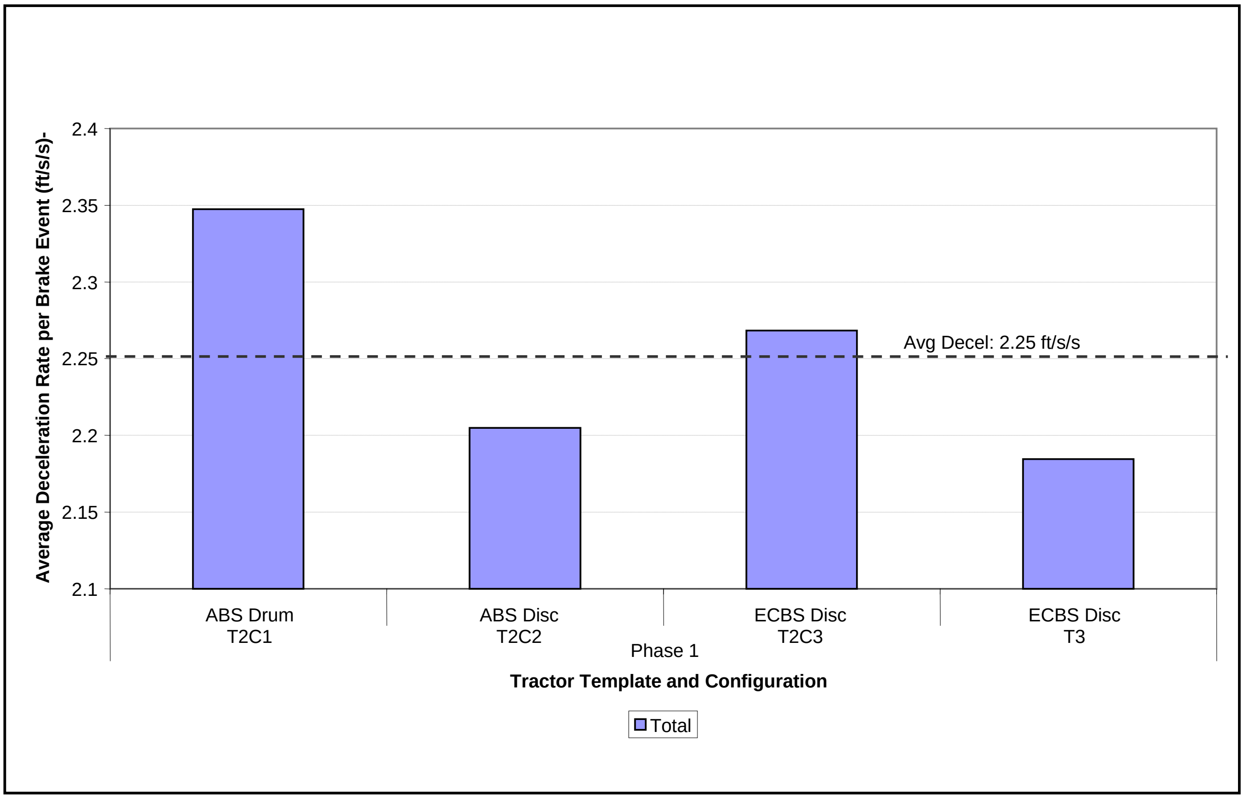
Exhibit 6-23: ACC Brake Activations

TEMPLATE	Miles	Engine Brake Count	Foundation Brake Count	Engine Brake per 1000 miles	Foundation Brake per 1000 miles
T2C1	30,615	5	239	0.16	7.81
T2C2	22,812	4	157	0.17	6.88
T2C3	57,797	0	326	0	5.64
T3	70,711	11	214	0.15	3.02
Total	181,935	20	936	0.11	5.14

As Exhibit 6-23 shows, there is no significant difference observed among templates for engine brake activations. Caution should be taken before making any conclusions because of the low number of engine brake activations throughout the FOT. Foundation brake activations, however, vary somewhat. Perhaps as stated earlier, ECBS-equipped trucks (T2C3 and T3) experience fewer brake activations because the system is able to apply the brakes for longer duration while maintaining slow deceleration. However, the pneumatic brakes achieve the same overall reduction of speed by successive short brake applications, leading to a greater count of brake applications.

Phase 1 deceleration data is illustrated in Exhibit 6-24, which shows that drivers decelerate with an overall average intensity of 2.25 feet per second per second. The deceleration rate varies somewhat between templates, but no firm conclusions can be made. Comparing this result to the average ACC activated deceleration (1.52 feet per second per second) shown in Exhibit 6-21 shows that drivers are approximately 30-percent more aggressive than the ACC system during braking.

Exhibit 6-24: Driver Applied Brake Deceleration

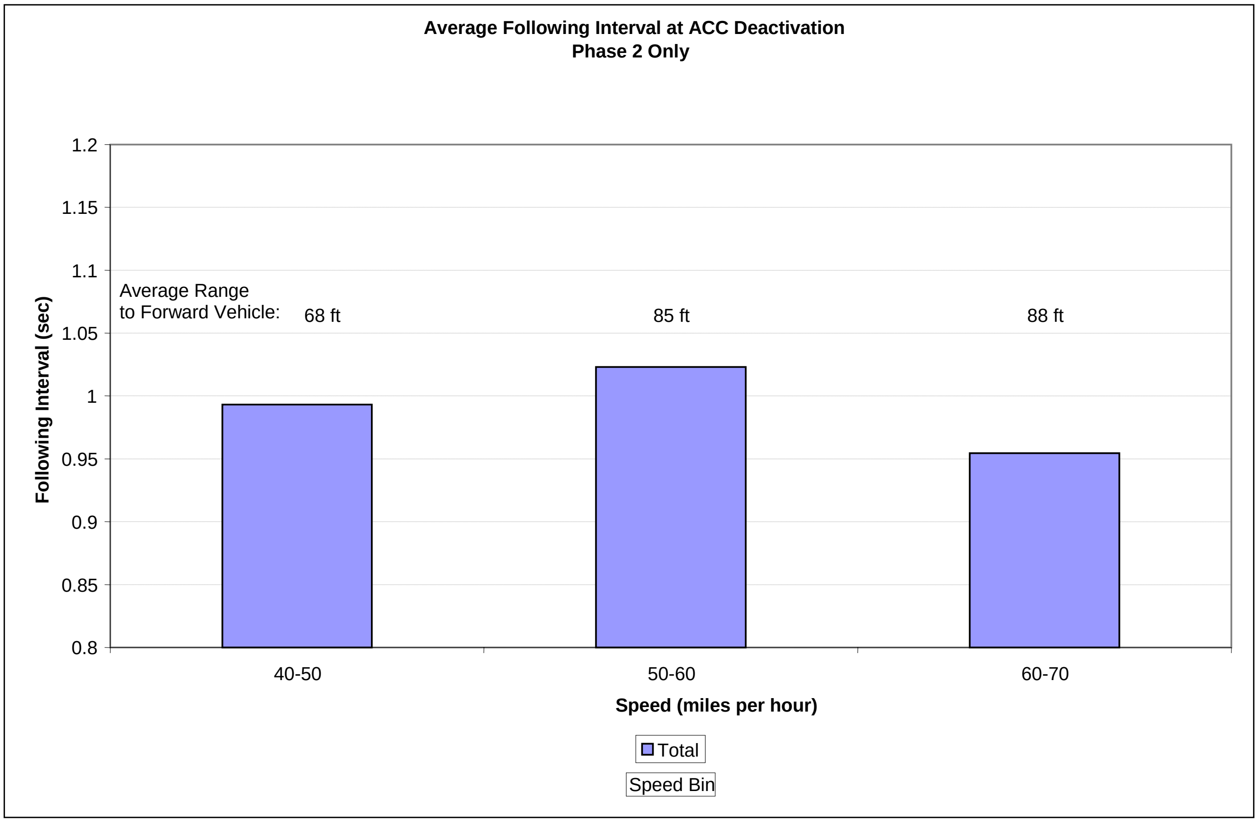


Overall, the system responds slightly more cautiously than the drivers do. However, as shown in Section 6.3, ACC usage of approximately 50 percent suggests that drivers do not find it overly cautious, and it does not appear to discourage drivers from using it.

To gauge driver perception of the reliability of the system in preventing rear-end collisions, application of the brakes by the driver when the system was active was measured. This, in fact, measures when the driver feels that the system is not responding quickly enough and, thus, chooses to disengage the system. Of course, a second possibility is that the driver has reached a point in his route where he may choose to disengage ACC for other reasons, such as exiting the highway or entering a slower speed limit zone.

Exhibit 6-25 shows the following interval and the target range when ACC is manually deactivated. The following interval is significantly closer than expected. Each is approximately at a 1-second interval. Although no indication is given as to what the lead vehicle is doing, a 1-second interval is significantly closer than the 3-second following interval established in the system. It is possible that vehicles are unexpectedly crossing into the truck's 3-second envelope, causing the driver to apply the brakes.

Exhibit 6-25: Following Interval at ACC Deactivation



To evaluate the possibility that drivers are in fact applying the brakes to avoid a collision that otherwise would not be prevented by the system, the same analysis is performed while measuring time to collision.

Exhibit 6-26: Time to Collision at ACC Deactivation

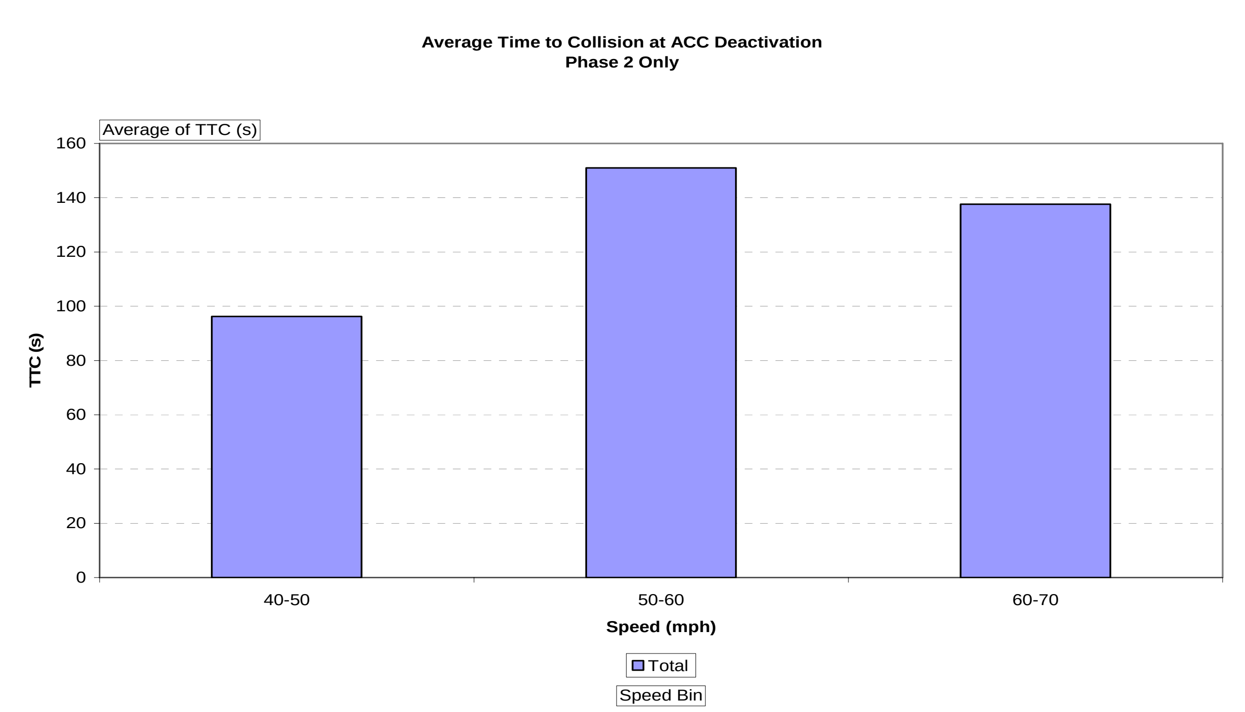
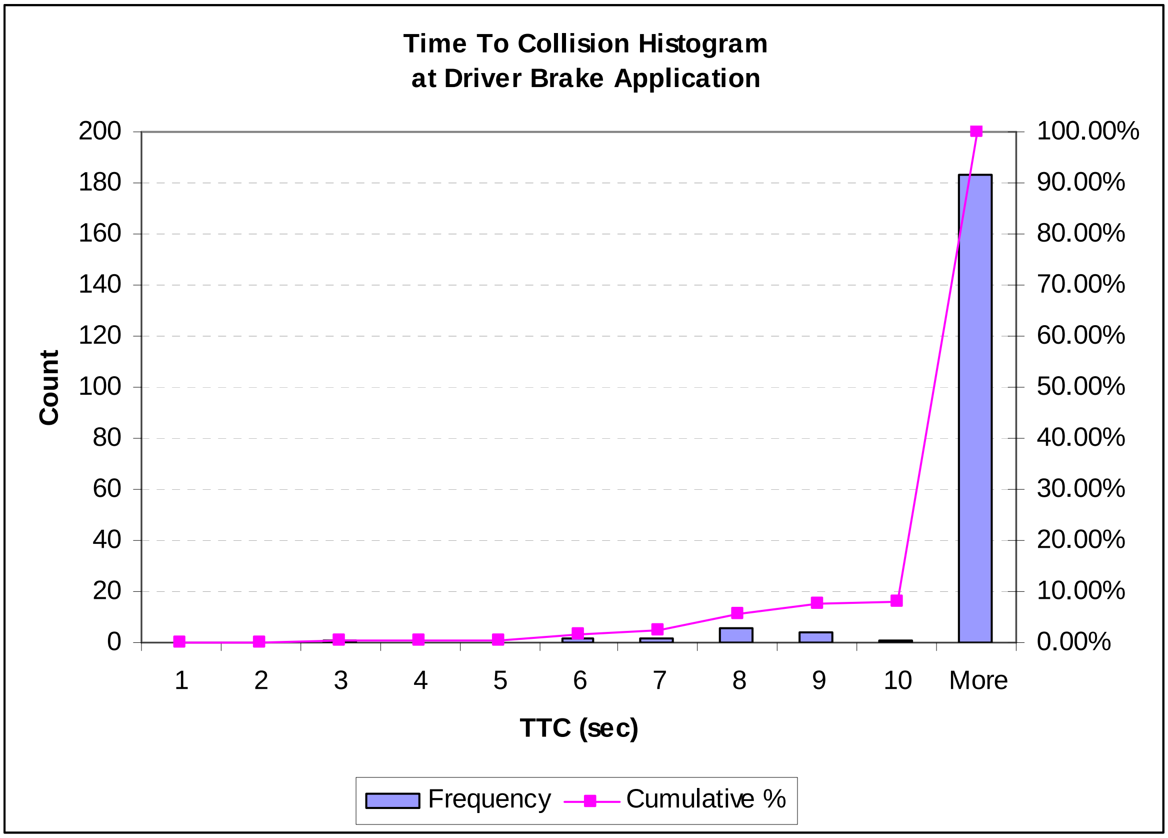


Exhibit 6-26 shows that the average time to collision (TTC) is so long that no collision is imminent. To ensure that these data are reliable and no outlying events are disproportionately affecting the average value shown, Exhibit 6-27 shows the distribution of the TTC at the ACC deactivation point.

Exhibit 6-27: TTC Histogram



Clearly, from the figure above, we can determine that drivers most often disengage ACC by applying the brake for reasons not related to collision avoidance. No events occur prior to a TTC of 6 seconds, and very few events occur with a TTC of less than 10 seconds. This observation suggests that the ACC system is adequately preventing the truck from entering dangerous situations (i.e., low time to collision), and drivers feel comfortable with the system and seldom disengage it to prevent an undetected collision. These observations could have profound implications when calculating the safety benefits of using ACC, which are addressed in the following section.

6.6 Safety Benefits of ACC

The ACC's impact on safety is of key importance. The simplest analysis to calculate accident reduction is of course to directly measure the number of accidents before a given technology is installed and compare to the number of accidents after the technology is installed. This methodology is only applicable given a very large dataset and not applicable during this FOT. In addition, there were no accidents recorded during the FOT, hence that methodology is not applicable. The procedure used in this section follows the generally accepted Benefits Equation (1) with the probability of accidents occurring based on specific criteria that are estimated to precede an accident.

In general, the potential reduction (R) of accidents is:

$$R = P_{wo}(C) - P_w(C) \qquad (1)$$

Where $P_{wo}(C)$ is the probability of an accident without the use of the new technology, while $P_w(C)$ is the probability of an accident with the technology in use. The Benefits Equation is widely accepted as an accurate probabilistic measure of safety benefits. It can be manipulated to show:

$$R = N_{wo}(C) \times \sum_i P_{wo}(S_i \mid C) \times \left[1 - \frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)} \times \frac{P_w(S_i)}{P_{wo}(S_i)}\right] \qquad (2)$$

Where S_i is a driving conflict of type *i*, and $P_w(C \mid S_i)$ is the conditional probability of a crash given an involvement of conflict type S_i with ACC present, and $P_w(S_i)$ is the probability of the driving conflict type S_i per unit of exposure occurring with ACC present. Quantities subscribed with "*wo*" have the same interpretation but with ACC technology not present.

There are two key components in the Benefits Equation, namely $\frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)}$ known as the prevention ratio (PR), and $\frac{P_w(S_i)}{P_{wo}(S_i)}$ known as the exposure ratio (ER). In addition, an important quantity is $N_{wo}(C) \times \sum_i P_{wo}(S_i \mid C)$, which is the actual historical accident rate from the General Estimate System (GES) for each type of accident *i*. A value of less than one for each ratio indicates a reduction of potential crashes. These ratios form the basis of the benefits equation, and along with the GES crash data, an estimate of the actual accident reduction can be calculated.

To calculate the exposure ratio, we must define several parameters that identify an event that is likely to precede a rear-end accident. The exposure ratio is then directly calculated from the exposure to these events during the FOT. Further discussion on the definition of these events (or conflicts) is discussed in Section 6.6.2: Exposure. The number of conflicts is tabulated during Phase 1 ("system not available") and Phase 2 ("system available"), and the ratio is thus calculated directly.

The prevention ratio is a measure of the ability of the technology to prevent a crash after the event has met the predefined criteria preceding a crash. This measure cannot be directly calculated. To analyze the safety benefit, the prevention ratio is assumed to have a value of one. This neutral value will not adversely affect the results, nor artificially inflate benefits. Similar studies[1] have attempted to estimate the prevention ratio under similar FOTs before, only to find that a high degree of uncertainty is introduced, and the results then become statistically indistinguishable from a value of PR= 1. This result is particularly true in low-intensity events

[1] *Evaluation of the Freightliner Intelligent Vehicle Initiative Field Operational Test*, Battelle, May 2003

such as those observed during this FOT. For this reason, this analysis will not attempt to interpret a different value.

6.6.1 Historical Crash Data

As expected, there were no actual accidents during the FOT. Historical crash data and fatality rates for representative samples of commercial trucks came from the National Automotive Sampling System (NASS) GES. The GES data were reviewed for rear-end crash and fatality information for the years 2002 through 2005.

GES data are categorized by type of collision, vehicles involved, and resulting injuries among other criteria. Published data from GES for heavy trucks shows that during the years of 2002 to 2005, a total of 301,000 rear-end crashes occurred that resulted in 3,179 fatalities. Average annual rear-end accident and fatality rates over these four years therefore are as follows:

Exhibit 6-28: Four-Year Heavy-Truck Rear-End Statistics (2002-2005)[2]

Rear-End	4-Year Total	4-Year Annual Rate
Crashes	301,000	75,250
Fatalities (related to)	3,179	795
Injuries (related to)	55,000	13,750

The number of accidents and fatalities from rear-end accidents highlights the extent of the problem. Clearly, rear-end collisions are of great concern, as they contribute an average of 795 fatalities annually. These results are crucial for determining the potential safety impact of ACC technology which factors in to any rear-end collision while ACC is operating, which is further discussed in the next section.

6.6.2 Exposure

As discussed earlier, the evaluation of the safety benefits relies on calculating the exposure to an event with a certain probability to precede an accident (in this case, a rear-end collision). The exposure to these events is measured by determining and categorizing following intervals during the operation of the trucks. The working assumption is that close following intervals are more likely to lead to a rear-end collision. Further explanation of the categorization of these events is highlighted below. The exposure to these events was compared for trucks during Phase 1 (ACC unavailable) and Phase 2 (ACC available). As detailed earlier, the normalized ratio of exposure during Phase 2 to Phase 1 is the exposure ratio used in the safety benefits equation.

Total verified data miles accumulated during Phase 1 was slightly over 1.8 million miles, while Phase 2 accumulated approximately 630,000 miles.

Defining Event and Conflict

Calculating the safety benefit of ACC relies on accurate and consistent definition of what defines an event and a conflict preceding a rear-end collision. The database was first searched to

[2] *(Annual) Traffic Safety Facts for 2002-2005, Table 46-"All Crashes" for each year.*

define the events. Those events were then analyzed to find the subset that defined the conflicts. The exposure rate to these conflicts will determine any potential safety impacts. The working hypothesis was that ACC would reduce exposure to conflicts and have a beneficial impact on safety.

Several data mining options/filters were considered to help define the event and conflict thresholds. The database contains vast amounts of data that may not be relevant to this analysis. Only those events that represent likely scenarios when trucks use ACC should be considered. Additionally, the duration of said events is considered to ensure that values in the database are accurate and not temporary inconsistencies in the data. Due to the nature of ACC functionality, events were selected based on vehicle speed, following distance, closing rate, braking force, and event duration. The process of defining the event revealed the nature of data collected. As stated earlier, these data contain mostly low-intensity events, so defining events required taking this fact into account.

Exhibit 6-29 lists some approaches considered.

Exhibit 6-29: Approaches Considered

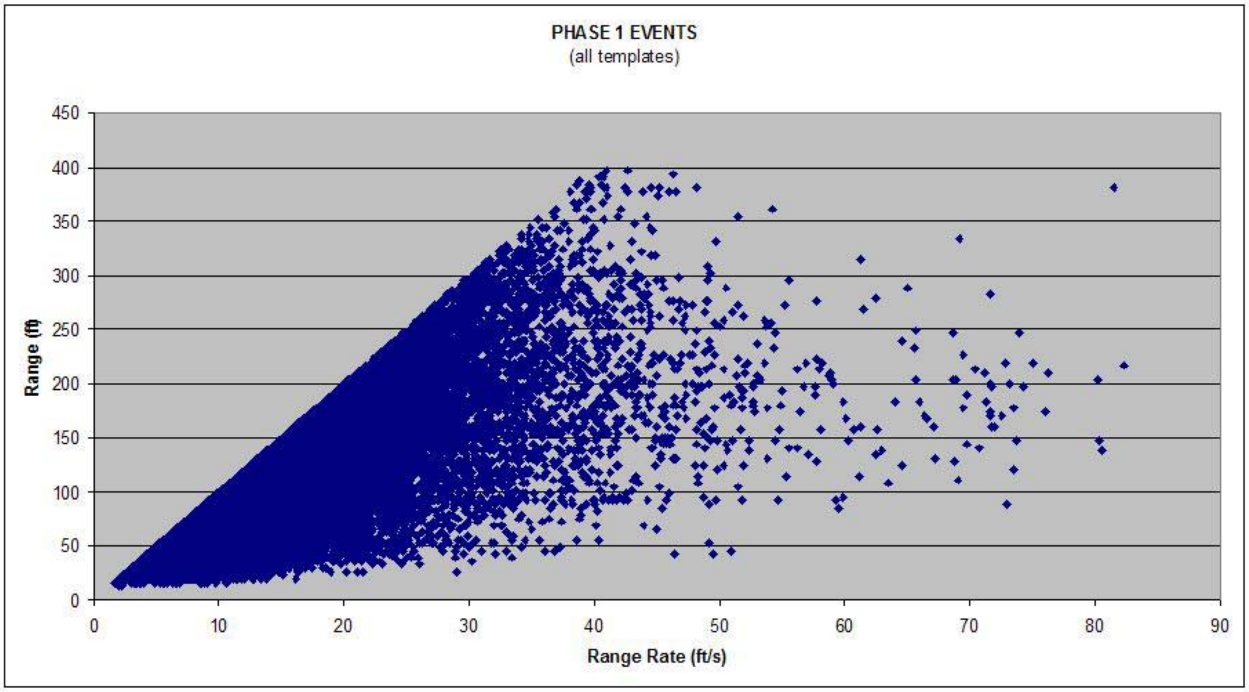
Method	Remarks
Separate by braking "g" force	Intended to provide a measure of the severity of the event. Found low-data resolution AND only low-intensity events.
Separate by "Target Range" within speed bins	No clear way to simplify and combine target range, speed, and other variables. Not intuitive to the reader, and not a normal basis for driver reaction.
Numerical Analysis (i.e., top x% of brake events)	Mostly low-intensity events lead to many false positive identifications. Single driver can skew results. No clear threshold for conflict cut-off point.
Separate by Time to Collision	Most intuitive, not arbitrary. Self regulates for speed, range, and range rate. Most likely basis for driver reaction. Final threshold established by iterative process.

After several failed attempts using the approaches shown above, the TTC approach was selected. The event was then defined as follows:

- *Maximum Range of Lead Vehicle:* 400 feet
- *Range Rate:* Less than 0 feet per second (i.e., lead vehicle approaching)
- *Vehicle Speed:* Greater than 20 feet per second
- *Duration of Event:* Greater than 4 seconds

The final search parameters were selected to most accurately reflect real-world conditions. Recall that the event does not yet define the conflict. This is only the first step in separating these data to ensure that later results can be confidently defined as conflicts. Exhibit 6-30 shows the events identified with this method. Note that each point shown represents an event that lasts 4 seconds or greater. The point graphed is that point at which TTC is lowest during the 4+ second event. Events where the minimum TTC was greater than 10 seconds are of low intensity and not graphed.

Exhibit 6-30: Phase 1 Events

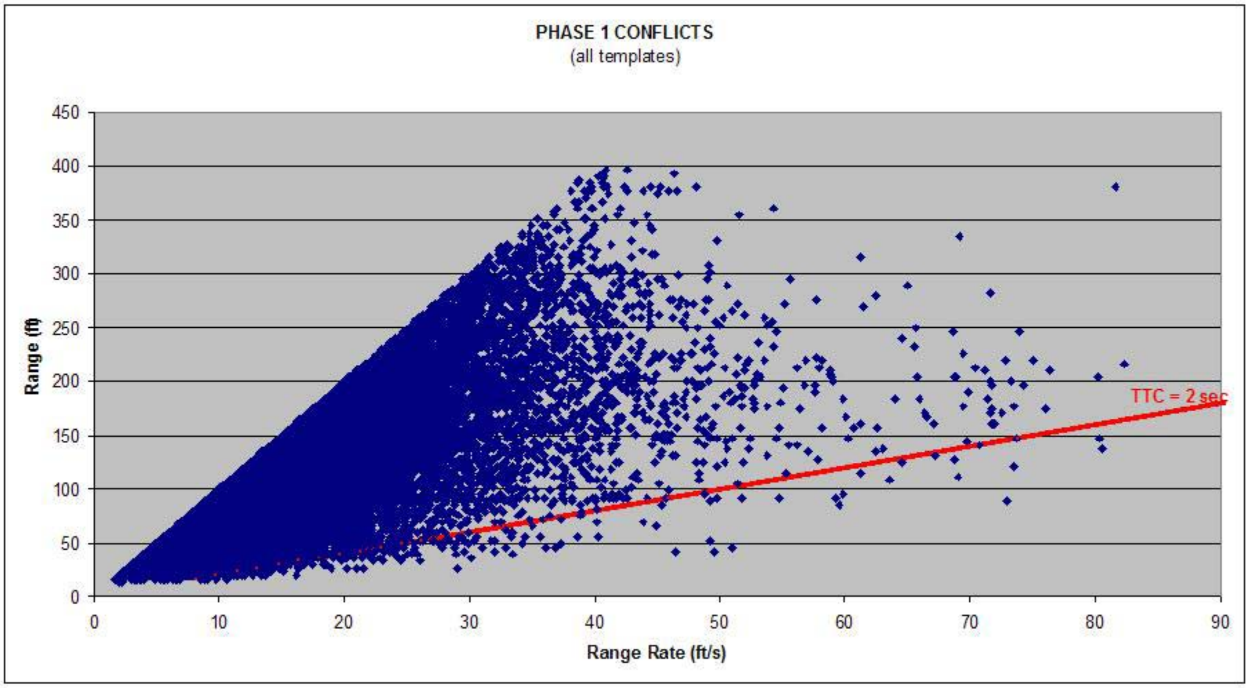


As expected, most events are located in low-intensity zones (i.e., either far away or approaching slowly). The next step requires finding the subset of the events that can be categorized as conflicts. The conflicts encountered can be thought of as the events that have larger probability of resulting in a rear-end collision.

The ACC system is preprogrammed to maintain a 3-second following interval. It is then useful to define a conflict based on the lead vehicle entering the envelope where the ACC reacts, but not exiting that envelope in a timely manner. The definition of conflict also had to take into account the fact that these data are mostly of low intensity (e.g., no hard decelerations, no accidents). The drivers' reaction to the conflict could not be used for its definition. Lastly, this analysis hoped to define an approach that provided an intuitive feel to the reader of what was occurring during the conflicts as defined. The database was mined to identify the events that had a TTC of less than 2 seconds. Two seconds was used as an intuitive point at which a driver is expected to take action, otherwise an accident may occur. At that point, the driver is expected to make an aggressive avoidance maneuver to prevent an accident (either by braking or turning).

It is useful to note that using a range-versus-range rate graph helps to visualize the severity of the event. The event severity can be quickly identified as located low and to the right in the graph (i.e., at close range and approaching quickly). Exhibit 6-31 graphs the events, but a TTC line is now added. All points that fall below the TTC=2 seconds line are now defined as conflicts. Again, the points plotted in the exhibit represent the point in time during each event when TTC was at a minimum.

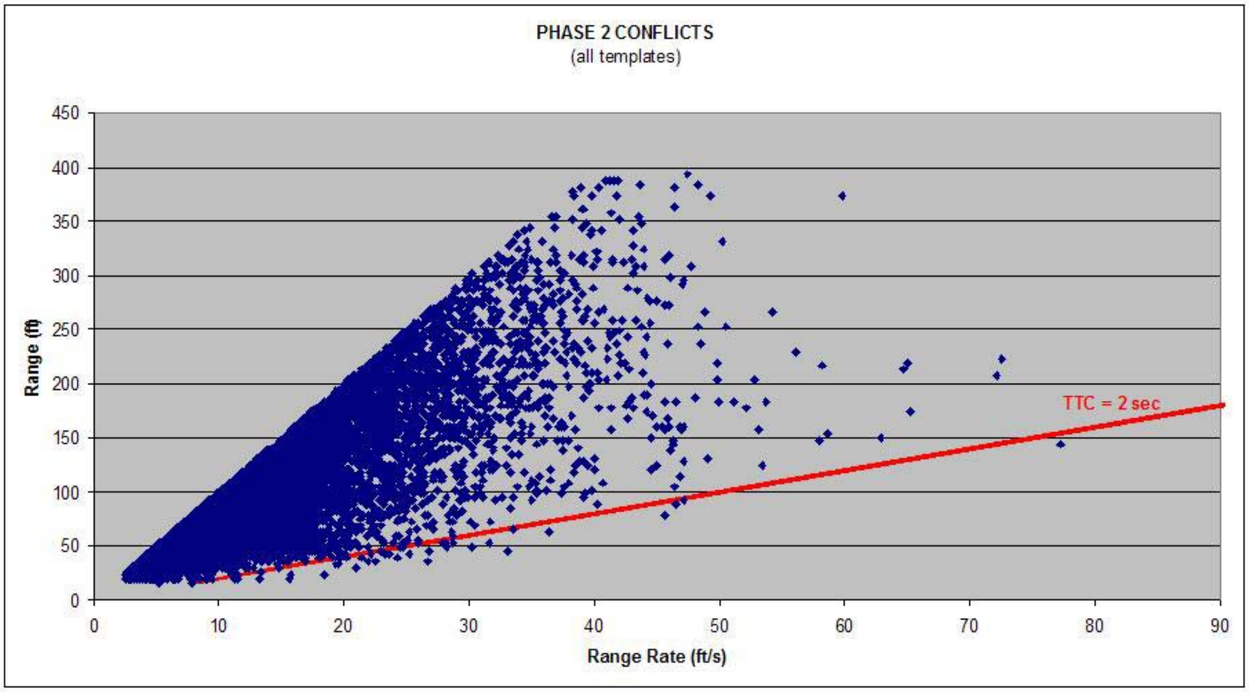
Exhibit 6-31: Phase 1 Conflicts



Not surprisingly, most events occur in regions with higher TTC, which means that drivers generally take action to prevent the trucks from entering the area most would deem unsafe. From the safety benefits point of view, the points above the TTC=2 line are not very interesting. Only the conflicts (i.e., points below TTC= 2 seconds) are used to calculate safety benefits. There were 193 such conflicts identified during Phase 1.

For Phase 2, the same approach was followed. ACC was available and was expected to play a role in preventing trucks from reaching potential rear-end collisions (low TTC). Recall that ACC is programmed to maintain a following interval of 3 seconds. Clearly, if the TTC is below 2 seconds, the system is either not activated, not capable of responding fast enough, or not responding for other reasons, and the driver is expected to take action. As Exhibit 6-32 shows, the number of conflicts during Phase 2 is greatly reduced. This, of course, is expected for two reasons. First, the trucks operated only about a third of the miles during Phase 2 compared to Phase 1. Second, when the ACC system is used, the following interval should be maintained at approximately 3 seconds. Since ACC is used over 50 percent of the time (see Section 6.3.1) during Phase 2, the system will have a significant impact on exposure to conflicts. Only 39 conflicts were identified during Phase 2.

Exhibit 6-32: Phase 2 Conflicts



To gauge the true effect of ACC on safety, the conflicts identified must be normalized by mileage for each phase. As Exhibit 6-33 shows, the availability of ACC reduced the exposure to rear-end collision conflicts by approximately 40 percent. This result is significant and is used in the next section to calculate accidents avoided and lives saved by having ACC available.

Exhibit 6-33: Conflicts Observed

	Miles Recorded	Conflicts Observed	Conflicts Observed (per million miles)
Phase 1	1,861,526	193	103.67
Phase 2	630,749	39	61.83

6.6.3 Predicted Accident Reduction From ACC

To study the benefits of ACC, only rear-end accidents are considered. Data shown in previous sections show that the exposure during Phase 1 was 104 per million vehicle miles traveled, VMT. The exposure during Phase 2 was 62 per million miles. The exposure ratio, ER, for ACC use is therefore:

$$ER_i = [P_{wi}]/[P_{woi}] = 61.63 / 103.67 = 0.596$$

The results confirm a significant reduction in driving conflicts of approximately 40 percent. As previously mentioned, GES data show an average of 75,250 rear-end collisions resulting in 795 deaths annually and a rate of fatalities per crash. From the safety benefits equation (2), using a PR value of one assuming that there is an equal likelihood of a crash with or without ACC, the resulting reduction in accident and fatalities is quickly calculated below using the averages from Exhibit 6-28. Since a crash is always preceded by a driving conflict, crash reduction may be calculated.

Rear end crash reduction:
$R = 75{,}250[1-(1\times 0.596)] = 30{,}373$

Also assuming an average fatality reduction of 795 / 75,250 = 0.011 fatalities per crash without ACC, fatality reduction for full deployment of ACC is potentially:
R = (795 / 75,250)30,373 = 321

Exhibit 6-34: Predicted Annual Reductions

Rear End Accidents	Fatalities
30,373	321

While this FOT is based only on long-haul truck use, equipping commercial trucks with ACC can therefore be shown to have a significant impact on safety. If used nationwide, an average maximum of 30,401 rear-end collisions could be prevented and 321 lives could be saved.

To have a certain degree of confidence in the above-calculated results, a statistical model describing the events must be formulated. From our definition of conflict, it is clear that each conflict is an individual occurrence that is independent of the last occurrence. A Poisson distribution will appropriately model the experiment and assist in calculating the reliability of the results.

Each phase is assumed to follow a Poisson distribution. The difference in mean occurrences of two Poisson distributions can be considered to have a normal distribution when large sample sizes are used. Since this is the case during the FOT, the confidence interval for the difference in occurrence rates during Phase 1 and Phase 2 is calculated as follows:

$$(\lambda_1-\lambda_2)\pm Z\left(\sqrt{\frac{\lambda_1}{n_1^2}+\frac{\lambda_2}{n_2^2}}\right) \qquad (3)$$

Where λ_1, λ_2 is the mean occurrence rate during each phase. We choose a value of Z=1.96 for 90-percent confidence. The sample sizes n_1 and n_2 are represented by the mileage accumulated in each phase, namely 1,861,526 and 630,749 miles, respectively.

Using the values shown in Exhibit 6-33, (λ_1 =104, λ_2 =62), and Z=1.96, the calculated result with a 90-percent confidence interval is a reduction of 42 ±0.03 rear-end conflicts / million-miles.

CHAPTER 7. BRAKE MAINTENANCE ANALYSIS

The Wal-Mart maintenance practices were analyzed to understand the long-term reliability, durability, and maintainability of advanced brake systems and enabled technologies. The analysis focuses on three primary measures:

- Frequency of unscheduled system maintenance and/or component failures (to assess reliability);
- Brake system performance degradation during the test period (to assess durability); and
- Total maintenance requirements, both scheduled and unscheduled (to assess impact on fleet maintenance and costs).

This chapter first provides the background information that was required to complete the analysis. This includes a description of data collected, the source for all the data, and the tractor configurations that were assigned. The chapter also provides a general overview of all the maintenance data that was collected over the course of the FOT. An in-depth analysis follows to identify the maintenance cost, maintainability, and reliability of ADBs, advanced ABS, and ECBS.

7.1 Data Collection

To complete the maintenance analysis, four different sources of data were collected:

- Vehicle maintenance records;
- Driver surveys;
- Mechanic surveys; and
- On-board driving data.

Wal-Mart vehicle maintenance records were the largest source of data for completing the maintenance analysis of the braking technology. The Wal-Mart electronic maintenance records database is structured according to the Technology and Maintenance Council Vehicle Maintenance Reporting Standards (VMRS). According to the standards, all failure reports entered into the system are to include a code for the affected system, the reason for the repair, the work accomplished, the replacement part, and the labor hours. For this analysis, a query was run on the maintenance database for all brake (code 013) and tire (code 017) failures for the entire FOT period. The query results tracked vehicle ID, date, failure code, category, action taken, remarks, labor hours, and cost (see Exhibit 7-1). In addition to the sample data, the database also tracked vehicle mileage and parts replaced.

Exhibit 7-1: Sample Data From Wal-Mart Maintenance Database

VIN	Date	Problem Description	Category	Action	Tech Remarks	Hours	Cost
WMT41861	1/23/05	Driver said ABS light stays on for trac	BRAKES - ANTI-LOCK	Inspect	No light on and no codes found	0.02	$0.46
WMT41860	2/2/05	ABS light come on, didn't find anything wrong	BRAKES - ANTI-LOCK	Repair	Checked out no lights no repair	1.02	$23.46
WMT41863	1/3/05	Tractor losing air after sitting loose air line on air tank	BRAKE LINES AND FITTINGS - HYDRAULIC AND AIR	Overhaul	Tightened hose fitting on air tank	1.1	$25.30
WMT41863	2/14/05	ABS light on/ flash codes 53&55 sensor signal erratic/tire size RR drive axle & RR additional axle	BRAKES - ANTI-LOCK	Overhaul	Started trouble shooting problem	4.65	$106.95
WMT41863	2/15/05	ABS light on/ flash codes 53&55 sensor signal erratic/tire size RR drive axle & RR additional axle	BRAKES - ANTI-LOCK	Overhaul	Right front drive axle sensor out of adjustment, Wheel bearing tight	0.78	$17.94
WMT41860	4/22/05	Driver would like extensions to be installed on his glad hands	BRAKES - AIR	Repair	Driver would like extensions installed	0.73	$16.79

Driver surveys were distributed to all participating drivers in the FOT. A total of 59 responses were received. The surveys requested feedback from the drivers in three general areas—interoperation of tractor and trailer with installed equipment, general confidence in ADBs, and number of system failures. Drivers also voiced their reactions to the new technologies that were installed on the tractor-trailers. The survey assisted in determining the driver's confidence level in operating vehicles with ADBs, ECBS, and / or ABS. In addition, the drivers were asked to provide feedback on their experience with the braking systems and the number of failures reported to the maintenance staff.

Maintenance surveys were distributed to the maintenance personnel in the Wal-Mart maintenance facility. A total of 73 responses were received from the maintenance personnel. The surveys requested feedback on the technician's overall confidence in the reliability and maintainability of each technology. The surveys tracked the estimated number of interactions each technician experienced with the installed technologies. From those experiences, the technicians ranked the ability to diagnose and repair faults, the improvement (or lack thereof) over existing technologies, and the overall opinion of the new technology.

The final data source for the maintenance analysis was the on-board vehicle data, obtained from the DAS installed on each of the FOT tractors and trailers. The focus of the DAS data types used to conduct the maintenance analysis was on the foundation brake data, the vehicle data, and the powertrain.

7.2 Collection Methodology

The conductor team with project management and coordination responsibilities was responsible for gathering all the necessary data requested during the FOT. Working with the host fleet, they used various methods to obtain data for the final analysis.

The tractor-trailer on-board equipment was monitored using a DAS that recorded specific data in 10-minute “blobs” onto 1-gigabyte PCMCIA data storage cards.

The conductor team administered the driver and mechanic surveys three times during the FOT—immediately prior to testing, at 6 months, and at 12 months (FOT end). The surveys were completed anonymously by the technicians and drivers and returned to their appropriate supervisors. Upon completion, they were collected by the conductor team and shipped to Booz Allen Hamilton in their original format. The surveys were reviewed and entered into a database for future analysis and filtering.

The maintenance data used to complete the maintenance analysis was collected from Wal-Mart’s vehicle maintenance records. Wal-Mart’s maintenance recording system follows the VMRS formatting recommendations. Booz Allen requested Wal-Mart vehicle repair orders pertaining to all tractors and trailers participating in the FOT that also contained brake- or tire-related maintenance actions. The FOT conductor team queried Wal-Mart’s database two separate times during the FOT and applied filters that searched specifically for repair orders containing brake- or tire-related maintenance actions, with VMRS codes of 013 and 017 respectively. The conductor team was unable to export electronic copies of the queried repair orders from the database, but was able to print hard copies of the repair orders. Hard copies of the maintenance repair orders were sent to Booz Allen for analysis. The repair orders provided information on failure codes, tractor mileage, labor costs, parts costs, etc. Information contained in the repair orders was entered into a searchable database to provide a convenient source for analyzing the maintenance tasks over the course of the test period.

7.3 Tractor Test Configuration

For the experimental design, four tractor configurations were established by Freightliner to aid in the analysis of the technologies. Each configuration is a combination of a service brake type (drum, ADB), braking control system technology (ABS, advanced ABS, ECBS), and enabled safety technologies. Exhibit 7-2 outlines the specifics of each configuration.

Configuration 1 (T2C1) was established as the test baseline, outlined in red in Exhibit 7-2. The configuration was manufactured according to Wal-Mart’s current vehicle specification. The tractors were manufactured with a standard ABS and drum brakes. As the configuration was based on the current fleet, data gathered established the historical fleet data. The configuration operated in conditions experienced by the existing fleet, and can be expected to provide similar maintenance data. The remaining configurations were established to assist in the evaluation of advanced braking technologies, such as ADB, ECBS, and advanced ABS (ABS6).

Exhibit 7-2: Experimental Design Tractor Configuration

		Service Brakes	Brake Technology
Configuration 1	T2C1	Drum	ABS
Configuration 2	T2C2	ADB	ABS
Configuration 3	T2C3	ADB	ECBS
Configuration 4	T2C4	ADB	ABS6
Configuration 5	T3	ADB	ECBS

7.4 General Testing Overview

The maintenance evaluation began in December 2004, for a period of 22 months. During this period, the tractors accumulated approximately 3.5 million miles and generated 582 repair orders. Exhibit 7-3 provides a breakdown of the tractor mileage among the five test configurations broken out into total mileage and mileage accumulated in each test phase.

Exhibit 7-3: FOT Tractor Mileage (Graph)

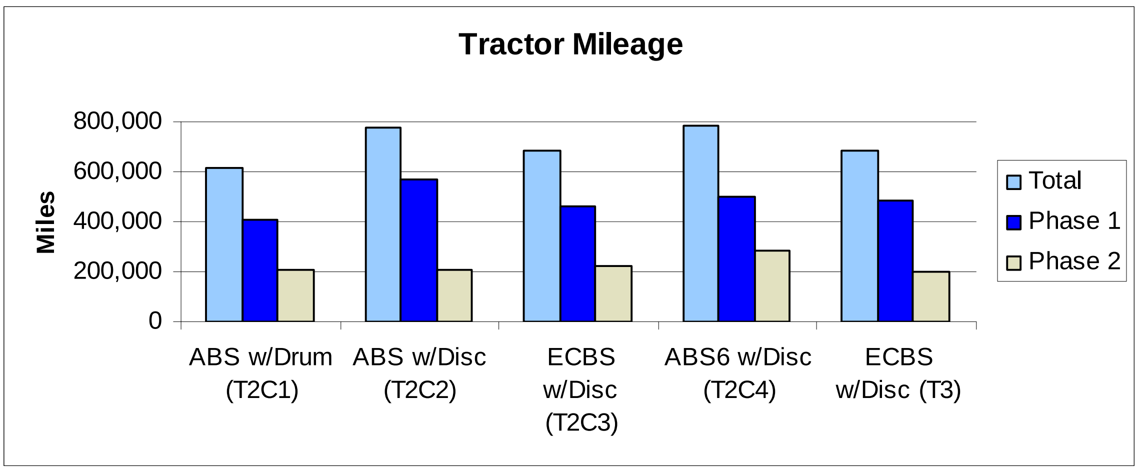


Exhibit 7-4 lists the number of tractors and mileage statistics for each tractor configuration in the FOT.

Exhibit 7-4: Overall FOT Tractor Mileage (Table)

Template	# Tractors	Total Mileage	Phase 1 Mileage	Phase 2 Mileage
ABS w/Drum (T2C1)	10	614,961	410,857	204,103
ABS w/Disc (T2C2)	10	775,131	570,061	205,069
ECBS w/Disc (T2C3)	10	683,485	459,032	224,452
ABS6 w/Disc (T2C4)	9	785,044	501,798	283,246
ECBS w/Disc (T3)	8	685,315	484,784	200,530

The final mileage for each configuration was used to normalize all maintenance data for this analysis. To allow a direct comparison, all data will be presented based on a "per million miles" basis. These data were normalized using the following formula:

$$NormalizedData = \frac{Data * 1{,}000{,}000}{TotalMileage}$$

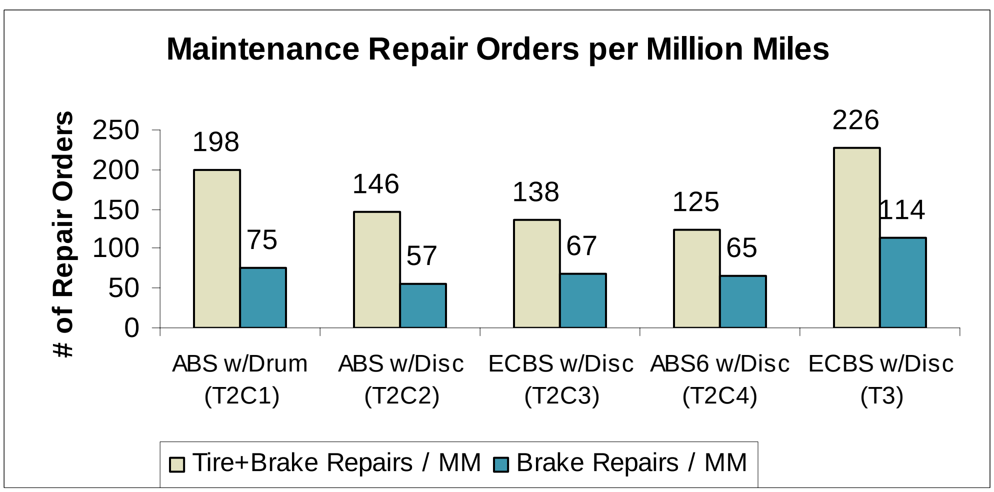
During the FOT, 582 brake and tire repair orders were collected from the Wal-Mart maintenance facility. Exhibit 7-5 provides the breakdown of repair orders for each configuration. Using the normalized data, the T3 configuration accumulated the largest number of repair orders per million miles at 226 repair orders.

Exhibit 7-5: Repair Orders per Million Miles (MM)

Template	Repair Orders (ROs)	RO Brake Related	RO Tire Related	Total Repairs/ MM	Brake Repairs/ MM	Tire Repairs/ MM
ABS w/Drum (T2C1)	122	46	76	198	75	124
ABS w/Disc (T2C2)	113	44	69	146	57	89
ECBS w/Disc (T2C3)	94	46	48	138	67	70
ABS6 w/Disc (T2C4)	98	51	47	125	65	60
ECBS w/Disc (T3)	155	78	77	226	114	112
Total	582	265	317			

A comparison of normalized total maintenance repair orders and brake-related repair orders for all FOT tractor configurations is shown in Exhibit 7-6.

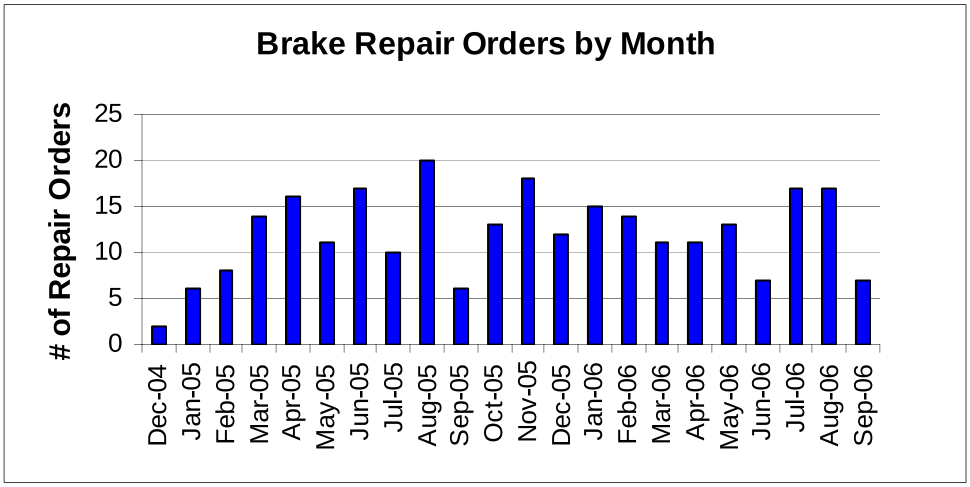
Exhibit 7-6: Brake Repair Orders per Million Miles



The FOT was conducted from May 2005 until May 2006. The assigned tractors were put into normal operation by Wal-Mart in December 2004. The maintenance facility immediately began generating repair orders for these vehicles. For the maintenance analysis, the experimental design incorporates all repair orders generated from December 2004 until September 2006.

Unlike the on-board vehicle data that the DAS was constantly recording, the maintenance data could only "record" when a failure was reported to the maintenance facility. The extended test period provided a greater sample size for the maintenance analysis. Exhibit 7-7 provides a monthly breakdown of repair orders.

Exhibit 7-7: Monthly Repair Orders Generated



The Wal-Mart repair orders include labor hours, labor cost, and parts cost. Using the vehicle ID, the repair orders were organized by tractor configuration. For each configuration, Booz Allen analyzed total labors hours, total cost, total parts cost, and total labor cost (Exhibit 7-8).

Exhibit 7-8: Brake Repair Costs (Actual)

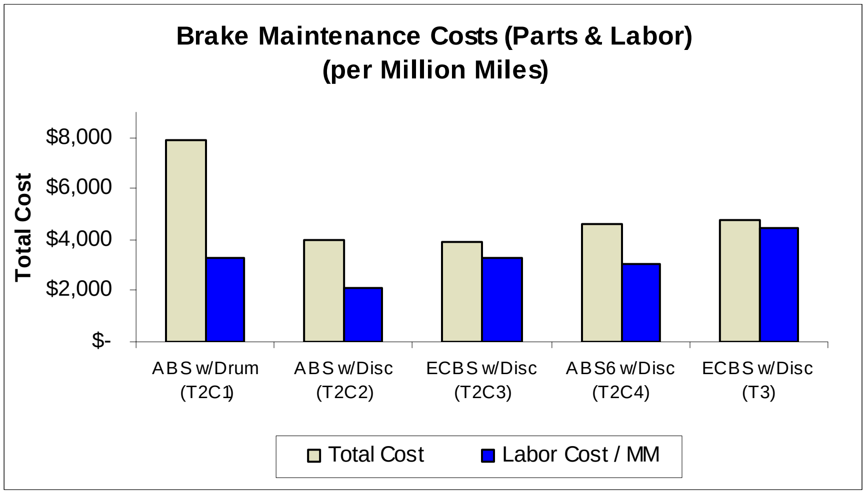
Template	Man Hours	Labor Costs	Parts Costs	Total Costs
ABS w/Drum (T2C1)	73.9	$2,005.50	$2,834.01	$4,839.51
ABS w/Disc (T2C2)	71.7	$1,648.28	$1,419.92	$3,068.20
ECBS w/Disc (T2C3)	98.1	$2,255.83	$432.50	$2,688.33
ABS6 w/Disc (T2C4)	92.7	$2,416.42	$1,187.78	$3,604.20
ECBS w/Disc (T3)	131.0	$3,064.12	$227.69	$3,291.81

Exhibit 7-9 and Exhibit 7-10 present these data from Exhibit 7-8, normalized to reflect costs based on operating the tractors for 1 million miles.

Exhibit 7-9: Brake Repair Costs (Normalized)

Template	Man Hours/ MM	Labor Costs/ MM	Parts Costs/ MM	Total Costs/ MM
ABS w/Drum (T2C1)	120.1	$3,261.18	$4,608.44	$7,869.62
ABS w/Disc (T2C2)	92.5	$2,126.45	$1,831.85	$3,958.30
ECBS w/Disc (T2C3)	143.5	$3,300.48	$632.79	$3,933.27
ABS6 w/Disc (T2C4)	118.0	$3,078.07	$1,513.01	$4,591.08
ECBS w/Disc (T3)	191.2	$4,471.11	$332.24	$4,803.35

Exhibit 7-10: Brake Maintenance Costs



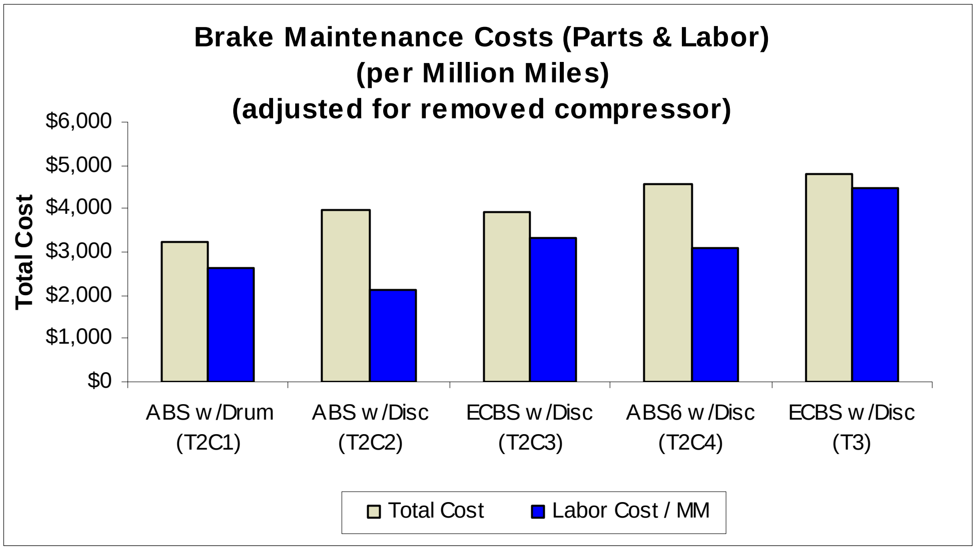
In Exhibit 7-8, Exhibit 7-9, and Exhibit 7-10, a large cost differential is evident between configuration T2C1 and the other FOT configurations. The higher cost was attributed to the replacement of two air compressors on the T2C1 tractors during the course of the field test. The costs of the compressors and associated labor were removed from the analysis because the compressors failed early in the test period and the failures were due to defects unrelated to the braking system.

Exhibit 7-11 and Exhibit 7-12 provide the adjusted costs after removing the associated costs of the defective compressors on the T2C1 tractors. Exhibit 7-11 demonstrates that the costs for T2C1 are within an expected range of the other configurations. With the adjusted T2C1 values, the total cost generated by each of the five configurations is within $1,600 per million miles.

Exhibit 7-11: Normalized Brake Maintenance Costs (Compressor Costs Removed) (Table)

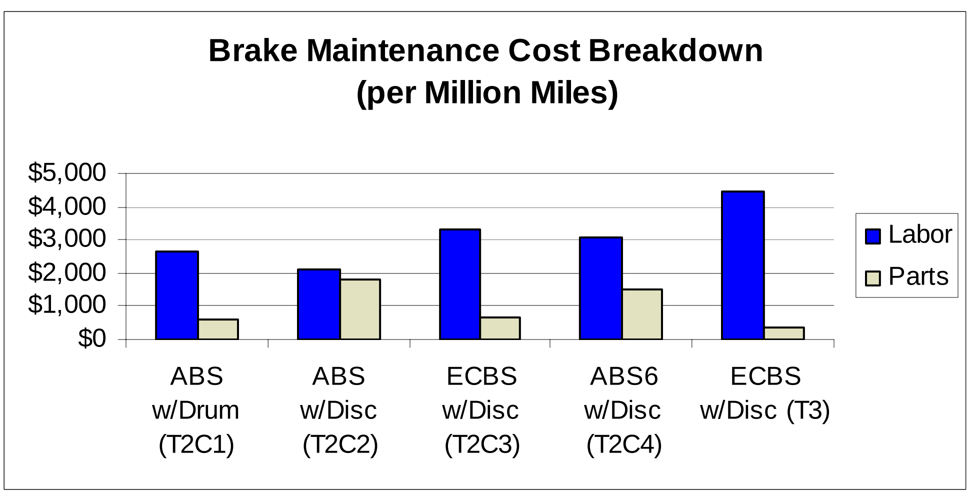
Template	Man Hours/ MM	Labor Costs/ MM	Parts Costs/ MM	Total Costs/ MM
ABS w/Drum (T2C1)	92.2	$2,620.50	$595.00	$3,215.50
ABS w/Disc (T2C2)	92.5	$2,126.45	$1,831.85	$3,958.30
ECBS w/Disc (T2C3)	143.5	$3,300.48	$632.79	$3,933.27
ABS6 w/Disc (T2C4)	118.0	$3,078.07	$1,513.01	$4,591.08
ECBS w/Disc (T3)	191.2	$4,471.11	$332.24	$4,803.35

Exhibit 7-12: Normalized Brake Maintenance Costs (Compressor Costs Removed) (Graph)



To provide a clearer understanding of the source of the total maintenance costs, the total costs were separated into labor costs and parts costs (Exhibit 7-12). Exhibit 7-13 illustrates that although the total costs were similar, a comparison of labor costs and parts costs for each configuration had a much larger price variation. The T2C1 configuration had the second lowest labor costs, but had the highest parts costs. The lower labor cost may be attributed to the technician's experience with the control fleet. They are able to quickly diagnose the problem, but the parts costs are higher than for the other configurations. The T2C3 and T3 configurations, which are identical, had the highest labor costs, but the lowest parts costs. The large labor costs may be attributed to the technician's limited knowledge of the ECBS technology.

Exhibit 7-13: Brake Maintenance Cost Breakdown



The reviewed data provides insight into the maturity of the tested systems. There were no major failures of the systems in any of the tested configurations. To fully understand the maintainability and reliability of each system, the remaining analysis is focused on particular technologies. This analysis will further establish the differences between specific technologies and the benefits, if applicable, of each.

7.5 ADB Analysis

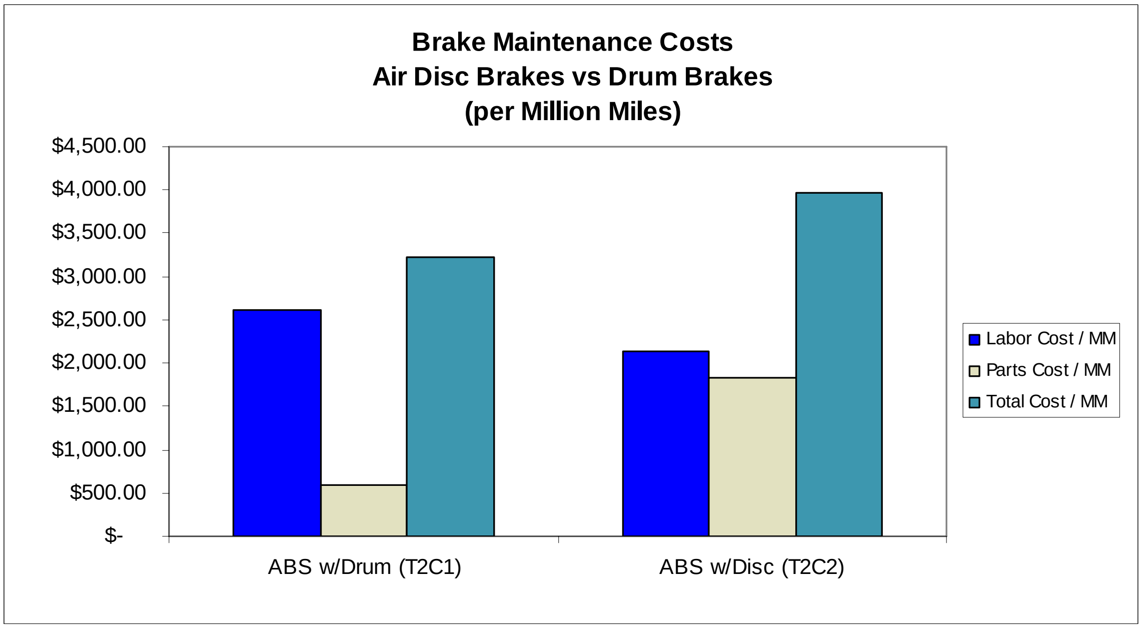
Drum brakes are used on 95 percent of the commercial vehicles in the United States. In comparison, 95 percent of the commercial vehicles in Europe operate with ADBs. ADBs have been proven to provide shorter stopping distances (up to 40%) and reduced brake fade throughout the braking cycle.[3] While the improvements in performance are significant, commercial vehicle operators have not embraced the use of ADBs in the United States due to increased purchase cost and in some designs, increased component weight. In this section, maintenance and inspection data are examined to determine ADB maintenance costs, reliability, and durability.

The analysis uses data gathered for the T2C1 and the T2C2 configurations. The T2C1 configuration was the same as the current tractor used by the Wal-Mart facility. The T2C2 configuration was selected to provide an equal comparison between the two tractors. Each vehicle operated with ABS control technology, but had different foundation brake systems. The T2C1 configuration used drum brakes, while the T2C2 tractors were equipped with disc brakes.

The cost analysis shown in Exhibit 7-14 demonstrates that ADB and drum brakes exhibited similar total costs over the course of the test. Drum brakes experienced a total cost of $3,216 per million miles. The analysis has removed the cost required to replace the two air compressors during the test. In comparison, ADBs cost the company $3,958 per million miles for repairs. The total costs for brake maintenance are within 23 percent.

[3] Kelley, T. "Super Stopping," *Driving Force Magazine.* November 2006.

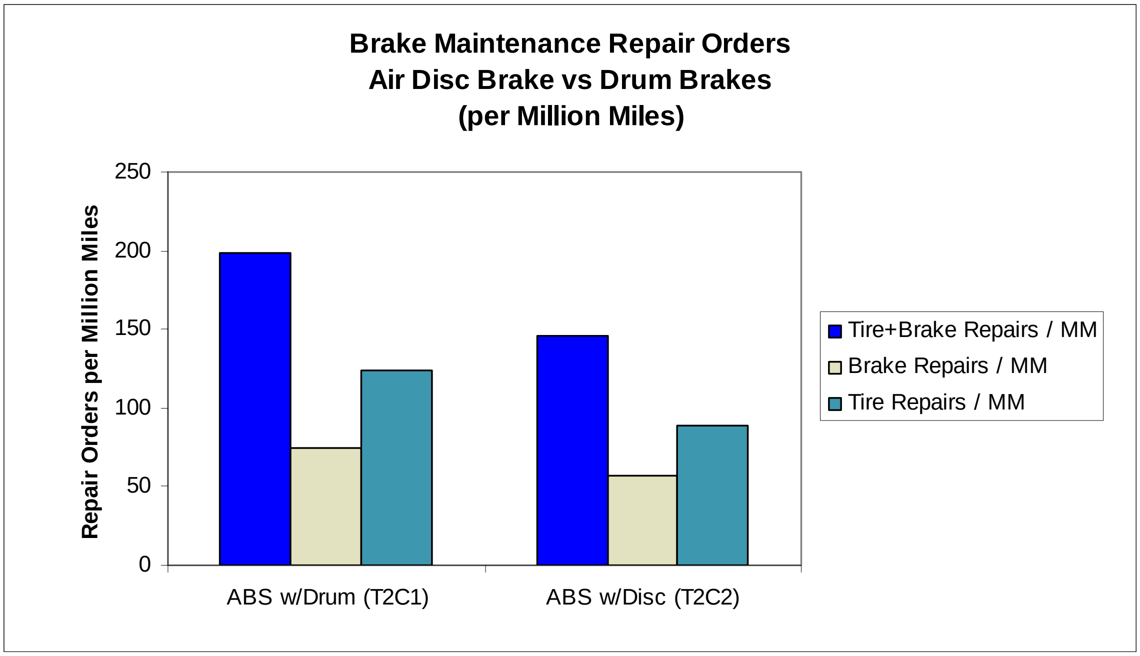
Exhibit 7-14: Drum Brake versus ADB Maintenance Costs



Further investigation shows that the cost breakdown is not equivalent for each of these systems. For example, labor costs for drum brakes accounted for nearly 85 percent of the brake maintenance costs. In comparison, the total cost for ADB was evenly distributed between labor and parts. The increased labor cost for the drum brakes may be attributed to the increased repair orders generated by drum brakes.

Exhibit 7-15 shows that drum brakes accumulated 51 more repairs per million miles than the ADB. The labor attributed to the drum brakes exceeded the ADBs by nearly 20 repairs per million miles.

Exhibit 7-15: Drum Brake versus ADB Repair Orders



A teardown of the brake systems on 15 tractors was conducted to inspect the drum and ADB brake assemblies for wear and overall assembly condition. The truck configurations had accumulated 230,000 miles prior to the teardown. The inspected tractors included nine with ADB assemblies and six with drum brake assemblies.[4]

Exhibit 7-16 displays the ADB assembly on the right steer axle of an FOT tractor. The ADB assembly in Exhibit 7-16 is typical of the condition of the ADB assemblies after approximately 230,000 miles of operation at the end of the FOT.

[4]*Bendix Spicer Brake Inspection Travel Report*, dated October 6, 2005 – October 11, 2006.

Exhibit 7-16: Air Disc Brake Assembly

The inspection team measured the disc brake pad wear on each of the nine tractors with ADB assemblies. A total of 108 brake pads were measured, including the outer and inner pads.

Exhibit 7-17 shows the location of the eight measurements taken on each inspected brake pad. These pads are from the right and left front steer tires of an FOT tractor.

Exhibit 7-17: Air Disc Brake Pad Measurement Locations

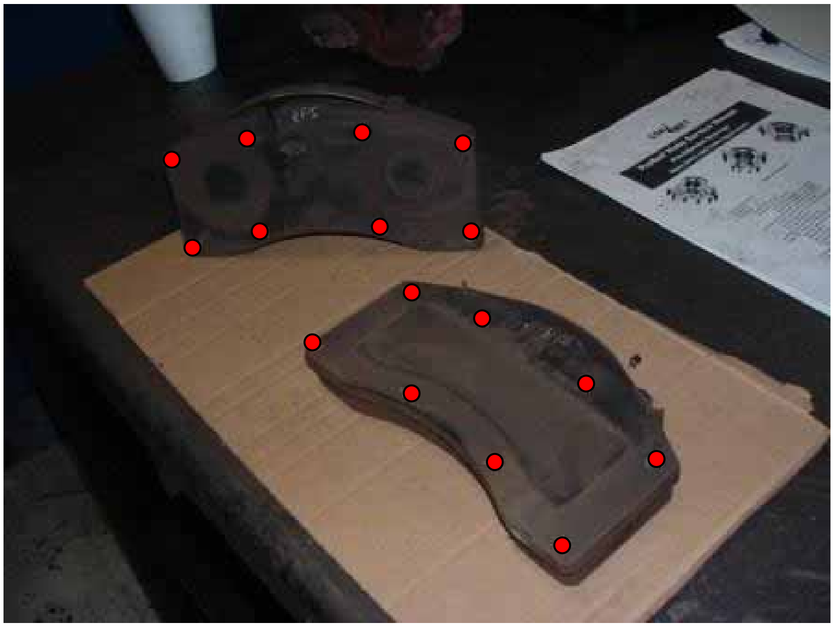


Exhibit 7-18 illustrates the method of determining pad thickness. A micrometer was used to measure the thickness of the pads.

Exhibit 7-18: Air Disc Brake Pad Thickness Measurement

A comparison of the measurements is shown in Exhibit 7-19. The maximum brake pad wear criterion is 0.740 inches of material worn away. During the inspection, a single tractor experienced extreme brake wear, and accounted for the 8 percent of the brake pads that would not be expected to meet the minimum wear expectancy of 500,000 miles. Due to this abnormality, these measurements will not be considered as part of the normal maintenance period. Removing this outlier, the inspection determined that 63 percent of the brake pads would have an expected life in excess of 1 million miles. The remaining pads had an expected life of approximately 700,000 miles. Exhibit 7-20 outlines the component life expectancy for the ADB assemblies.

Exhibit 7-19: Disc Brake Pad Wear

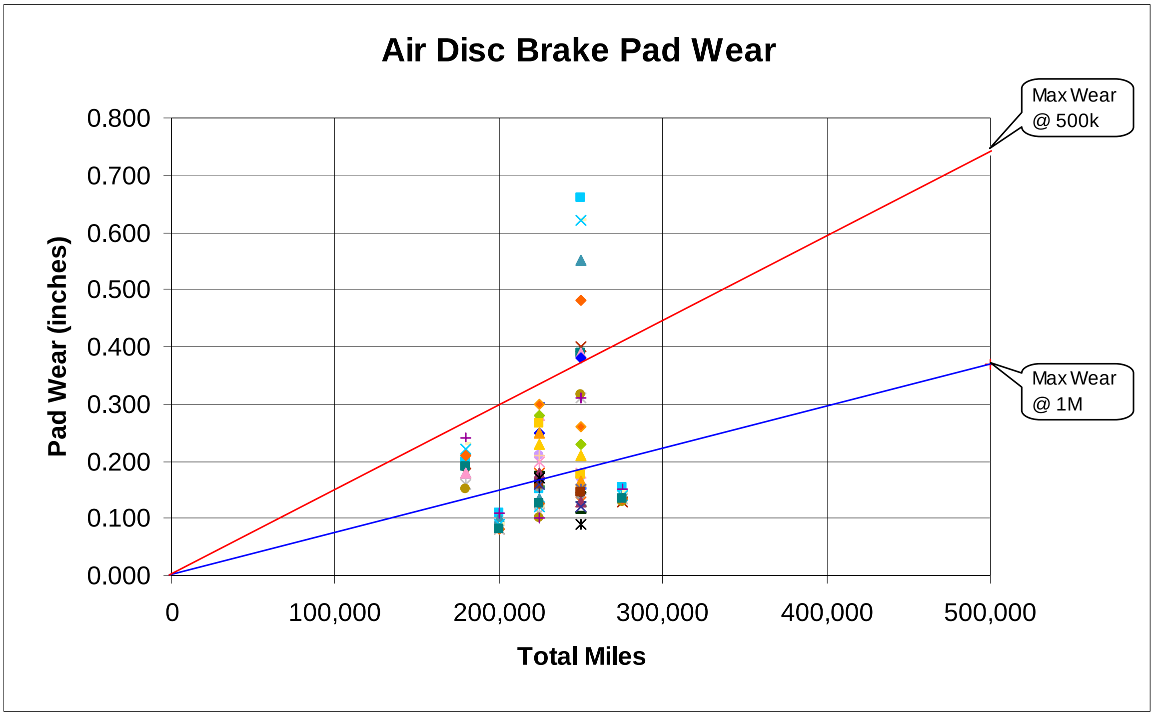


Exhibit 7-20: Expected Life of Air Disc Brake Components[5]

Unit #	Mileage	Steer Rotors	Mid Rotors	Rear Rotors	Steer Pads	Mid Pads	Rear Pads	Control System
1854	199,289	>>1M*	>>1M	>>1M	>1M	>1M	>1M	Bendix ABS6
1855	256,246	1M**	1M**	1M**	300K**	500K	500K	Bendix ABS6
1857	259,625	>>1M	>>1M	>>1M	>1M	>1M	>1M	Bendix ABS6
1858	226,323	>>1M	>>1M	>>1M	>1M	>1M	>1M	Bendix ABS6
1861	229,305	>1M	>1M	>1M	700K	700K	700K	Bendix ABS6
1873	244,697	>>1M	>>1M	>>1M	1M***	1M***	1M***	Bendix ABS6
1884	225,972	>>1M	>>1M	>>1M	1M	1M	1M	Meritor ECBS
1888	252,418	>>1M	>>1M	>>1M	>1M	>1M	>1M	Meritor ECBS
1890	184,307	>1M	>1M	>1M	700K	700K	700K	Meritor ECBS

* >>1M denotes significantly greater than 1 million miles
** Unit #1855 showed evidence of extreme brake usage.
*** The outer left front pad of Unit #1873 was installed backwards. Wear on all wheels of this tractor were affected.

[5] Ibid.

In comparison, Exhibit 7-21 and Exhibit 7-22 depict the measurements for the primary and secondary drum brake shoes respectively. Brake shoes have a maximum wear criterion of 0.591 inches of material used for the drive assemblies and 0.496 inches of material used for the steer assemblies. The inspection team measured 72 brake shoes. All the steer shoes, approximately 33 percent of the measured shoes, had an expected life in excess of 1 million miles. The remaining shoes had an average expected life of 500,000 miles, with the worst shoes not expected to meet a life expectancy of more than 400,000 miles.

Exhibit 7-21: Primary Drum Shoe Wear

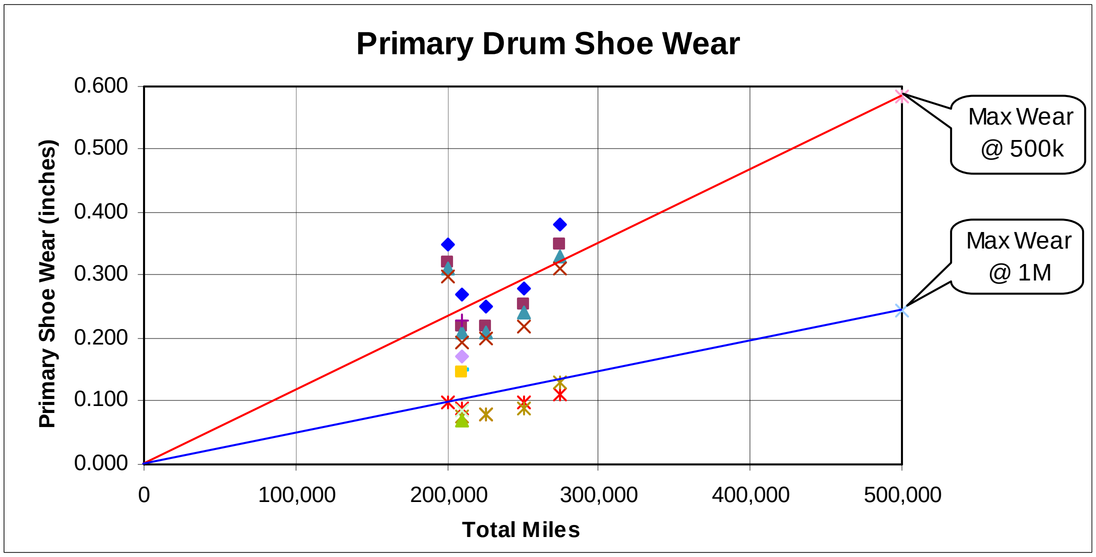
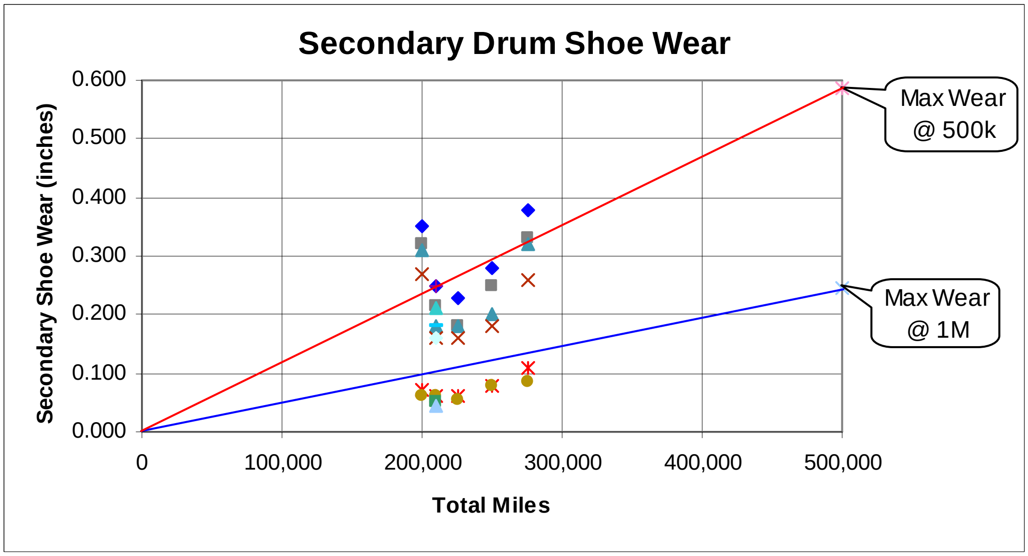


Exhibit 7-22: Secondary Drum Shoe Wear



In drum-brake-equipped vehicles, the tractor's steer axle drum brake assemblies have an extended life expectancy due to the braking dynamics. The drive axles provide more of the braking force and, thus, will require replacement at shorter intervals. Exhibit 7-23 details the component life expectancy for the drum brake assemblies.

Exhibit 7-23: Expected Life of Drum Brake Components[6]

Unit #	Mileage	Mid Drums	Rear Drums	Steer Shoes	Mid Shoes	Rear Shoes	Control System
1843	203,287	>1M, >>1M*	>1M	1M	400K	400K	Meritor ABS
1845	215,794	>1M, >>1M*	1M, >>1M*	>1M	600K	600K	Meritor ABS
1846	239,510	>1M, >>1M*	1M, >>1M*	>1M	600K*	600K*	Meritor ABS
1847	272,115	800K	800K, <800K	>1M	500K	500K	Meritor ABS
1849	211,761	>>1M*	>>1M	>1M	550K	550K	Meritor ABS
1852	213,318	>1M, >>1M*	>1M, >>1M*	>1M	600K	600K	Meritor ABS

* Data for these values is scattered. Refer to graphs in Exhibit 7-21 and Exhibit 7-22 for more information.

A comparison of the brake pad wear between ADBs and drum brakes shows that the maintenance interval for ADBs brake pad replacement is nearly twice the period of drum brake shoes. ADB life expectancy is significantly longer than drum brakes. The even wear rate of brake pads on all the brakes of a given vehicle permits longer periods between maintenance. The increased maintenance interval translates to reduced maintenance hours and reduced parts costs.

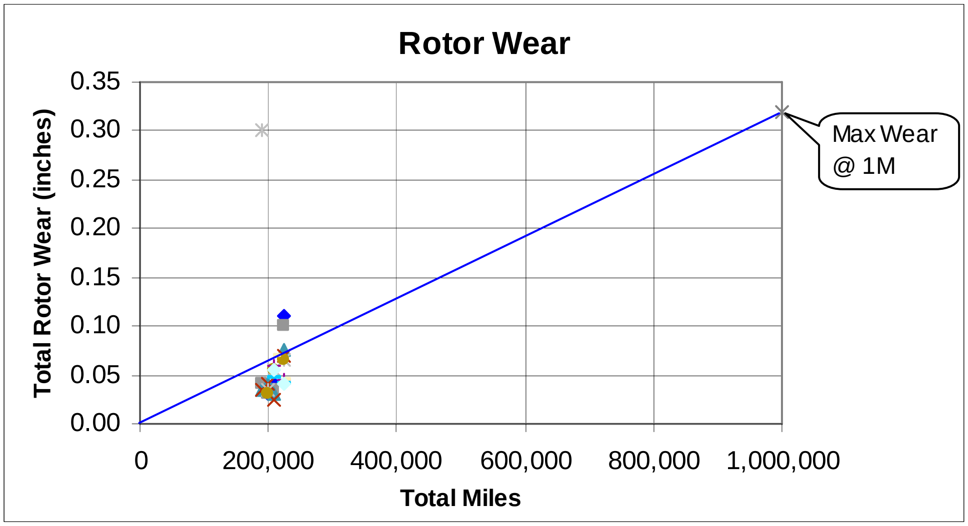
Brake system maintenance schedules also include the replacement of brake rotors or brake drums. The inspection team inspected the brake rotors on each of the nine tractors, inspecting a total of 54 brake rotors. Exhibit 7-24 displays the method used to determine rotor thickness. The rotors were each measured in several locations to determine wear trends and remaining service life.

[6] Ibid.

Exhibit 7-24: Air Disc Brake Rotor Thickness Measurement

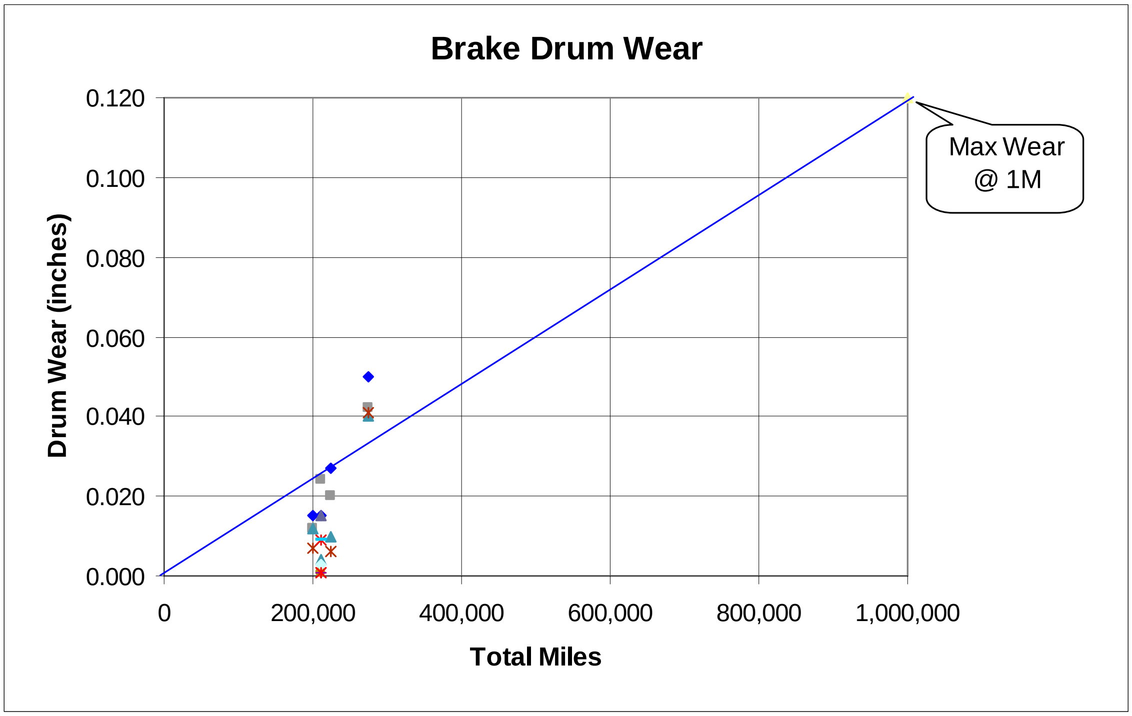
A comparison of these measurements is shown in Exhibit 7-25. The maximum allowable rotor wear is 0.320 inches. Two rotors experienced excessive rotor wear. These rotors were removed from the single tractor that was exposed to extreme braking conditions discussed during the analysis of the ADB brake pads. Taking these rotors out of the analysis, 100 percent of the inspected brake rotors have an expected life in excess of 1 million miles. In addition, almost 50 percent of the brake rotors are expected to have a service life in excess of 1.5 million miles.

Exhibit 7-25: Air Disc Brake Rotor Life Expectancy



The inspection team also measured the brake drum wear after approximately 200,000 miles of operation. The drum inspections did not include the steer axle drums. As shown in Exhibit 7-26, 4 of the 24 brake drums would not meet a life expectancy of 1 million miles using a wear limit of 0.120 inches. Based upon the inspections performed, the drums are expected to have a total service life of less than 700,000 miles. As the drums were installed on the same vehicle, the wear rate may be attributed to extreme braking conditions. Of the remaining 20 drums, 70 percent will meet or exceed a life expectancy of 2 million miles. The remaining 30 percent have a life expectancy in excess of 1 million miles.

Exhibit 7-26: Brake Drum Life Expectancy



The analysis has determined that brake drums and brake rotors experience a similar life expectancy even though brake rotors have higher allowable wear limits. A comparison of the two charts finds that the brake rotors continue to experience even wear rate across all tractors. A review of the rotor wear values of each tractor finds that within a tractor, the wear rate for each wheel location is consistent. In terms of maintainability, this is expected to provide increased maintenance intervals and lower rotor replacement costs. If all the rotors on a single vehicle are replaced according to a regular maintenance schedule, the loss of useful material will be minimal due to the consistency of rotor wear. Drum brake wear consistency was not present within a single vehicle. Each tractor experienced varying brake drum life expectancies. Although the life expectancy was between 1 million and 2 million miles, the complete replacement of all drums on a single vehicle based on scheduled maintenance would result in loss of significant amounts of useful materials and remaining part life. Small costs savings could be realized by replacing the drums in axle pairs, but these data did not show consistent wear patterns between drum assemblies on a single axle.

The uneven wear patterns on the drums may be related to initial installation brake adjustment. Although regular maintenance was not performed during the FOT, if the initial brake adjustments are not properly done, brake assemblies may not provide even braking throughout the vehicle. ADBs had better wear characteristics than drum brakes. The ADB design provides automatic brake adjustment, providing even wear rates for the brake pads and brakes rotors.

Drum brakes offer a significant advantage over the ADBs in the cost of replacement parts. As seen in Exhibit 7-14, the costs for ADB parts are currently close to three times the cost for drum brake parts.

Regardless of the parts costs, the real cost savings related to ADBs is obtained through reduced maintenance intervals. It was estimated that the pad replacement schedule is more than double that of the drum shoe replacement. In addition, the time required for replacing ADB pads is significantly shorter than drum brake replacement. ADB pad replacement requires only the removal of the wheel. At that time, the caliper can remain attached to the tractor and the pads can be removed through the opening within the caliper. The caliper includes a manual adjuster to open the caliper for the new pads and for manual adjustment after the new pads are installed. The process is not expected to exceed 5 minutes after the tire has been removed. Exhibit 7-27 displays the removal of the ADB brake pads. The removal process of the brake pads is straightforward and requires a minimum of time and tools once the wheel is removed.

Exhibit 7-27: Air Disc Brake Pad Removal

In contrast, drum brakes are estimated to take in excess of 30 minutes to replace after the removal of the tire. The maintenance technician must remove the brake drum from the tractor to access the drum shoes. After the shoes have been removed and replaced, the technician must verify the brake adjustment before releasing the tractor to service. In addition, drum brakes require several other maintenance tasks that are not required with ADBs.

As part of the ADB and drum brake maintenance review, the air compressor duty cycle for each foundation brake system was calculated. A compressor's duty cycle is used to determine the required maintenance schedule of the compressor. In Exhibit 7-28, the compressor run time is shown in seconds per mile for each phase of the test and tractor configuration. These data show the vehicles operated at an average speed of 45 miles per hour.

Exhibit 7-28: Compressor Run Time (sec/mile)

	ABS w/ Drum (T2C1)		ABS w/ ADB (T2C2)		ECBS w/ ADB (T2C3)		ABS6 w/ ADB (T2C4)		ECBS w/ ADB (T3)	
Phase	On	Off	On	Off	On	Off	On	Off	On	Off
1	24.71	58.11	10.34	70.47	10.33	77.56	10.10	78.61	8.18	72.24
2	25.79	48.15	7.95	65.58	17.01	59.13	13.83	58.71	7.99	62.07

The air compressor run time was consistent between the phases with the first phase only operating an additional 10 seconds per mile. In contrast, the compressor run-time differed greatly between ADB-equipped tractors and drum brake-equipped tractors. For ADB-equipped tractors, air compressors operated for 10.3 seconds per mile—equating to an average duty cycle of 13 percent. In comparison, air compressors on the drum brake-equipped tractors operated for 24.7 seconds per mile—equating to a 30-percent duty cycle. Drum brake compressors operated at twice the duty cycle of the ADB compressors. The reduced duty cycle for the ADB compressors is expected to result in significantly reduced wear and extended service life.

It should be noted that the comparison of the duty cycles is based on identical air compressors operating in each configuration. If ADB manufacturers reduced the size of the compressor due to the reduced duty cycles, the new compressor may require a higher duty cycle to maintain an identical pressure output.

The analysis of these data related to ADBs shows that they offer a significant advantage to an operator over drum brakes. Scheduled maintenance intervals can be increased, parts replacement is reduced, and the unscheduled maintenance of the ADBs was significantly less than that of drum brakes.

7.6 Advanced ABS Analysis

ABS modulates the air pressure in the brake chamber to prevent wheel lock-up while providing effective braking. In general, the addition of ABS to vehicles has enhanced vehicle stability and control during emergency braking, particularly when operating on slippery roads in a lightly loaded condition. With the addition of ABS to tractor-trailers, vehicles are expected to experience less jack-knifing and other dangerous loss-of-control situations.

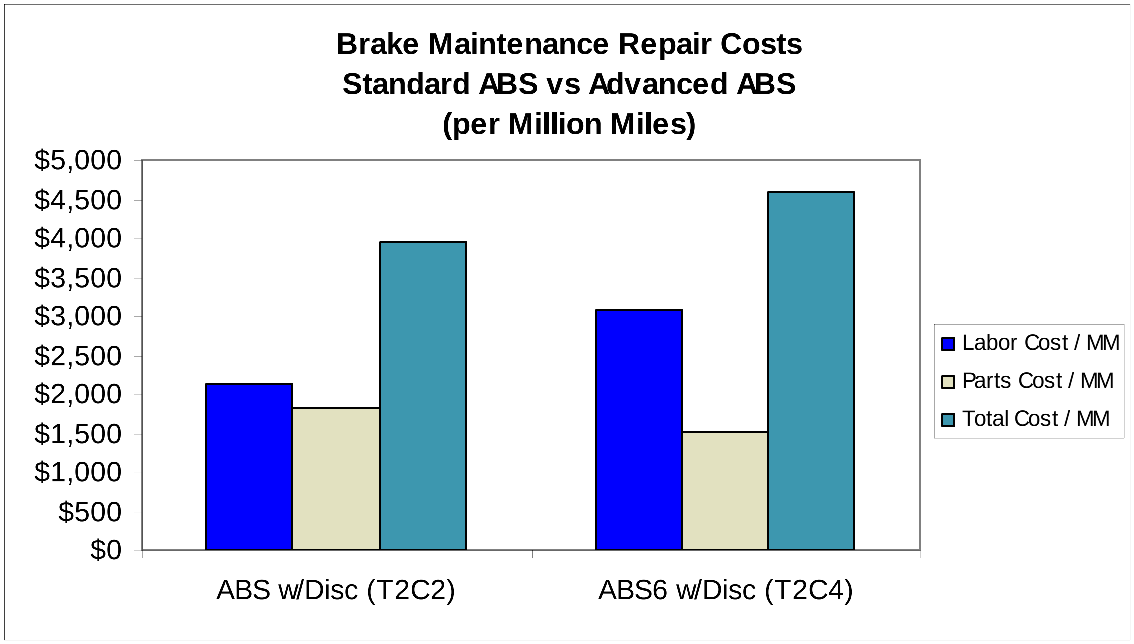
ABS manufacturers have begun introducing the next-generation of ABS. Advanced ABS (ABS6) uses current ABS technology and automatic traction control (ATC) components for added functionality. In addition to the traditional ABS functions, ABS6 offers roll stability control and advanced brake diagnostics to detect weak foundation brake performance on individual wheels.

This section examines the performance of standard ABS and ABS6 and determines the benefits and drawbacks of each technology. Through an examination of the data, Booz Allen compares maintenance costs, component maintainability, and component reliability.

Examining the four configurations available, the ideal comparison involves T2C2 and T2C4. Each of these configurations has ADBs installed on the vehicles, with ABS installed on T2C2 and ABS6 installed on T2C4. By using configurations with the identical foundation brakes, the analysis will be able to focus on the braking control technologies.

The cost analysis, Exhibit 7-29, determined that the standard ABS has a 4-percent cost savings over vehicles with ABS6. The standard ABS experienced a total maintenance cost of $3,958 per million miles. The cost for maintaining ABS6 was $500 per million miles more expensive, at $4,591 per million miles. By examining Exhibit 7-29, the labor cost for maintaining ABS6 was the largest contributor to the cost differential. Maintenance for standard ABS is two-thirds the labor costs for ABS6.

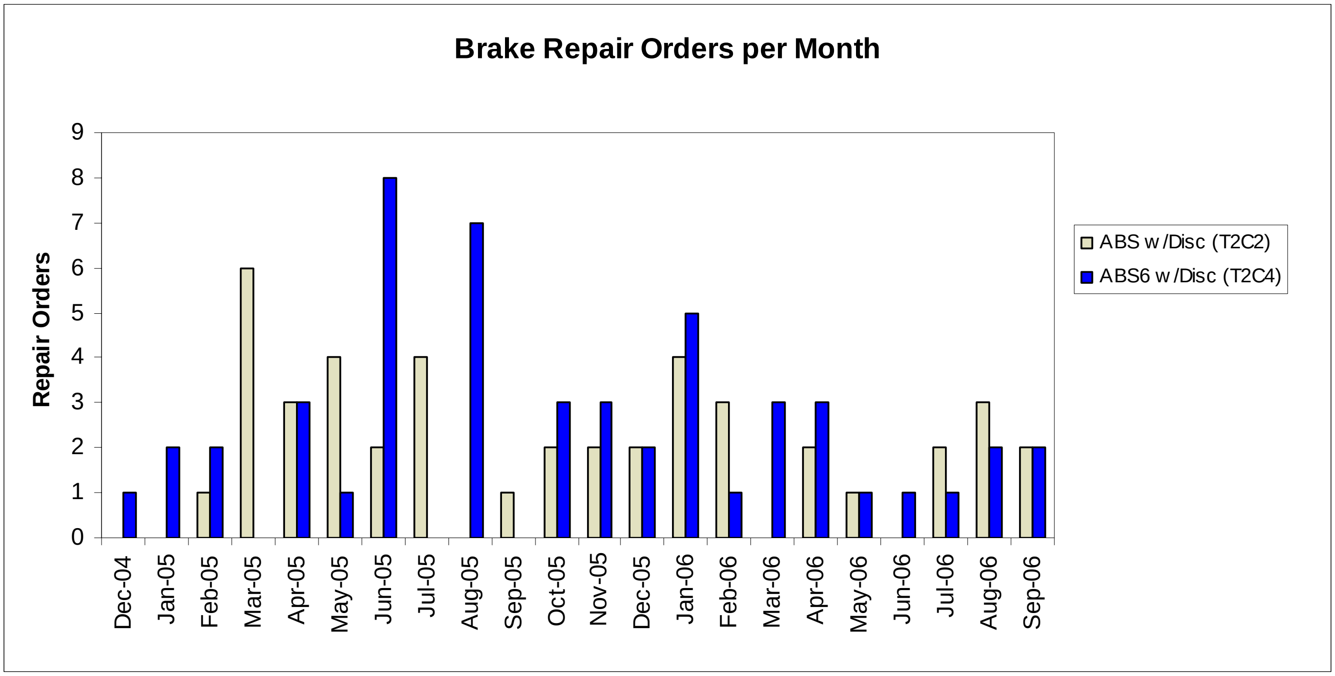
Exhibit 7-29: Standard ABS versus Advanced ABS Maintenance Costs



The increased labor cost for maintaining ABS6 may be attributed to the increased complexity and lack of familiarization with the technology. The additional features provided by ABS6 may be beneficial to vehicle operation, but the technology increases the complexity for routine maintenance tasks. Exhibit 7-29 shows that parts procurement for ABS6 is $300 per million miles less expensive than standard ABS. The cost difference in labor for ABS6 has the most effect on the overall cost for brake maintenance. Thus, ABS6 costs more to maintain.

The length of the FOT may not have overcome the learning curve required for the maintenance technicians to troubleshoot the ABS6 technology efficiently. However, a review of the monthly repair orders suggests this theory may be incorrect. Exhibit 7-30 provides an overview of the monthly distribution of the repair orders over the course of the FOT. These data are shown as raw mileage and has not been normalized, because monthly tractor mileage could not be collected to properly normalize the data. However, as each configuration experienced similar total mileage, the exhibit provides accurate insight to the monthly repair order distribution.

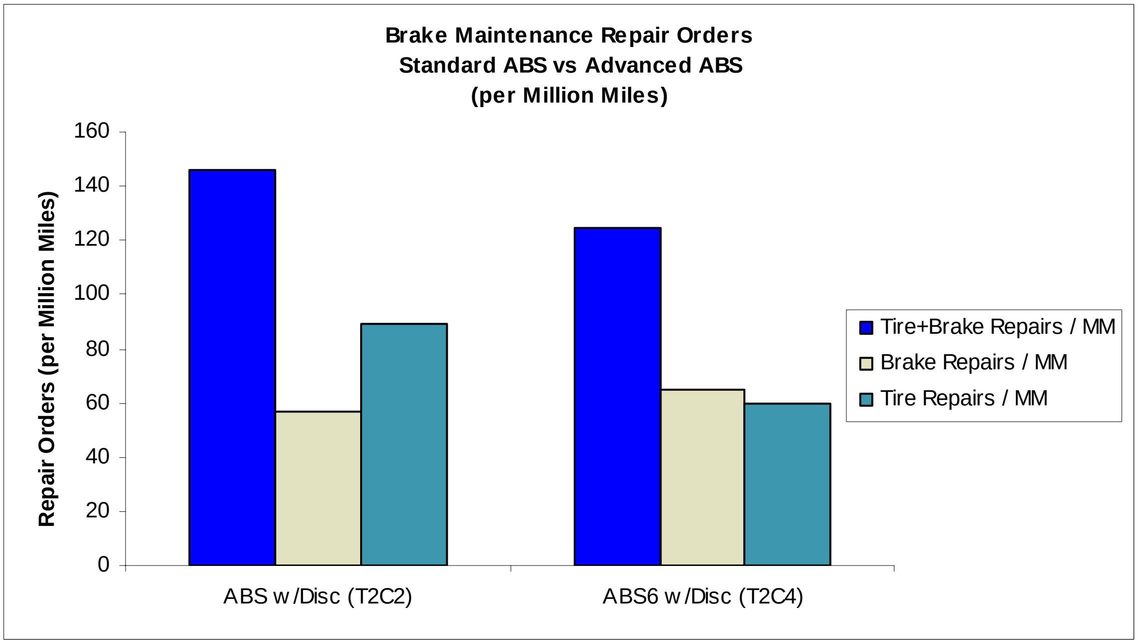
Exhibit 7-30: ABS Monthly Repair Orders (Not Normalized)



The exhibit shows that at the beginning of the FOT, both technologies experienced similar numbers of repair orders. As the test continued, the standard ABS failures steadied at about two repair orders per month, but the ABS6 continued to experience an average of three repair orders per month. The cumulative analysis of the repair orders shows the ABS6 continues to generate repair orders at a faster rate than the ABS. At this rate, the chart demonstrates that the ABS6 did not experience a reduced number of repair orders over time as would be expected with new technology. It appears that the ABS6 technology may require increased maintenance labor hours to provide a reliable and functioning system.

As has been shown in previous exhibits, the total repair orders generated between each technology are similar. Exhibit 7-31 shows that 146 repair orders per million miles were generated for T2C2. This is only 15 percent more than that generated by T2C4. Exhibit 7-31 shows the major contribution to the difference in total repair orders generated was due to the tire repair costs. The brake repair orders for each system were within 12 percent of each other. With such a low number of repair orders generated, this only represents a difference of eight repair orders per million miles.

Exhibit 7-31: Standard ABS versus ABS6 Repair Orders



The analysis set out to determine which of the two technologies exhibited better maintainability and reliability. Based on data gathered, neither system is substantially more reliable than the other. The reason for this may be based on the technology. ABS has been an established technology for many years. Manufacturers took a reliable system and enhanced it to provide ABS6. The failures generated by each technology are expected to be similar in nature. The additional features for ABS6 are not recognizable at a maintenance level. To discern the two technologies from each other, a review of the driver and technician surveys is required to prove which system will receive more positive feedback over time.

Unlike the reliability analysis, the maintainability analysis did identify a substantial difference between the systems. The collected data verified that as systems become more complicated, the maintenance required to maintain those systems increases. For ABS6, the labor costs were $1,000 per million miles more expensive to maintain. Maintenance technicians dedicated an additional 30 labor hours per million miles to the ABS6 technology to repair faults generated during the FOT. For these reasons, the standard ABS technology provides a 12-percent cost savings to the fleet operator based solely on the reduced demand for labor hours. As noted earlier, ABS6 may not have moved beyond its learning curve for the technicians during the course of the FOT.

7.7 ECBS Analysis

ECBS replaces the pneumatic braking control application with a brake-by-wire application. In ABS, the application pressure at the driver's brake pedal equates to the brake pressure applied at the wheel. ECBS does not rely on pneumatic application pressure at the brake pedal for control. Instead, ECBS monitors the brake pedal deflection and correlates that to the driver's desired deceleration rate. The rate is converted to the pressure required at the wheel, and the system applies the brakes accordingly. Pneumatic control lines are replaced with wire and electronic sensors.

ECBS technology provides an enhancement of the ABS technology. Unlike traditional ABS, ECBS can determine the pressure that causes the wheels to lock up. After the wheel lock-up is detected, the ECBS will apply a lighter braking force to attempt to prevent a second wheel lock-up. The reduction of braking pressure will continue until a constant pressure can be applied to the wheels without locking them up for improved braking performance. In addition to ABS functionality, the ability of ECBS to control each brake independently provides a platform for advanced control systems (i.e., stability control and automatic cruise control).

This section of the analysis examines whether ECBS has reduced maintenance costs and labor hours compared with ABS.

In this analysis, ECBS controls were installed with ADBs under two separate test configurations. Although labeled as separate tests, the configurations can be combined for the maintenance analysis, as the examined components were identical under both configurations (T2C3 and T3). The use of all of the available data between these two configurations will provide a larger data source than using a single configuration. For the ideal comparison of ECBS and ABS, the T2C2 configuration was chosen for analyzing the ABS data. Each of these three configurations has ADBs installed on the vehicles, with ABS installed on T2C2 and ECBS installed on T2C3 and T3. By using these configurations, with the same foundation braking systems, it is assumed that any differences in operation can be attributed to the braking system electronic components and not the braking system's mechanical components.

Exhibit 7-32, Exhibit 7-33, and Exhibit 7-34 were generated to demonstrate the data elements that were accumulated for the ECBS versus ABS analysis. The change in numbers is attributed to combining T2C3 and T3.

Exhibit 7-32: Total Mileage for ECBS Configurations

Template	# Tractors	Total Mileage
ABS w/Disc (T2C2)	10	775,131
ECBS w/ Disc (Total T2C3 & T3)	18	1,368,800
ECBS w/Disc (T2C3)	10	683,485
ECBS w/Disc (T3)	8	685,315

Exhibit 7-33: ECBS Brake Repair Costs (Normalized)

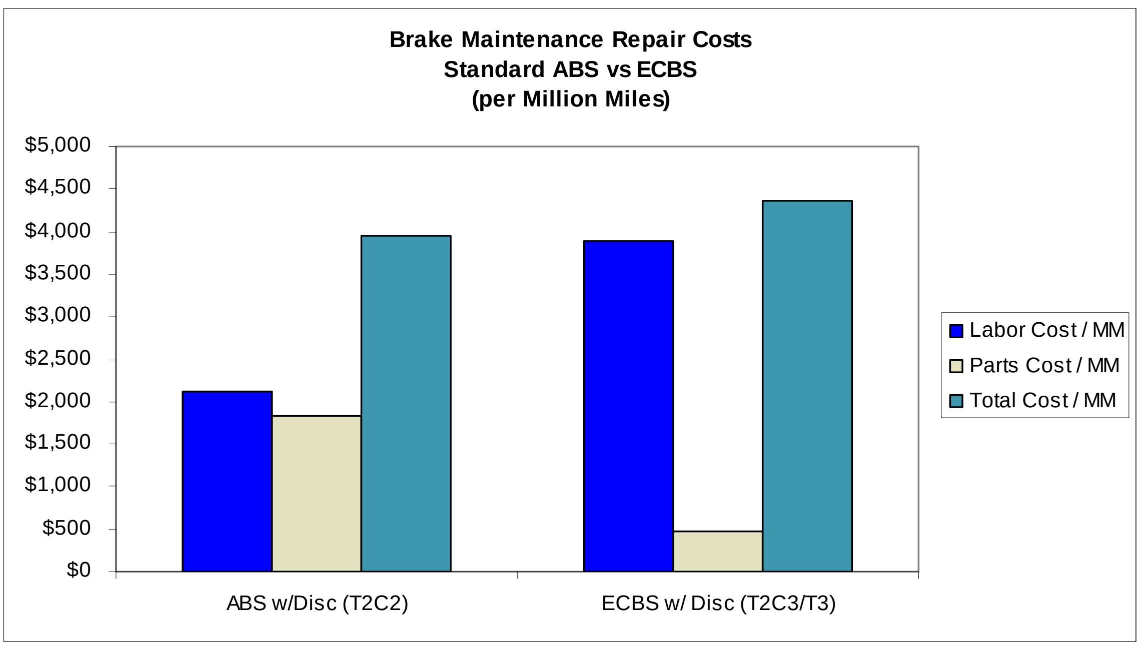
Template	Man Hours/ MM	Labor Costs/ MM	Parts Costs/ MM	Total Costs/ MM
ABS w/Disc (T2C2)	92.5	$2,126.45	$1,831.85	$3,958.30
ECBS w/ Disc (Average of T2C3 & T3)	167.4	$3,886.58	$482.31	$4,368.89
ECBS w/Disc (T2C3)	143.5	$3,300.48	$632.79	$3,933.27
ECBS w/Disc (T3)	191.2	$4,471.11	$332.24	$4,803.35

Exhibit 7-34: ECBS Brake Repair Orders (Normalized)

Template	Repairs/ MM (Per Million Miles)	Brake Repairs/ MM	Tire Repairs/ MM
ABS w/Disc (T2C2)	146	57	89
ECBS w/ Disc (Average of T2C3 & T3)	182	91	91
ECBS w/Disc (T2C3)	138	67	70
ECBS w/Disc (T3)	226	114	112

With the combined parts and labor data, the cost analysis demonstrated that ABS costs less to maintain than ECBS. At $3,958 per million miles, ABS exhibited a cost savings of 10 percent over ECBS average total costs of $4,368. The largest contributor to the savings was the difference in labor costs. Reviewing Exhibit 7-35, the labor cost for ECBS was found to be almost twice the cost of ABS. Although the parts costs for ECBS is significantly less than ABS, the labor required to maintain the system exceeds the labor costs required for ABS.

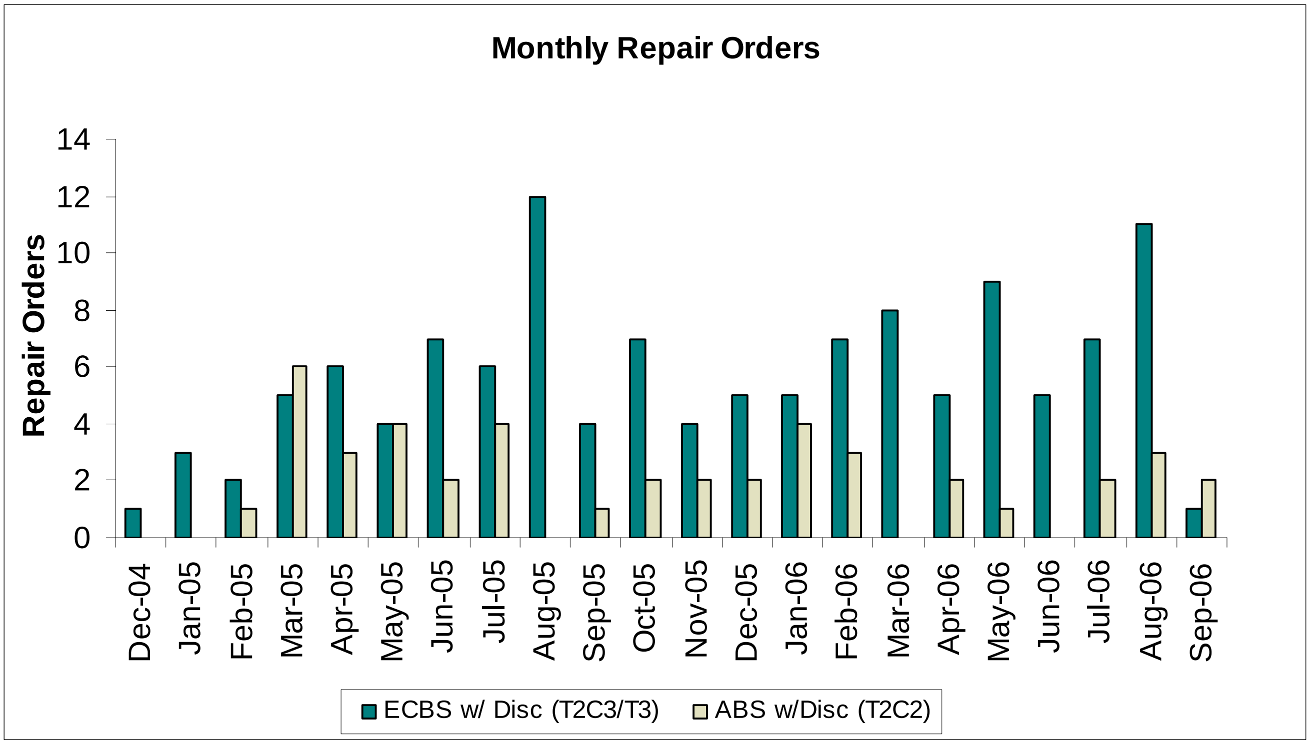
Exhibit 7-35: ABS versus ECBS Brake Maintenance Costs



The introduction of new technologies does not always present a cost savings to the owner. Electronics require significant troubleshooting expertise over basic technology. Like the advanced ABS, the time period of the experimental design was not significant enough to demonstrate long-term benefits of the ECBS. It could be expected that over time, labor costs for ECBS would decrease as the technicians become more knowledgeable in ECBS failures.

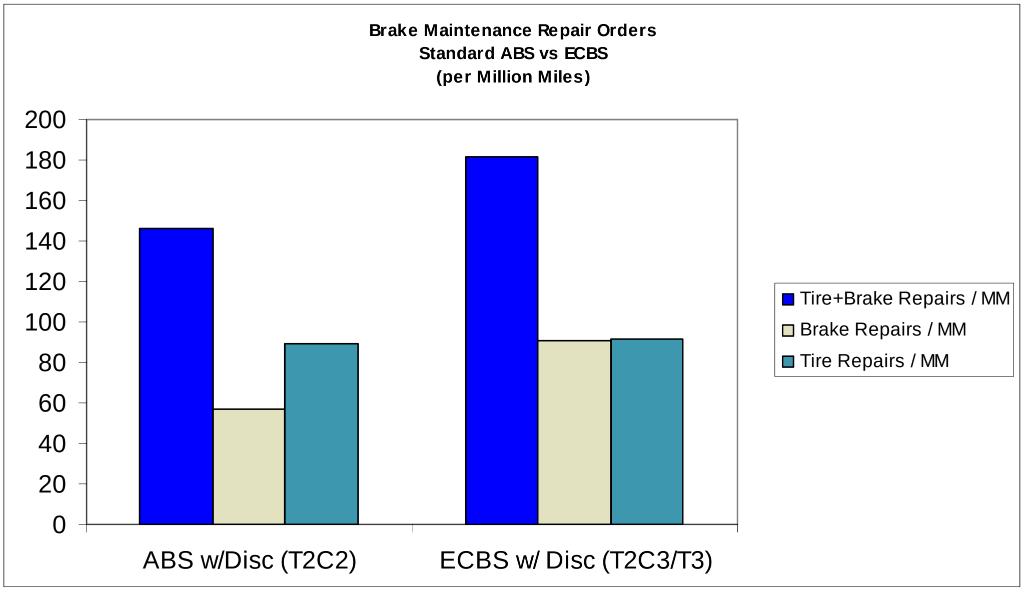
Due to the lack of monthly mileage numbers for each configuration, a normalized view of monthly repair orders cannot be completed. If the total mileage is considered, it can be estimated that the T2C3 and T3 configuration accumulated mileage at approximately twice the rate of the T2C2 configuration. A review of Exhibit 7-36 provides a non-statistical view of the monthly accumulation of repair orders for each configuration. Although these data are not normalized, it can be deduced that the ECBS faults are currently still steadily increasing at more than two times that of the ABS faults. ECBS is experiencing an average of five repair orders per month. As these data show, the ECBS continues to operate in an infant mortality stage. If ECBS continues to experience the number of repairs orders generated during the FOT, with labor costs similar to that experienced during the FOT period, a cost benefit may not be feasible until much further into its service life. This information cannot be proven with the experimental design's small test period, but can be estimated by looking at the current repair orders generated.

Exhibit 7-36: ABS and ECBS Monthly Repair Order Generation



Over the course of the FOT, ECBS experienced 25 percent more repair orders per million miles than ABS. At 182 repair orders per million miles, it generated an additional 36 total (tire and brake) repair orders over the ABS configuration (Exhibit 7-37). The difference can be directly attributed to the difference in brake repair orders between ABS and ECBS. ECBS generated an additional 34 brake repair orders per million miles.

Exhibit 7-37: ECBS versus ABS Repair Orders



The final analysis is based on the understanding that all these data were taken during the infancy stages of the ECBS installation. With only this information, and no method to forecast future labor costs, the ABS technology would appear to offer a 10-percent cost advantage for fleet operators. ECBS is not widely utilized among the U.S. commercial truck fleet. In addition, the largest advantage to ECBS is the ability to provide additional vehicle safety control features that are not offered by ABS. U.S. truck manufacturers have witnessed the interest in ECBS, and are now offering advanced ABS technologies that provide 90 percent of the features in ECBS. The maintenance cost analysis of advanced ABS conducted in the previous section revealed that both the standard ABS and the advanced ABS offered similar total maintenance requirements.

CHAPTER 8. DRIVER AND MECHANIC SURVEYS

Driver and mechanic surveys were created to capture user feedback on the advanced braking technologies installed on the tractor-trailers for the FOT. The surveys were distributed at the Wal-Mart maintenance facility in Loveland, Colorado. The surveys were completed anonymously by the drivers and mechanics participating in the FOT. The survey results were retuned to Booz Allen with all data relevant to personnel identity masked.

The conductor team identified the individual drivers participating in the FOT and operating the tractor-trailer combinations equipped as FOT templates. The surveys were also used as a method to measure driver behavioral changes between the two phases of the FOT. In addition, responses were gathered throughout the FOT from mechanics to track technology acceptance, reliability, and level of maintenance requirements as compared to the standard ABS with drum tractor-trailer.

Drivers were surveyed three times throughout the FOT. The first survey was administered prior to introducing the new technologies. The surveys identified baseline driver background, information, and existing knowledge on the advanced braking systems to be used during the FOT. The baseline surveys included information such as:

- Years of experience;
- Age;
- Average daily miles driven;
- Normal loaded weight; and
- Perception of technologies under test.

The remaining driver surveys identified driver's perception of the advanced brake technologies. A survey was administered after six months of operating FOT tractor-trailers, which was administered prior to the activation of the ECBS-enabled technologies on the ECBS with disc tractor-trailers. The final survey was administered at the conclusion of the FOT. The survey captured any changes in driver opinions based on increased exposure to the technologies or on experience gained from operating the ECBS-enabled vehicles.

Technicians were also surveyed three times throughout the FOT. The first survey was administered to identify baseline information and subjective opinions of the FOT technologies. The baseline surveys included information such as:

- Years of experience;
- Age; and
- Perceptions of maintenance requirements of the technologies under test.

The remaining technician surveys identified the technician's perception of working with the advanced brake technologies. A survey was administered after six months of troubleshooting the FOT tractor-trailers to capture the reactions to the maintenance and reliability of ADBs, advanced ABS, and ECBS tractors without the enabled technologies. The survey was administered prior to the activation of ECBS-enabled technologies on the ECBS with disc tractor-trailers. The final survey was administered at the conclusion of the FOT. The survey captured any changes in opinions based on increased exposure to the technologies or on experienced gained from working with the ECBS-enabled vehicles.

8.1 Driver Surveys

The driver surveys were distributed to all participating drivers in the FOT. A total of 58 completed surveys were returned to Booz Allen. Exhibit 8-1 provides a snapshot of the number of driver surveys received during the FOT, organized by template and phase.

Exhibit 8-1 : Driver Surveys Received

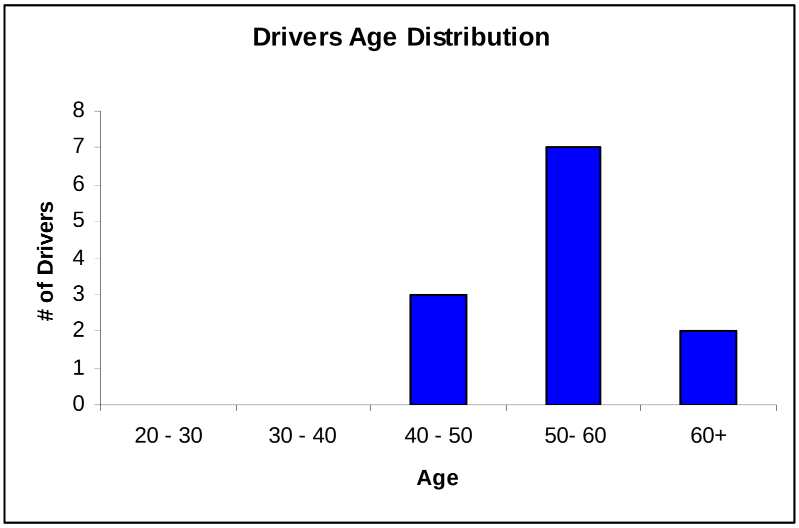
Driver	Baseline	6 Months	12 Months
ABS w/Drum (T2C1)	2	0	8
ABS w/Disc (T2C2)	1	2	9
ECBS w/Disc (T2C3)	1	3	4
ABS6 w/Disc (T2C4)	0	3	8
ECBS w/Disc (T3)	0	2	8
Unknown	8	0	0
Total	12	10	37

8.1.1 Baseline Driver Surveys

The driver surveys were administered prior to the start of the FOT solicited profile information from the drivers. Twelve drivers completed the surveys. The following information provides background on the drivers, including the driver’s age, years of experience, and daily miles traveled. The baseline survey also queried the drivers on their experience in operating tractors and trailers equipped with ADBs, advanced ABS, ECBS, ACC systems, and other safety-related technologies.

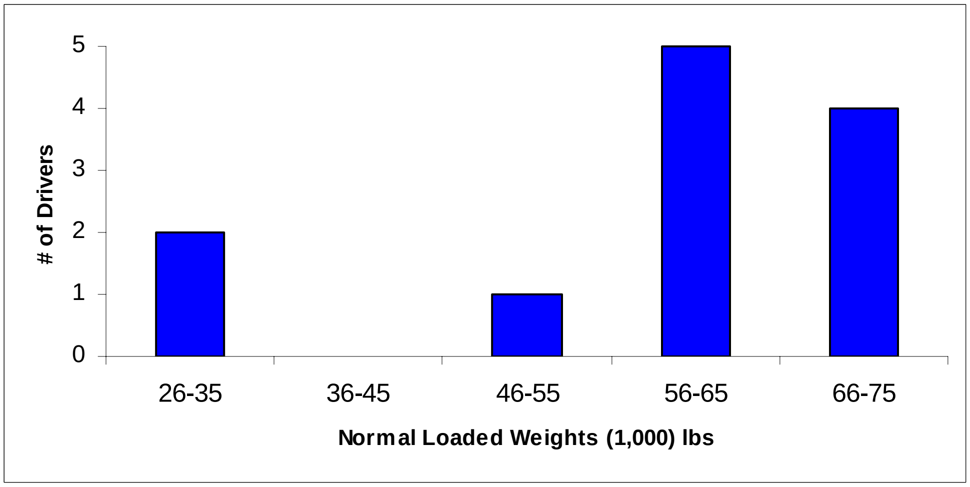
As shown in Exhibit 8-2, all of the profiled drivers were over the age of 40 with more than 10 years of experience driving commercial vehicles. Seven of the 12 drivers were between 50 and 60 years old, and two drivers were over 60 years old.

Exhibit 8-2: Distribution of Drivers' Ages



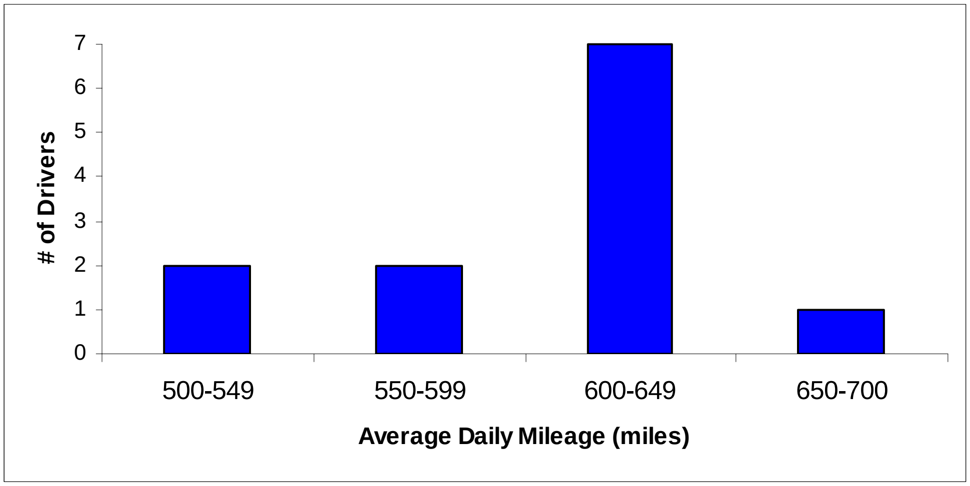
The normal loaded weights of tractor-trailers varied among the 12 profiled drivers. Exhibit 8-3 illustrates the normal loaded weights of the tractor-trailer combinations hauled by the profiled drivers, with 41 percent of the drivers having a normal loaded weight between 56,000 and 65,000 pounds.

Exhibit 8-3: Normal Loaded Weights of Tractor-Trailers



As shown in Exhibit 8-4, 58 percent of the drivers averaged between 600 and 649 miles of driving per day. An additional 33 percent of the drivers averaged between 500 and 599 miles of driving per day. The final driver reported driving an average of 650 to 700 miles per day.

Exhibit 8-4: Average Daily Mileage



The final questions on the baseline survey were to determine the drivers' existing knowledge of operating vehicles with advanced brake technologies. As shown in Exhibit 8-5 and Exhibit 8-6, most drivers had no experience operating tractors or trailers equipped with the advanced brake technologies.

Exhibit 8-5: Driver Experience Operating Tractors with Advanced Technologies

Driver Experience with Advanced Technology	Yes	No
Disc Brakes	1	11
Advanced ABS w/ Stability Control	1	11
ECBS	0	12
ACC	1	11
Collision Warning	0	12

Exhibit 8-6: Driver Experience Operating Trailers with Advanced Technologies

Driver Experience with Advanced Technology	Yes	No
Disc Brakes	1	11
Advanced ABS w/ Stability Control	1	11
ECBS	1	11

8.1.2 Mid-FOT and Post-FOT Driver Surveys (6 months and 12 months)

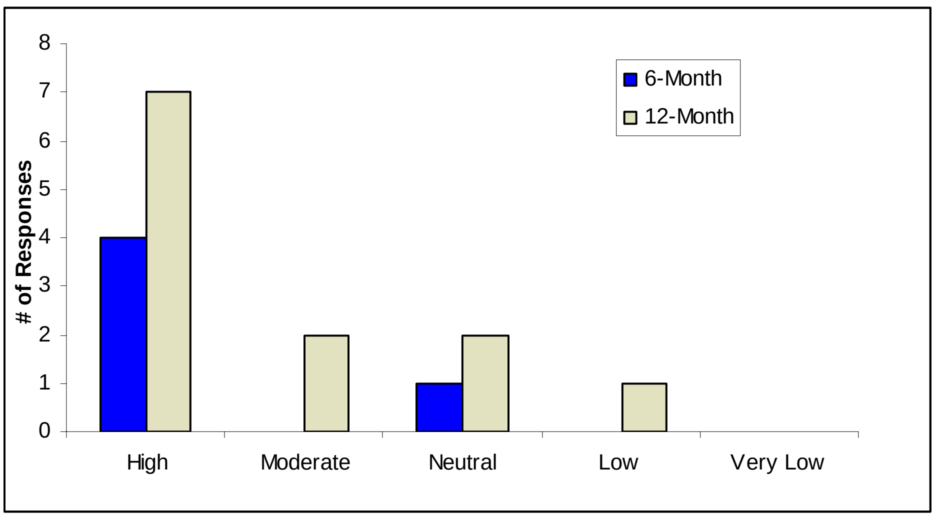
The 6-month and 12-month surveys gathered feedback from the Wal-Mart drivers on their experience with operating vehicles with advanced brake technologies. The survey queried drivers on their confidence in the advanced braking systems, differences in operating advanced brake technologies as compared to conventional brakes, the presence of improved braking performance, and any changes in driving behavior as a result of the advanced braking systems. The following sections summarize the survey findings on ECBS, ADBs, advanced ABS, and ACC.

Electronically Controlled Braking Systems (ECBS)

Surveys were administered specifically to drivers of the ECBS tractors equipped with ADBs (T2C3 and T3). The surveys questioned the drivers on their acceptance of, confidence in, and behavior while operating vehicles with ECBS and stability control programs. Five drivers submitted 6-month surveys, and 12 drivers submitted 12-month surveys.

The drivers were asked to rate their level of acceptance of and confidence in ECBS. A five-point scale, ranging from high to very low, was used to rate the responses. After operating the vehicles for 12 months, the ratings for the acceptance of and confidence in ECBS were identical. The surveys showed 58 percent of the drivers had a high level of acceptance and confidence in ECBS (Exhibit 8-7). One driver stated he was driving a tractor with a load of pallets on the trailer when the left steer tire blew out. According to his statement, the ECBS enabled him to maintain control of the vehicle until it could be brought to a stop. The surveys show that the majority of the drivers that did not have a high rating commented on the inability to keep the system functioning. One driver rated his confidence as low because he could not get a feel of operating the truck with ECBS. He stated the brake application gave the impression of being all on or all off. He could not ease the brakes on or off. This comment was provided during the 6-month survey only. No similar comments were provided at the 12-month survey.

Exhibit 8-7: Level of Driver Acceptance of and Confidence in ECBS



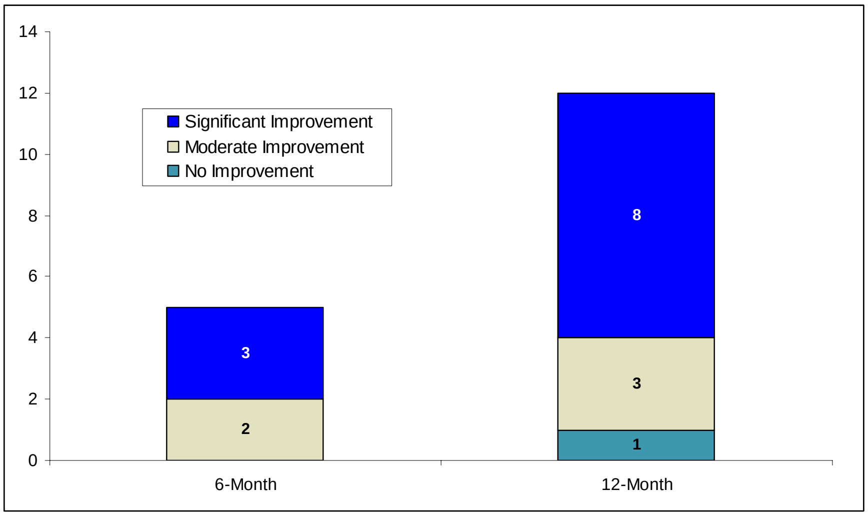
The 12-month survey found that 66 percent of the drivers experienced the activation of the ECBS fault light during the FOT, with only 40 percent of the 6-month surveys stating an activation occurred.[7] In 12-month surveys, half of the drivers indicated the light activated frequently. During the activation of the light, 50 percent of the drivers noticed a change in the operation of the brakes. Several drivers commented on sluggish brake pedal response during the ECBS light activation. They stated the brake pedal had to be pressed almost to the floor to activate the brakes, as compared to the brake pedal sensitivity when the light was not activated.

[7] As the surveys were not taken at the time of any failure, the source of the failure cannot be identified.

Eleven of the 12 drivers responded during the 12-month survey that the brake pedal on the ECBS-equipped tractor felt different from the brake pedal on tractors equipped with the conventional brake system. Of the surveyed drivers, 70 percent were able to adjust to the feel of the brake pedal within 2 weeks. One driver stated it took 3 to 6 months to adjust. Brake pedal feedback was reduced as a result of ECBS for 70 percent of the drivers.

After operating the vehicles for 12 months, 92 percent of the drivers stated that ECBS improved braking performance. As shown in Exhibit 8-8, the majority of the drivers (72% of the drivers surveyed) found that ECBS significantly improved braking performance. The remaining drivers only saw moderate or no improvements in braking performance.

Exhibit 8-8: Improved Braking Performance Due to ECBS



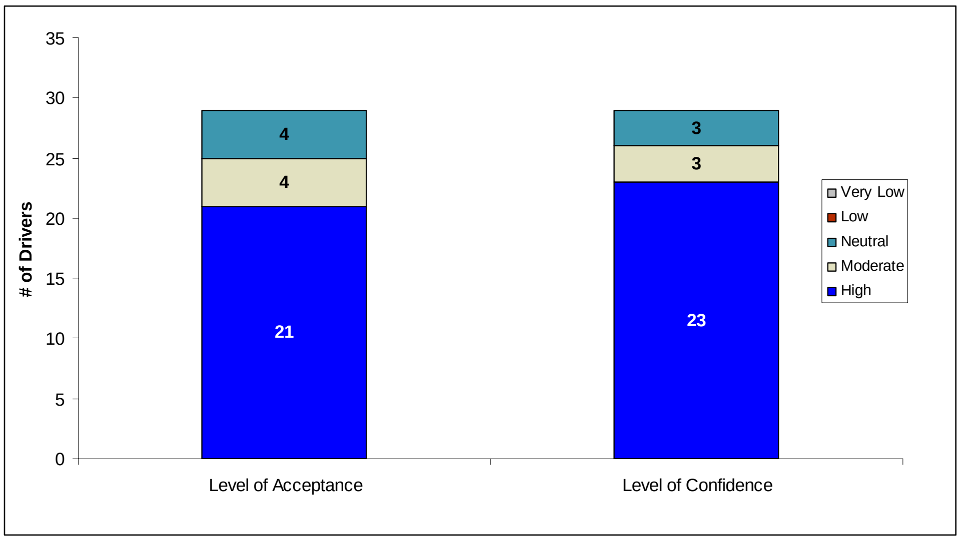
The ECBS-equipped tractor-trailers were bundled with an ESC system designed to improve vehicle stability during high lateral acceleration maneuvers such as evasive lane changes and tight radius curves. Although the system was available on the tractor-trailers throughout the FOT, it was only enabled during the last 6 months of the FOT. In the 12-month surveys, the 12 affected drivers were asked if they noticed the stability control program operating during the test period. In response to the surveys, 66 percent of the drivers stated they noticed the ESC system operating during the test period. The drivers stated the system was mainly active while operating in the mountains and through curves. The eight drivers all stated that ESC assisted in maintaining control of the vehicle. Because of the ESC-enabled vehicles, half of the drivers stated they would operate the vehicle differently than they would operate a conventional vehicle. One driver stated that he entered a curve at a higher than normal speed to experience the ESC functionality.

Air Disc Brakes (ADBs)

ADBs were installed on all tractors except the T2C1 (ABS w / Drum) Template. The surveys for ADBs questioned the drivers on their acceptance of, confidence in, and behavior while operating vehicles with ADBs as compared to drum brakes. A total of 10 drivers submitted 6-month surveys and 29 drivers submitted 12-month surveys.

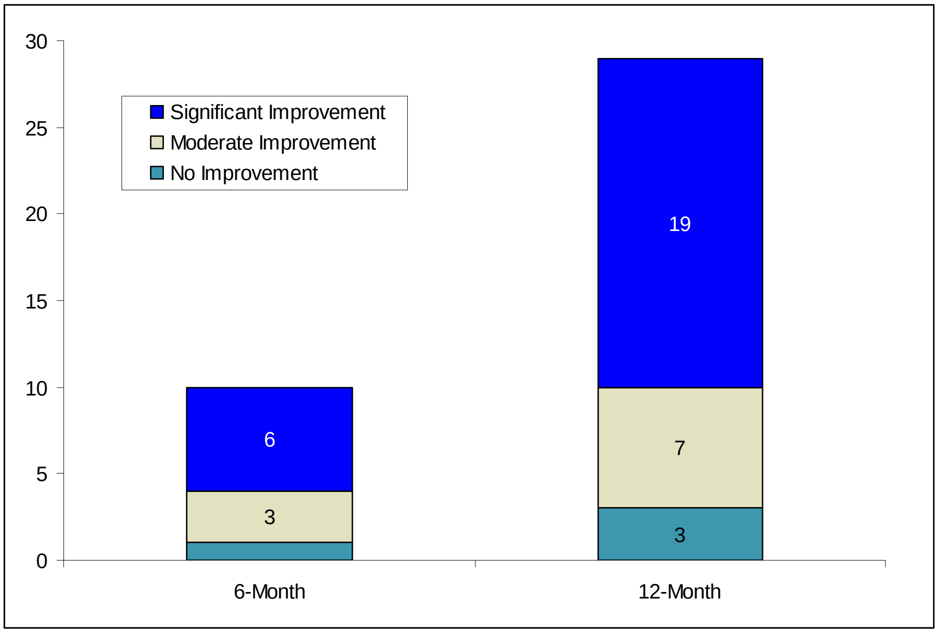
The drivers were asked to rate their level of acceptance of and confidence in ADBs. A 5-point scale, ranging from high to very low, was used to rate the responses. Exhibit 8-9 shows 72 percent of the drivers surveyed after 12 months had a high level of acceptance of ADB and 79 percent had a high level of confidence in ADB. The drivers stated the ADBs improved the braking response and control of the vehicle. One driver stated ADBs were by far the best brakes he had used. Because of the ADBs, some drivers stated they did not experience the brake fade associated with drum brakes. One driver whose confidence was neutral on ADB stated that he was unable to visually check ADB pads for wear. A second neutral driver stated that ADBs worked safely and had a good pedal feel when both the tractor and trailer were equipped with ADB. The driver did not like to operate tractor-trailers with different foundation brakes on the tractor and trailer.

Exhibit 8-9: Level of Driver Acceptance of and Confidence in ADB (12 months)



Nineteen of the 29 drivers (65%) responded during the 12-month survey that ADBs improved the feel of the brake pedal as compared to drum brakes. As shown in Exhibit 8-10, 90 percent of the drivers felt that ADBs improved braking performance. The pedal feel and performance differences when compared to drums was significant enough that a few drivers noted that they had to make a mental note of which foundation brake technologies were on the tractor.

Exhibit 8-10: Improved Braking Performance Due to ADB



Drivers were asked whether they operated a tractor equipped with ADBs in a different manner than a tractor equipped with conventional drum brakes. Five of the eight drivers responding to the mid-FOT survey said that they operated an ADB-equipped tractor differently; however, 86 percent of the drivers responding to the 12-month survey stated that they did not operate the ADB-equipped tractor any differently from a tractor equipped with conventional brakes. Driver comments to this question noted the reduced pressure required to apply adequate pressure to ADBs. One driver stated a difference was noticed in descending long grades due to the lack of brake fade.

As part of the ADB surveys, drivers were requested to provide their experience with hauling a trailer equipped with ADB. Drivers stated trailers with ADBs could not regulate the stopping. The driver found that after the vehicle went below 5 miles per hour, the tractor-trailer wanted to stop immediately. It was also stated that if an ADB tractor was pulling a drum brake trailer, the driver felt the tractor was provided all the braking effort.

Advanced Antilock Braking Systems (ABS)

Advanced ABS was installed on three tractor configurations—T2C1 (ABS with Drum), T2C2 (ABS with Disc), and T2C4 (ABS6 with Disc).

The drivers were asked to rate their level of acceptance of and confidence in advanced ABS. A 5-point scale, ranging from high to very low, was used to capture drivers' responses. No driver gave a rating lower than neutral regarding their level of acceptance of advanced ABS. In the mid-FOT survey, 75 percent of drivers surveyed said that they had a high level of acceptance of and confidence in the advanced ABS. In the post-FOT survey, 66 percent of drivers said that they had a high or moderate level of acceptance of advanced ABS.

Seventy percent of the drivers who responded to the mid-FOT survey said that the ABS light had come on during the test period.[8] Eighty-nine percent of those drivers said that the light did not come on often, and 50 percent responded that it was clear why the light had come on. Four of the seven drivers said that they responded to the warning light by continuing to the next service station before stopping, one driver pulled over immediately, and two drivers did nothing. Seventy-one percent of drivers who responded to the post-FOT survey said that the ABS light had come on during the test period. Fifty-five percent of those drivers said that the light did not come on often, and 71 percent responded that it was clear why the light had come on. Ten of the 20 drivers said that they responded to the warning light by continuing to the next service station before stopping, one driver pulled over immediately, and nine drivers did nothing. Only 30 percent of the drivers responded in each survey that they noticed the advanced ABS operating during the test period.

RSC is designed to improve vehicle stability during high lateral acceleration maneuvers such as evasive lane changes and tight radius curves. RSC was installed on T2C1 and T2C2 tractors throughout the FOT, but was only active during the last 6 months of the FOT. In the 12-month surveys, the 15 affected drivers were asked if they noticed the RSC program operating during the test period. In response to the surveys, 47 percent of the drivers stated they noticed the RSC operating during the test period. Four of the seven drivers stated that RSC assisted in maintaining control of the vehicle, with two stating it had no effect and one stating that it contributed to the loss of control of the vehicle. The driver who lost control of the vehicle stated the system cut fuel to the tractor as the roll started to occur. Depowering is expected of RSC. With regard to changing operating behavior due to RSC-enabled vehicles, 93 percent of the drivers stated they did not operate the vehicle differently from a conventional vehicle.

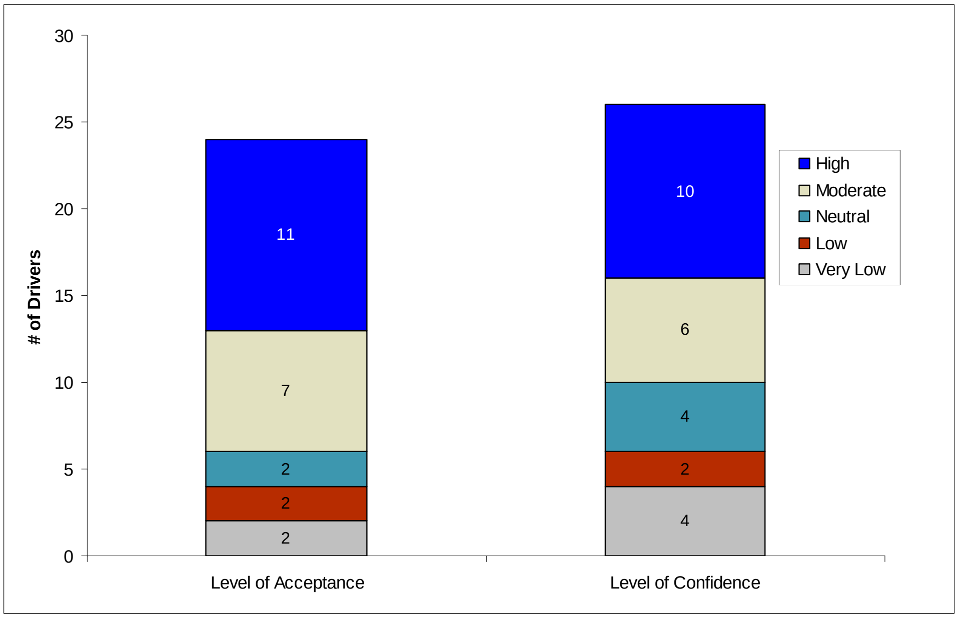
Adaptive Cruise Control (ACC)

ACC systems were installed on four tractor configurations—T2C1 (ABS with Drum), T2C2 (ABS with Disc), and T2C3/T3 (ECBS with Disc). ACC was installed on the tractors throughout the FOT, but was only active during the last 6 months of the FOT. A total of 29 drivers submitted 12-month surveys with feedback on the ACC system.

The drivers were asked to rate their level of acceptance of and confidence in ACC. A 5-point scale, ranging from high to very low, was used to rate the responses. Exhibit 8-11 shows 31 percent of the drivers surveyed had a high level of acceptance of ACC and 24 percent had a high level of confidence. The drivers stated that the system operated inconsistently and intermittently. In the surveys, drivers expressed dissatisfaction in vehicle detection sensitivity. Driver comments varied greatly for the acceptance of and confidence in ACC. Further comments are included in the appendix.

[8] As the surveys were not taken at the time of any failure, the source of the failure cannot be identified.

Exhibit 8-11: Level of Driver Acceptance of and Confidence in ACC (12 months)



When asked if ACC reduced fatigue while driving, 34 percent of the drivers stated it reduced daytime fatigue and 40 percent stated it reduced nighttime fatigue. The drivers stated the system should not be used as a supplement to combat driver fatigue. A few statements included the concern that drivers would become complacent, and drivers should not use ACC to combat fatigue. One driver did note that ACC is useful during nighttime driving as it may react quicker than the driver can see an upcoming object.

When compared to conventional cruise control, 57 percent of the drivers stated ACC is better, while 19 percent stated it was the same. The remaining 23 percent of the drivers stated that they did not like ACC better than conventional cruise control. The drivers commented on the ACC remaining alert even if the driver becomes distracted. All of the comments from the drivers were based on the fact that the ACC is not only a cruise control system, but also a collision warning system.

8.2 Mechanic Surveys

Mechanic surveys were distributed to the maintenance technicians in Wal-Mart's Loveland, Colorado, maintenance facility. A total of 73 completed surveys were returned to Booz Allen. Exhibit 8-12 provides a snapshot of the number of mechanic surveys received during the FOT, organized by phase.

Exhibit 8-12: Mechanic Surveys Received

	Baseline	6-Month	12-Month
Total	34	19	20

8.2.1 Baseline Mechanic Surveys

The mechanic surveys were administered prior to the start of the FOT solicited profile information from the mechanics. Thirty-four mechanics completed the surveys. The following information provides background on the mechanics' age, years of experience, and typical maintenance duties. The baseline survey also queried the mechanics on their experience maintaining tractors and trailers equipped with ADBs, advanced ABS, ECBS, and other safety-related technologies.

As shown in Exhibit 8-13, 55 percent of the profiled mechanics were over the age of 41, with 91 percent of the mechanics falling in the age range of 30 to 50 years. The number of years of experience maintaining heavy vehicles varied among the mechanics. Exhibit 8-14 shows that 88 percent of the mechanics had at least 3 years of maintenance experience and 53 percent had greater than 5 years of experience.

Exhibit 8-13: Age of Wal-Mart Mechanics

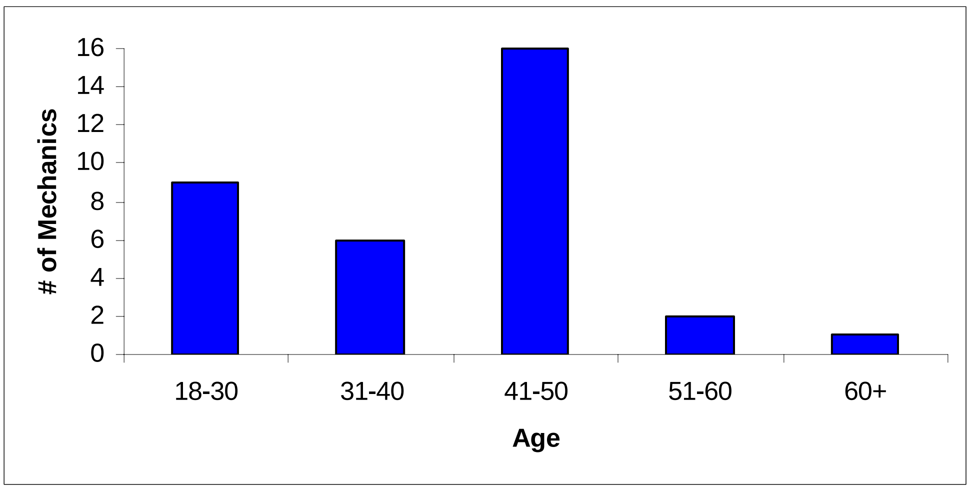
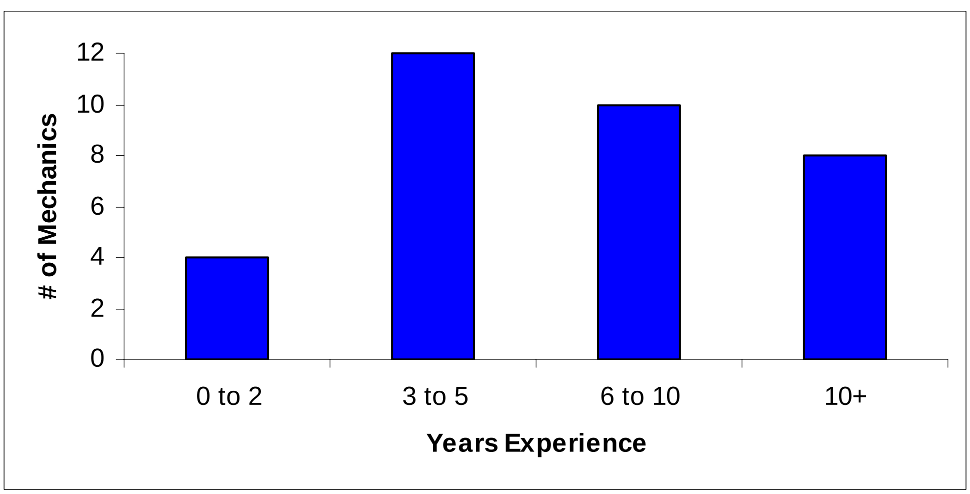


Exhibit 8-14: Wal-Mart Mechanic Experience



Unlike Wal-Mart drivers, Wal-Mart mechanics had more experience working with advanced braking systems and advanced safety technologies. Exhibit 8-15 displays the mechanics' responses to questions regarding their experience maintaining vehicles equipped with advanced brake technologies.

Exhibit 8-15: Mechanic Experience Maintaining Tractors With Advanced Technologies

Mechanic Experience with Advanced Technology	Yes	No
Disc Brakes	9	25
Advanced ABS w/ Stability Control	4	30
ECBS	1	33
ACC	1	33
Collision Warning	1	33
Lane Tracking / Road Departure	1	33

8.2.2 Mid-FOT and Post-FOT Mechanic Surveys (6 months and 12 months)

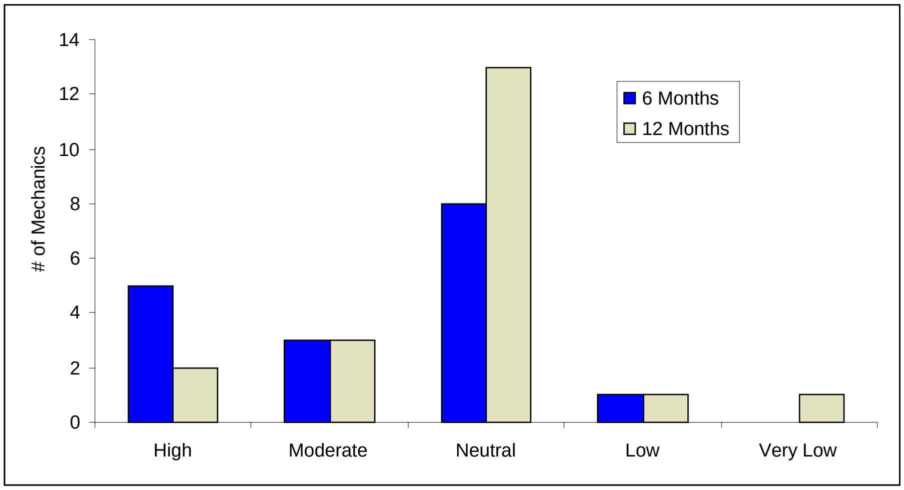
The 6-month and 12-month surveys gathered feedback from Wal-Mart mechanics on their experience in maintaining vehicles with advanced braking systems, including their confidence in performing maintenance, the difficulty of diagnosing and repairing the advanced braking technologies, and the frequency of replacing components as compared to conventional braking systems. The following sections summarize the survey findings on ECBS, ADBs, and advanced ABS.

ECBS

Surveys were administered to all mechanics at Wal-Mart's Loveland, Colorado, truck maintenance facility on their perception of ECBS maintenance. Seventeen mechanics submitted 6-month surveys and 20 mechanics submitted 12-month surveys.

The mechanics were asked to rate their level of confidence in the reliability and maintainability of ECBS. A 5-point scale, ranging from high to very low, was used to capture mechanics' responses. The surveys showed that 25 percent of the mechanics had high or moderate confidence in the reliability and maintainability of ECBS, with 68 percent of the mechanics neutral on the subject, after maintaining the vehicles for 12 months (Exhibit 8-16). The mechanic comments from the surveys indicate little interaction occurred with ECBS during the FOT. Mechanics also noted the lack of knowledge for troubleshooting the new technology.

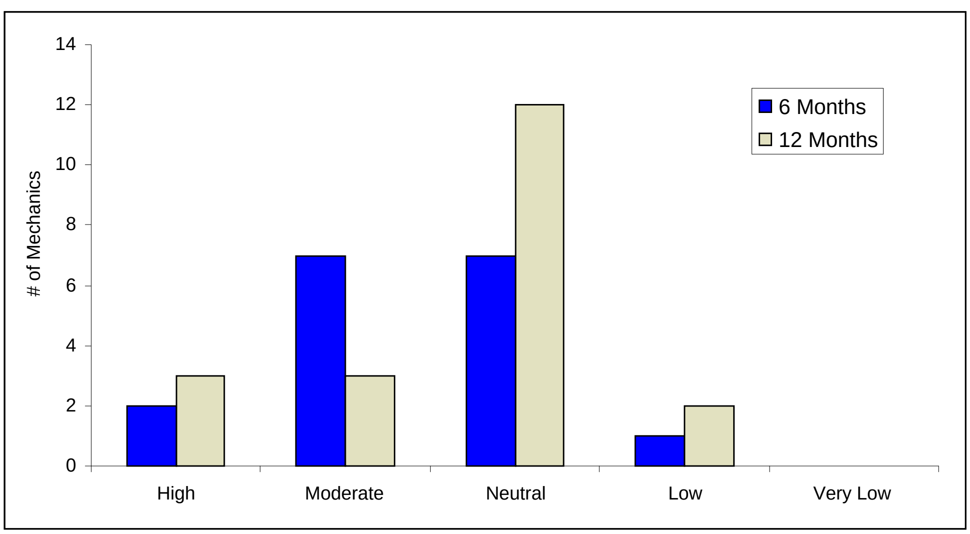
Exhibit 8-16: Level of Mechanic Confidence in ECBS



Few mechanics reported performing maintenance on ECBS during the test period. Only five mechanics, 25 percent of the 12-month surveyed mechanics, performed any maintenance on ECBS during all phases of the FOT. During the 12-month survey, 53 percent of the mechanics reported the ECBS generated fault codes during the last 6 months of the FOT.

After working with ECBS for 12 months, 28 percent of the mechanics found ECBS highly to moderately difficult to diagnose and repair on tractors and trailers. As shown in Exhibit 8-17, 62 percent of the mechanics rated the difficulty as neutral. The mechanics were equally divided in their ratings on the frequency of required maintenance on ECBS. At the 12-month survey, 75 percent of the mechanics rated the frequency of maintenance as low to neutral.

Exhibit 8-17: Level of Difficulty to Diagnose and Repair ECBS



The 12-month surveys stated 78 percent of the mechanics found maintenance requirements for ECBS were either more difficult or just as difficult as maintaining current ABS technology. The mechanics continued to state the lack of knowledge in troubleshooting ECBS, absence of replacement parts, and lack of exposure.

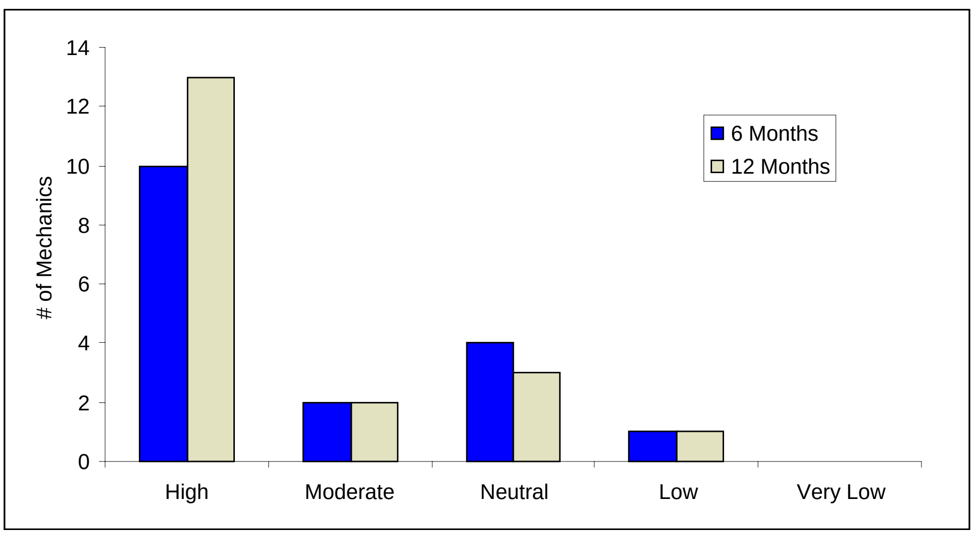
In terms of component replacement, the 12-month surveys stated that 70 percent of the mechanics did not feel ECBS required more frequent component replacement as compared to ABS. The majority of the mechanics also did not experience maintenance of the high-speed cable.

ADBs

ADBs supplied by Bendix were installed on 38 tractors, as well as on 85 of the 100 trailers participating in the FOT. ADBs were controlled pneumatically on 20 tractors and 30 trailers, while the ADBs were controlled electrically on the other 28 tractors and 70 trailers. Seventeen mechanics submitted 6-month surveys and 19 mechanics submitted 12-month surveys.

The mechanics were asked to rate their level of confidence or trust in the reliability and maintainability of ADBs. A five-point scale, ranging from high to very low, was used to capture the mechanics' responses. From the 12-month surveys, 68 percent of the mechanics had a high level of confidence in ADB (Exhibit 8-18). One mechanic stated the ADBs were a very good system with long-lasting parts and better performance. Numerous mechanics commented that no problems were encountered with ADBs during the 12-month FOT. Mechanics also commented on reduced pad wear as compared to drum brakes.

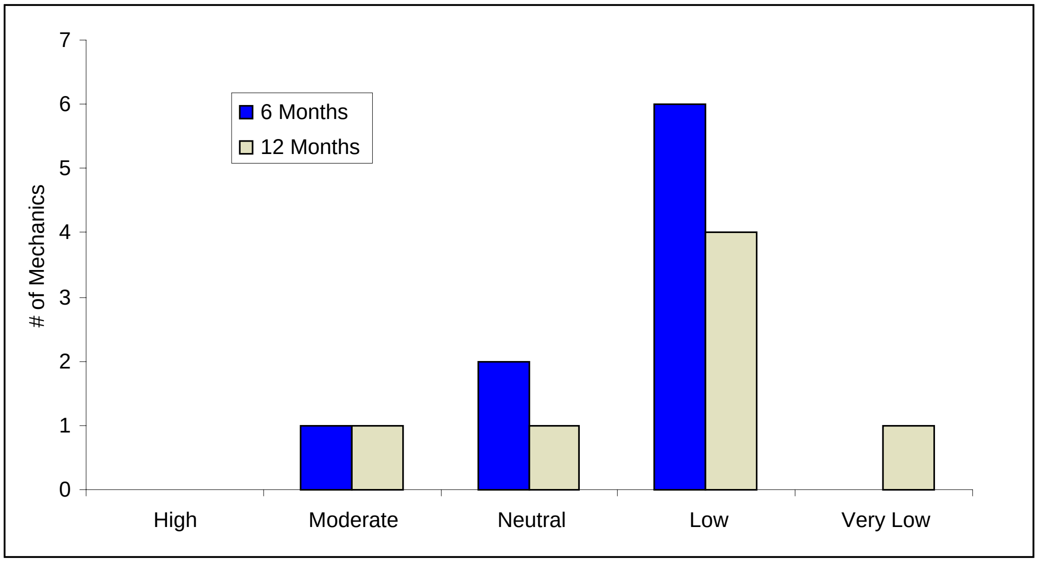
Exhibit 8-18: Level of Mechanic Confidence in ADB



Only 5 percent of the surveyed mechanics reported in the 12-month surveys of performing maintenance on ADB. Of the 20 surveyed mechanics during the 12-month survey, only a single mechanic performed adjustments on the brakes. The majority of the mechanics that adjusted the ADB said that the adjustment procedures were less difficult as the adjustment procedures for drum brakes.

The 12-month surveys showed 85 percent of the mechanics found the difficulty of maintaining ADB from neutral to very low. No mechanics rated the difficulty as high. The survey also indicated 85 percent of the mechanics rated the frequency of maintenance as low to very low. The 12-month surveys indicated 75 percent of the mechanics found ADBs less difficult to maintain as compared to drum brakes. The mechanics stated the maintenance was less difficult due to the reduced parts for an ADB system, faster component change-out, and reduced adjustment requirements. A single mechanic stated the maintenance was more difficult due to use of new tools and difficulty in removing bolts.

Exhibit 8-19: Level of Difficulty to Diagnose and Repair ADB

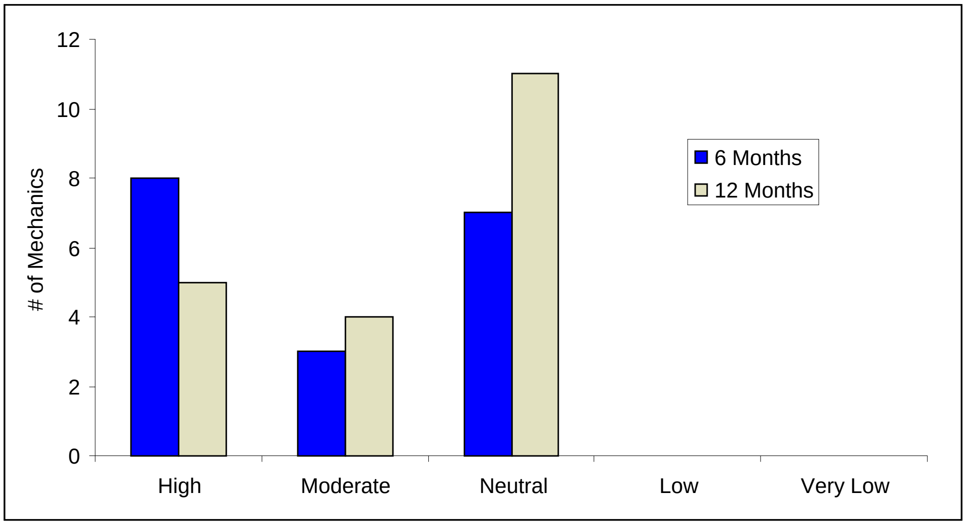


Advanced ABS

ABS was installed on all FOT tractor configurations. The MeritorWabco advanced ABS was installed on T2C1 and T2C2 tractors, and the Bendix ABS6 next-generation ABS was installed on T2C4 tractors. The surveys were not separated into the specific advanced ABS system. The survey responses provide general feedback for all ABS tested in the FOT. Eighteen mechanics submitted 6-month surveys and 20 submitted 12-month surveys.

The mechanics were asked to rate their level of confidence or trust in the reliability and maintainability of advanced ABS. A five-point scale, ranging from high to very low, was used to capture the mechanics' responses. No mechanic gave a rating lower than neutral regarding their confidence in advanced ABS. In the 12-month survey, 45 percent of the mechanics were found to have a high or moderate level of confidence in advanced ABS (Exhibit 8-20). Most mechanics commented on the absence of ABS problems, resulting in no feedback on confidence level in advanced ABS. A single mechanic commented on the lack of knowledge in troubleshooting advanced ABS technologies.

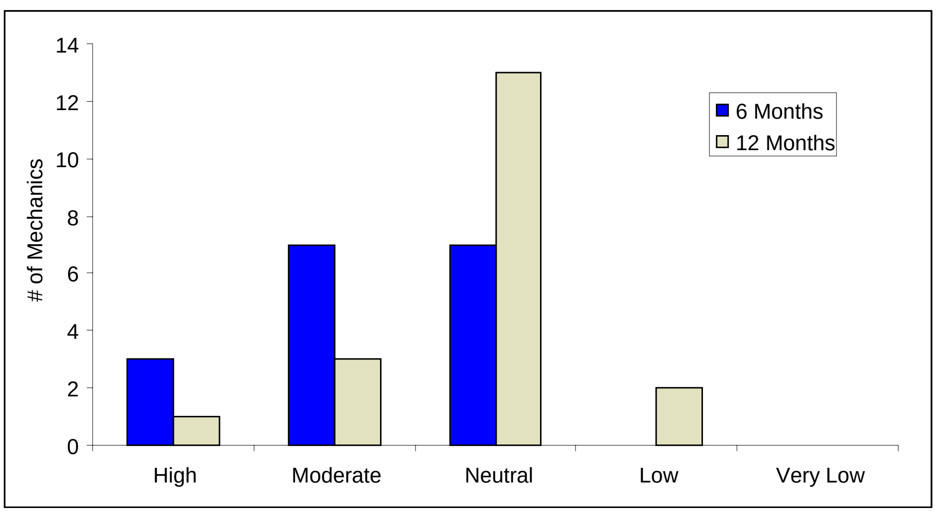
Exhibit 8-20: Level of Mechanic Confidence in ABS



Few mechanics performed maintenance on advanced ABS during the FOT test period. Only 15 percent of the mechanics surveyed at 12 months performed maintenance on advanced ABS during the test period. During the 12-month survey, 35 percent of the mechanics reported the ABS generated fault codes, with 29 percent reporting fault codes during the first 6 months.

When asked to rate the level of difficulty in diagnosing and repairing advanced ABS during the 6-month surveys, 58 percent of the mechanics found the difficulty level to be high to moderate, as compared to 21 percent in the 12-month surveys. As shown in Exhibit 8-21, 68 percent of the mechanics were neutral on the difficulty of diagnosing and repairing advanced ABS. At the 12-month survey, 74 percent of the mechanics rated the frequency of maintenance as moderate to neutral.

Exhibit 8-21: Level of Difficulty to Diagnose and Repair ABS



The 12-month surveys found 42 percent of the mechanics found advanced ABS to be more difficult to maintain than conventional ABS, with 47 percent ranking the difficulty as neutral. Fourteen of the mechanics (78% of those surveyed) stated that advanced ABS does not require more frequent replacement of electronic components than current ABS. The complaints from the mechanics included the increased steps for troubleshooting, the increased components to fail, and the continued lack of knowledge in troubleshooting.

APPENDIX A: HYPOTHESIS ANALYSIS

Hypothesis 1

Description Statement:
Drivers operating with disc brakes reduce their average following interval.

Analysis:
Details of the analysis are found in Section 5.3.1. Following events were used to determine a true "steady state" following interval. A following event was defined to have a vehicle speed of greater than 10 miles per hour, with a target detected in front of the tractor for a minimum of 15 consecutive seconds. The event duration was specifically chosen to determine a steady state following interval and eliminate any short duration events such as vehicles crossing in front of the tractor. For this particular analysis, CCC and ACC were off.

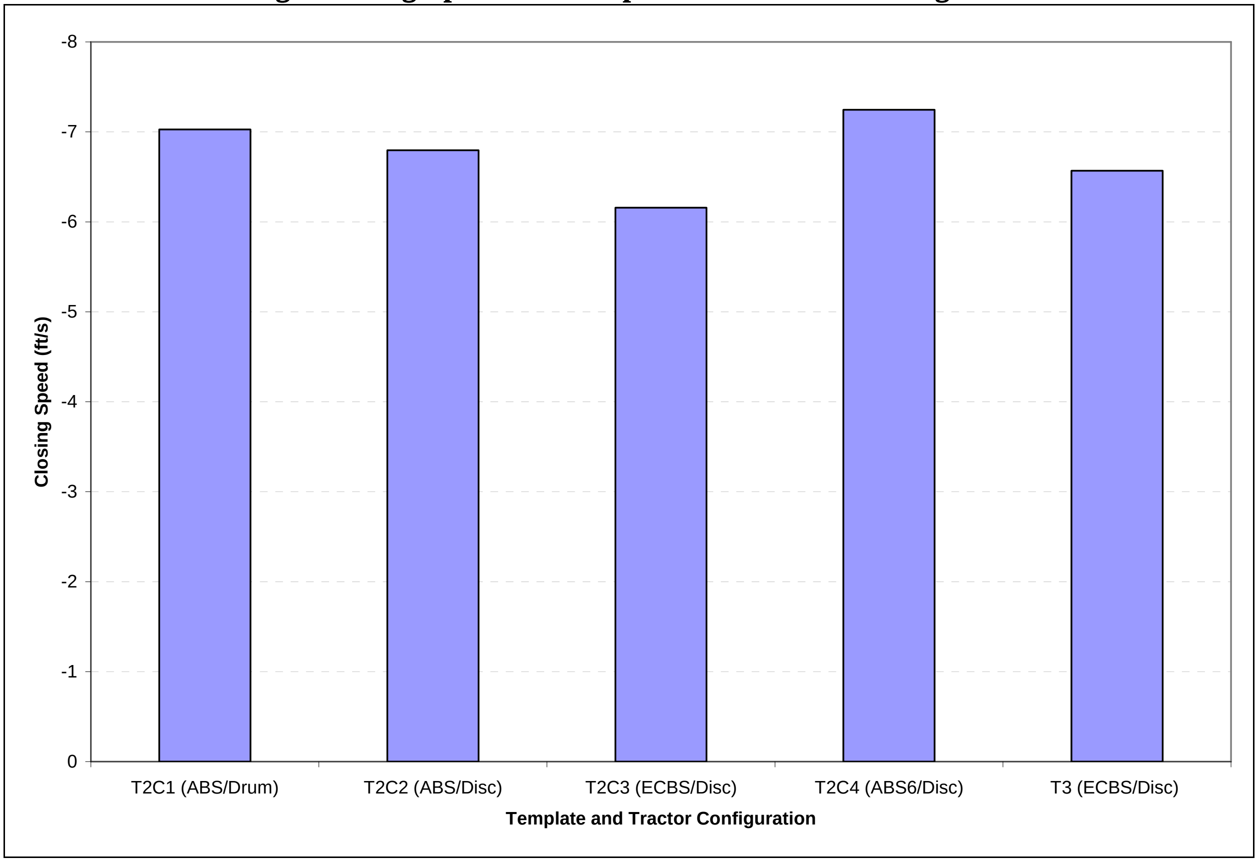
Result:
Tractors equipped with ABS and ADBs were not found to have reduced following intervals compared to ABS/drum tractors.

Hypothesis 2

Description Statement:
Drivers operating vehicles with disc brakes increase their average closing speeds before applying the brakes.

Analysis:
To determine the closing speed prior to brake application, the database was mined for events where the tractor was traveling above 20 miles per hour with a forward target detected for at least 5 seconds, and where the target range rate was negative. The duration was specified to eliminate insistences of vehicles cutting in front of the tractor. As shown below, all tractor groups had a closing speed between 6 and 7 feet per second, except for the T3 profiling tractors, which recorded a closing speed of just of 2 feet per second.

Average Closing Speed for Template and Tractor Configurations



Result:

ECBS / Disc tractors showed slightly lower closing speeds prior to brake application.

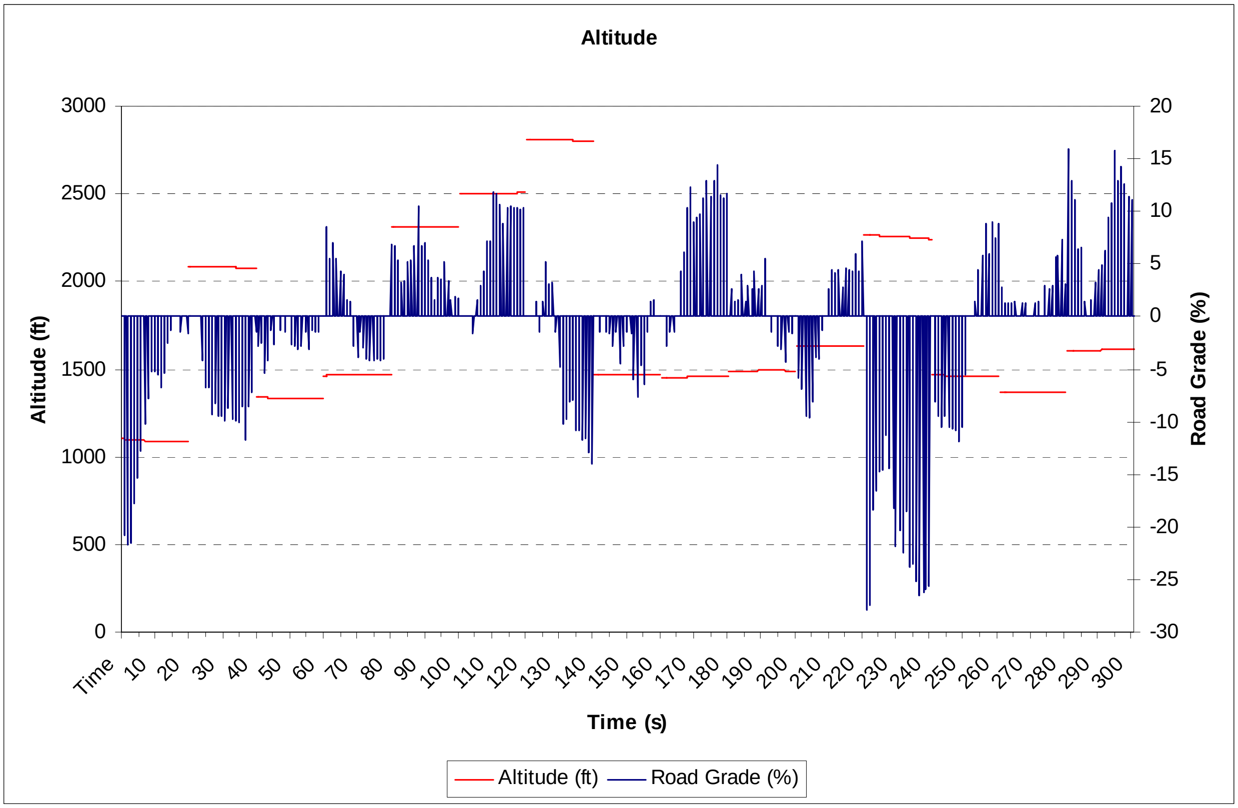
Hypothesis 3

Description Statement:

Drivers operating vehicles with disc brakes increase their average downhill speeds.

Analysis:

GPS altitude data were used to determine when trucks were operating on grades. The altitude data provided by the GPS unit was deemed unusable for two reasons: slow refresh rate (1 Hz), and low precision.



The sampling rate of the DAS was 10 Hz, but the altitude refresh rate was only 1 Hz. Even when altitude data varied by only a foot or so, the DAS interpreted the change over 0.1 second and the estimated road grade could be calculated to be as much as 10 times the actual grade. Over long periods of time, the altitude data were usable. However, the analysis being performed required greater precision than was possible with data available. The sample graph above shows 15 separate events. The road grade calculated is unstable and returns values as high as 30-percent grade.

Result:
The limitation on the precision of the altitude data, coupled with the mismatch of the sampling rate between the DAS and the GPS altitude data, led to road grade data that was unusable for any sophisticated analysis. Road grade could not be used in any of the analyses required for hypotheses 3, 11, 22, and 35.

Hypothesis 4

Description Statement:
Drivers operating vehicles with disc brakes increase their average deceleration rates.

Analysis:
Details of the analysis are found in Section 5.3.2. The brake events were determined using the brake application (BA) channel. The channel records either a “1” or “0” as the driver depresses and releases the treadle valve. For each time value, the deceleration rate was calculated by using the derivative of the velocity channel (J1939 vehicle speed) or the change in speed from two

consecutive time points. The average deceleration rate is then determined by taking the sum of the deceleration rates and dividing it by the number of time points. The average deceleration rate was calculated for all 1.15 million braking events.

Result:
Drivers operating ABS tractors with disc brakes were not found to increase their average deceleration rates.

Hypothesis 5

Description Statement:
ADBs reduce frequency of trucks failing State safety inspections.

Analysis:
No analysis was possible. State inspection records were not recorded during the FOT. No comparison was possible.

Result:
No results were available due to lack of State inspection records.

Hypothesis 6

Description Statement:
ADBs improve the straight-line stability during braking due to improved brake balance.

Analysis:
Details of the analysis are found in Section 5.3.5. The yaw rate data from tractors and trailers was recorded and compared. The difference between the two yaw rate sensors was used to determine the stability of the combination unit under braking. The greatest difference in yaw rate was seen on the drum tractor / drum trailer combination with an average difference of 3.5 to 4.25 degrees per second varying with speed. Conversely, the disc tractor / disc trailer combination had some of the lowest differential yaw rate between the two units. A drum tractor / disc trailer had similarly low differential yaw.

Result:
ADBs were found to improve the straight-line stability of the combination under braking.

Hypothesis 7

Description Statement:
ADBs improve straight-line stability during braking due to reduced brake hysteresis effects.

Analysis:
Available data is not sufficient to characterize the cause of the improved stability. For this reason, this hypothesis is treated along with Hypothesis 6 and generalized to describe the stability of vehicles with ADBs.

Result:
Analysis proves that straight-line stability increases when using ADBs. See Hypothesis 6 discussion. The cause of the improved stability must be generalized as ADBs and cannot be attributed directly to a reduced hysteresis effect.

Hypothesis 8

Description Statement:
Brake pedal responsiveness is improved with ADBs.

Analysis:
The driver surveys were analyzed to determine the driver's reaction to the brake pedal feel in vehicles with ADBs. The surveys asked if the drivers noticed an improved brake pedal feel in vehicles operating with ADBs. A total of 39 responses were received throughout the FOT.

Drivers Responses to Inquiry on Improved Brake Feel

6-Month Survey		12-Month Survey	
Improved Feel	No Improvement	Improved Feel	No Improvement
8	2	19	10

Varying responses were generated by the drivers, including:

- "These brakes have a great feel—less air pressure to stop than drum brakes—and a lot faster to activate."
- "…When hooked to disc brake-equipped trailer, the ADBs are very safe and have a good pedal feel to them…"
- "No feel, as far as how much pressure to apply. The disc brakes grab, not gentle."

Result:
After 12 months, 65 percent of the drivers reported that the ADBs improved the feel of the brake pedal.

Hypothesis 9

Description Statement:
ADBs reduce the frequency of impending wheel lock up and ABS activation.

Analysis:
ABS activation events were examined to identify all instances of ABS activation on ADB-equipped tractors and drum-brake-equipped tractors. The ABS activation (ABSA) is a 2-bit signal transmitted as part of the ECB1 signal on the J1939 communication line. ABS is considered inactive when ABSA = '00' and active when ABSA = '01'. All other signals for ABSA were considered "Null." The data query demonstrated an excessive amount of Null events for the MeritorWabco equipped vehicles.

ABSA Event Duration (Hours)

	ABS w/ Drum (T2C1)	ABS w/ ADB (T2C2)	ECBS w/ ADB (T2C3)	ABS6 w/ ADB (T2C4)	ECBS w/ ADB (T3)
0	1,580.93	1,023.16	983.59	17,953.14	568.57
1	452.41	78.74	1.04	0.19	1.12
NULL	11,574.79	15,828.72	14,716.55	21.27	14,081.90
Grand Total	13,608.14	16,930.62	15,701.18	17,974.60	14,651.59

The MeritorWabco ABS systems experienced ‘Null’ events for almost 90 percent of the total duration of the recorded queries. In comparison, the Bendix ABS6 system experienced ‘Null’ events for less than 0.1 percent of the total duration of the recorded queries. Available data is not adequate to provide a detailed comparison between ADBs and Drum Brakes.

Result:

The data stream flaw was reported to the MeritorWabco engineering representatives to identify the potential source of the error. Further investigation by the MeritorWabco team identified a corrupted ECB1 message that resulted in a shortened message to the data logger. The issue was forwarded to the conductor team to determine if the correct message could be mined from the original blob files. At this time, no resolution has been forthcoming from the conductor team.

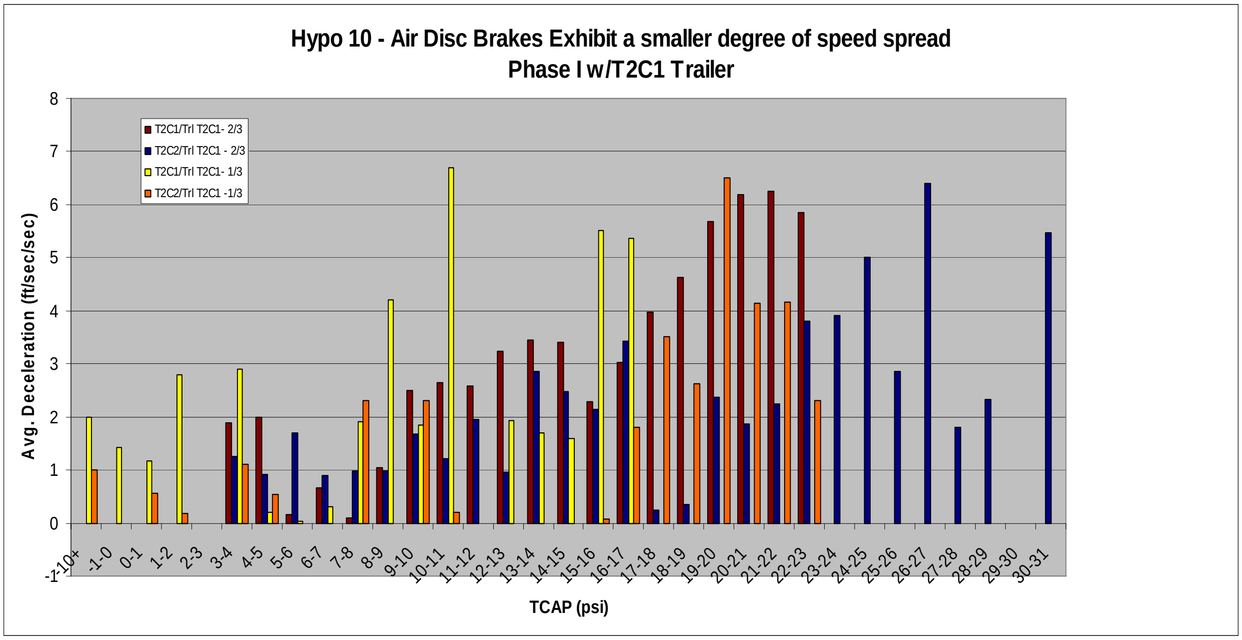
Hypothesis 10

Description Statement:

ADBs exhibit a smaller degree of speed spread (i.e., variation in speed versus deceleration level).

Analysis:

Deceleration rates were examined as a function of the brake control air pressure and the duration of the braking event. Various braking events were examined (high deceleration rate, long duration, high-speed scrub, etc.) to determine the impact on braking performance.



These data proved inconclusive. Available data is of low intensity and no repeatable high-stress braking parameter was found. This type of analysis is better suited for laboratory condition testing.

Result:
Data is inconclusive. Speed spread is most prevalent during high-intensity, long-duration braking events. FOT data is low intensity and therefore not helpful in this analysis.

Hypothesis 11

Description Statement:
ADBs exhibit less fade during downhill braking

Analysis:
See Hypothesis 3.

Result:
See Hypothesis 3.

Hypothesis 12

Description Statement:
Advanced ABS with roll stability control programs reduce instability leading to rollover.

Analysis:
As shown in Section 5.3.5, ADBs improve overall stability during braking. Due to the limitations of data gathered, no quantifiable results can be made with respect to the percentage of rollover accidents that could be prevented with usage of advanced ABS systems.

Result:
Section 5.3.5 summarizes the increased stability from ADBs. No quantifiable results are possible to determine the actual reduction of truck rollover accidents.

Hypothesis 13

Description Statement:
ABS6 reduces instability leading to jackknifing.

Analysis:
ABS6 stability control functionality was not available for evaluation.

Result:
ABS6 stability control functionality was not available for evaluation.

Hypothesis 14

Description Statement:
ABS6 reduces instability leading to oversteer/understeer.

Analysis:
ABS6 stability control functionality was not available for evaluation.

Result:
ABS6 stability control functionality was not available for evaluation.

Hypothesis 15

Description Statement:
ABS6 reduces instability leading to dynamic drift.

Analysis:
ABS6 stability control functionality was not available for evaluation.

Result:
ABS6 stability control functionality was not available for evaluation.

Hypothesis 16

Description Statement:
Advanced ABS with roll stability control programs reduce instability during high-speed lane change maneuvers.

Analysis:
All brake technologies were evaluated to measure the stability of trucks during braking. High-speed lane change maneuvers could not be segregated for separate analysis. Only the complete system was analyzed and compared for stability.

Result:
While high-speed lane change maneuvers were not considered separately, ADBs are found to be considerably more stable than drum brakes. Section 5.35 evaluates the differences in greater detail.

Hypothesis 17

Description Statement:
ABS6 reduces instability during low- to high-friction surface transitions during braking.

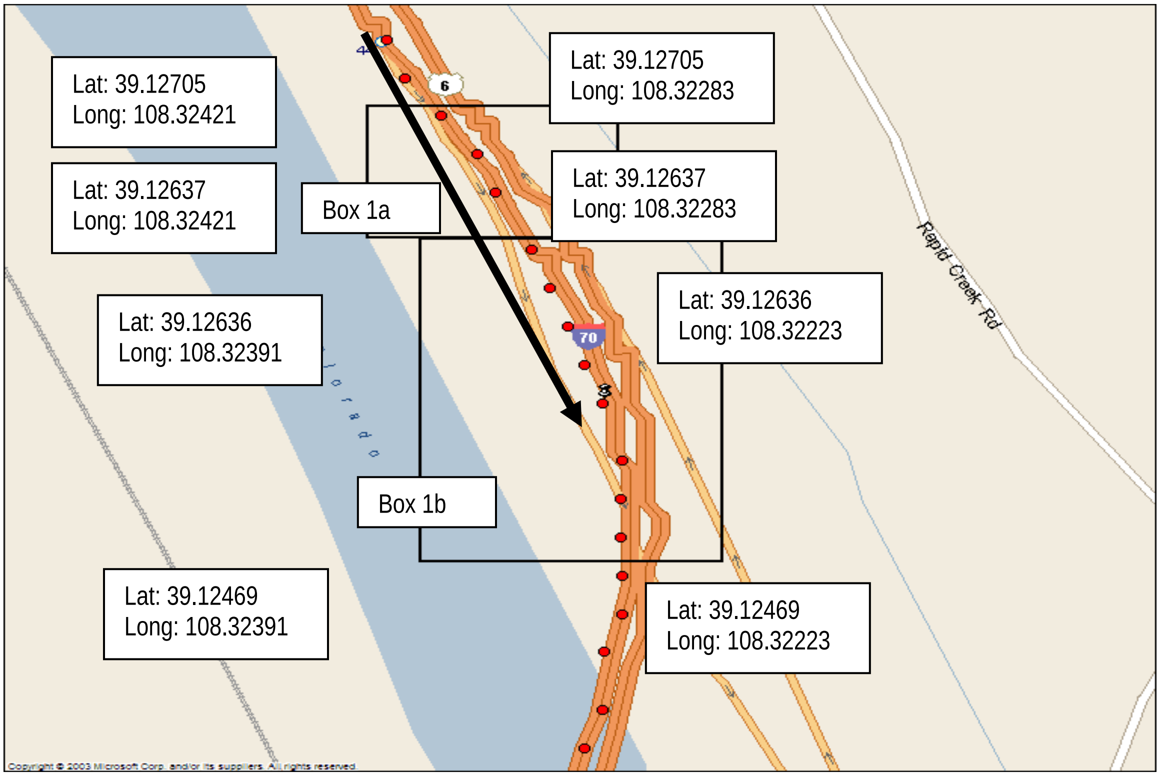
Analysis:
ABS6 stability control functionality was not available for evaluation.

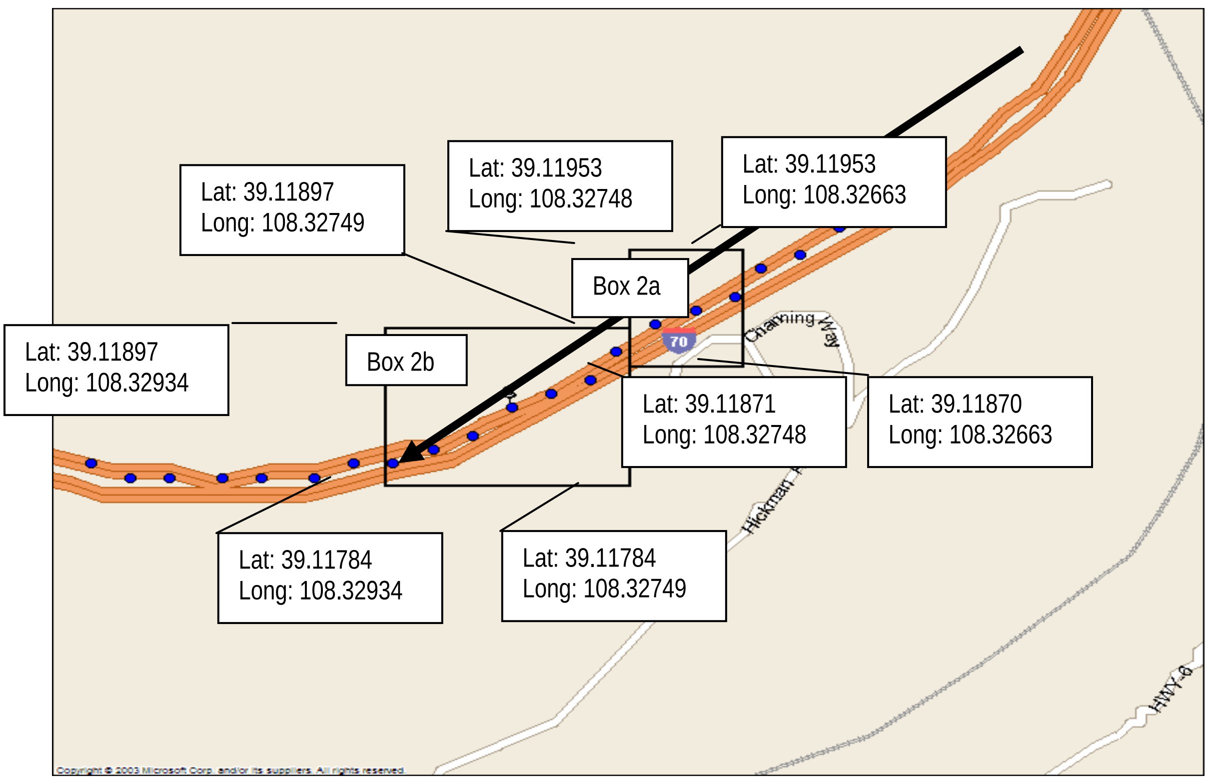
Result:
ABS6 stability control functionality was not available for evaluation.

Hypothesis 18

Description Statement:
Drivers operating vehicles with advanced ABS with roll stability control programs increase approach speed to curves.

Analysis:
Vehicle speed through selected curves was analyzed for ECBS-equipped tractors. ESC activation was only available on ECBS-equipped tractors, and therefore separate analysis for each brake technology was not possible. Please see Section 5.5 for full discussion. The figures below represent the geographical boxes with their respective longitude and latitude coordinates used for the analysis.





Result:

Advanced ABS was not separately analyzed for speed through curves. Please see Section 5.5 for a discussion of speed through curves for ECBS-equipped tractors.

Hypothesis 19

Description Statement:
Drivers operating vehicles with advanced ABS with roll stability control programs increase cornering speeds.

Analysis:
Please refer to Hypothesis 18.

Result:
Advanced ABS was not analyzed for speed through curves. Please see Section 5.5 for a discussion of speed through curves for ECBS-equipped tractors.

Hypothesis 20

Description Statement:
Drivers operating vehicles with advanced ABS reduce their average following distances.

Analysis:
Details of the analysis are found in Section 5.3.1. Following events were used to determine a true "steady state" following interval. A following event was defined to have a vehicle speed of greater than 10 miles per hour, with a target detected in front of the tractor for a minimum of 15 consecutive seconds. The event duration was specifically chosen to determine a steady state following interval and eliminate any short duration events such as vehicles crossing in front of the tractor. For this particular analysis, CCC and ACC were "off."

Result:
Tractors equipped with advanced ABS were not found to have reduced their following intervals.

Hypothesis 21

Description Statement:
Drivers operating vehicles with advanced ABS increase their average closing speeds.

Analysis:
See Hypothesis 2.

Result:
See Hypothesis 2.

Hypothesis 22

Description Statement:
Drivers operating vehicles with advanced ABS increase their average downhill speeds.

Analysis:
See Hypothesis 3.

Result:
See Hypothesis 3.

Hypothesis 23

Description Statement:
Advanced ABS equipped vehicles exhibit increased stability during tire blowouts.

Analysis:
No tire blowouts experienced on advanced ABS equipped vehicles.

Result:
Data not available to confirm or disprove hypothesis.

Hypothesis 24

Description Statement:
ECBS with electronic stability programs reduce instability leading to rollovers.

Analysis:
Stability program impact on rollover, jackknifing, oversteer, understeer, dynamic drift, and emergency lane change maneuvers, were analyzed together under ESC activations in Section 5.4. See Section 5.4 for detailed discussion of all ESC activations. As discussed in Section 4.8, there was insufficient clarity in these data to be able to accurately quantify safety benefits.

Result:
The impact of the stability program of ECBS cannot be independently studied for different dynamic situations. ESC activation is detailed in Section 5.4 and is assumed to have a large positive impact, but due to data quality limitations outlined in Section 4.8, no quantifiable results could be obtained. This result holds true for hypothesis 24, 25, 26 27, and 28.

Hypothesis 25

Description Statement:
ECBS with electronic stability programs reduces instability leading to jackknifing.

Analysis:
See Hypothesis 24.

Result:
See Hypothesis 24.

Hypothesis 26

Description Statement:
ECBS with electronic stability programs reduces instability leading to oversteer / understeer.

Analysis:
See Hypothesis 24.

Result:
See Hypothesis 24.

Hypothesis 27

Description Statement:
ECBS with electronic stability programs reduces instability leading to dynamic drift.

Analysis:
See Hypothesis 24.

Result:
See Hypothesis 24.

Hypothesis 28

Description Statement:
ECBS with electronic stability programs reduces instability during emergency high speed, high lateral acceleration lane change maneuvers.

Analysis:
See Hypothesis 24.

Result:
See Hypothesis 24.

Hypothesis 29

Description Statement:
ECBS with electronic stability programs reduces instability during braking on a split coefficient of friction surface.

Analysis:
Data were mined in an attempt to find instances when the right and left side of the vehicle are on different coefficient of friction surfaces and the brakes are applied, and compare vehicle dynamics on ECBS-equipped vehicles versus ABS-equipped vehicles.

No data were available that could be used to identify the vehicle as being on a split friction surface. Method used for evaluating friction coefficient was to look at differential in wheel speed while vehicle was braking. In addition, driver surveys and incident reports were examined for possible split friction coefficient scenarios. None were found.

Result:
Data were not available to confirm or disprove this hypothesis.

Hypothesis 30

Description Statement:
Drivers operating vehicles with ECBS with electronic stability programs increase approach speeds to curves.

Analysis:
Section 5.5 and hypothesis 18 detail the analysis performed to evaluate the speed through curves.

Result:
ECBS tractors were evaluated and their speed measured while traversing two curves on I-70 east of Grand Junction Colorado. The results show no appreciable difference in speed through curves between tractors.

Hypothesis 31

Description Statement:
Drivers operating vehicles with ECBS with electronic stability programs increase cornering speeds.

Analysis:
Details of the analysis are found in Section 5.5.

Result:
Tractors equipped with ECBS were found to have no appreciable difference in their cornering speed. See Section 5.5, Hypothesis 18, and Hypothesis 30 for further discussion.

Hypothesis 32

Description Statement:
ECBS reduces impending wheel lockup and duration of ABS events.

Analysis:
ABS activation events were examined to identify all instances of ABS activation on the ECBS equipped tractors. The ABS activation (ABSA) is a 2-bit signal transmitted as part of the ECB1 signal on the J1939 communication line. The ABS is considered inactive when ABSA = '00' and active when ABSA = '01'. All other signals for ABSA were considered "Null". The data query demonstrated an excessive amount of Null events for the MeritorWabco equipped vehicles.

ABSA Event Duration (Hours)

	ABS w/ Drum (T2C1)	ABS w/ ADB (T2C2)	ECBS w/ ADB (T2C3)	ABS6 w/ ADB (T2C4)	ECBS w/ ADB (T3)
0	1,580.93	1,023.16	983.59	17,953.14	568.57
1	452.41	78.74	1.04	0.19	1.12
NULL	11,574.79	15,828.72	14,716.55	21.27	14,081.90
Grand Total	13,608.14	16,930.62	15,701.18	17,974.60	14,651.59

The MeritorWabco ECBS systems experienced 'Null' events for almost 95 percent of the total duration of the recorded queries. In comparison, the Bendix ABS6 system experienced 'Null' events for less than 0.1 percent of the total duration of the recorded queries. Available data is not adequate to provide a detailed comparison between ECBS and ABS systems.

Result:
The data stream flaw was reported to the MeritorWabco engineering representatives to identify the potential source of the error. Further investigation by the MeritorWabco team identified a corrupted ECB1 message that resulted in a shortened message to the data logger. The issue was forwarded to the conductor team to determine if the correct message could be mined from the original blob files. At this time, no resolution has been forthcoming from the conductor team.

Hypothesis 33

Description Statement:
Drivers operating vehicles with ECBS reduce their average following distances.

Analysis:
Details of the analysis are found in Section 5.3.1. Following events were used to determine a true "steady state" following interval. A following event was defined to have a vehicle speed of greater than 10 miles per hour, with a target detected in front of the tractor for a minimum of 15 consecutive seconds. The event duration was specifically chosen to determine a steady state following interval and eliminate any short duration events such as vehicles crossing in front of the tractor. For this particular analysis, CCC and ACC were "off."

Result:
Drivers operating tractors equipped with ECBS were found to have reduced their average following intervals compared to ABS / drum tractors.

Hypothesis 34

Description Statement:
Drivers operating vehicles with ECBS increase their average closing speeds.

Analysis:
See Hypothesis 2.

Result:
See Hypothesis 2.

Hypothesis 35

Description Statement:
Drivers operating vehicles with ECBS increase their average downhill speeds.

Analysis:
See Hypothesis 3.

Result:
See Hypothesis 3.

Hypothesis 36

Description Statement:
Drivers operating vehicles with ECBS increase their average deceleration rates.

Analysis:
Details of the analysis are found in Section 5.3.2. The brake events were determined using the brake application (BA) channel. The channel records either a “1” or “0” as the driver depresses and releases the treadle valve. For each time valve, the deceleration rate was calculated by using the derivative of the velocity channel (J1939 vehicle speed) or the change in speed from two consecutive time points. The average deceleration rate is then determined by taking the sum of the deceleration rates and dividing it by the number of time points. The average deceleration rate was calculated for all 1.15 million braking events.

Result:
Drivers operating ECBS tractors with disc brakes were found to increase their average deceleration rates.

Hypothesis 37

Description Statement:
ECBS-equipped vehicles are stable during tire blowouts.

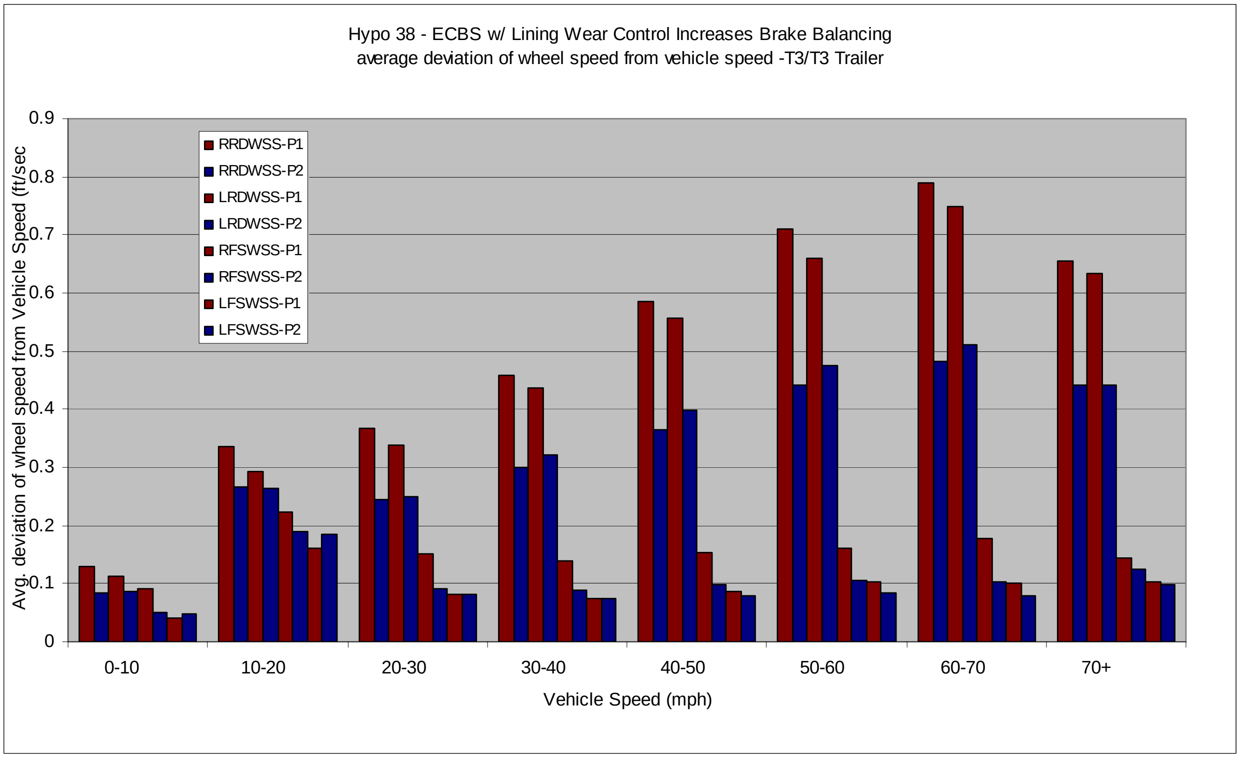
Analysis:
A driver indicated he experienced a tire blowout followed by an ESC activation. The driver commented that the ESC prevented him from losing control of the vehicle. Every attempt was made to identify this event without success.

Result:
Data were not available to confirm or disprove this hypothesis.

Hypothesis 38

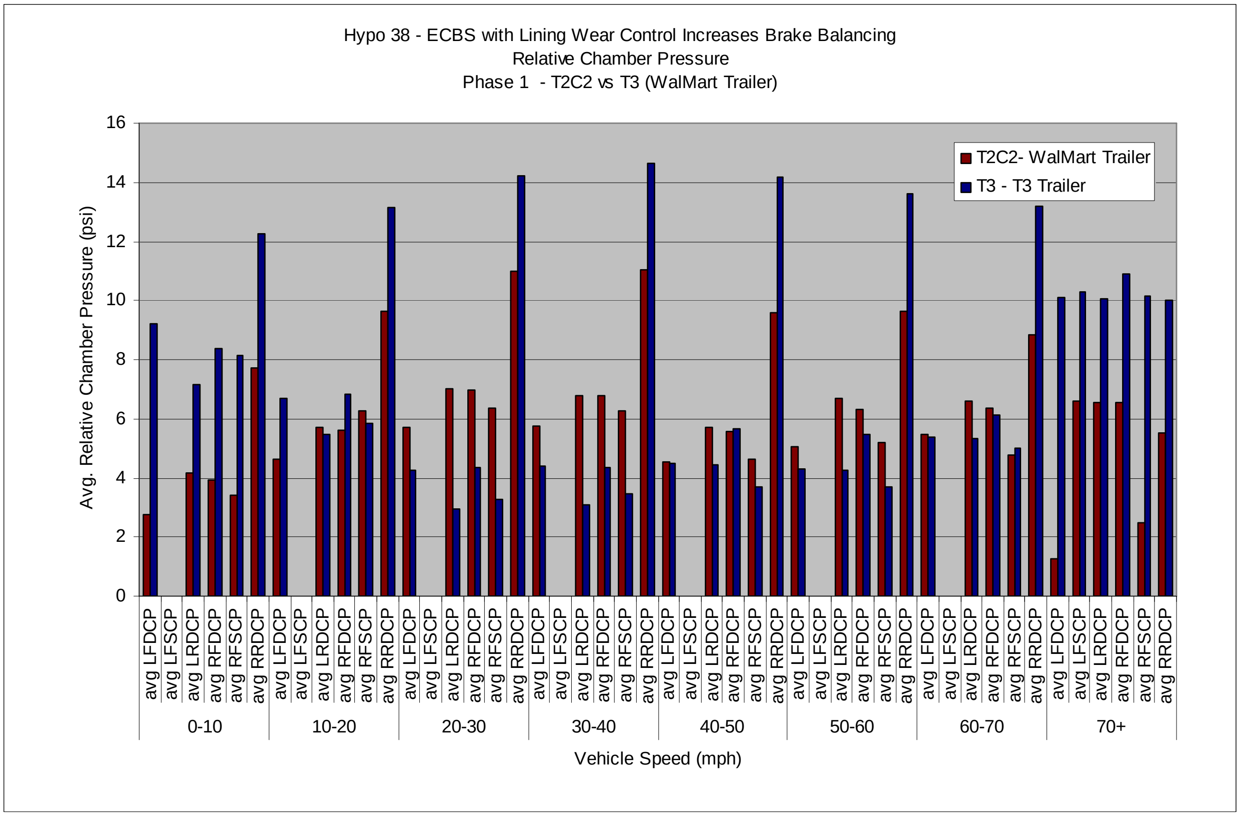
Description Statement:
ECBS with lining wear control increases balanced braking.

Analysis:
Individual wheel speed was studied under different braking conditions to evaluate the effect that lining wear control has on brake balancing. The expected result is to show increased braking force to balance braking wear at lower speeds.



The effect could not be accurately demonstrated by looking at wheel speeds. The main problem with these data was its large variability, not showing any distinguishable pattern.

To mitigate some of this effect, the analysis also looked at individual brake chamber pressures in the hope of finding varying pressures. Once again, no clear pattern could be observed in the data.



Result:
Inconclusive. These data do not support nor disprove the effect of brake lining wear control on brake balancing.

Hypothesis 39

Description Statement:
ECBS reduces pedal feedback to the driver, which masks the effects of brake fade.

Analysis:
The driver surveys were analyzed to determine the driver's reaction to the brake pedal feel in vehicles with ECBS. The surveys asked if the drivers noticed a reduced brake pedal feel in vehicles operating with ECBS. A total of 14 responses were received throughout the FOT.

Drivers Responses to Inquiry on Reduced Brake Feel

6-Month Survey		12-Month Survey	
Reduced Feel	No Change	Reduced Feel	No Change
4	0	7	3

Responses to ECBS brake pedal feel generated by the drivers included:

- "… difference in pedal feel too much when not working."

- "Cannot get a sense of how the brakes are going to work. Sometimes it takes more pressure on pedal. Most often the slightest application relay clichs (sic) and the vehicle jerks to stop. Brakes are either applied or not, no easing on or off."
- "Better stopping – more control on hills."

Result:
After 12 months, 70 percent of the drivers reported that ECBS reduces the brake pedal feedback. The surveys had no specific reactions to ECBS and brake fade.

Hypothesis 40

Description Statement:
Decreased brake activation delay with ECBS results in improved stopping distances.

Analysis:
The analysis attempted to verify that brake activation would occur faster with ECBS compared to conventional pneumatic systems. The electrical signal from the pedal to the brake chamber is expected to be faster than it would otherwise be from a pneumatic signal.

The analysis required very precise monitoring and timing of brake pedal activation and brake chamber pressurization. The DAS installed was not able to provide the sufficient resolution in timing for this analysis.

Result:
There was insufficient resolution in these data to determine if in fact brake activation time is shorter with ECBS.

Hypothesis 41

Description Statement:
High-speed tractor-trailer ECBS connection is frequently coupled.

Analysis:
Counting the instances when ECBS tractors connected to ECBS trailers are driven without the high-speed connector attached would provide sufficient data to compare. Unfortunately, determining when the cable was connected was not available in the dataset.

Result:
Inconclusive. Data were not available to be collected.

Hypothesis 42

Description Statement:
ECBS reduces accidents.

Analysis:
There were no accidents during the FOT. Direct calculation of accident reduction was not possible, and a reliable safety benefits analysis was not possible due to the data limitations discussed in Section 4.8 Discussion on ESC activations is found in Section 5.4.

Result:
Quantifiable safety benefits could not be performed. ESC activations shown in Section 5.4 are expected to have a positive impact on safety.

Hypothesis 43

Description Statement:
ECBS reduces near collision events.

Analysis:
ECBS's impact on safety cannot be separately analyzed. Safety benefits of ECBS-equipped tractors while using ACC is discussed in detail in Section 6.6.

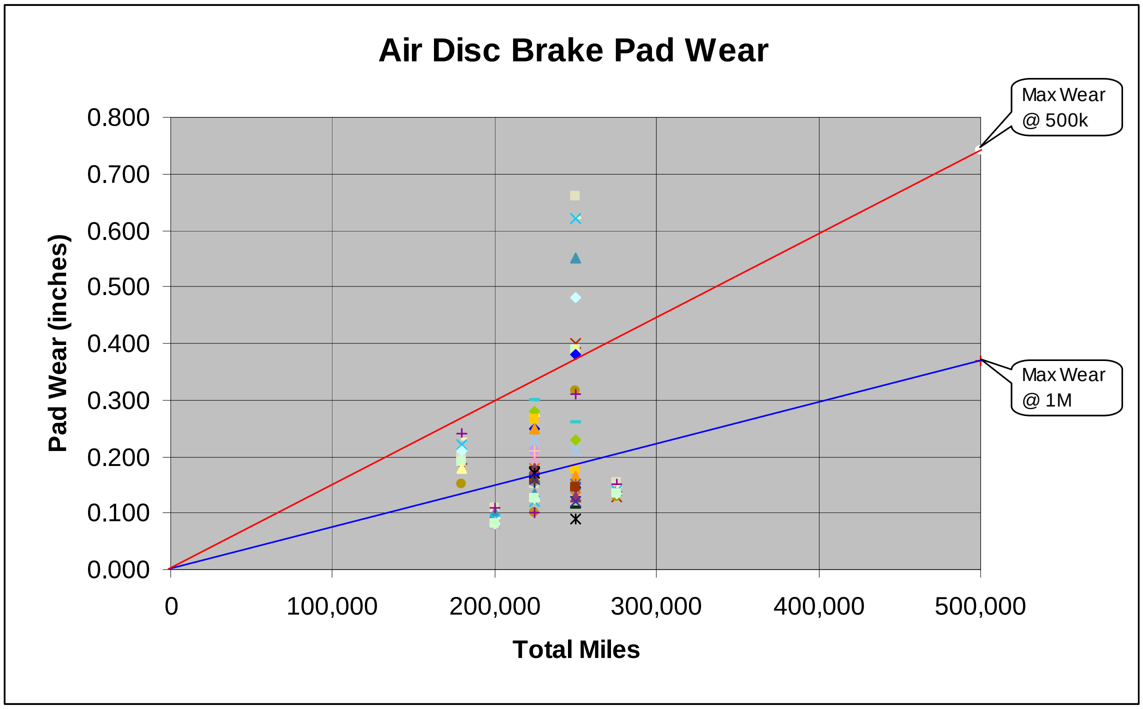
Result:
No safety benefit could be conducted based on ECBS alone. Tractors equipped with ECBS and ACC showed a considerable improvement in reducing the exposure to 'near-collision' events as defined in Section 6.6.

Hypothesis 44

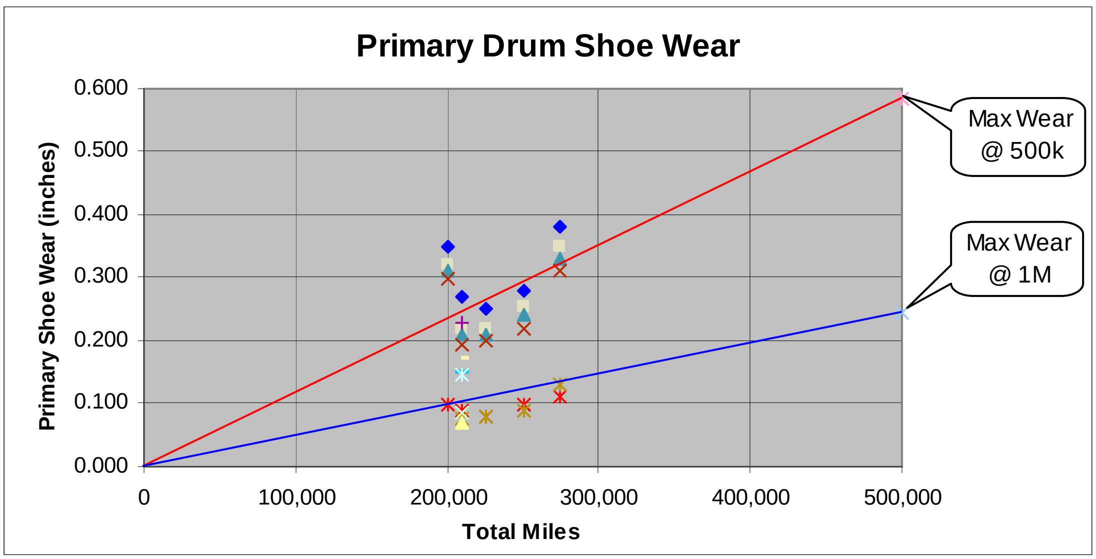
Description Statement:
ADB pads experience less wear than drum brake shoe linings.

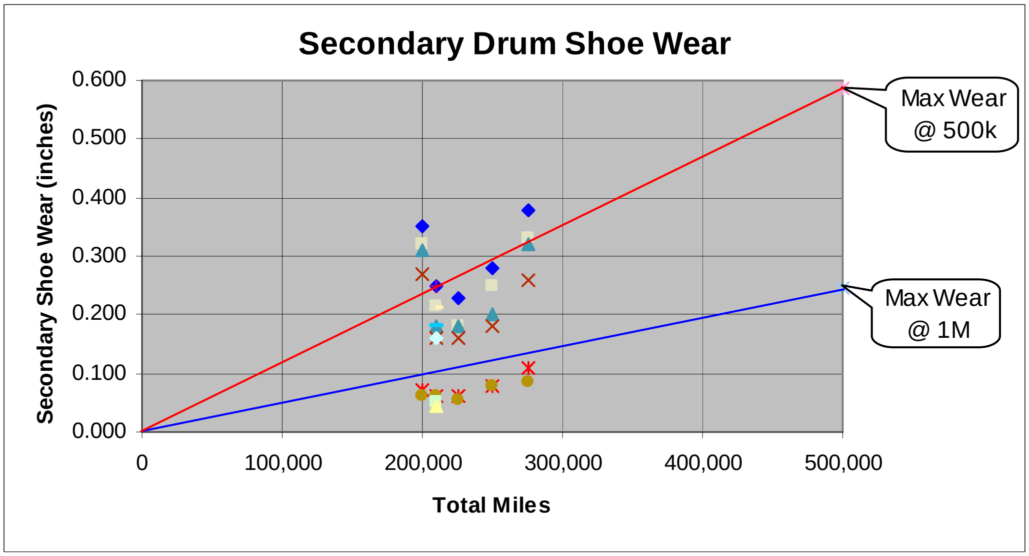
Analysis:
The interim field report was analyzed to compare brake pad usage to drum shoe usage during the first six months of the FOT. The findings for this analysis are based on empirical data that was gathered during a single inspection after approximately three months of testing. The analysis based on this report provided possible trends, but was not based on final measured values.

Of the 108 brake pads measured, the inspection identified a single tractor with extreme brake usage. The trend line for these brake pads, 8 percent of the inspected pads, estimated an expected life of less than 500,000 miles. For the remaining disc brake pads, the trend line estimated that 63 percent of the brake pads would have an expected life in excess of 1 million miles. The remaining pads were estimated to have a useable life of approximately 700,000 miles.



For drum brakes, the trend line estimated that the steer shoes (approximately 33% of the measured shoes) would have an expected life in excess of 1 million miles. The trend line for the remaining shoes would have an expected life of 500,000 miles. The worst shoes would not meet a life expectancy of more than 400,000 miles.





Further details of this analysis can be found in Section 7.5. As a supplement to the inspection report, the maintenance surveys were reviewed. The results were inconclusive. The number of mechanics that reported completing maintenance tasks on ADBs throughout the FOT was insufficient to perform an acceptable analysis on the mechanics' perception of pad / shoe wear.

Result:
The trends established from the single brake inspection appear to demonstrate that brake pads will experience less wear than drum shoes. With the current wear rate shown during the inspection, the maintenance interval for brake pads may be twice that of drum shoes.

Hypothesis 45

Description Statement:
Labor costs for rebuilding ADBs are less than S-cam drum brakes.

Analysis:
VMRS data were mined to find and measure the labor costs for brake rebuild. No brake rebuilds took place during the FOT and therefore no actual costs were gathered.

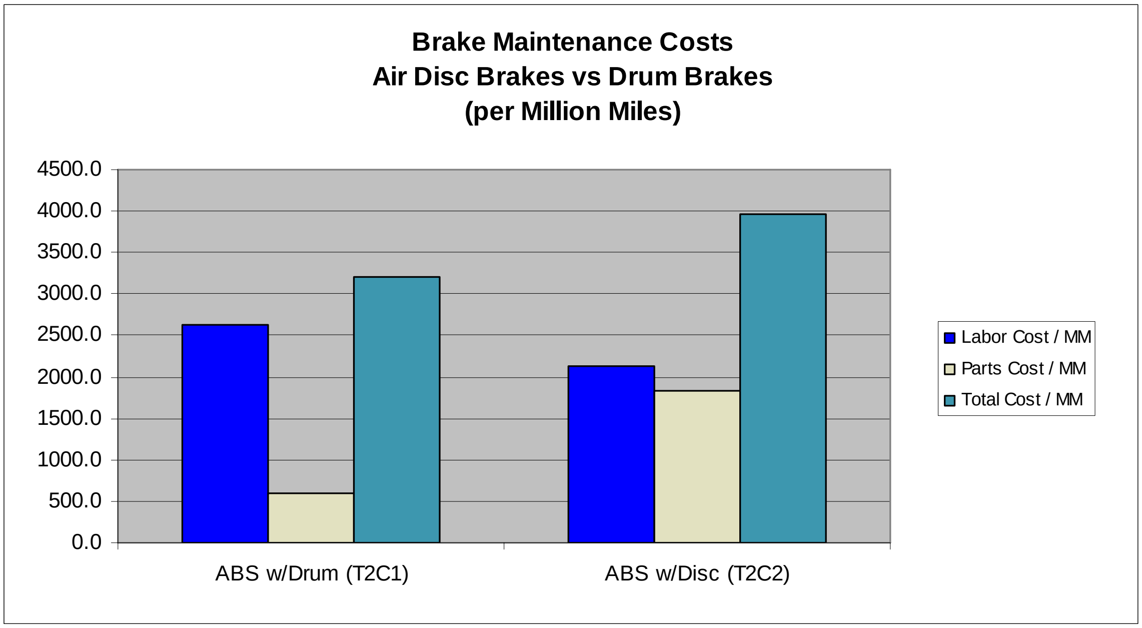
Result:
No data were available to support analysis. No brake rebuilds during FOT. Information from vendors and other fleets suggest that ADBs require less labor for rebuilding compared to drum brakes.

Hypothesis 46

Description Statement:
Parts replacement costs of ADBs are less than S-cam drum brakes.

Analysis:
VMRS data were mined to separate the cost incurred for replacing component parts of ADBs and drum brakes. The parts costs for drum brakes totaled $595 per million miles. As stated in

the report, the compressor failures that were attributed to a manufacturer defect were not included in the analysis. In comparison, ADBs cost the company $1,832 per million miles for parts.



Drum brakes offer a significant advantage over the ADBs in the purchase cost of replacement parts. As seen in the exhibit above, the costs for ADB parts are close to three times the cost for drum brake parts.

The VMRS data did not include parts costs for consumables. The costs accumulated for consumables (drums, shoes, rotors, pads, etc.) must be considered to provide an overall analysis on parts costs attributed to each foundation brake system.

See Section 7.5 for detailed discussion on parts replacement costs of ADBs and S-cam drum brakes.

Result:
The analysis of the accumulated costs for drum brake parts and ADB parts show a significant savings for drum brakes over ADBs. Data mined from VMRS does not include the replacement of consumables, including brake pads/shoes and drums/rotors. As demonstrated in Section 7.5, during the brake inspection, trend lines showed that brakes pads could be changed at half the rate of brake shoes (ref: Hypothesis 44). Without cost information for consumables, data gathered for this analysis is insufficient to provide an all-encompassing analysis of parts costs.

Hypothesis 47

Description Statement:
ADBs require less frequent adjustment than S-cam drum brakes.

Analysis:

VMRS data and mechanic surveys were analyzed to find instances of brake adjustments. No brake adjustments took place; no analysis could be performed.

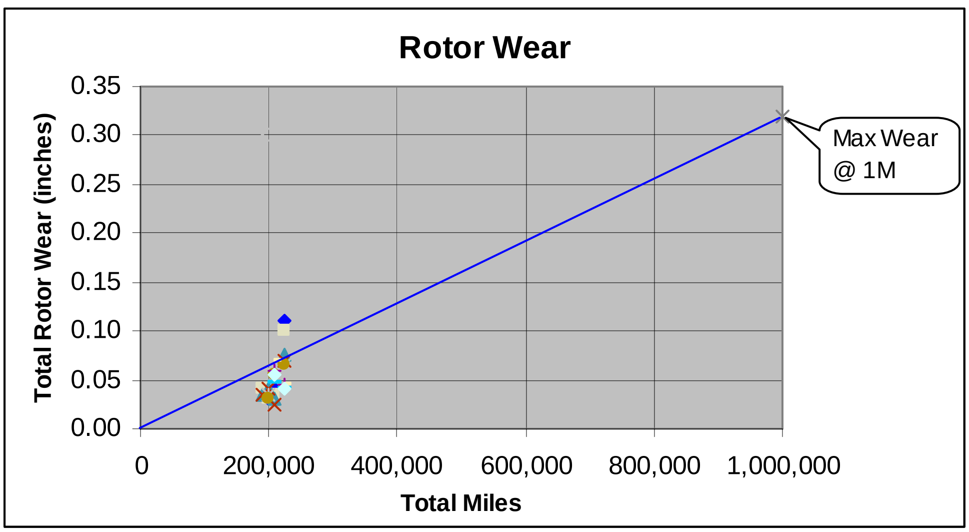
Result:
No data were available to support this analysis.

Hypothesis 48

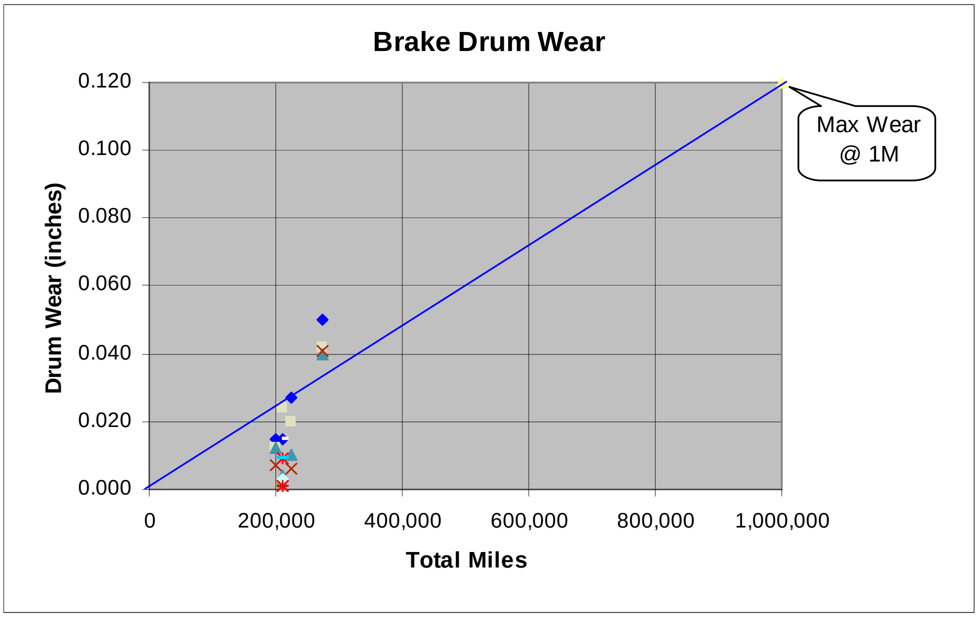
Description Statement:
Drums require turning more frequently than rotors.

Analysis:
The interim field report was analyzed to compare brake rotor wear to brake drum wear during the first six months of the FOT. The findings for this analysis are based on empirical data that was gathered during a single inspection after approximately three months of testing. The analysis based on this report provided possible trends, but was not based on final measured values.

The inspection of the tractors with ADBs identified two rotors with excessive rotor wear. These rotors were associated with a tractor that was exposed to extreme braking conditions. Without these rotors, the trend lines estimated 100 percent of the inspected brake rotors could have an expected life in excess of 1 million miles. In addition, almost 50 percent of the brake rotors could expect to experience a service life in excess of 1.5 million miles.



The inspection of the drum brake tractor identified four brake drums that would not meet a life expectancy of 1 million miles. Using the trends lines, the life of these drums was estimated at less than 700,000 miles. The identified drums were from a single tractor, and could be attributed to extreme braking conditions for the particular tractor. The trend line for the remaining 20 drums estimate 70 percent will meet or exceed a life expectancy of 2 million miles. The remaining 30 percent would have a life expectancy in excess of 1 million miles.



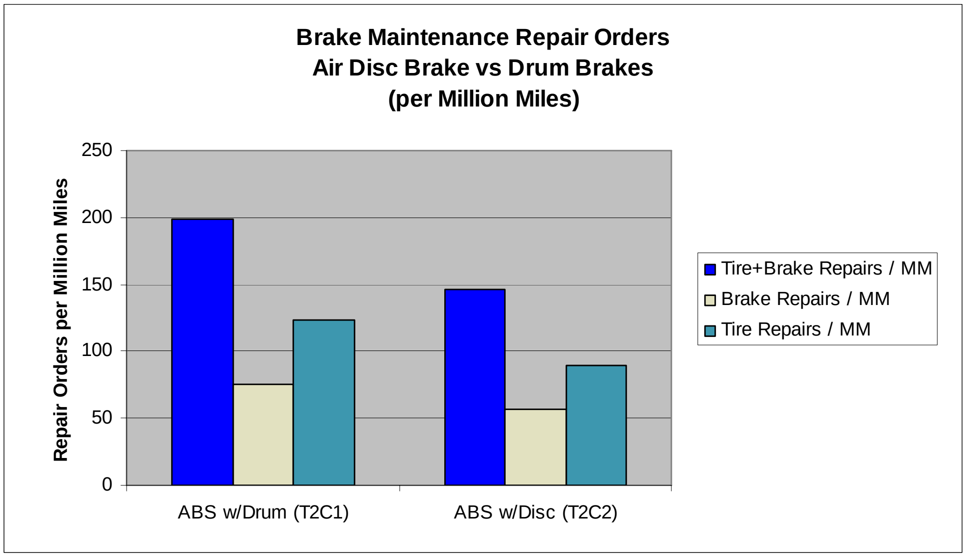
Further details of this analysis can be found in Section 7.5. As a supplement to the inspection report, the maintenance surveys were reviewed. The results were inconclusive. The number of mechanics that reported completing maintenance tasks on ADBs throughout the FOT was insufficient to perform an acceptable analysis on the mechanics' perception of pad / shoe wear.

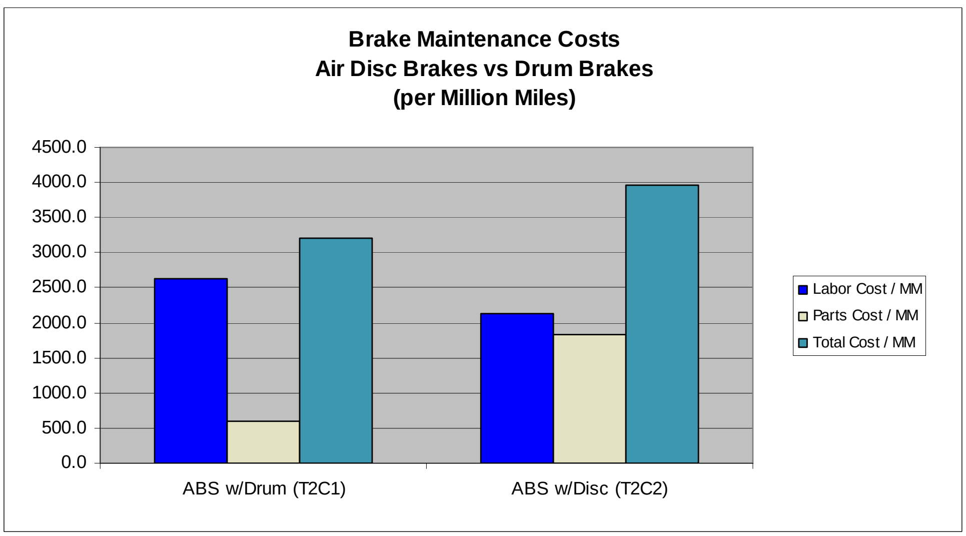
Result:
The trends established from the single brake inspection appear to demonstrate that brake drums and brake rotors experience a similar life expectancy. With the current wear rate shown during the inspection, the maintenance interval for brake pads and drum shoes will be similar.

Hypothesis 49

Description Statement:
ADB systems are more reliable than S-cam drum brake systems.

Analysis:
Drum brakes accumulated 20 more repairs per million miles than the ADB. The repairs orders can be broken down into labor costs. Drum brakes experienced a total labor cost of $2,621 per million miles. The cost was 20-percent more than the ADB labor costs of $2,126 per million miles. These figures do not include the labor costs associated with the replacement of the air compressors that failed due to a manufacturer's defect.





In addition, the mechanic surveys were analyzed to identify maintenance's perception throughout the course of the FOT. By the end of the FOT, 7 of the 10 mechanics surveyed had performed maintenance on ADBs. The majority of the mechanics noted a low frequency of required maintenance for ADB and less difficulty maintaining ADBs over conventional drum brakes.

Performed Maintenance on ADBs (Mechanic Surveys)

6-Month Survey		12-Month Survey	
Yes	No	Yes	No
4	0	7	3

In general, the mechanics found the frequency of maintenance on ADBs to be low or very low in comparison to drum brakes. One mechanic noted that disc brake pads have minimal wear and shorter repair times. A second mechanic noted that the ADBs are a very good system, and have long-lasting parts and better performance.

Mechanics Responses to Inquiry on Frequency for ADB Maintenance (Mechanic Surveys)

6-Month Survey			12-Month Survey		
High	Low	Very Low	High	Low	Very Low
2	5	2	1	3	3

Mechanics were also surveyed on the level of maintenance required for ADBs as compared to drum brakes. At the end of the FOT, 75 percent of the mechanics stated the level of maintenance for ADBs was less difficult than drums. The mechanics stated that the ADBs have "less moving parts that need maintenance."

Level of Maintenance for ADBs as compared to Drums (Mechanic Surveys)

6-Month Survey			12-Month Survey		
More Difficult	Same	Less Difficult	More Difficult	Same	Less Difficult
2	1	7	2	0	6

Additional comments from mechanics concerning ADB maintenance versus drum maintenance included:

- "Less parts to replace and [sic] faster total replacement when needed."
- "More simple, no slacks (adjusters)."
- "Very simple – fewer components to have the elements get to. No S-cams and bushings to constantly replace."

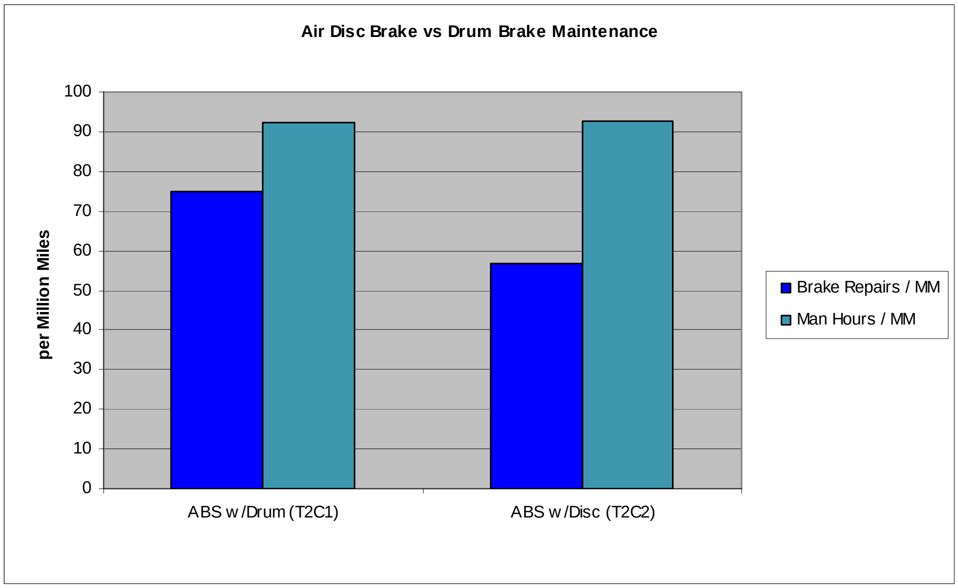
For a more detailed discussion on the reliability of each system during the course of the FOT, reference Section 7.5.

Result:
The accumulated repair orders for ADB systems were less than drum brakes. In addition, the mechanics who participated in the surveys found the ADBs more reliable than drum brakes. As a result, the analysis shows that ADB systems are more reliable than drum brake systems.

Hypothesis 50

Description Statement:
Maintenance on ADBs is less complicated compared with S-cam drum brakes.

Analysis:
VMRS data were analyzed to identify the number of repair orders generated and the number of labor hours experienced by each brake system. Drum brakes accumulated 20 repairs per million miles more than ADBs. The charts demonstrate that the labor hours accumulated for the repair orders are within 0.3 labor hours per million miles for each brake system.



The chart shows that drum brakes accumulated less time per repair order (1.2 hours per repair) than ADBs (1.6 hours per repair). Data collected from VMRS are not reflected in the responses from the mechanic surveys. The survey results stated the majority of the mechanics felt that ADBs were less difficult to maintain versus drum brakes. As part of the surveys, the mechanics commented on the ease of replacement, the reduced time required for replacements, and the elimination of drums requiring replacement/adjustment.

Level of Maintenance Difficulty for ADBs versus Drums (Mechanic Surveys)

6-Month Survey			12-Month Survey		
More Difficult	Same	Less Difficult	More Difficult	Same	Less Difficult
1	2	6	1	1	5

See Section 7.5 for a more detailed discussion on the hours dedicated to maintenance of each brake system. See Section 8.2.2 for a detailed discussion on the mechanics perception of brake system maintainability.

Result:
Data gathered were contradictive. If the FOT had been extended, the labor hours per repair for ADBs may have been reduced due to a learning curve with the mechanics.

Hypothesis 51

Description Statement:
Air compressor maintenance is lower with ADBs than with S-cam drum brakes.

Analysis:
VMRS data were analyzed to identify air compressor failures during the FOT. Data provided were insufficient to perform the analysis. All failures identified within the VMRS data were related to compressor warranty failures and not use failures.

Next, a query was conducted on the total run time for air compressors for each tractor configuration. As the table below demonstrates, the compressors on the tractors with ADBs were running for half the time of the compressors on the tractors with drums. The air compressors that were operating drum brakes had a duty cycle of approximately 30 percent. The air compressors that were operating ADBs had a duty cycle of approximately 13 percent. The duty cycle of an air compressor determines the required maintenance schedule. As the duty cycle for compressors operating ADBs is less than half the duty cycle for drum brakes, the required maintenance for these compressors would be significantly less. In addition, the compressor for the ADB can be expected to last longer with a shorter duty cycle.

Compressor Run Time (sec/mile)

	ABS w/ Drum (T2C1)		ABS w/ ADB (T2C2)		ECBS w/ ADB (T2C3)		ABS6 w/ ADB (T2C4)		ECBS w/ ADB (T3)	
Phase	On	Off	On	Off	On	Off	On	Off	On	Off
1	24.71	58.11	10.34	70.47	10.33	77.56	10.10	78.61	8.18	72.24
2	25.79	48.15	7.95	65.58	17.01	59.13	13.83	58.71	7.99	62.07

It should be stated that this comparison is based on identical air compressors operating in each configuration. ADB manufacturers have expressed an interest in reducing the size of the compressor due to the reduced duty cycles. If this plan were put in place, the new compressor may require a higher duty cycle to maintain the pressure output of the current compressor.

Result:
From data gathered on compressor run-times, the maintenance on compressors with ADBs will be less when compared with identical compressors used with drum brakes.

Hypothesis 52

Description Statement:
Higher operating temperature of the ADB causes increased maintenance in seals, bearings, and other wheel end components compared with drum brakes.

Analysis:
VMRS data were not available to show replacement of wheel end seals, bearings, or other components.

Result:
No maintenance records were available to perform analysis.

Hypothesis 53

Description Statement:
Parking brake maintenance is lower on vehicles with ADBs.

Analysis:
Maintenance records were analyzed to determine the frequency of parking brake adjustments/repairs. No parking brake repairs were found in the data.

Result:

There was insufficient data to support analysis.

Hypothesis 54

Description Statement:
ADB caliper life is longer than S-cam life.

Analysis:
Maintenance data were received to study brake life. No caliper replacements or rebuilds occurred. It is expected that with sufficient time and mileage accumulation, some replacements would be necessary. Analysis was not performed due to lack of data.

Result:
Due to insufficient time and miles accumulated during the FOT, no analysis could be performed.

Hypothesis 55

Description Statement:
Advanced ABS requires more frequent replacement of sensors, components, wiring, and connectors than ABS.

Analysis:
Maintenance data were studied to determine the replacement rate of brake components of advanced ABS. No data to support the analysis was available.

Result:
Inconclusive, there was no data to support analysis.

Hypothesis 56

Description Statement:
Maintenance on advanced ABS is more complicated than ABS.

Analysis:
Mechanic surveys were analyzed and contrasted to labor time required for ABS tractor maintenance. Historical repair times were required for the comparative analysis but were never received.

Result:
Historical data were not available to compare with FOT repair times. Results were inconclusive due to lack of data.

Hypothesis 57

Description Statement:
Advanced ABS component cost is greater than ABS.

Analysis:

Historical repair costs were to be evaluated with FOT repair costs. No historical data were provided.

Result:
Historical data were not available to compare with FOT repair costs. Results were inconclusive due to lack of data.

Hypothesis 58

Description Statement:
Advanced ABS generates fault codes more frequently than ABS.

Analysis:
Historical fault code data were going to be compared to FOT fault code generation. No historical information was provided.

Result:
Historical data were not available to compare with FOT fault codes. Results were inconclusive due to lack of data.

Hypothesis 59

Description Statement:
Increased duty cycle with traction control valves on advanced ABS increases wear and replacement frequency compared with ABS.

Analysis:
Replacement traction control valves would be evaluated and compared to historical trends. No traction control valves were replaced during the FOT making comparison impossible. It is possible that a longer-term test may reveal increased wear.

Result:
Inconclusive. There were no traction control valve replacements during FOT. There was insufficient time and mileage accumulation to accurately predict wear.

Hypothesis 60

Description Statement:
ECBS electrical component (sensor, wires, connectors) replacement occurs more frequently than ABS.

Analysis:
Maintenance data were studied to determine the replacement rate of brake components of ECBS. No data to support the analysis was available.

Result:
Inconclusive, there was no data to support analysis.

Hypothesis 61

Description Statement:
ECBS generates fault codes more frequently than ABS.

Analysis:
Identical tractor groups (T2C3 and T3) were shown to have generated completely different fault code results. This led to confidence issues with the ABSF data channel and the decision not to present the findings.

Result:
No quantifiable results are possible to determine due to a lack of confidence in the data.

Hypothesis 62

Description Statement:
ECBS with lining wear control increases pad life.

Analysis:
The interim field report was analyzed to determine if ECBS lining wear control increases pad life during the first six months of the FOT. The findings for this analysis are based on empirical data that was gathered during a single inspection after approximately three months of testing. The analysis based on this report provided possible trends, but was not based on final measured values.

The inspection report was analyzed to determine if the tractors with the ECBS technology experienced an increased pad life over vehicles with ABS technology. The inspection only included three ECBS tractors. As demonstrated in the chart below (also referenced in Section 7.5), no discernable difference was noted between the ABS and ECBS control systems.

Unit #	Mileage	Steer Rotors	Mid Rotors	Rear Rotors	Steer Pads	Mid Pads	Rear Pads	Control System
1854	199,289	>>1M	>>1M	>>1M	>1M	>1M	>1M	Bendix ABS6
1855	256,246	1M*	1M*	1M*	300k*	500k	500k	Bendix ABS6
1857	259,625	>>1M	>>1M	>>1M	>1M	>1M	>1M	Bendix ABS6
1858	226,323	>>1M	>>1M	>>1M	>1M	>1M	>1M	Bendix ABS6
1861	229,305	>1M	>1M	>1M	700k	700k	700k	Bendix ABS6
1873	244,697	>>1M	>>1M	>>1M	1M**	1M**	1M**	Bendix ABS6
1884	225,972	>>1M	>>1M	>>1M	1M	1M	1M	Meritor ECBS
1888	252,418	>>1M	>>1M	>>1M	>1M	>1M	>1M	Meritor ECBS
1890	184,307	>1M	>1M	>1M	700k	700k	700k	Meritor ECBS

Result:
The brake inspection was completed after approximately 185,000 to 250,000 miles. Due to the low mileage, and limited number of ECBS tractors inspected, there is insufficient data. To provide a conclusive result, additional tractors would have to be inspected throughout the life of the brake pads. As the pads only experienced approximately one-third of their expected life, the advantage of ECBS over ABS could not be determined.

Hypothesis 63

Description Statement:
ECBS infrequently utilizes backup pneumatic system.

Analysis:
The on-board electronic data were mined for occurrences where the ABS red warning light and the ECBS amber warning light were illuminated at the same time indicating failure of the electronically controlled brake system. The data revealed that the system failed and reverted back to pneumatic control six times on 3 of the 18 tractors during the course of the FOT. Two of the tractors had a single failure and the remaining tractor had four failures. The first failure occurred in month four (August 2005) of the test. Failures two through five occurred on a single tractor in February 2006. The four failures were treated as separate instances because the tractor was serviced and operated for a period of time (as much as seven days) before the dashboard lights re-illuminated indicating a problem. The final failure occurred at the end of the FOT in April 2006.

Result:
The ECBS failed infrequently when considering the 18 ECBS tractors accumulated 1.38 million miles during the FOT. Furthermore, four of the failures appear to be due to either a single intermittent problem or one that was not properly corrected.

Hypothesis 64

Description Statement:
Maintenance on ECBS is more complicated than ABS.

Analysis:
The VMRS data were mined to identify the labor hours incurred for ECBS and ABS maintenance. With the combined parts and labor data, the cost analysis demonstrated that ABS costs less to maintain than ECBS. At $3,958 per million miles, ABS exhibited a cost savings of 10 percent over ECBS's average total costs of $4,368. The largest contributor to the savings was the difference in labor costs. Reviewing the table below, the labor cost for ECBS was found to be almost twice the cost of ABS. Although the parts costs for ECBS is significantly less than ABS, the labor required to maintain the system exceeds the labor costs required for ABS. See Section 7.7 for a more detailed discussion on the hours dedicated to the maintenance of each technology.

Template	Man Hours/ MM	Labor Costs/ MM	Parts Costs/ MM	Total Costs/ MM
ABS w/Disc (T2C2)	92.5	$2,126.45	$1,831.85	$3,958.30
ECBS w/ Disc (Average of T2C3 & T3)	167.4	$3,886.58	$482.31	$4,368.89
ECBS w/Disc (T2C3)	143.5	$3,300.48	$632.79	$3,933.27
ECBS w/Disc (T3)	191.2	$4,471.11	$332.24	$4,803.35

The maintenance surveys indicated only 5 technicians out of 25 performed maintenance on ECBS vehicles. The following comments were received from the technicians on the maintenance requirements for ECBS:

- "More difficult due to lack of exposure."
- "Many defective electronic parts and not enough available replacements, maintenance manuals, or computer programs."

According to the comments from the technicians, ECBS maintenance is currently more difficult than ABS maintenance. It cannot be determined from the comments in the surveys if the difficulty is due to ECBS being a new technology or if it is due to the need for more intensive maintenance practices.

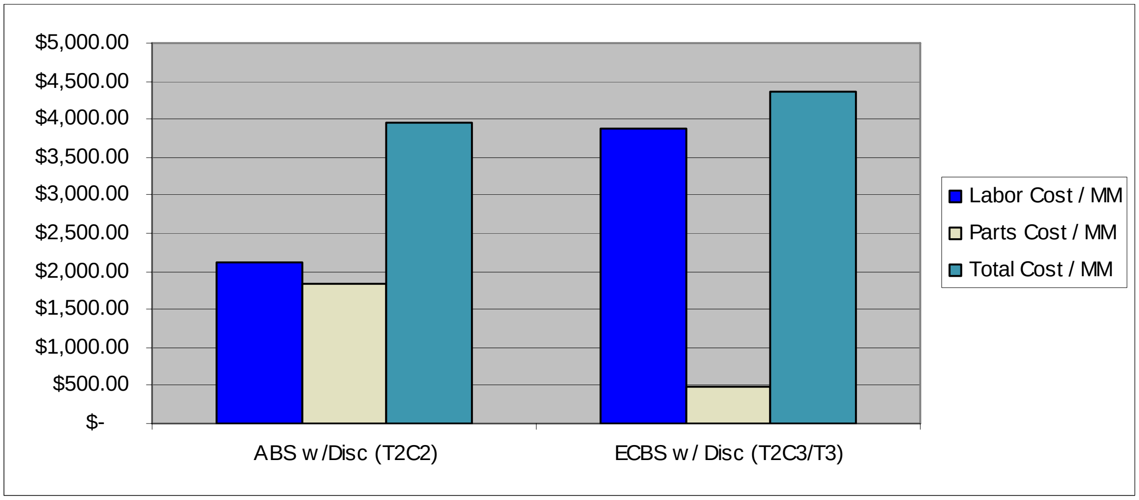
<u>Result</u>:
Based on data gathered in the analysis, ECBS is more complicated to maintain than ABS. The labor hours required for ECBS maintenance was twice the time required for ABS. In addition, the technicians reported more maintenance difficulties for ECBS. Further data may be required to determine if continued maintenance on ECBS will reduce the maintenance difficulty.

Hypothesis 65

<u>Description Statement</u>:
ECBS costs more than ABS to maintain.

<u>Analysis:</u>
The VMRS data were analyzed to identify the labor and parts costs associated with each brake technology. At $3,958 per million miles, ABS exhibited a cost savings of 10 percent over the ECBS average total cost of $4,368. The largest contributor to the savings was the difference in labor costs. Reviewing the chart below, the labor cost for ECBS was found to be almost twice the cost of ABS.

Template	Man Hours/ MM	Labor Costs/ MM	Parts Costs/ MM	Total Costs/ MM
ABS w/Disc (T2C2)	92.5	$2,126.45	$1,831.85	$3,958.30
ECBS w/ Disc (Average of T2C3 & T3)	167.4	$3,886.58	$482.31	$4,368.89
ECBS w/Disc (T2C3)	143.5	$3,300.48	$632.79	$3,933.27
ECBS w/Disc (T3)	191.2	$4,471.11	$332.24	$4,803.35



The introduction of new technologies does not always present a cost savings to the owner. Electronics require significant troubleshooting expertise over basic technology. The time period of the experimental design was not significant enough to demonstrate long-term benefits of ECBS. It could be expected that over time, labor costs for ECBS would decrease as the technicians became more knowledgeable in ECBS failures.

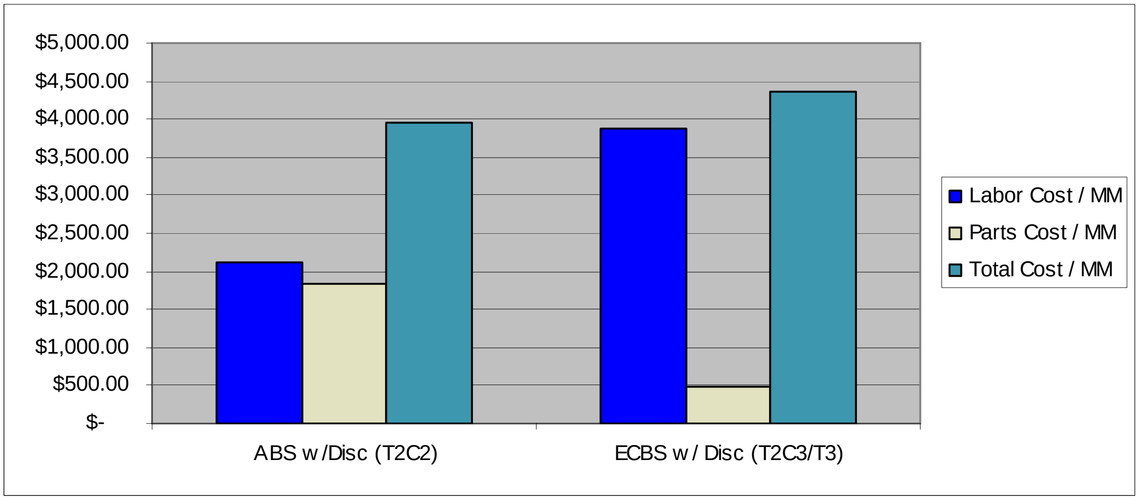
Result:
With the combined parts and labor data, the cost analysis demonstrated that ECBS costs more to maintain than ABS. As the technicians gain experience with ECBS, the findings may change. See Section 7.7 for a more detailed discussion on the costs dedicated to the maintenance of each technology.

Hypothesis 66

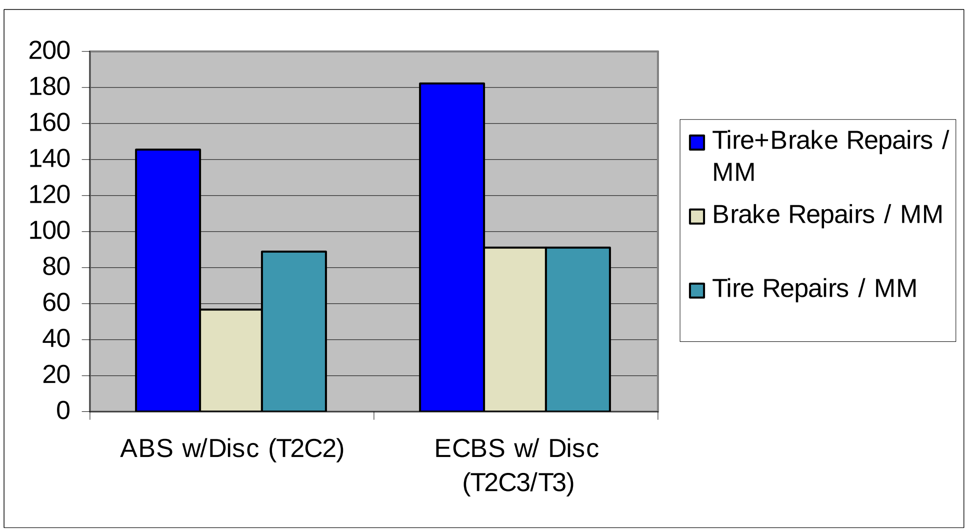
Description Statement:
Parts costs for ECBS are greater than ABS.

Analysis:
The VMRS data were analyzed to identify the parts costs associated with each brake technology. ABS accumulated parts costs of $1,832 per million miles. The cost was approximately 3.5 times the ECBS accumulated parts costs of $482 per million miles.

Template	Man Hours/ MM	Labor Costs/ MM	Parts Costs/ MM	Total Costs/ MM
ABS w/Disc (T2C2)	92.5	$2,126.45	$1,831.85	$3,958.30
ECBS w/ Disc (Average of T2C3 & T3)	167.4	$3,886.58	$482.31	$4,368.89
ECBS w/Disc (T2C3)	143.5	$3,300.48	$632.79	$3,933.27
ECBS w/Disc (T3)	191.2	$4,471.11	$332.24	$4,803.35



To ensure the cost differential was not due to an increased number of maintenance requests, the repair orders generated during the FOT were analyzed. As shown in the chart below, 40 more repair orders per million miles were generated by ECBS. The parts cost per repair for ECBS was $2.74. In comparison, the parts cost per repair for ABS was $30.17. The number of repair orders was not a cause of the increased parts costs for ABS. The ABS parts costs are more expensive than ECBS parts costs.



Result:
The analysis demonstrated that the cost for parts incurred for ABS was almost 3.5 times the parts costs incurred by ECBS. The parts costs for ECBS are not greater than ABS. See Section 7.7 for a more detailed discussion on the costs dedicated to the maintenance of each technology.

Hypothesis 67

Description Statement:
ECBS high-speed connection between tractor and trailer is prone to wear/failure.

Analysis:
The VMRS data and the driver / mechanic surveys were analyzed to identify all cases of loose connections between the tractor and trailer. See Sections 8.1.2 and 8.2.2 for a detailed discussion of drivers and mechanics views on ECBS operation.

Result:
The VMRS data did not contain instances of faults generated due to the ECBS high-speed connection. All connection failures were attributed to other tractor-trailer combinations. The surveys provide subjective data on the ECBS operation. Within the surveys, only a single driver made a note of difficulties with a connector. This failure was not attributed to a particular tractor-trailer combination. As a result of this review, results were inconclusive.

Hypothesis 68

Description Statement:
ECBS reduces tire wear.

Analysis:
Maintenance data were studied to determine the wear rate of tractors tires that had ECBS installed.

Result:
The VMRS data does not include routine maintenance tasks. During the FOT, no measurements of tire tread were compiled. There is no data available to support this analysis.

Hypothesis 69

Description Statement:
Brake pad / shoe lining wear is accelerated when foundation brake technologies are mixed on a tractor-trailer combination.

Analysis:
Foundation brake wear would be studied for those trucks that did not have matched trailers and compared with those trucks with matched trailers. There is insufficient mileage accumulated on matched tractor / trailers to be able to determine any wear pattern. In template 2, less than 1 percent of the mileage was accumulated with matched tractor-trailer combinations.

Result:
Insufficient data were collected on matched tractor-trailers.

Hypothesis 70

Description Statement:
Disc brake tractors coupled to drum brake trailers (or vise versa) will not be unstable during hard braking events.

Analysis:
The analysis was performed under Hypothesis 6. The vehicle stability during braking was addressed for all combinations of brake technologies and compared in aggregate form.

Result:
See Hypothesis 6.

Hypothesis 71

Description Statement:
An ECBS tractor coupled with an ABS trailer results in an oversteering condition in hard-braking events.

Analysis:
The database was analyzed to find events of hard deceleration with ECBS tractor / ABS trailer combination. No events were found that matched the described conditions.

Result:
Unable to determine; no event matched the described condition.

Hypothesis 72

Description Statement:
An ABS tractor with an ECBS trailer results in an understeering condition during hard-braking events.

Analysis:
The database was analyzed to find events of hard deceleration with ABS tractor / ECBS trailer combination. No events were found that matched the described conditions.

Result:
Unable to determine; no event matched the described condition.

Hypothesis 73

Description Statement:
ECBS high-speed data link between a tractor and trailer from different manufacturers is not compatible.

Analysis:
The FOT contained ECBS high-speed data connector from a single vendor; hence, no testing of compatibility between manufacturers could be conducted.

Result:
Unable to determine. Single vendor for connector prevented compatibility testing.

Hypothesis 74

Description Statement:
ECBS tractor coupled with another manufacturer's ECBS trailer results in more frequent occurrence of fault codes.

Analysis:
The FOT contained ECBS brake systems from a single vendor; hence, no testing of compatibility between manufacturers could be conducted.

Result:
Unable to determine. Single vendor for connector prevented compatibility testing.

Hypothesis 75

Description Statement:
An ECBS tractor coupled with another manufacturer's ECBS trailer results in brake activation delays due to incompatible communication link.

Analysis:
The FOT contained ECBS brake systems from a single vendor; hence, no testing of compatibility between manufacturers could be conducted.

Result:
Unable to determine. Single vendor for connector prevented compatibility testing.

Hypothesis 76

Description Statement:
ECBS (MeritorWabco) tractor coupled with an ECBS trailer (Bendix) results in instability issues because of control conflict between the two manufacturers' algorithms.

Analysis:
There were no occurrences of this tractor-trailer combination to analyze. There were 51 electronic stability control (ESC) activations with the MeritorWabco ECBS equipped tractors during Phase 2 of the FOT. Thirty-one of these activations occurred with MeritorWabco ECBS trailers. The other 20 activations occurred connect to existing non-FOT Wal-Mart ABS / drum trailers. No activations occurred when connected to Bendix TEBS4 trailer.

Result:
No data were available to determine any instability issues.

APPENDIX B: SURVEY FORMS

Mechanic

How would you rate your level of confidence or trust in the reliability and maintainability of air disc brakes?
17 Responses - 10 High, 2 Moderate, 4 Neutral, 1 Low (6-Month Survey)
Not enough data.
Less to go wrong and ease of preparation.
Disc brake pads have minimal wear and shorter repair times.
No problems.
Haven't had that much experience with them.
Not enough data.
Faster response time.
Simple system, effective, well thought-out.
Less brake shoe wear.
They work well.
No problems with them.
Proven technology.
Very easy system and do have a little information on air brakes.
Have not had any problems so far.

How would you rate your level of confidence or trust in the reliability and maintainability of air disc brakes?
19 Responses - 13 High, 2 Moderate, 3 Neutral, 1 Low (12-Month Survey)
Disc brakes have been proven on cars.
Few problems with system.
Have not had to do anything with the disc brake systems other than an occasional wheel seal failure.
No problems with the braking system itself.
No enough experience.
No opportunity to work on disc brakes.
No problems.
No problems.
No problems.
They grab a lot better and less brake pad changing.
Very confident, just need an easier way to check pads.
Very good system – long-lasting parts and better performance.
No performance or breakage problems.

Overall, how would you rate the maintenance requirements of air disc brakes compared with S-cam drum brakes?
10 Responses - 7 Less Difficult, 1 Same Difficulty, 2 More Difficult (6-Month Survey)
Easier system.
Less moving parts that need maintenance.
Less parts to replace and even faster total replacement when needed.
Less parts.

Overall, how would you rate the maintenance requirements of air disc brakes compared with S-cam drum brakes?
Less problems.
Redesign tools, as some bolts are hard to remove for adjusting.

Overall, how would you rate the maintenance requirements of air disc brakes compared with S-cam drum brakes?
8 Responses - 6 Less Difficult, 2 More Difficult (12-Month Survey)
Easy to replace and less overall time needed to replace.
It is a little more involved.
More simple, no slacks.
No S-cams to replace.
Very simple – fewer components to have the elements get to. No scams and bushing to constantly replace.

How would you rate your level of confidence or trust in the reliability and maintainability of electronically controlled braking systems (ECBS)?
17 Responses - 5 High, 3 Moderate, 8 Neutral, 1 Low (6-Month Survey)
Driver feedback.
Haven't had to do anything to any of them yet.
Is the future. Go with it.
More control.
No issues have been brought forth so far.
Not enough data.
Not enough data.
Not too many things going wrong.
Very few problems – system works well.
Very little info on system for troubleshooting problems that are coming up.

How would you rate your level of confidence or trust in the reliability and maintainability of electronically controlled braking systems (ECBS)?
20 Responses - 2 High, 3 Moderate, 13 Neutral, 1 Low, 1 Very Low (12-Month Survey)
Lack of doing much with the system.
More components to have problems with.
No diagrams and parts.
No problem.
Quicker response.
Still don't know much about ECBS.
Still has some problems.

Overall, how would you rate the maintenance requirements of electronically controlled braking systems compared with current ABS technology?
16 Responses - 6 More Difficult, 7 Same Difficulty, 3 Less Difficult (6-Month Survey)
A lot I don't understand.
At this time it is more difficult due to lack of exposure.
Explained in earlier question.
Have had no issues yet.
Haven't worked on them.
More complicated system.
More computer experience.
More stuff to go wrong.
No info to troubleshoot.

Overall, how would you rate the maintenance requirements of electronically controlled braking systems compared with current ABS technology?
18 Responses - 8 More Difficult, 6 Same Difficulty, 4 Less Difficult (12-Month Survey)
Because there have been less incidents with the systems.
Have not worked with new ABS much.
Lots of defective electronic parts and not enough available material parts or manuals, computer programs.
No blink code to trailer ABS light.
No blink code to trailer ABS light.
No opportunity to work on them.
Too many computers to communicate together.
Trapping the wiring.

How would you rate your level of confidence or trust in the reliability and maintainability of next-generation ABS?
18 Responses - 8 High, 3 Moderate, 7 Neutral (6-Month Survey)
Don't work on them much.
Good driver feedback.
Great technology, just need more experience working on the system.
Have not seen many problems yet.
I can fix all the normal things on these units but new codes and systems are coming up and don't have enough training on them or computer technology to troubleshoot.
Lack of training from manufacturer.
New technologies.
No problems.
Not enough data sampled.
Not enough data sampled.
Not enough experience with system.
Not much time working on those systems.

How would you rate your level of confidence or trust in the reliability and maintainability of next generation ABS?
20 Responses - 5 High, 4 Moderate, 11 Neutral (12-Month Survey)
Have not had many problems.
Have not worked with the system enough to determine a level of confidence.
Haven't been around during the whole test.
Haven't had any issues with stopping.
I like the disc brakes, but not enough information on electric wiring.
It is a good system if you can incorporate the systems together for easier maintenance.
It seems to be good system.
No opportunity.
No problem.
No problems.
No problems.
System is good, but trailer system seem to be very easy to disconnect (i.e., plugs pull apart easily).
The more parts put in a system, the higher likelihood of problems or failures.

Overall, how would you rate the maintenance requirements of next-generation ABS compared with current ABS technology?
17 Responses - 5 More Difficult, 10 Same Difficulty, 2 Less Difficult (6-Month Survey)
Don't know much on ABS.
Lack of technical info or training provided by vendor.
Many diagnostic steps.
More stuff to deal with.
More technical.
No troubleshooting information; the book we have is just basic stuff with part descriptions.
Not enough experience.
Road hazards.
Seems similar ABS list-code-diagnose problem.

Overall, how would you rate the maintenance requirements of next-generation ABS compared with current ABS technology?
19 Responses - 8 More Difficult, 9 Same Difficulty, 2 Less Difficult (12-Month Survey)
Because of the new safety rules [it is hard] to troubleshoot. Not used to it.
Has more things to go wrong.
There is not that much difference.
Mini-training.
More components to fix.
More components.
No opportunity to work on ABS.
Programs need to be simplified.
Still have wires rubbing through, and moisture gets in system.
The wiring is all over and no seal or diagrams for tracing.
There is more to it and the computer.
We seem to have less documentation and troubleshooting flow charts.

Driver

How would you rate your level of acceptance of air disc brakes?
10 Responses - 8 High, 2 Neutral (6-Month Survey)
Better braking, smoother stop.
Braking power is a lot better than drum brakes.
Disc brakes have proven they are better than drum. All newer vehicles - Plus. Cars have them.
Don't notice anything different.
Ease of operation.
Improved response of vehicle.
Performance.
Run cooler, don't fade.
These brakes have a great feel – less air pressure to stop than drum brakes; a lot faster to activate.
When hooked to disc-brake-equipped trailer, the air disc brakes are very safe and have a good pedal feel to them. Otherwise I feel like a driver who has only been driving for less than a week.

How would you rate your level of acceptance in air disc brakes?
29 Responses - 21 High, 4 Moderate, 4 Neutral (12-Month Survey)
Because they stop better and are safer.
Better braking.
Better braking control.
Better, more consistent braking.
Brakes feel good in any weather condition.
Can tell any difference from drum.
Could tell no difference.
Disc brakes are by far the best brakes I've used. All new cars and pickup trucks come with them. They run much cooler and just plain work better than drum brakes.
Disc brakes give better braking power, but don't work well with trailers without disc brakes and/or ABS. Braking becomes very jerky.
Good stopping no fade.
Great brakes.
Have yet to either overheat or smoke on steel downgrades.
Helped to stop faster.
It had more stopping power.
More effective.
Noticed no difference.
Quicker response.
Run cooler, last longer, better braking.
Stop faster.
They are the best. Driver can tell the difference as soon as one's foot is on the pedal. Hope I never get assigned in a truck that doesn't have disc brakes.
They stop really well.
Vehicle felt like it had a more stable and firm stopping power. Less pedal pressure was required to stop vehicle.
Very easy braking and so-so fade.

How would you rate your level of confidence or trust in air disc brakes?
10 Responses -8 High, 2 Neutral (6-Month Survey)
Because they operate well in mountains, stay cooler, and don't have much brake fade, unlike drum brakes. Air disc brakes do a great job of stopping unit.
Don't fade from use.
I feel that the brakes will activate instantly when applied.
I just trust the air brake system.
Less heat – no brakes froze up.
No problems at this point.
Same.
These brakes have a great feel – less air pressure to stop than drum brakes; a lot faster to activate.
Unable to visually check pads for wear, no idea when brakes are wearing out.

How would you rate your level of confidence or trust in air disc brakes?
29 Responses -23 High, 3 Moderate, 3 Neutral (12-Month Survey)
After a year and a half, I believe in this system.
Better control of vehicle, good safety feature.
Definitely will stop truck and trailer.
Felt they would stop me in "assured clear distance" when I need them.
Had no trouble at all with air disc brakes in winter or mountain driving.
I believe that smoother breaking helps prevent jackknives.
I feel they stop better and are safer.
I have done no hard braking to determine the difference.
I've had 250,000 miles of experience now.
More even braking.
No problems so far. Less grabbing or loss of traction on ice or snow.
No smoke, no fade, better wear.
Same.
Same as above, plus pedal does not get spongy.
Same as above.
See above.
Stop truck fine.
They run cooler and have less mechanical parts.
They last longer and stop better.
They stop well and never seemed to heat up when stopping hard.

During the testing program, have you experienced any issues with hauling a trailer with one of the following technologies:
(6-Month Survey)
(Drum brakes) Drum bakes on some trailers lock up – very touchy.
(Drum brakes) Have trouble getting a feel for how much pedal to use. Brakes will grab and hold, stopping vehicle abruptly at slow speeds.
(Drum brakes) Older trailer without ABS. Brakes too touchy.
(Drum brakes) Some older units don't work well with the new brake system. Some are REALLY sensitive when applying brakes. (They tend to grab.)
(Drum brakes) Yes – with trailers without ABS. The trailer will lock-up or grab first.
(ECBS brakes) Don't know. I have pulled a couple, but don't have a connector on this tractor to use that system.

During the testing program, have you experienced any issues with hauling a trailer with one of the following technologies:
(ECBS brakes) Pig tail for electronic brake is the one on the left side, to passenger side.
(ECBS brakes) TR2, 106128 would cause my ABS light to stay on. Wrote TRL up three times. Last time I hauled it ABS was off. Some other ABS came on but went back off. Seem to be in plug. Need a plug holder to protect female end. I've cleaned it, but it still looks dirty.

During the testing program, have you experienced any issues with hauling a trailer with one of the following technologies:
(12-Month Survey)
(Disc brakes) Response is somewhat delayed.
(Disc brakes)Two of the trailers keep activating the ABS light, shutting down the screen. Only those same two everything works after dropping, the shop says that is impossible.
(Drum brakes) Braking is all at once, very jerky. Can't just ease to a stop. As vehicle begins to slow below five miles per hour, vehicle wants to stop on a dime, instead of easing to stop.
(Drum brakes) Difference in lag time before brakes respond.
(Drum brakes) More pressure applied to slow truck.
(Drum brakes) Older trailer.
(Drum brakes) Older trailers without ABS seem to lock up brakes very easily, especially when empty.
(Drum brakes) Some have a grabbing problem when you first touch brake pedal, mainly when trailer is empty.
(Drum brakes) Some older trailers are a little "sensitive;" their brakes may grab.
(Drum brakes) Sometimes they lock up; it only happened a few times.
(Drum brakes) The older 48 trailers would finally activate after the tractor had the job about done.
(Drum brakes) They seem to get hotter quicker.
(Drum brakes) When you have disc on tractor and drum on trailer. I feel like the tractor is doing all the braking.
(Drum brakes) You had to push harder on the brake pedal and took longer to stop.
(ECBS brakes) Because that is the way you designed it.
(ECBS brakes) Don't know what you want me to explain. Is this a statement or a question? They can be identified by second connector.
(ECBS brakes) I guess that's where we plug the other cord we have from our tractor.
(ECBS brakes) Maybe?
(ECBS brakes) The braking time between the tractor and the truck were not the same.
(ECBS brakes) The computer connector.
(ECBS brakes) The in plug is larger.

Do you operate a tractor equipped with air disc brakes in a different manner than one equipped with drum brakes?
8 Responses - 5 Yes, 3 No (6-Month Survey)
I know disc brakes are a lot better so I make a mental note: you need more room to stop.
I do not have to press very hard on pedal for brakes to respond.
No feel, as far as how much pressure to apply. The disc brakes grab, not gentle.
Lighter feather on the pedal, going downhill.
I feel the difference descending long grades with heavy loads. There is no brake fade.

Do you operate a tractor equipped with air disc brakes in a different manner than one equipped with drum brakes?
28 Responses - 4 Yes, 24 No (12-Month Survey)
Have to apply more pressure to non-disc brakes.
Lighter touch on pedal.
Make a mental note as to whether I have drum brakes.
Pedal performance is better than drum brake.
The only difference is in the way I operate the brake pedal.
You don't have to push the brake pedal as hard.

How would you rate your level of acceptance of ECBS?
5 Responses - 4 High, 1 Neutral (6-Month Survey)
After becoming familiar with the "feel," I have more confidence and actually prefer the performance and response, (to the old style braking system).
Has good points, but needs to work better in all applications of braking (ECBS, ABS, Non-ABS trailers).
I like the quick response.
More responsive to stop.
Work well.

How would you rate your level of acceptance of ECBS?
12 Responses -7 High, 2 Moderate, 2 Neutral, 1 Low (12-Month Survey)
Because they stop the truck more efficiently than air bakes.
Because when we have problems with the system, there is nobody in our shop that knows enough about it to do any good. I had problems for a long time and nobody knew enough about it to help.
Better stopping – more control on hills.
Had a blowout on LF steer/ half of load of pallets on truck. Was able to maintain control of unit and not lay it over.
I like the "feel;" very responsive.
I should be in control of my vehicle and stay focused at all times and not let electronics do my job.
Made the truck more stable under hard braking also the brakes reacted quicker to the brake pedal especially when pulling a trailer equipped with ECBS.
Never noticed any increased control.
Stops well.
The smoothness of it that brings the trailer back on track rather than hitting all the brakes was outstanding.
Very hard to get fixed.
When working, it is a very good system. But difference in pedal is felt too much when not working.

How would you rate your level of confidence or trust in ECBS?
5 Responses - 4 High, 1 Low (6-Month Survey)
Because it is new technology.
Cannot get a sense of how the brakes are going to work. Sometimes it takes more pressure on pedal. Most often the slightest application relays clicks and the vehicle jerks to stop. Brakes are either applied or not, no easing on or off.
Haven't had failure in the system.
Systems work well in all weather conditions.

How would you rate your level of confidence or trust in ECBS?
12 Responses -7 High, 2 Moderate, 2 Neutral, 1 Low (12-Month Survey)
Because of the problems I've had.
Better control in braking. Better tracking in hard braking.
Good system.
Hope it will work properly.
I feel it stops the tractor-trailer better and I feel safer.
It failed once during the test, but the warning light came on before the failure and the truck's brakes still worked (the transmitter failed).
It's electronic and can fail.
My run has several inside curves, could feel truck maintaining stability (braking).
No fade.
No problems.
Same as above, but it performed as well as older systems.
The brakes work when I press the pedal!

If the ECBS warning light came ON, did you notice a change in the operation of the brakes?
3 Responses - 1 Yes, 2 No (6-Month Survey)
Brake pedal was very stiff and had to be pushed almost to the floor to activate brakes, and then made brakes on trailer lock up.

If the ECBS warning light came ON, did you notice a change in the operation of the brakes?
8 Responses - 4 Yes, 4 No (12-Month Survey)
Because most of the trailers I pulled at that time were non-program trailers.
Brake pedal had to be pushed almost all the way to floor, before activating. Rather than just barely touching.
Had to push the brake pedal harder to stop the truck. When you push the brake pedal slower there is no braking action, then all at once the brakes would grab.
Nothing got done.
They were not sensitive to pedal pressure at all but came on suddenly stopping very hard.
Took a littler longer to grab hold properly – maybe three seconds difference.

Have you had any difficulties connecting the communication link (wire harness) between an ECBS tractor and an ECBS trailer?
9 Responses - 4 Yes, 5 No (12-Month Survey)
During freezing conditions.
Not hooked up on 4-1882 on back of cab.
Some trailers turn on ABS light.
The truck was taken off the test program and no ECBS-equipped trailers were pulled in the last year.
When hooked to trailer comm. Link would set off ABS light, and shut down ACC.
When the rollers on the plug in lock get dirty, it is hard to lock.

How would you rate your level of acceptance of adaptive cruise control (ACC)?
24 Responses - 11 High, 7 Moderate, 2 Neutral, 2 Low, 2 Very Low (12-Month Survey)
ACC worked approximately one tenth of the time (maybe even less). It's a total JOKE that a 6817 technician was not trained to work on this. I've been told to "not" write it up. Nobody can work on it. WABCO will be here in a couple of weeks.
Always kept unit a safe distance from vehicle ahead.
Because I felt safer, I could trust the system to keep a constant distance to vehicle ahead.
Do not work, can't get it fixed.
When passing bigger or oversize equipment, system shuts down. Going around minor or major curves, system shuts down.
Good idea but needs some refinement – over-responsive and unreliable. Why weren't we asked for feedback during test so adjustments could have been tried?
Has some issues that need to be worked out.
Helps to maintain a better distance from vehicle in front.
I don't like a machine thinking for me.
It keeps the following distance at five seconds and slows you down, sometimes before you realize the vehicle ahead is moving significantly more slowly than you are.
I've used it off and on, but I would rather maintain my own space depending on condition.
Keeps safe distance.
Keeps you aware of what is going on in front of you.
Love it.
On two separate occasions, it warned me of something I did not see (potential disaster).
Overall very good system. Would buy a truck equipped with system in future.
Tells how fast vehicle in front of me is going and how many feet they are away, for me to adjust to traffic flow or conditions.
The buzzer is very annoying. It goes off steadily during rush hour traffic. It is TOO LOUD and may cause hearing loss.
The radar picks up vehicles that are turning out/away from my direction of travel; it will then beep very loudly just before I pass by. This usually makes me flinch.
The system activates in enough time to slow the vehicle, which feels safe; however, one could become too dependent on it.
Tracking system is very good. Better than conventional system. Problem in passing most overrides to get close to pass.
Truck surges too much, not smooth.
When a vehicle turns or is slowing down to get off freeway, the slight angle of vehicle is sensed as an obstruction. At this time the brakes are engaged.
When in traffic you can keep a buffer zone.
Works great in low traffic areas. In heavy traffic areas it is a waste of time to use ACC.
Wrote it up to get fixed; did not get; did not work.

How would you rate your level of confidence in adaptive cruise control (ACC)?
26 Responses - 10 High, 6 Moderate, 4 Neutral, 2 Low, 4 Very Low (12-Month Survey)
Do not need a machine to tell me when a crash is going to happen.
Great when it works.
I prefer to be in control of my vehicle.
It would warn me even when I was aware it was there.
It always worked.

How would you rate your level of confidence in adaptive cruise control (ACC)?
It's a JOKE. But I am confident and I do trust it will never get fixed. (Oh I forgot, WABCO will be here to fix it.)
It's electronic and can fail. The best thing about the ACC is the system will give me 65 miles per hour. On the other cruise it only gives you 63.7 miles per hour.
Keeps me alert.
Once or twice driving along next to a railroad track the ACC would shut off.
Radar unit set too close. Speed on pedal and ACC don't match.
Radar was inconsistent; sometimes would not detect vehicle until it was closer than set limit. Sometimes would keep losing then detecting vehicle which would cause radical slowing and acceleration. Sometimes would allow truck to get too close to vehicle
Reactions by ACC are inconsistent.
Same answers as previous.
Same as above.
Shuts itself off at odd times. Alarm goes off all the time.
So far, so good.
System overall is very good. Has few bugs. System continues to "see" vehicle in front after vehicle has left area and set off CWS.
The ability to keep a safe following distance.
Very good system.
Works great but can cause problems.
Works great.
Works without failure of any kind.

Do you feel that ACC assists in reducing driver fatigue?
25 Responses - 10 Yes, 15 No (12-Month Survey)
Any CC causes less fatigue.
At night it picks up unlit objects before you can react to them after the headlights illuminate them. As stated in question 20.
Both daytime and night – Picks up side objects.
Cruise control helps with fuel mileage and is great on the open highway, but there is always the possibility of fatigue. In our territory the system is good but back east I would hardly use the system due to traffic.
Driver becomes too comfortable with system and can get lazy. Driver may not be as alert as needed.
Easier to drive.
Fatigue is fatigue. I think that ACC may give a tired driver a false sense of security.
Gives you advance warning of what’s happening in front of you.
I think a driver should not be complacent even with this device.
If driver is that tired, he should park.
It gives added security but does not replace level of concentration.
It is too annoying to use.
It wore me out trying to get it to work. Example: Hey it's working. Now it's not. It's working, now it's not. Working, not, working, not (see what I mean).
Nobody should be using it for that purpose.
Proper rest - not electronics!
Same as above.
Slower vehicle is picked up and truck matches that speed.
The screen is a distraction. The screen and buzzer are aggravating and contribute to driver fatigue.
The system can pick something up that you may not see.
There is less fatigue because I am not as stressed. I know ACC assist is going to maintain a safe distance.

Compared to conventional cruise control, would you say you like ACC:
26 Responses - 15 Better, 5 Same, 6 Less (12-Month Survey)
ACC picks up object ahead. Corner turn keeps unit safe.
ACC remains alert while driver may not be.
As stated above.
As stated in questions 20 and 22.
Glitches not withstanding, system is very nice to use and will be a help in future. Very nice when in heavy traffic, except truck needs to be an automatic.
If every vehicle had this you wouldn't see tailgating, or if you wanted to make a pass, you would know that there is a space to pass back info.
If I don't correct, it will warn me to for better safety.
If someone pulls in front of you the system works faster than you can react.
If you're paying attention it really doesn't make any difference.
It cannot make decisions as well as I can.
It didn't work long enough for me to compare. P.S. - It might appear to whomever reads this that I am agitated with ACC. I am not. I am agitated with the person or persons who should have fixed it.
It had the potential to be better, but mine wasn't set properly. It wouldn't run 65 miles per hour so I was limited to how much I could use the cruise.
It shows the speed of the vehicle you are approaching and the distance between vehicles.
Keeps safe distance.
Maintains proper distance by itself.
Not much difference between the two.
Radar is good, IF it works.
Same as 15 & 16.
Same as above.
See #15 (truck surges too much, not smooth).
The added control is a benefit; regular cruise is less of a tool.
The problem is when you apply brakes your jake brake isn't activated on the ACC. At night, I like my jake to be on in case of deer.

Did you notice the roll stability control operating during the test period? When did it primarily operate?
27 Responses - 15 Yes, 12 No (12-Month Survey)
Cut fuel. Brake hard to handle.
In curves, in mountains when cruise was on.
In the mountains and on curves.
Only I-84 near Lime, OR; not sure if it was about to keel over or if it was the neck hitting the cement center loader.
When going around curves.
When it should have, on curves with a heavy load.

Do you operate a tractor with equipped stability control in a different manner than a tractor not equipped with stability control?
26 Responses - 5 Yes, 21 No (12-Month Survey)
Conventional brake system you need to pay attention to curves.
Cut off fuel as roll started and beep.
Does not take as much pressure on the brake pedal.
I take it a little easier on brake pedal, ECBS grabs.

Do you operate a tractor with equipped stability control in a different manner than a tractor not equipped with stability control?
I went into the curve faster than normal to see how it would function.
Tractors with out ECBS brake slower and harder.

APPENDIX C: DATA CHANNEL GLOSSARY

Template 2 Tractor Data Channels

TEMPLATE 2 TRACTOR DATA CHANNEL REQUIREMENTS									
FIELD NAME	DATA NAME	UNITS	SOURCE	CVS COLUMN POSITION	SAMPLE TYPE	SAMPLE RATE (Hz)[1]	DATA FIELD TYPE	FIELD SIZE (byte)	BYTE / HOUR
TractorVIN	Tractor ID	string	SAE J1708 Bus		By Blob	10	char(17)	17	612,000
TripID	Trip ID	Numeric	Wal-Mart Records		By Blob	10	tinyint	1	36,000
DriverID	Driver ID	Numeric	Wal-Mart Records		By Blob	10	tinyint	1	36,000
DTStamp	Absolute Tractor Time	h-min-s	DAS Clock		Continuous	10	datetime	8	288,000
DEBLOBFILENAME	Deblobbed File Name	string	DAS		By Blob	10	char(40)	40	1,440,000
GPS Data									
GPSLONG	Tractor Longitude	deg	GPS Receiver		Continuous	10	real	4	144,000
GPSLAT	Tractor Latitude	deg	GPS Receiver		Continuous	10	real	4	144,000
GPSALT	Tractor Alititude	ft	GPS Receiver		Continuous	10	real	4	144,000
GPSHEADING	Tractor Heading	deg	GPS Receiver		Continuous	10	real	4	144,000
Vehicle Data									
ODO	Odometer	miles	SAE J1939 Bus		Continuous	10	real	4	144000
SAP	Suspension Airbag Pressure	psi	External Sensor		Continuous	10	real	4	144000
APP	Accelerator Pedal Position	%	SAE J1939 Bus		Continuous	10	real	4	144000
ES	Engine Speed	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
ET	Engine Torque	ft-lb	SAE J1939 Bus		Continuous	10	real	4	144000
VS	Vehicle Speed	ft/s	SAE J1939 Bus		Continuous	10	real	4	144000
SA	Steering Angle	deg	External Sensor		Continuous	10	real	4	144000
AMBTEMP	Ambient Temperature	deg F	External Sensor		Continuous	10	real	4	144000
CA	Clutch Activation	0-1	SAE J1939 Bus		Continuous	10	real	4	144000
	~~Gear~~	~~Numeric~~	~~SAE J1939 Bus~~		Continuous	10	~~tinyint~~	~~1~~	~~36000~~
EBA	Engine Brake Activation	0-1	SAE J1939 Bus		Continuous	10	bit	1/8	4500
EBP	Engine Brake Percentage	%	SAE J1939 Bus		Continuous	10	real	4	144000
CCNTRLA	Cruise Control Activation	0-1	SAE J1939 Bus		Continuous	10	bit	1/8	4500
WWA	Windshield Wiper Activation	0-1	External Sensor		Continuous	10	bit	1/8	4500
CGS	Compressor Governor Signal	0-1	External Sensor		Continuous	10	bit	1/8	4500
HLLOW	Headlights Low Activation	0-1	External Sensor		Continuous	10	bit	1/8	4500
HLHIGH	Headlights High Activation	0-1	External Sensor		Continuous	10	bit	1/8	4500
TSRIGHT	Turn Signal Right Activation	0-1	External Sensor		Continuous	10	bit	1/8	4500
TSLEFT	Turn Signal Left Activation	0-1	External Sensor		Continuous	10	bit	1/8	4500
HZ	Hazard Light Activation	0-1	External Sensor		Continuous	10	bit	1/8	4500
Foundation Brake Data									
BA	Brake Activiation	0-1	SAE J1939 Bus		Transition	10	bit	1/8	4500
BPP	Brake Pedal Position	%	SAE J1939 Bus		Continuous	10	real	4	144000
TCAP	Tractor Control Air Pressure	psi	SAE J1939 Bus		Continuous	10	real	4	144000
TRLCAP	Trailer Control Air Pressure	psi	SAE J1939 Bus		Continuous	10	real	4	144000
LFSCP	LFS Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
RFSCP	RFS Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
LFDCP	LFD Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
RFDCP	RFD Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
LRDCP	LRD Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
RRDCP	RRD Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
MFAWSS	Mean Front Axle J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
LFSWSS	LFS J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
RFSWSS	RFS J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
LDFWSS	LFD J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
RFDWSS	RFD J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
LRDWSS	LRD J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000

Template 2 Tractor Data Channels (continued)

FIELD NAME	DATA NAME	UNITS	SOURCE	CVS COLUMN POSITION	SAMPLE TYPE	SAMPLE RATE (Hz)[1]	DATA FIELD TYPE	FIELD SIZE (byte)	BYTE / HOUR
ABS / ECBS Data									
ABSA	Tractor ABS Activation	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
TRLABSA	Trailer ABS Activation	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
ATCECA	ATC Engine Control Activation	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
ATCBCA	ATC Brake Control Activation	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
YCECA	Yaw Control Engine Control Activation	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
YCBCA	Yaw Control Brake Control Activation	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
RCECA	Roll Control Engine Control Activation	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
RCBCA	Roll Control Brake Control Activation	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
AWS	Amber Warning Light Status	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
RWS	Red Warning Light Status	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
TWS	Trailer Warning Light Status	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
ABSF	ABS Fault	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
VDCF	Vehicle Dynamic Control Fault	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
Accelerometer Data									
ACCELLONG	Longitudinal Acceleration (tractor)	ft/s^2	Internal Sensor		Continuous	10	real	4	144000
ACCELLAT	Lateral Acceleration (tractor)	ft/s^2	Internal Sensor		Continuous	10	real	4	144000
YAW	Yaw Rate (tractor)	deg/s	External Sensor		Continuous	10	real	4	144000
Forward Radar / ACC Data									
ACCTR	Target Range	ft	ACC System		Continuous	10	real	4	144,000
ACCTRR	Target Range Rate	ft/s	ACC System		Continuous	10	real	4	144,000
ACCTA	Target Azimuth	deg	ACC System		Continuous	10	real	4	144,000
ACCTDETECT	Target Detected	0-1	SAE J1939 Bus		Continuous	10	bit	1/8	4,500
Raw Messages									
MSGERC1	Message: Electronic Retarder Control 1	string	SAE J1939 Bus		Continuous	10	char(16)	16	576,000
MSGEBC1	Message: Electronic Brake Control 1	string	SAE J1939 Bus		Continuous	10	char(16)	16	576,000
MSGVDC1	Message: Vehicle Dynamic Control 1	string	SAE J1939 Bus		Continuous	10	char(16)	16	576,000
MSGXBR1	Message: External Brake Request 1	string	SAE J1939 Bus		Continuous	10	char(16)	16	576,000
MSGDIAGNOSTIC	Message: Diagnostic from Battelle	string	SAE J1939 Bus		Continuous	10	char(16)	16	576,000
MSGBRAKES	Message: Brakes	string	SAE J1939 Bus		Continuous	10	char(16)	16	576,000
	TOTALS							215 B	7.38 MB

Template 2 Trailer Data Channels

TEMPLATE 2 TRAILER DATA CHANNEL REQUIREMENTS									
FIELD NAME	DATA NAME	UNITS	SOURCE	CVS COLUMN POSITION	SAMPLE TYPE	SAMPLE RATE (Hz)[1]	DATA FIELD TYPE	FIELD SIZE (byte)	BYTE / HOUR
TrailerVIN	Trailer ID	string	SAE J1708 Bus		By Blob	10	char(17)	17	612,000
TripID	Trip ID	Numeric	Wal-Mart Records		By Blob	10	tinyint	1	36,000
DriverID	Driver ID	Numeric	Wal-Mart Records		By Blob	10	tinyint	1	36,000
DTStamp	Absolute Trailer Time	h-min-s	DAS Clock		Continuous	10	datetime	8	288,000
DEBLOBFILENAME	Deblobbed File Name	string	DAS		By Blob	10	char(40)	40	1,440,000
GPS Data									
GPSLONG	Trailer Longitude	deg	GPS Receiver		Continuous	10	real	4	144,000
GPSLAT	Trailer Latitude	deg	GPS Receiver		Continuous	10	real	4	144,000
GPSALT	Trailer Alititude	ft	GPS Receiver		Continuous	10	real	4	144,000
GPSHEADING	Trailer Heading	deg	GPS Receiver		Continuous	10	real	4	144,000
Vehicle Data									
SAP	Suspension Airbag Pressure	psi	External Sensor		Continuous	10	real	4	144000
Foundation Brake Data									
TRLCAP	Trailer Control Air Pressure	psi	SAE J1939 Bus		Continuous	10	real	4	144000
AP	Application Pressure	psi	SAE J1939 Bus		Continuous	10	real	4	144000
LFTCP	LFT Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
RFTCP	RFT Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
LRTCP	LRT Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
RRTCP	RRT Chamber Pressure	psi	External Sensor		Continuous	10	real	4	144000
LFTWSS	LFT J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
RFTWSS	RFT J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
LRTWSS	LRT J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
RRTWSS	RRT J1939 Wheel Speed Signal	rpm	SAE J1939 Bus		Continuous	10	real	4	144000
ABS / ECBS Data									
ABSA	ABS Active	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
ABSF	ABS Fault	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
RCBCA	RSS/TRSP Brake Control Active	0-1	ABS/ECBS System		Continuous	10	bit	1/8	4500
Accelerometer Data									
ACCELLONG	Longitudinal Acceleration (trailer)	ft/s^2	Internal Sensor		Continuous	10	real	4	144000
ACCELLAT	Lateral Acceleration (trailer)	ft/s^2	Internal Sensor		Continuous	10	real	4	144000
YAW	Yaw Rate (trailer)	deg/s	External Sensor		Continuous	10	real	4	144000
Forward Radar / ACC Data									
TOTALS								72 B	2.48 MB

Template 3 Tractor Data Channels

TEMPLATE 3 (ECBS/Disc)- TRACTOR DATA SET								
FIELD NAME	DATA NAME	UNITS	SOURCE	SAMPLE TYPE	SAMPLE RATE (Hz)[1]	DATA FIELD TYPE	FIELD SIZE (byte)	BYTE / HOUR
TractorVIN	Tractor ID	string	SAE J1708 Bus	By Blob	10	char(17)	17	612,000
TripID	Trip ID	Numeric	Wal-Mart Records	By Blob	10	tinyint	1	36,000
DriverID	Driver ID	Numeric	Wal-Mart Records	By Blob	10	tinyint	1	36,000
DTStamp	Absolute Tractor Time	h-min-s	DAS Clock	Continuous	10	datetime	8	288,000
DEBLOBFILENAME	Deblobbed File Name	string	DAS	By Blob	10	char(40)	40	1,440,000
	GPS Data							
GPSLONG	Tractor Longitude	deg	GPS Receiver	Continuous	10	real	4	144,000
GPSLAT	Tractor Latitude	deg	GPS Receiver	Continuous	10	real	4	144,000
GPSALT	Tractor Alititude	ft	GPS Receiver	Continuous	10	real	4	144,000
GPSHEADING	Tractor Heading	deg	GPS Receiver	Continuous	10	real	4	144,000
	Vehicle Data							
ODO	Odometer	miles	SAE J1939 Bus	Continuous	10	real	4	144,000
TSAP	Tractor Suspension Airbag Pressure	psi	External Sensor	Continuous	10	real	4	144,000
TRLSAP	Trailer Suspension Airbag Pressure	psi	External Sensor	Continuous	10	real	4	144,000
APP	Accelerator Pedal Position	%	SAE J1939 Bus	Continuous	10	real	4	144,000
ES	Engine Speed	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
ET	Engine Torque	ft-lb	SAE J1939 Bus	Continuous	10	real	4	144,000
VS	Vehicle Speed	ft/s	SAE J1939 Bus	Continuous	10	real	4	144,000
SA	Steering Angle	deg	External Sensor	Continuous	10	real	4	144,000
AMBTEMP	Ambient Temperature	deg F	External Sensor	Continuous	10	real	4	144,000
CA	Clutch Activation	0-1	SAE J1939 Bus	Continuous	10	real	4	144,000
EBA	Engine Brake Activation	0-1	SAE J1939 Bus	Continuous	10	bit	1/8	4,500
EBP	Engine Brake Percentage	%	SAE J1939 Bus	Continuous	10	real	4	144,000
CCNTRLA	Cruise Control Activation	0-1	SAE J1939 Bus	Continuous	10	bit	1/8	4,500
WWA	Windshield Wiper Activation	0-1	External Sensor	Continuous	10	bit	1/8	4,500
CGS	Compressor Governor Signal	0-1	External Sensor	Continuous	10	bit	1/8	4,500
HLLOW	Headlights Low Activation	0-1	External Sensor	Continuous	10	bit	1/8	4,500
HLHIGH	Headlights High Activation	0-1	External Sensor	Continuous	10	bit	1/8	4,500
TSRIGHT	Turn Signal Right Activation	0-1	External Sensor	Continuous	10	bit	1/8	4,500
TSLEFT	Turn Signal Left Activation	0-1	External Sensor	Continuous	10	bit	1/8	4,500
HZ	Hazard Light Activation	0-1	External Sensor	Continuous	10	bit	1/8	4,500
	Foundation Brake Data							
BA	Brake Activiation	0-1	SAE J1939 Bus	Transition	10	bit	1/8	4,500
BPP	Brake Pedal Position	%	SAE J1939 Bus	Continuous	10	real	4	144,000
AP	Application Pressure	psi	SAE J1939 Bus	Continuous	10	real	4	144,000
TCAP	Tractor Control Air Pressure	psi	SAE J1939 Bus	Continuous	10	real	4	144,000
TRLCAP	Trailer Control Air Pressure	psi	SAE J1939 Bus	Continuous	10	real	4	144,000
LFSCP	LFS Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
RFSCP	RFS Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
LFDCP	LFD Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
RFDCP	RFD Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
LRDCP	LRD Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
RRDCP	RRD Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
LFTCP	LFT Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
RFTCP	RFT Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
LRTCP	LRT Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
RRTCP	RRT Chamber Pressure	psi	External Sensor	Continuous	10	real	4	144,000
MFAWSS	Mean Front Axle J1939 Wheel Speed Sig.	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
LFSWSS	LFS J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
RFSWSS	RFS J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
LDFWSS	LFD J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
RFDWSS	RFD J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
LRDWSS	LRD J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
RRDWSS	RRD J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
LFTWSS	LFT J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
RFTWSS	RFT J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
LRTWSS	LRT J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
RRTWSS	RRT J1939 Wheel Speed Signal	rpm	SAE J1939 Bus	Continuous	10	real	4	144,000
	ECBS Data							
ABSA	Tractor ABS Activation	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
TRLABSA	Trailer ABS Activation	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
ATCECA	ATC Engine Control Activation	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
ATCBCA	ATC Brake Control Activation	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
YCECA	Yaw Control Engine Control Activation	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
YCBCA	Yaw Control Brake Control Activation	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
RCECA	Roll Control Engine Control Activation	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
RCBCA	Roll Control Brake Control Activation	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
AWS	Amber Warning Light Status	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
RWS	Red Warning Light Status	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500
TWS	Trailer Warning Light Status	0-1	ABS/ECBS System	Continuous	10	bit	1/8	4,500

Template 3 Profiling Tractor Data Channels

TEMPLATE 3 PROFILING TRACTOR DATA CHANNEL REQUIREMENTS									
FIELD NAME	DATA NAME	UNITS	SOURCE	CVS COLUMN POSITION	SAMPLE TYPE	SAMPLE RATE (Hz)[1]	DATA FIELD TYPE	FIELD SIZE (byte)	BYTE / HOUR
TractorVIN	Tractor ID	string	SAE J1708 Bus	HEADER	By Blob	10	char(17)	17	612,000
TripID	Trip ID	Numeric	Wal-Mart Records		By Blob	10	tinyint	1	36,000
DriverID	Driver ID	Numeric	Wal-Mart Records		By Blob	10	tinyint	1	36,000
DTStamp	Absolute Tractor Time	h-min-s	DAS Clock	HEADER, [1], [2]	Continuous	10	datetime	8	288,000
DEBLOBFILENAME	Deblobbed File Name	string	DAS	HEADER	By Blob	10	char(40)	40	1,440,000
GPS Data									
GPSLONG	Tractor Longitude	deg	GPS Receiver	[6]	Continuous	10	real	4	144,000
GPSLAT	Tractor Latitude	deg	GPS Receiver	[5]	Continuous	10	real	4	144,000
GPSALT	Tractor Alititude	ft	GPS Receiver	[7]	Continuous	10	real	4	144,000
GPSHEADING	Tractor Heading	deg	GPS Receiver	[4]	Continuous	10	real	4	144,000
Vehicle Data									
ODO	Odometer	miles	SAE J1939 Bus	HEADER, [14]	Continuous	10	real	4	144,000
APP	Accelerator Pedal Position	%	SAE J1939 Bus	[16]	Continuous	10	real	4	144,000
ES	Engine Speed	rpm	SAE J1939 Bus	[22]	Continuous	10	real	4	144,000
ET	Engine Torque	ft-lb	SAE J1939 Bus	[16]	Continuous	10	real	4	144,000
EL	Engine Load	%	SAE J1939 Bus	[15]	Continuous	10	real	4	144,000
VS	Vehicle Speed	ft/s	SAE J1939 Bus	[14]	Continuous	10	real	4	144,000
	~~Gear~~	~~Numeric~~	~~SAE J1939 Bus~~						
EBA	Engine Brake Activation	0-1	SAE J1939 Bus	[18]	Continuous	10	bit	1/8	4,500
EBP	Engine Brake Percentage	%	SAE J1939 Bus	[20]	Continuous	10	real	4	144,000
CCS	Cruise Control Status	0-1	SAE J1939 Bus	[19]	Continuous	10	bit	1/8	4,500
AMBTEMP	Ambient Temperature	Deg F	SAE J1939 Bus	[21]	Continuous	10	real	4	144,000
Foundation Brake Data									
BA	Brake Activiation	0-1	SAE J1939 Bus	[13]	Transition	10	bit	1/8	4,500
~~BPP~~	~~Brake Pedal~~	~~%~~	~~SAE J1939 Bus~~						
PBA	Parking Brake Activation	0-1	SAE J1939 Bus	[11]	Continuous	10	bit	1/8	4,500
ABS / ECBS Data									
ABSA	Driver Interface Data (ABS Active)	0-1	ABS/ECBS System	[28]	Continuous	10	bit	1/8	4,500
ABSF	Driver Interface Data (ABS Fault)	0-1	ABS/ECBS System	[28]	Continuous	10	bit	1/8	4,500
ABSRC	ABS Retarder Control	0-1	ABS/ECBS System	[28]	Continuous	10	bit	1/8	4,500
	~~ABS Fault Codes (tractor)~~		~~ABS/ECBS System~~						
Accelerometer Data									
ACCELLONG	Longitudinal Acceleration (tractor)	ft/s^2	Internal Sensor	[8]	Continuous	10	real	4	144,000
ACCELLAT	Lateral Acceleration (tractor)	ft/s^2	Internal Sensor	[9]	Continuous	10	real	4	144,000
YAW	Yaw Rate (tractor)	deg/s	Internal Sensor	[10]	Continuous	10	real	4	144,000
Forward Radar / ACC Data									
ACCTR	Target Range	ft	ACC System	[24]	Continuous	10	real	4	144,000
ACCTRR	Target Range Rate	ft/s	ACC System	[25], [14]	Continuous	10	real	4	144,000
ACCTA	Target Azimuth	deg	ACC System	[26]	Continuous	10	real	4	144,000
ACCTDETECT	Target Detected	0-1	SAE J1939 Bus	[27]	Continuous	10	bit	1/8	4,500
TOTALS								140 B	4.80 MB

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